

IMC 2022 Conference Papers

Table of Contents

SESSION 1 - Naval Ship Seaworthiness 05

The design and development of a sovereign and contemporary naval classification framework for Australia 06

Achieving lifecycle seaworthiness on the Hobart-class guided missile destroyer (DDG) through reliability centred maintenance analysis and probabilistic risk assessment 22

SESSION 2 - Nuclear Engineering 35

Nuclear propulsion is a game changer. What are the new rules? 36

New capability, new problems, new thinking 47

A training pipeline for nuclear submarine crews 63

SESSION 3 - Naval Ship Technology 73

High-Temperature superconductors: technologies and solutions for naval applications *Refereed* 74

Naval platform design considerations for meeting increased hotel load demand 91

Naval platform survivability analysis for mission capability resilience 106

Novel penetration equipment to optimise naval indirect firefighting attack efficacy by means of simplifying systems and training 120

SESSION 4 - Commercial Ships 134

Maritime cyber safety - results of real-world application on ship systems 135

Influence of water depth on roll natural period and damping coefficient of large commercial ships in shallow water regions 145

Digitally enabled smart port and ship ecosystems and synthetic training using the new IHO S-100 framework model 160

The environmental and economic assessment of using liquefied natural gas as a fuel onboard bulk carrier ships 171

SESSION 5 - Autonomous Vessels 188

Accelerating maritime trusted autonomous systems 189

Introducing Autonomous Systems into Tropical Marine Operations - a Case Study into AIMS Journey 201

Australian defence opportunities for un-crewed vessels 211

SESSION 6 - Ship Design 224

Development of virtual ship-helicopter operational limits for a replenishment type ship 225

Current developments of wind turbine installation vessels 235

Development of Nauti-craft's 3rd generation deck pitch and roll control system 245

Fast generation of highly representative 3D models of large maritime platforms 260

SESSION 7 - Naval Ship Technology 273

Macro trends in propulsion system selection for warships to facilitate maritime carbon emissions reduction from an engine builder's perspective 274

A cost-effective approach to extending the life of naval surface platforms
Refereed 286

Digital twin for naval platform operations
Refereed 297

Real-time digital-twin for naval platform through-life support and life-cycle risk reduction 312

SESSION 8 - Autonomous Vessels 324

An Australian code of practice for autonomous and remotely operated vessels
Refereed 325

An enabling framework to support COLREGS compliance for autonomous and remotely operated vessels 341

Technological readiness of XLUUV autonomy for effective anti-submarine warfare operations 356

Mission and situation awareness autonomy delivered through Artificial Intelligence and Machine Learning 366

Session 9 - Digital Twins (Panel Session)

SESSION 10 - Environment 373

The role of alternative fuels, electrification, and energy storage in achieving net zero
No paper provided

A zero-carbon framework for shipping 375

The pathway leading to carbon free shipping
Refereed
Paper only - No presentation 410

SESSION 11 - Ship Design 425

Naval architecture at UNSW Canberra 426

Maritime industry research past, present and future - Collaborations between academia and industry 439

Nav archs (you gotta) fight for your right (to margins)! 448

Development of an Australian sovereign shock testing and assurance capability 463

SESSION 12 - Submarine Hydrodynamics 475

Hydrodynamic issues associated with out-of-plane loads on the turning of a submerged submarine
Refereed 476

Captive model experiments to determine the hydrodynamic loads for a submarine operating near the free surface
Refereed 486

Manoeuvring performance of a submarine with different sail designs 498

Enhancing the propulsive performance of a ducted propeller for a full scale BB2 underwater vehicle
Refereed 509

SESSION 13 - Shipbuilding **525**

Production optimisation through a direct connection between project data and the workshop
Refereed **526**

SESSION 14 - Submarine Hydrodynamics **539**

Near free surface behaviour of a submarine
Refereed **540**

Promoting submarine stealthy by reducing submarine mast hydrodynamics
Refereed **551**

Wakes of surface-piercing cylinders
Refereed **559**

SESSION 15 - Submarine Technology **569**

Multi-phase brushless DC propulsion motors: dynamic modelling for platform integration studies **570**

The sustainable submarine **581**

Defence-industry collaboration for Australian collapse testing project **586**

An end to submarine corrosion issues
Paper only - No presentation **601**

SESSION 16 - Autonomous Vessels **628**

Comparison of acceleration prediction methods for an underwater vehicle
Refereed **629**

Underwater networks connecting Robotic Autonomous Systems (RAS) **642**

Persistent autonomous data gathering and monitoring - a future vision
for autonomous ocean observations
No paper provided **657**

SESSION 17 - Ship Sustainment **658**

Hey Siri!' for the marine coalface
Paper only - No presentation **659**

Lessons learnt from oil and gas: Practical opportunities to increase operability
and capability through optimising inspection, engineering and repairs **665**

Innovative concepts within LCM analytics **679**

SESSION 18 - Ship Design / Shipbuilding **687**

GMA welding ARC ID designation: using welding Arc acoustic signatures
Refereed **688**

Propeller dynamometer wake modification using a 3D printed wake device
for behind-hull-condition testing
Refereed **697**

Naval promas system **709**

SESSION 1

Naval Ship Seaworthiness

The design and development of a sovereign and contemporary naval classification framework for Australia

Achieving lifecycle seaworthiness on the Hobart-class guided missile destroyer (DDG) through reliability centred maintenance analysis and probabilistic risk assessment

The Design and Development of an Australian Sovereign and Contemporary Naval Classification Framework

Colin Dagg

Department of Defence (RAN), Canberra, ACT, Australia

cndagg@icloud.com

Arvind Sinha

Department of Mechanical Engineering, The University of Melbourne, Victoria, Australia

Jonathan Mead

Department of Defence, Canberra, ACT, Australia

ABSTRACT

Australia has laid the foundation for the largest recapitalisation of the Royal Australian Navy in modern history, underpinned by a continuous National Naval Shipbuilding Plan (NNSP) (Australian Government, 2017) [2]. The formation of the National Naval Shipbuilding Group (NNSG), a nationally significant program, will drive the NNSP in its implementation. The Department of Defence currently lacks a sovereign naval classification framework to prescribe and issue rules, design standards and classification certificates to assure the materiel seaworthiness of its naval vessels specific to Australian regulatory and capability requirements.

This paper investigates the need for a "Sovereign and Contemporary Naval Classification Framework for Australia"; identifying those questions that must be answered to secure a mandate for change and to protect key characteristics of the existing Defence Seaworthiness Management System (Australian Government, 2018) [3], ensuring that the process of classification supports seaworthiness. The inaugural paper on the subject covers the issues to be addressed through an "Adapted Soft-systems Approach" (Peter Checkland, 1999) [16], with an agile and continuous learning cycle, to ensure the new naval classification framework adapts to changes in the NNSP and informs the development of potential and future international conventions in naval classification.

The paper also covers the design principles, benefits, implementation strategy and the design and development approach through a three tranche process. The required "Application Research" to support the Project is being planned, through "Doctoral Research Candidature" at The University of Melbourne, by the author.

INTRODUCTION

Australia has laid the foundation for the largest recapitalisation of the Royal Australian Navy (RAN) in modern history, underpinned by a continuous National Naval Shipbuilding Plan (NNSP). The recent Defence Strategic Update has seen the Australian Government continuing to invest in this nationally significant program, which oversees up to $183 billion of current maritime programs, with over a trillion-dollar investment committed into the future. Every major shipbuilding project is now considered to be running late (Economics References Committee, 2021) [10]. The Attack Class Submarine program has been cancelled, in part due to cost and schedule overruns, and the Department of Defence is poised for sweeping changes with the formation of the National Naval Shipbuilding Group (NNSG) (Department of Defence Australia, 2020) [8]. While this new Group will do much to remediate project and contracting shortfalls in delivering the NNSP, significant reform is also required in the design, construction, classification, and maintenance of Australia's naval vessels. The Department of Defence requires a further updated naval classification framework to prescribe and issue rules, design standards and classification certificates to assure the materiel seaworthiness outcome of its naval vessels.

This paper explores the need for a new and contemporary naval classification for Australia, identifying those questions that must be answered to secure a mandate for change and to protect key characteristics of the existing Defence Seaworthiness Management System (Australian Government, 2018) [3]. This paper proposes these questions be answered through an adapted soft-systems approach (Peter Checkland, 1999) [16] with an agile and continuous learning cycle, to ensure the new naval classification framework adapts to change, and can be informed and informs the development of potential and future international conventions in naval classification.

Current Framework Neither Credible Nor Defensible

While the historical framework for design, construction, and certification of naval vessels in Australia has served us well in the past, the bespoke set of orphaned Australian design standards is no longer credible nor defensible by modern engineering standards and contemporary safety and environmental legislation in Australia (Dagg, 2021) [6]. Hence, there is a requirement to design and develop a new and contemporary Australian Naval Classification (ANC) Framework.

The importance of growing an Australian sovereign shipbuilding capability for our industrial and strategic future has been recognised, and is supported by, the Australian Government.

The definition of an Australian sovereign ship is one designed, built, operated and maintained in Australia by Australians (Economics References Committee, 2021) [10]. Thus, growing a sovereign design capability supports the industrial and strategic ambitions of the Australian Government.

Presently, most Australian naval vessels acquired for Australian Defence Force (ADF) purposes are derived from a number of foreign civilian or navy designs with over-prescribed customisation of differing standards through the restrictive application of *DEF(AUST) 5000 – ADF Maritime Material Requirements Set* (henceforth, DEFAUST) to meet Australian requirements. This circumstance may limit the ability to utilise advances in technology or other solutions to meet the outcomes required for Defence in the future. Hence, DEFAUST fails to address one of the key challenges in Australia's National Naval Shipbuilding Program (NNSP) – the absence of sovereign and contemporary standards for the design, construction, and maintenance of naval vessels in Australia.

While historical design standards have been promulgated in DEFAUST, they are bespoke in nature and based on a historical technical regulatory system (Chief of Defence Force, 2013; Department of Defence (Navy Headquarters), 2009; Director of Technical Regulations - Navy, 2003) [5] [7] [9]. This technical regulatory system was replaced by the Defence Seaworthiness Management System (DSwMS) in 2018 (Australian Government, 2018) [3]. As a result, the requirements within DEFAUST are overly prescriptive and not outcome-focussed. This does not allow for the necessary flexibility to support Defence outcomes within the NNSP, and the materiel requirement set is not integrated into the respective ship's lifecycle policy and procedure to its full potential. This circumstance can result in unnecessary issues including schedule delays, and limited ability to incorporate new commercial approaches or technologies, tending towards out-dated approaches that are conservative and unresponsive to operational decision-making cycles in a military context.

DEFAUST is difficult and expensive to maintain and lacks coverage of contemporary classification areas such as cyber, digital classification, artificial intelligence, augmented reality, trusted automation and additive manufacturing among other emerging technologies. As illustrated in Figure 1, only four of the 129 DEFAUST standards have been approved as current, correct, and applicable since introduction of the new DSwMS.

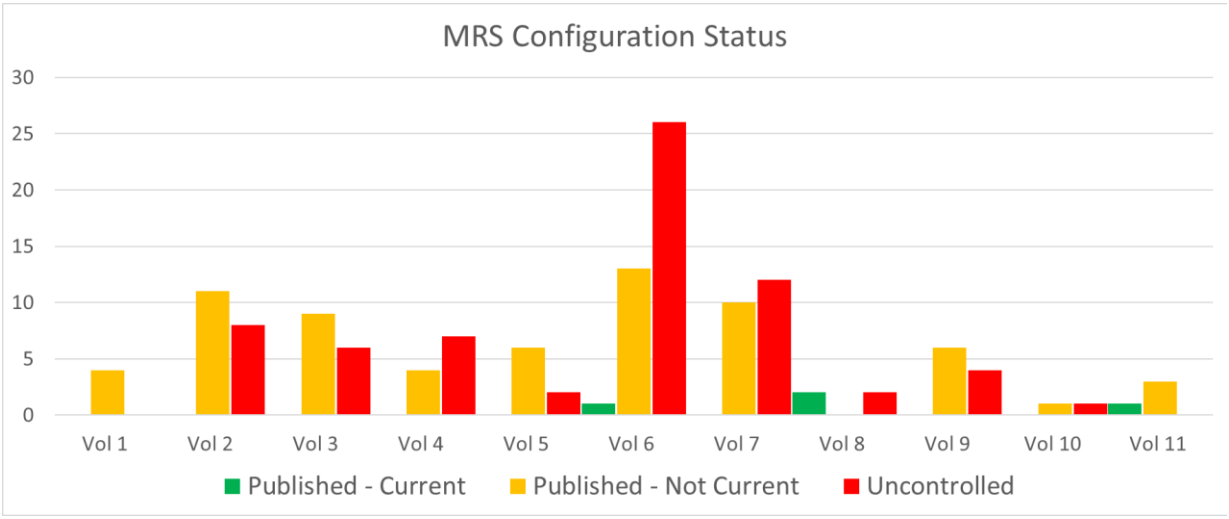


Figure 1. Status of Australian naval design standards

The 'Uncontrolled' identifies those DEFAUST standards that are still in a draft stage of development and yet to be peer reviewed and approved. The 'Published – Not Current' identifies those DEFAUST standards that were formally published under the historical Navy technical regulations and lack any update since the introduction of the DSwMS. While these DEFAUST standards have been approved, they are neither current nor useable within the current seaworthiness regulatory framework in Australia. The 'Published' indicates the four DEFAUST standards that have been formally published since DSwMS was introduced, and that are suitable for full inclusion in the new ANC Framework.

The current design standards in the DEFAUST are neither credible nor defensible and attempts in the past to remediate the issue have been unsuccessful (Rizzo, 2011) [17]. While some changes have been made, amounting to temporary solutions, other problems have been introduced and the Chief of Navy (CN) in his role as the Defence Seaworthiness Authority (DSwA) has since endorsed a full remediation strategy requiring the design and development of a completely new ANC Framework for Australia.

NEW ANC FRAMEWORK

The new ANC Framework will be contemporary and outcome-based, founded on international conventions (International Naval Safety Association, 2019) [12], while incorporating Australian unique requirements. Similarly, the ANC Framework will be founded on the principles of the traditional role of commercial Class Societies within a shipbuilding ecosystem (working to, and as a delegate of, the independent regulator), while incorporating military unique requirements.

Design Principles

To address the above, two driving principles will steer the design and development of the new ANC Framework as follows:

- As international as possible and as Australian as necessary; and,
- As commercial as possible and as military as necessary.

Use of these principles in the design of the ANC Framework will comprehensively resolve the deficiencies with the current DEFAUST and better support the delivery of naval power in defence of Australia and its sovereign interests. Additionally, these principles will enhance the technical interoperability with coalition and partner forces while optimising industrial support for Australia's sovereign shipbuilding capability. The use of NATO's naval ship and submarine codes to support the design of the ANC Framework will comprehensively align Australia to international design standards for naval vessels and allow for the necessary inclusion of sovereign design standards where required by Australian legislation.

To illustrate, NATO's *Naval Ship Code - ANEP 77* and the *Naval Submarine Code* (International Naval Safety Association, 2019) [12] have been developed by a group of international navies and classification societies and offer the most contemporary and goal-based framework for the classification of naval ships and submarines. The codes employ risk management principles that are based on *ISO 31000 : 2018 Risk Management* (International Standards Organisation, 2018) [13], such as reducing risk 'As Low As is Reasonably Practicable (ALARP)' with defined tolerance levels. This approach is inconsistent with the Australian *Work Health and Safety Act 2011* (Australian Government, 2011) [1]. Unlike other countries, Australian legislation strictly requires hazards to be eliminated 'So Far As is Reasonably Practicable (SFARP)' and, if this is not possible, be minimised SFARP. Therefore, NATO's *Naval Ship* and *Naval Submarine Codes* must be Australianised as necessary to ensure operational commanders formally eliminate hazards before any risk reduction activities commence, and do not cease risk reduction activities prematurely (even if very low risk), to remain compliant with sovereign statutory requirements for safety risk management in peacetime, peace-keeping and warlike operations.

As illustrated at Figure 2, the new ANC Framework will incorporate ANEP 77 (International Naval Safety Association, 2019) [12] and Australian Defence Force (ADF) specific requirements to cover the full scale of potential Conditions (Operational, Threat and Damage) that might potentially occur on a naval vessel, encompassing the full scale of potential military operations that the naval vessel might undertake, from peacetime operations to maritime security and combat operations.

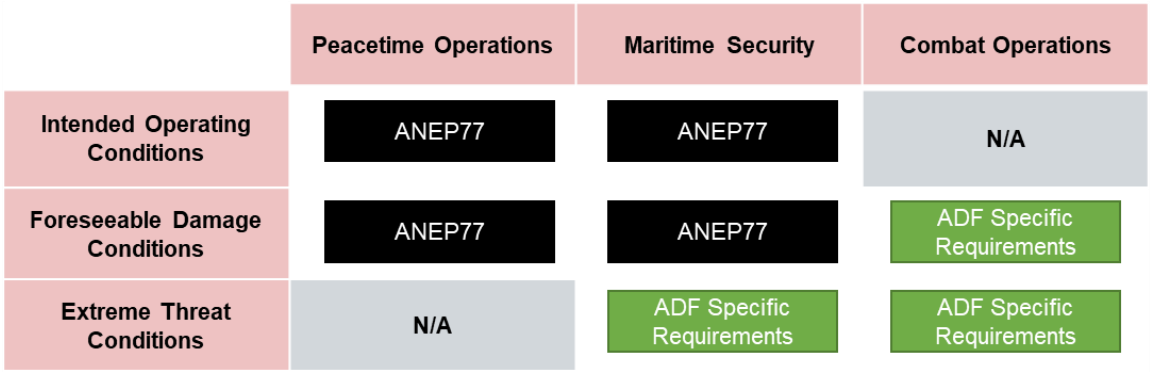


Figure 2. Design of the new ANC Framework

Thus, the design and development of a new ANC Framework for Australia is a natural evolution of the Royal Australian Navy's ten-year reform of naval engineering and seaworthiness management and is consistent with Defence's drive for excellence in naval capability, safety, and environmental protection.

Benefits

The ANC Framework will provide operational commanders with enhanced flexibility and defensibility in the use of naval vessels. Naval operations are different to commercial operations, and hence naval classification is different to commercial classification (International Association of Classification Societies, 2021) [11]. Commercial classification is provided by a classification society. Classification societies are independent, self-regulating bodies that develop engineering rule sets to support the safety of operating maritime vessels through the design and maintenance of design standards. This expertise has been garnered over centuries of maritime experience. For example, Lloyd's Register originated in 1760 (Lloyd's Register, 2021) [15].

Commercial classification through classification society rule sets provides verification that the structural integrity and strength of areas such as the hull, propulsion and steering systems among other critical systems, have been designed and built in order for the ship to maintain essential services (International Association of Classification Societies, 2021) [11]. This supports the owner of the vessel in their ability to meet international and national statutory regulations, whilst also providing insurance companies with the necessary confidence to underwrite the potential loss of the ship and cargo at sea. In contrast, while naval classification will still be required to meet these commercial classification design criteria as a minimum, Naval operational environments dictate naval classification design (Figure 2).

Australian Naval Classification will provide operational commanders with the necessary materiel baseline against which informed risk decisions can be made. This will include decisions made during both the design, operation and maintenance of the Naval vessel. Flexibility will be provided through the ANC Framework to support clear, well-informed risk decisions in defence of Australia and its sovereign interests. Under the ANC Framework, naval

commanders will be permitted to operate a vessel beyond its naval classification certificate (often routinely) while still satisfying their statutory obligations in the *Work Health and Safety Act 2011* [1]. Accordingly, the ANC Framework will provide operational commanders with enhanced flexibility and increased defensibility in the operational use of naval vessels.

The ANC Framework will be structured to support Australia's NNSP. The Australian Government has established an enduring sovereign shipbuilding program and Defence has a significant role to play within this new ecosystem. One important role is the specification of materiel seaworthiness requirements against which naval vessels are designed, constructed, certified and maintained. The implementation of the ANC Framework will deliver against this important role and address the issues in Australia's sovereign shipbuilding ecosystem.

Cost Effectiveness: Overall, implementation of the Australian Naval Classification Framework will be inexpensive and offers significant savings in acquisition and sustainment costs. Naval classification frameworks are designed to operate organically within a shipbuilding ecosystem and support the efficient design, construction and maintenance of naval vessels. A proposed ANC rule set needs to be founded on common international conventions. This will provide a system that is well understood by industry, offers significant benefits in materiel assurance, and will support a design review on shipbuilders. That is, it will allow innovation through design and construction by the ship designer and builder, and still meet Australia's regulatory requirements.

Specifically, the introduction of the ANC Framework will reduce materiel assurance overheads in the sovereign shipbuilding ecosystem in the long-term, through the following:

- Providing Industry with greater certainty and familiarity in specification of design, construction, certification and maintenance standards;
- Reducing the administrative burden on the RAN and CASG/NNSG to process waivers against civilian class requirements that would not exist under an Australian naval classification framework;
- Support the elimination of any disfunction or technical disputes between the RAN, CASG/NNSG and Industry about competing interests and requirements when a difference occurs between the as-designed and as-built vessel; and,
- Reducing the burden of ongoing seaworthiness assurance through the tailored application of naval class rules rather than disparate and varying international commercial maritime rules.

International Engagement: The ANC Framework also provides substantial opportunities to enhance international engagement with coalition and regional partners and delivers against Australia's Strategic Defence Interests. As valued and non-lethal commodity, Australia will be able to offer the new ANC Framework as an alternative option for international engagement where a strong naval presence (military exercise or visit) is not desirable. Additionally, the

framework will be based on emerging global conventions in naval classification and Australia is well placed to influence and strengthen the convention within the context of a rules-based global order.

Submarine Program: Australia's submarine program will also benefit under the new ANC Framework, providing trusted assurance in the acquisition and sustainment of future submarines. Australia has something of a fractured history in the design and construction of sovereign submarines particularly with the historical introduction and support of the Collins Class submarine (John Coles, 2012) [14] and recent cessation of the Attack Class submarine. Australia does not have an independent and contemporary suite of naval classification rules for Australian submarines. The new naval classification framework could include a suite of naval submarine classification rules and would provide trusted assurance that all future submarines can be certified as meeting their materiel seaworthiness requirements.

Autonomous Platforms: The ANC Framework will also enable the trusted introduction and expansion of autonomous vessels. Autonomous vessels are an emerging capability with unique challenges around the specification of materiel requirements to achieve safety, environmental and fitness for service outcomes. The proposed framework needs to include a suite of naval autonomous classification rules that can guide Defence's effort in the capability definition, acquisition, design, and construction of new naval autonomous vessels.

Inter and Intra Departmental Alignment: From a government perspective, the new ANC Framework allows for greater technical alignment and cooperation between the Australian Maritime Safety Authority (AMSA) and other Government Departments. The compliance requirements within the DSwMS are quite unique (arguably much advanced) in meeting specific operational outcomes with little direct alignment to other regulators in Defence or the broader Australian Government. The ANC Framework is based on global conventions and aligns well with AMSA's systems, allowing for increased technical interoperability and mutual recognition between white, red and State flagged vessels. The ANC Framework will contain specific rules on ship's aviation facilities that work well with the Defence's Aviation Safety Framework (Australian Government, 2021) [4] and support civilian equivalent linkages between AMSA and the Civil Aviation Safety Authority (CASA). The naval classification framework is therefore based on common conventions (not bespoke or prescriptive) and offers the possibility of increased inter-Departmental coordination and cooperation across the Australian Government.

Implementation Strategy

The implementation of a new ANC Framework is a strategically significant undertaking for Defence and Industry in Australia and requires necessary research investigations to ensure that problematic concepts and structures are replaced, while retaining those concepts and structures that continue to support and enable high levels of materiel seaworthiness in naval vessels. The first step must therefore be to understand the issue; be very clear on the merits

of the current framework; the merits of the new framework; and how these might be implemented under a continuous learning strategy. The strategy will require the following issues to be addressed:

- What are the identified demerits and merits (across Defence and Defence Industry) within current DEFAUST that enables to a limited degree the ability to support Australia's sovereign and enduring shipbuilding program?
- How are these identified issues evidenced practically and is there sufficient evidence to develop new concepts that might be tested, and success criteria determined for implementation?
- Based on research what are the specific concepts, ideas and/or philosophies that is limiting or preventing the development of contemporary naval classification framework in Australia?
- Can causality be established between these specific concepts, ideas and/or philosophies and the present practicality in Defence, as the basis for design and development?
- Based on research, are there new concepts, ideas and/or philosophies available to design/develop a new ANC Framework for Australia?
- How will these new concepts, ideas and/or philosophies best be implemented practically to maximise the benefits and minimise the efforts and costs of introducing the new ANC Framework across Defence and Industry?

Approach – Adapted Soft Systems Methodology

The ANC Framework applied research project involves the development of codified rules and the design of a framework for implementation. The new and contemporary sovereign ANC Framework will have a significant impact on the National Naval Shipbuilding Program (NNSP) and on industry, in proving a detailed and defined baseline for the design and construction of all Naval vessels. Defence groups and services (for example, the RAN) will need to adjust how and when they provide clear guidance to stakeholders within the NNSP to ensure the right baselines are delivered for the right capability acquisition. The research methodology must provide for and account for organisational learning as the ANC Framework is implemented and investigate the current government and political imperatives of the NNSP. This may require agile adjustment during the design to address changing political direction.

The project will use an applied methodology comprised of the Soft Systems Methodology, with an incorporated agile development cycle, to enable iteration of the research and organisational learning as method of research verification. The Soft Systems Methodology (SSM) was first developed by Peter Checkland and University of Lancaster supported by UK colleagues in the 1970's (Peter Checkland, 1999) [16]. It is an action-based research method that is well suited for practical applications in which the researcher is embedded within the

organisation or framework under analysis. The adapted agile SSM (AASSM) methodology provides the ideal approach for addressing the identified issues above and delivering the new ANC Framework for Australia.

The AASSM application in the development of ANCF will cover the six phases as presented in Figure 3:

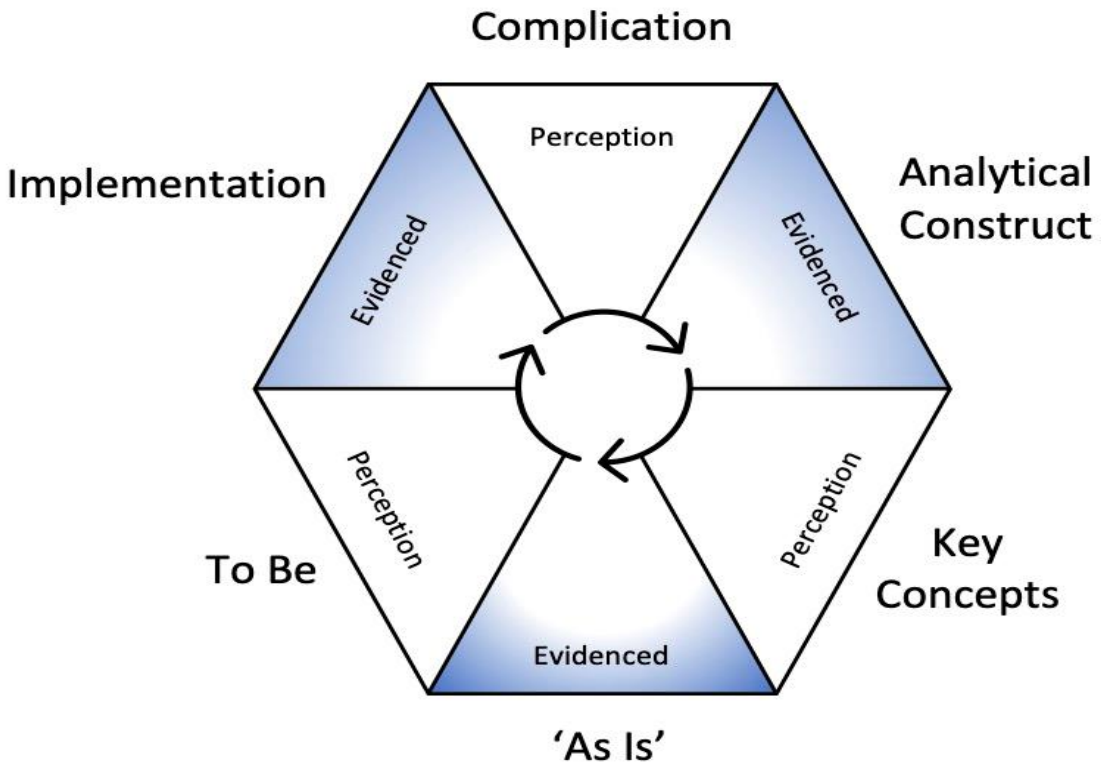


Figure 3. AASSM methodology for ANC Framework

Phase 1: Complication. This phase is concerned with understanding the *perceived* complication or problem with current DEFAUST, acknowledging that the different stakeholders (including the author) shall be differing in perspectives and understandings of the issue or problem that mandates the reason for change. In many respects, this step will provide the mandate for initiating an adapted soft systems research cycle, with complications (and associated cycles) likely to occur at the strategic operational and tactical levels of the program.

Phase 2: Analytical Construct. This phase will ground the previous perspectives in evidence to develop a 'rich picture' of the *real-world* problems against which future hypotheses can be tested and success factors for implementation created. The 'analytical construct' shall be created and embodied at various levels of the project depending on the scale of the research cycle. Strategic cycles are likely to produce larger repositories of evidence over a longer

timeframe in the form of qualitative examples and quantitative data analysis, while tactical cycles are likely to result in smaller records from structured workshops.

Phase 3: Concepts. This phase will then create a set of hypotheses in the form of identified key concepts, ideas and/or philosophies that might be limiting the development of the new ANC Framework. Substantial research and analysis will be required to identify these 'root cause' problems and based on the limited body of knowledge in this domain, new concepts (previously unidentified) shall be proposed by the author as part of the research cycle.

Phase 4: 'As Is'. This phase will test and verify the previous hypotheses in a *real-world* situation. Verification of the 'As Is' situation will require causality to be established between the identified concepts, ideas and/or philosophies and the *real-world* intellective construct evidence developed earlier in the research cycle. Fidelity of the approach is thus established to the extent that causality can or cannot be reasonably established.

Phase 5: 'To Be'. This phase is similar to Phase 3 yet seeks to develop additional hypotheses that enable a future ANC Framework to be established. This requires new concepts, ideas and/or philosophies to be identified in order replace old and limiting concepts and resolve the historical problems evidenced in the earlier rich picture description. Substantial research and analysis will likewise be required and based on the limited body of knowledge in this domain, new concepts (previously unidentified) will be proposed by the author as part of the research cycle.

Phase 6: Implementation. This phase, while similar to Phase 4, further tests and verifies the additional hypothesis through implementation and evaluation in the *real-world*. While success will be welcomed in this stage of the research cycle, complications are expected to arise at either the strategic, operational, or tactical level and may result in further iterations of the AASSM.

DESIGN AND DEVELOPMENT OF ANC FRAMEWORK

The ANC Framework design and development will occur through three Tranches comprising of three strategic AASSM cycles. Lower level AASSM cycles are expected to occur routinely throughout the project; these are not included in the Tranche descriptions in this paper.

Tranche 1

This tranche has commenced and involves stakeholder engagement, comprehensive communication, education/training, approved policy and rules, templates, and proof of concept demonstrations before ships are migrated to the new naval classification framework. All these Defence outputs shall be developed under the first strategic AASSM cycle.

Tranche 1 will include operational-level AASSM cycles to build the knowledge and capacity of staff in the RAN, CASG and Defence Industry so that the new framework can be implemented confidently and with minimal effort in future strategic Tranches. Tranche 1 will use

operational-level AASSM cycles to undertake a 'Proof-of-Concept' demonstration to inform policy development and refine procedures/instruments before implantation across the current RAN fleet; and develop and evaluate communication/education outcomes in support of future Tranches.

Tranche 2

This will migrate every naval vessel in Australia to the new naval classification framework with minimal impact on Defence and Industry. Migration is expected with minimal effort and minimal impact to Defence and Industry. Tranche 2 is schedule to commence in January 2022 and conclude by no later than January 2027. The impact on Defence and Industry will be minimised by the following:

- Using existing compliance data and certificates for RAN vessels
- Resisting strategies that seek to create or regenerate compliance data and certificates where there are shortfalls
- Using the broad application of 'grandfathering' principles and risk management to cover shortfalls in compliance data and
- Updating the classification certificate as new data becomes available through major upgrades in the future. Importantly, all RAN vessels will be issued a full naval classification certificate by the completion of Tranche 2 that attests to their materiel seaworthiness condition.

Tranche 3

This will ensure that all future naval vessels are designed, built, and maintained under a complete naval classification framework. Tranche 3 will establish the necessary policy and systems to ensure the Australian naval classification framework is applied during the acquisition of all future RAN vessels. Tranche 3 is scheduled to commence in January 2025 and will take effect in January 2027. While the current RAN fleet will migrate to the new framework with incomplete compliance data and rely on 'grandfathering' principles for issuance of a naval classification certificate, all future RAN vessels are expected to demonstrate full compliance with the materiel seaworthiness requirements.

As illustrated at Figure 4, the three Tranches are intended to overlap with later strategic AASSM cycles starting before the previous AASSM cycle has concluded. The timing and integration of respective cycles is inherently complex – particularly when operational-level and tactical-level AASSM cycles are considered – but the methodology is necessarily flexible and has the inbuilt design flexibility to adapt to new issues as they emerge. A traditional waterfall methodology would be simply unsuitable for a real-world project of this scale and complexity, particularly as new and unique knowledge is developed and applied (verified) iteratively throughout the project.

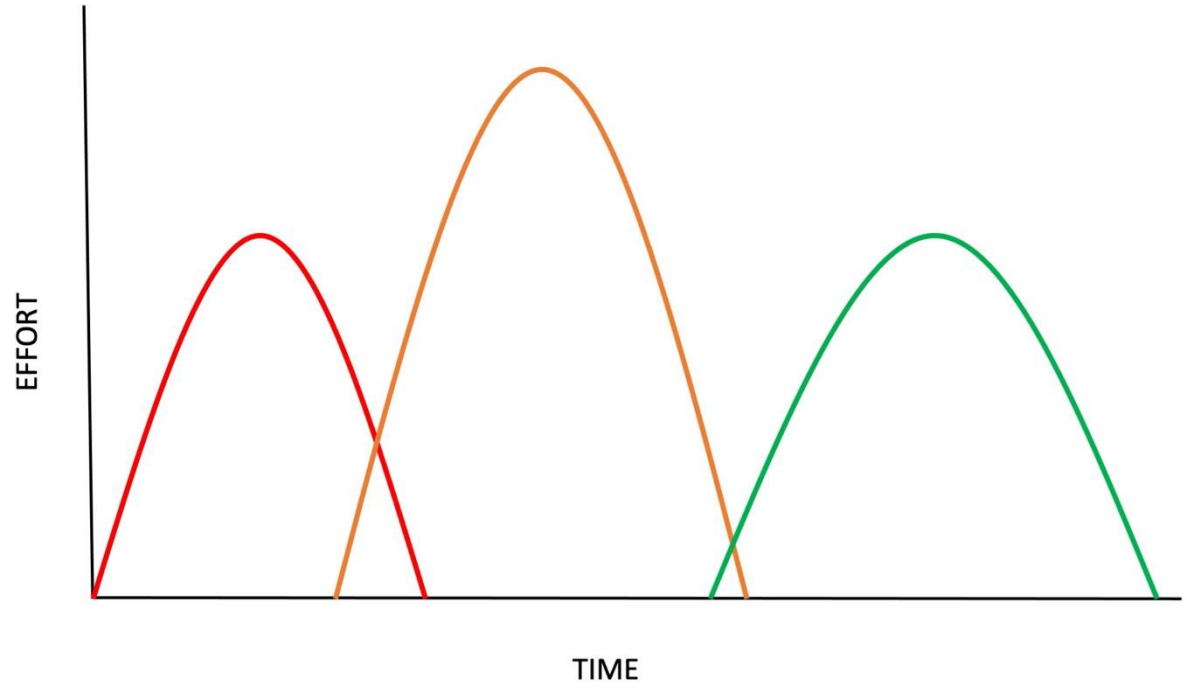


Figure 4. Three overlapping implementation Tranches

POTENTIAL COMPLICATIONS AND CHALLENGES

A project of this scale and complexity will be challenged by many complications. A simpler solution is to adopt an existing solution. The Defence Aviation Safety Authority (DASA) has been recently established in Australia and a new suite of Defence Aviation Safety Regulation (DASR) has been implemented for all State aircraft (Australian Government, 2021) [4]. Similarly, some countries have partnered with a civilian commercial Class Society to provide materiel assurance for their shipbuilding industry utilising Class Society developed Naval Rules, while others have adopted the NATO *Naval Ship Code* without adaptation or extension or a combination of both for their naval fleets. All these solutions singularly are incompatible with the established Defence Seaworthiness regulator and would overly complicate the Australian design and operational environment and frustrate the compliance ability of Groups and Services that operate naval vessels, and the newly established National Naval Shipbuilding Group.

As illustrated at Figure 5 below, the only real solution available to Australia is the formation of an Australian Naval Classification Authority (ANC Authority) within the sovereign shipbuilding ecosystem to perform an equivalent and militarised version of a commercial Class Society directly supporting the Defence Seaworthiness Authority (Regulator) by providing a Framework to set, manage, and implement Australian Naval Classification Rules.

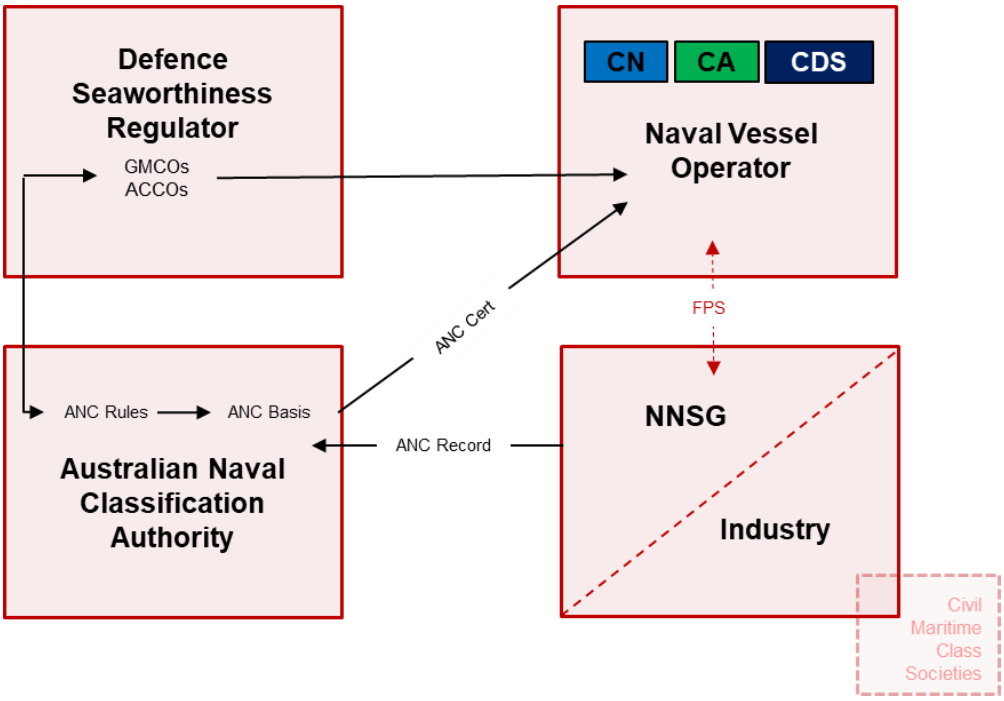


Figure 5. ANC Framework Entity Diagram (Quad Chart)

While commercial class societies still have a large role to play generating permissible evidence as competent organisations for Defence Industry, the ANC Authority has responsibility prescribing the ANC Rules, establishing an ANC Basis of compliance for every naval vessel in Australia, reviewing permissible evidence from the NNSG and Industry, and finally issuing an ANC Certificate that attests to the materiel seaworthiness condition of Australia's naval vessels. The generation of a sovereign rule set, and the dedicated framework under which it operates, provides an enormous challenge. Being a novel concept, substantial research will be required to generate and verify a new body of knowledge to design and develop an Australian sovereign and contemporary naval classification framework.

CONCLUDING REMARKS

Over the next three years, the project in parallel with a doctorate level application research program plan will deliver the design, development and initial implementation of the new ANC framework. The project plan itself is set to last for up to five years for complete implementation for all current and future naval vessels. The project will be undertaken through three over- lapping Tranches with clear entry and exit criteria as enumerated in the paper.

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Achieving Lifecycle Seaworthiness On The Hobart-Class Guided Missile Destroyer (DDG) Through Reliability Centred Maintenance Analysis And Probabilistic Risk Assessment

Nicholas Boustead, AMOG Consulting, nick.boustead@amog.consulting

Georgia Schreenan, AMOG Consulting, georgia.schreenan@amog.consulting

Alex Waugh, AMOG Consulting, alexander.waugh@amog.consulting

Daniel Johnstone, AMOG Consulting, daniel.johnstone@amog.consulting

Tim Lee, AMOG Consulting, tim.lee@amog.consulting

Alison Court, BAE Systems, alison.court@baesystems.com

Sally Busch, BAE Systems, sally.busch@baesystems.com

James Gawne, BAE Systems, james.gawne4@baesystems.com

ABSTRACT

A key tenet of the Royal Australian Navy Seaworthiness Management System is the achievement of operational effect, whilst ensuring safety and environmental protection. This paper examines a case study of application of reliability centred maintenance analysis to the Hobart-Class Guided Missile Destroyers (DDG), using probabilistic modelling to assess risk to both mission and safety performance. We outline in the paper a methodology for optimising forward planned maintenance over the vessel lifecycle to balance several competing goals such as maximising likelihood of successful functional performance, minimising safety risk so far as reasonably practicable (SFARP), reducing the forecast maintenance costs, whilst also considering constraints such as the projected upkeep and operational cycle. This methodology provides valuable insights into system reliability performance throughout deployments and other life cycle phases, which can inform decision makers when considering alterations to operational phasing (such as extending deployments or increasing utilisation).

We demonstrate, by means of example, a methodology for Reliability, Availability, and Maintainability (RAM) modelling of a system that can assist decision-makers by providing predictions of capability performance in hypothetical scenarios.

This methodology is also intended to shift focus towards optimisation of system performance by utilising a repeatable methodology for finding the optimal balance between cost of operation and minimisation of risks be it to Operation and Mission Capability, or Safety.

INTRODUCTION

The case study presented in this paper details how many different inputs may be considered in detailed Reliability Block Diagrams (RBDs) to quantify changes between different scenarios and ultimately provide predictions that can inform decision-making. This analysis can consider labour resource availability, system utilisation by mission type, lifecycle usage phasing (e.g. upkeep and deployment), maintenance activity types, failure modes, and limitations on resources for equipment repair. By considering all these aspects, AMOG has been able to extract insights which give relative impact of changes to mission lengths, increased utilisation or changes to maintenance regimes in the form of labour hours, component downtime and system availability.

The analysis method presented here has been completed in the context of the Hobart-Class Guided Missile Destroyers (DDG). The repeatable methodology for Reliability Centred Maintenance (RCM) presented is translatable to any context with continuous improvement at the core of maintenance activities, such as chemical process plants, manufacturing, roads, aircrafts or land vehicles.

System Overview

The system for this case study is presented in the Reliability Block Diagram (RBD) shown in Figure 1. It is generic in nature while still containing a mixture of redundant subsystems and single points of failure subsystems, the former represented as parallel blocks in the RBD and latter as blocks in series.

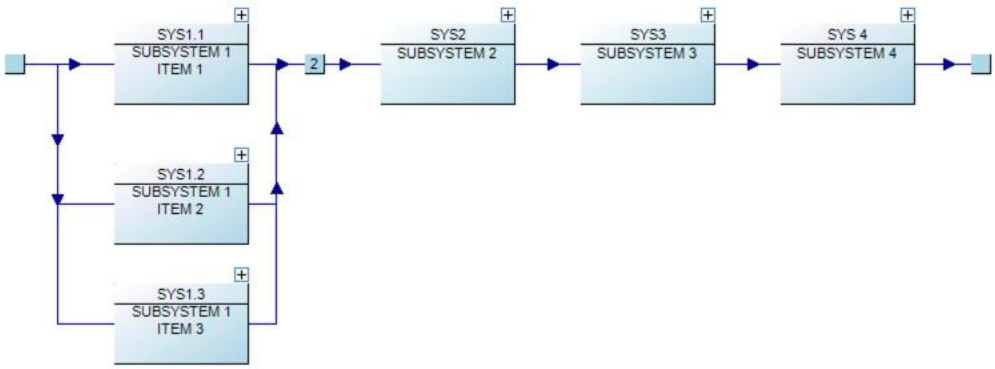


Figure 1 – The system structure used in this case study.

The availability output from the RBD analysis is computed as the probability at any one time that all blocks in the series are functioning as required. For SYS2, SYS3 and SYS4, everything inside these blocks must function to be available. For SYS1.1, SYS1.2 and SYS1.3, only 2 of the 3 parallel blocks must be functioning to be available (as is indicated by the “2” in the box after these items).

METHODOLOGY

High Level

The reliability and availability of the selected system functions were analysed using RBD analysis. For a selected function, components which were critical for successful operation of that function were modelled, with component failure rates and failure modes being tailored to those relevant to loss of the selected function's successful execution.

The RBD model building process consisted of the following general steps:

1. Establishing the context of the system functions and how they contribute to the overall delivery of operational capability or safety outcomes for the platform.
2. Review of system structure, including maintenance activity extracts, system information documents and drawings, for each of the relevant subsystems to verify the structure of the system before building the model.
3. Determine the criticality of system components and subsystems to the top-level function. Items identified as non-critical to the function are allowed to fail in higher numbers before affecting the function and items identified as having no functional impact are removed from the analysis.
4. Creation of a data registry to collate maintenance and failure data for all components and maintenance tasks in the model. Failure data was obtained from a variety of sources, including system reports, RIAC, OREDA, NPRD and EXIDA databases.
5. Implementation of event and operational phase-based logic into the RBD, such as phasing (periodic changes to utilisation of the system), maintenance inhibitions (maintenance, equipment, or personnel restrictions corresponding to specific phases or activities), or other case specific modelling criteria.
6. Building and simulating an RBD Model: This step includes the simulation of the baseline models as well as the various scenarios of interest. Simulations refers to Monte Carlo simulations of lifetimes of the vessel performed in AvSim (a software package that is a component of the Isograph Availability Workbench Software suite). The key results from these simulations are the outputs of manhours (which can be used to estimate cost), and availability (i.e. probability that the system is available to perform its function at a given time). These outputs are given for each individual component, as well as groups of components, subsystems and the combined overall system.

The following sections detail the methodology used for various aspects of the modelling, such as implementing maintenance activities and the operational phasing of the system.

Maintenance Tasks

Four different types of maintenance used on the DDG were represented in the RBD modelling, Planned Maintenance (PM), Predictive Inspections (PI), Corrective Maintenance (CM) and Condition-Based Maintenance (CBM).

Planned Maintenance (PI) activities are performed after a defined duration and repeated each time the interval duration is met. Planned maintenance tasks are maintenance actions which may or may not replace components. PM actions, such as cleaning, lubrication, and oiling, are considered required baseline maintenance to keep the component in line with the expected and quoted MTTF. Where items are replaced as a part of a maintenance action, the age of the component is returned to zero. If no replacement has occurred as a part of the maintenance action, then the age of the item remains as it was before the activity.

Predictive Inspections (PI) activities are predictive maintenance actions which are performed on a regular basis. Inspections include visual checks and measurements which are indicative of future failure. If these inspections occur within the Potential-to-Function Failure (P-F) interval, which is estimated as 10% of a component's MTTF, then a successful PI action may lead to a CBM activity. A sensitivity analysis was conducted on the effect of this assumption, varying the percentage from 5% to 20%. Table 1 shows the results of this sensitivity analysis.

Table 1 – Sensitivity analysis results for P-F Interval

Case ID	P-F Interval	Total Downtime at sea waiting for repair (as a percentage of the Medium interval selected for the analysis)
Low	5% of MTTF	152%
Medium	10% of MTTF	100%
High	20% of MTTF	71%
NOTE: These results were obtained using a sample model representative of a system function, but different to the model used in this case study. However, the trends shown by these results are representative of the version of the model presented herein.		

Condition Based Maintenance (CBM) activities are performed following a PI when a predicted failure of a component occurs. This action replaces the component before failure to avoid a future unexpected failure and with it the associated, unplanned downtime. Triggering of a condition-based maintenance action for an upcoming imminent failure allows for planning of resources and the ability to schedule maintenance at a convenient time (where possible).

Corrective Maintenance (CM) activities are performed following a non-predicted failure of a component. The condition of the component is restored to "good as new" (where the age of the component is restored to zero) following repair and the system is considered offline for the repair.

Further to the types of tasks, different labour categories with differing skills and availability characteristics were applied to each maintenance. Broadly these include:

- Organic: This refers to ship staff, who can complete maintenance regardless of phase.
- External: This refers to contractors at port, who can only complete maintenance tasks during certain phases.

Phasing

The model was configured to simulate a hypothetical 10-year Usage and Upkeep cycle for the DDG. Each lifecycle phase was categorised and represented in the model as one of four operational modes:

- "Deployment": This phase simulates high intensity periods where the vessel is out at sea on overseas deployments. This phase prohibits any External maintenance activities but allowed for Organic maintenance activities.
- "Intermittent Sea Periods": This phase simulates low intensity periods where the vessel is intermittently out at sea on training missions or other activities of short duration, but

close enough to a port to undertake External corrective maintenance. This phase allows Organic maintenance activities.

- "Other": This phase is similar activities to Intermittent Sea Periods, but the vessel is predominantly located at port, thus has lower system utilisation. This phase allows Organic maintenance activities and External corrective maintenance.
- "Upkeep": This phase simulates the vessel being at port for an extended period to conduct planned external maintenance. This includes short maintenance periods and longer, dry docking maintenance. This phase has no restrictions for maintenance and is the only time that planned External maintenance tasks can occur.

Maintenance task restrictions for each phase are shown in Figure 2.

	Organic Maintenance Tasks		External Maintenance Tasks	
Phases/States	Preventative Maintenance	Corrective Maintenance	Preventative Maintenance	Corrective Maintenance
Deployment				
Intermittent Sea Periods				
Upkeep				
Other				

Figure 2 – Maintenance Inhibitions by phase and type. Red indicates task is prohibited at that time; green indicates task can be completed.

Reliability Modelling Key Assumptions

The RCM models created using this methodology include many complexities to accurately represent the DDG service life. This includes life cycle phases, limitations on when maintenance can be performed, planned maintenance at intervals, predictive inspections generating condition-based maintenance to prevent failures and MTTFs.

The culminative result is a detailed and complex model, which is based on data and decisions provided by BAE through regular teleconferencing and interfacing. However, there were some key assumptions which had to be made in developing the RCM models. These are as follows:

- MTTF data: Where MTTF data was available from previous studies, it was reviewed and if not supported by a credible failure model, it was replaced by MTTF data derived from a combination of sources based on the authors of this paper's best engineering judgement, including DDG system reports, RIAC, OREDA, NPRD and EXIDA databases.
- Maintenance actions: The actions conducted in maintenance were identified from maintenance activity extracts, assuming that maintenance activities only apply to the items within the Facility Code and any items as specified within the Job Title. Where these two sources were inadequate to fully define the maintenance activity, maintenance procedures were consulted.
- Failure models, generally either Exponential or 2-parameter Weibull distributions, were selected to represent the types of failure modes experienced by components in the system. Exponential and 2-parameter Weibull distributions were primarily used. The selection of 2-parameters for the Weibull distributions means that components do not have an infant mortality region in their lifetime, which is reasonable in a

defence context where a premium is placed on component reliability in procurement. However, when applying the methodology to the general engineering sector greater weight must be given to consideration of infant mortality failures as when these are commonplace, they can have considerable impact on overall results [1].

- Non-linear impacts of altering maintenance regimes, for example, extending the interval between planned replacements of certain components which then leads to additional wear that can cause damage to other components in the system, are difficult to quantify and were not considered in the study presented here. It was assumed that all maintenance where components are not replaced with new components but rather maintained in some way (e.g. cleaned or lubricated) is required maintenance in order to achieve the component's MTTF.
- Detection probability is the probability that, during the given inspection activity, the maintainer will successfully identify/diagnose/predict the upcoming potential failure and thus schedule a corrective maintenance task to occur in the near future to replace the component in question before it fails. In the DDG study reported here the Detection Probability was assumed to be 0.4869, which is consistent with a "completely familiar, well designed, highly practised routine task, oft-repeated and performed by a well-motivated highly trained individual but with no significant job aids, a shortage of time to correct any errors made during the process, and little/no independent checking or testing of output" [2], but with only 50% of failure modes being detectable by any inspection.

Scenario Descriptions

A Baseline maintenance case and three further maintenance scenarios were conducted for this case study. Scenario 0 modelled system function for the purpose of providing a basis of comparison to proposed maintenance and system structures modelled in later scenarios. The baseline model was then varied in a series of studies that explored the effect of different scenarios on availability of the system's functions. These variations and comparisons had the following key performance metrics:

- System Reliability
- Mission Outcomes

These performance metrics are measured by several key factors:

- Availability on Demand – i.e. the probability that, in any given hour of operation, the function is available and will work as expected.
- Cost – this was estimated from the manhours expended in carrying out maintenance (both External and Organic). Equipment or component costs were not considered.

The scenarios investigated were as follows:

Scenario 0 – Baseline

Scenario 0 modelled to be a hypothetical baseline model of the DDG system configuration, usage and maintenance cycle for comparative purposes.

Scenario 1 – Extended Deployment

Scenario 1 was focused on the effect on the vessel systems of a combination of age and extended deployment durations. The scenario investigated the effects of lengthening the deployment periods in Year 4 and Year 9 by 70%.

Scenario 2 – Distributed additional days at sea

Scenario 2 analysed the effect of increasing the average sea days in each year of the Usage and Upkeep Cycle by adding approximately 30 days at sea in an evenly distributed manner throughout each year.

Scenario 3 – Maintenance Recommendations

Scenario 3 focused on the effect of implementing recommended changes to maintenance from FMECA and RCM review activities. This model showed how adding new tasks, amending current tasks and deleting current tasks could impact the overall performance throughout the life of the vessel. These results were compared against the Scenario 0 results to quantify the effect that Maintenance Changes have on deployment performance and safety.

Capability States

The capability states of the system were defined as follows:

- **Full Capability:** All components working as intended and available.
- **Degraded Capability:** Most critical components, and the majority of non-critical components working as intended and are available. Not been enough failures of critical or non-critical items to reach the criteria for Return to Port.
- **Return to Port:** This is the state reached when more than 5% of the critical components are unavailable, OR more than 50% of the non-critical components are unavailable.

Definitions of capability states are system and function dependent and can be altered to reflect the particular system being modelling.

RESULTS

Baseline Scenario

Analysis of the system availability through the usage and upkeep cycle gave insights into the drivers of downtime as a function of system age. The following figures and discussion show some high-level example results of this type of analysis.

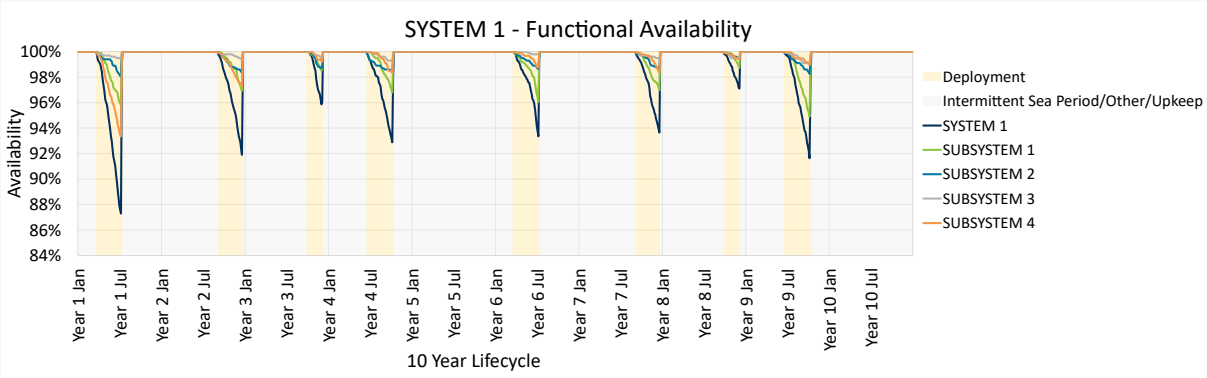


Figure 3 – System functional availability for Scenario 0, including all subsystems

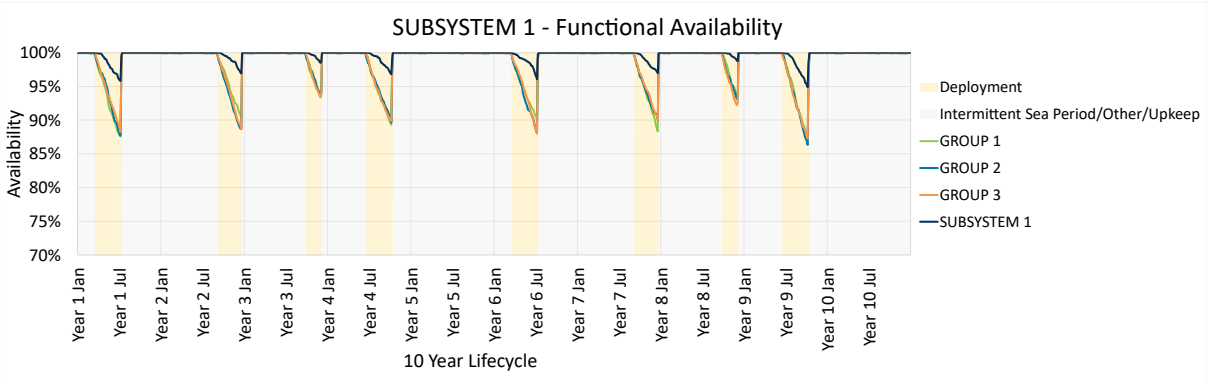


Figure 4 – Subsystem 1 functional availability for Scenario 0, including lower-level groups

Figure 3 presents the top-level results of the system, including major subsystems. The redundancy of subsystem 1 is shown in Figure 4, through the higher subsystem availability when compared to the three groups underneath. This is due to the two out of three availability requirements for this subsystem.

The general trend was found to be that during each deployment there will be a steady decrease in availability, due to the increasing likelihood that failures will occur at sea which cannot be repaired until the vessel returns to port. When the deployment is over, the vessel will return to a state where it can seek external repairs for any failed components, and thus the probability that subsystems and the overall function will be available return to higher levels. Failures of components that occur during phases other than deployment will be repaired within a small time: This will reduce the availability at the point in time. However, the duration of the repairs will be short and below the resolution of the plots in Figure 4.

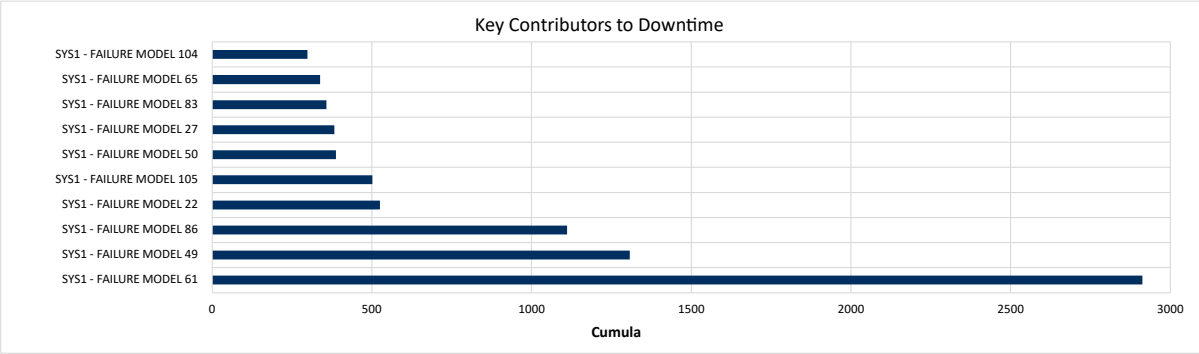


Figure 5 – Breakdown of key contributors to downtime of System 1 for Scenario 0

Figure 5 presents a breakdown of the key contributors to downtime of System 1. These results assist in both informing maintenance decision making and validating and calibrating the model: If certain components are found to drive unavailability but are not strongly represented in the real-life failure data for the vessel, then this indicates that the failure data for that component is inaccurate and requires revision.

The Maintenance team use this data to prioritise the inspection and maintenance of these components that are causing downtime in order to maximise the availability on deployment. The modelling team then use the suggested changes from the maintenance teams to quantify the improvement in system availability and the outcomes for operating effect and safety.

Deployments Analysis

Before conducting analysis of different maintenance or operating regimes, the baseline configuration of the DDG platform and maintenance plan was studied to give insight to the performance of the DDG during deployments in subsequent years of the Usage and Upkeep Cycle.

This analysis gives a breakdown of the probability of each capability state throughout a deployment, as shown in the example given in *Figure 6*. This data allows the following observations to be made about availability during the simulated hypothetical baseline deployment periods:

- The number of days where the vessel's most probable state changes (i.e. when degraded becomes more likely than full capability).
- Trends regarding average probability of each state depending on time through individual deployment or lifecycle of the vessel.

Percentage of Deployment Completed		14%	25%	50%	75%	100%
Example Deployment	System State:					
	FULL CAPABILITY:	83.01%	74.43%	57.94%	45.17%	35.68%
	DEGRADED:	16.15%	24.02%	37.53%	46.56%	52.20%
	RETURN TO PORT:	0.84%	1.56%	4.53%	8.26%	12.12%

Figure 6 – Example deployment analysis for the Scenario 0

Comparison Scenarios

Comparison between the findings of Scenario 0 to 3 are presented in Table 2 and Figure 7 and 8.

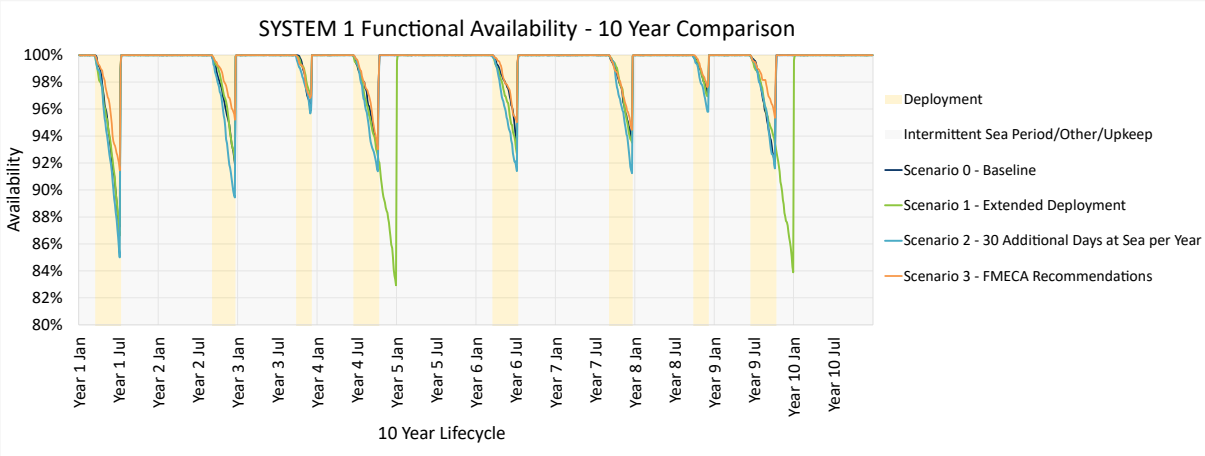


Figure 7 – Comparison of Functional availability of System 1 across the four scenarios

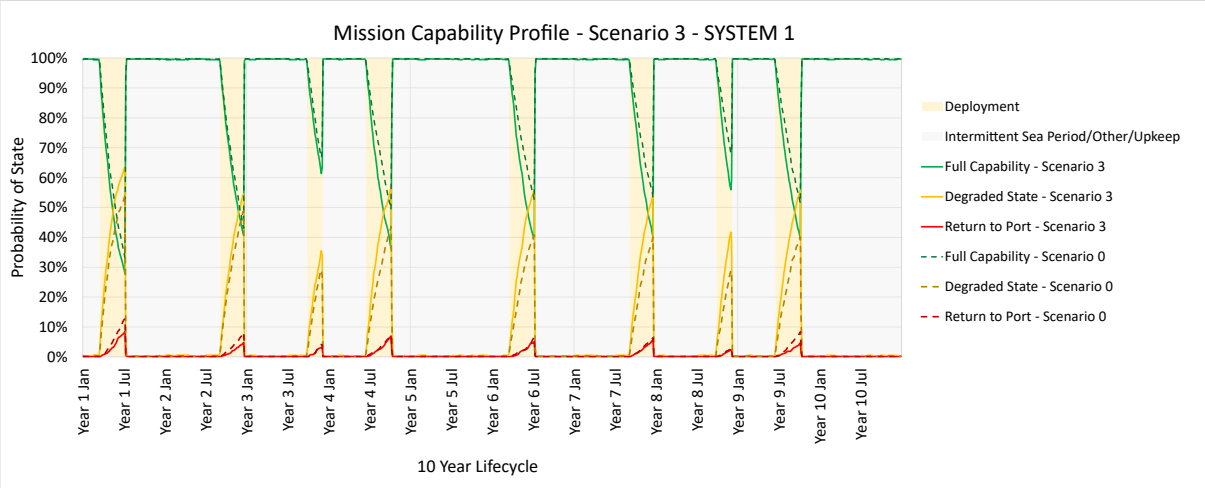


Figure 8 – Comparison of Mission Criticality profile for System 1 for Scenario 3 vs Scenario 0

Table 2 – Comparison of key results for simulated scenarios of System 1

Parameter of Interest		**Scenario 0**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Total 10-year Duration (hours)		87,600			
Total Time at Sea (hours)		28,800	31969	36000	28800
Total Downtime[1] (hours)		5,709	8301	6149	7270
Functional Availability		99.3%	98.7%	99.1%	99.5%
Total Life (hours)		3,887	3,897	3,909	4,175
Manhours Spent on Maintenance	Organic CM	330	338.5	349.3	331.0
	Organic CBM	6.8	7.0	7.4	7.8
	Organic PM	58.5	58.5	58.5	858.5
	External CM	49.2	50.8	52.2	44.4
	External CBM	10.1	10.6	10.4	13.0
	External PM	3,432	3,432	3,432	2,920

Parameter of Interest	Scenario 0		Scenario 1		Scenario 2		Scenario 3	
Average Probability of System State Results[2]								
Criteria	**FULL**	**PORT**	**FULL**	**PORT**	**FULL**	**PORT**	**FULL**	**PORT**
SYSTEM 1	93.5%	0.7%	90.5%	1.3%	93.0%	0.9%	91.7%	0.5%
SUBSYSTEM 1	99.7%	0.3%	99.5%	0.5%	99.7%	0.3%	97.1%	0.1%
SUBSYSTEM 2	99.8%	0.2%	99.7%	0.3%	99.8%	0.2%	99.9%	0.1%
SUBSYSTEM 3	96.3%	0.1%	94.4%	0.1%	96.1%	0.1%	96.5%	0.1%
SUBSYSTEM 4	96.7%	0.2%	95.3%	0.4%	96.4%	0.3%	96.5%	0.2%

Notes:

1. The downtime reported accounts for failures and unplanned corrective maintenance hours only. Any maintenance which is planned is not counted as downtime and only reported in labour hours.

2. Degraded state is defined as the difference between FULL and PORT capability.

DISCUSSION

The quality of the data obtained from this model is dependent on the number of simulations completed and the quality of the inputs utilised. This has been optimised through iterative review and re-simulation of the models and comparisons to real-life failure records wherever possible.

The results of these analyses could be used in a meaningful and powerful way. Simulations done to date with models have provided a number of valuable insights:

- **Extended Deployments:** Scenario 1 investigated the effects of extending the duration of every fourth deployment period by approximately 70%. The availability during those deployments was predicted to decrease near-linearly during the additional days, and by the end of the deployment the system would be at 84% availability.
- **Increased days at sea per year:** Scenario 2 demonstrated that additional sea days per year spread evenly across the Usage and Upkeep Cycle would not be overly detrimental to performance. The predicted overall availability does not significantly change (0.2% change overall), despite the additional 30 days at sea.
- **Maintenance optimisation recommendations should be implemented:** The maintenance optimisation recommendations made from the FMECA and RCM review activities conducted on this system focused on specific maintenance items and scheduling. The aim was to reduce the probability of failure in critical componentry whilst also optimising manhours of maintenance. The results showed an increase in functional availability whilst reducing the number of external maintenance manhours by 512 hours but increasing the number of organic maintenance hours.
- **Safety impacts:** The results obtained from these studies have been used for other work to estimate the subsequent safety impacts. Specifically, the availability results can be used as inputs for event trees and fault trees to quantify mishap likelihoods across larger systems.

CONCLUSIONS

The level of detail modelled, and extent of results obtained from RBD and RCM analyses is often much less than the full potential. This paper aimed to highlight where more value can be added and extracted from existing work.

The case study presented in this paper provides an example of how many different inputs may be considered in detailed RBD modelling to quantify changes between different scenarios. The outputs, such as availability through time, manhours maintenance, outage information on components, and more can ultimately be used effectively to inform decision-making.

The analysis method presented here has been completed in the context of the Hobart-Class Guided Missile Destroyers (DDG), however the methodology outlined is applicable to any context (both within Defence, or more widely in civilian sectors) with desire to explore changes to their maintenance and operational regimes, such as offshore facilities, chemical process plants, manufacturing, roads, aircrafts or land vehicles.

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SESSION 2

Nuclear Engineering

Nuclear propulsion is a game changer. What are the new rules?

New capability, new problems, new thinking

A training pipeline for nuclear submarine crews

Nuclear Propulsion is a game changer. What are the new rules?

Nigel Doyle, Frazer-Nash Consultancy <n.doyle@fncaustralia.com.au>

WHERE ARE WE NOW?

The AUKUS Trilateral Security Pact [1] was announced by the Prime Minister of Australia, the Prime Minister of the United Kingdom and the President of the United States of America on 15 September 2021. The first initiative under AUKUS is a commitment to a shared ambition to support Australia in acquiring nuclear-powered submarines for the Royal Australian Navy [1]. Under AUKUS, the three nations will focus immediately on identifying the optimal pathway to deliver at least eight nuclear-powered submarines for Australia [2].

A critical piece of early work is to examine the full suite of requirements that underpin nuclear stewardship and demonstrate a clear pathway to becoming a responsible and reliable steward of this sensitive technology. Australia has established a Nuclear-Powered Submarine Taskforce in the Department of Defence to lead this work [2].

At present, there is no nuclear component within Australia's armed forces. Australian civil nuclear reactor experience is limited to the operation of a 20MW thermal research reactor (which predominantly is used to generate neutrons for radioisotope creation or materials research and analysis [3]).

This means that there is a clear difference between the nature and scale of operational nuclear reactor experience in Australia, and what is now proposed to occur under the nuclear submarine program. This difference is important and needs to be treated as such. This paper examines this difference and proposes that the embedding of an effective nuclear safety culture into all the relevant Australian organisations is an important step in the process of demonstrating responsible stewardship, that is best taken now.

I firstly review the current constraints under which nuclear vessels are hosted. I then describe and emphasise the change in risk vectors when considering a mobile nuclear power plant. Finally the paper defines examine the definitions of "nuclear safety culture", and explores what effective nuclear safety culture really means, what it looks like, as well as why now is the best time to focus on it.

THE DIFFERENCE BETWEEN HOSTING VISITATION, AND OPERATING NUCLEAR POWERED FLEETS

Australia has hosted nuclear-powered warships (NPW) from friendly nations, on both the east and west coasts (specifically, the berths at Brisbane and HMAS Stirling were visited 9 times between 2017 and 2020 inclusive [4] [5] [6]). However, this is in no way equivalent to the challenges of operating nuclear powered fleets.

These previous visits by NPWs have all been authorised under the guidance in OPSMAN1[1] [7]. This document lays out rigorous and explicit conditions on the entry of UK, US and French vessels, including liability considerations and assurance around the ability to remove the

[1] OPSMAN1 is the formal guidance document on how visits to Australian ports of foreign nuclear-powered warships must be assessed for approval.

vessel (under its own or tug-power) away from the port in the event of an accident. Specifically, the conditions of entry are [8]:

a) Visits will be for purposes such as crew rest and recreation, and not for fuel handling or repairs to reactor plant (necessitating breach of reactor containment).
b) Visits will be subject to satisfactory arrangements concerning liability and indemnity, and to provision of assurances relating to the operation and safety of the warships while they are in Australian waters.
c) Movement of vessels must take place during daylight hours under conditions where visibility is not less than three-quarters of a nautical mile.
d) Navigational controls on other shipping will be applied during the time that nuclear powered ships are entering or leaving port.
e) There must be a capability to remove the vessel, either under its own power or under tow, to a designated safe anchorage or a designated distance to sea, as soon as possible within the time frame specified for the particular berth or anchorage, and in any case within 24 hours, if an incident should occur.
f) An operating safety organisation, competent to conduct a suitable radiation monitoring program and able to initiate actions and provide services necessary to safeguard the public in the event of a release of radioactivity following an accident, must exist in the port being visited.

The assessment completed for entry of foreign NPWs to a suitably authorised Australian port is based around a nuclear reference accident [8] which predicts the radiological consequences from a worst-case accident on board a nuclear-powered warship. However, a caveat of this reference accident, based on the forbidding of any fuel handling or reactor repairs, is the assumption that both the primary and secondary reactor containment are intact. This restriction significantly reduces the consequences, and also the complexity, of the assessment.

These restrictions, around both the reference accident and the entry conditions, would be neither feasible nor desirable for a fleet of Commonwealth owned and operated vessels. It would preclude the ability to do any significant reactor servicing or maintenance operations. In addition, the ownership of the vessel by the Commonwealth would also mean that significant non-nuclear servicing and operational activities could be taking place at the berth in the direct vicinity the vessel. Any such activity would then need to be viewed in light of the presence of the NPW, due to the added risk of operations affecting containment and/or nuclear risk (e.g. risk of impact from falling objects in vicinity, even if those are separately assured for workplace safety). This is a significant change in mindset for all working on this site, but one that is key to effective nuclear stewardship by the Royal Australian Navy. There is evidently a gap in where Australia is compared with where it needs to be.

Nuclear stewardship on this scale, where all activities on the dockyard must be considered for nuclear risk, will require more than simply the development of advanced nuclear-related technical and engineering capability and capacity. It will demand the development and broad uptake of an effective nuclear safety culture, beyond that which already exists in Australia.
A different approach to safety and risk management will be required for hosting our own nuclear-powered submarines – one that is both more in-depth whilst also being more manageable for routine activities. At time of writing, significant details around how the fleet

will be built, accepted, and operated are not published. That said, there are still some things that can be discussed as to how this approach will need to be driven to ensure maximum benefit to the Commonwealth whilst also continuing to ensure that the exemplary nuclear safety record demonstrated by both the US and UK fleets is upheld with Australia's new membership of this important strategic alliance.

HOW DOES NUCLEAR SAFETY DIFFER FROM NORMAL SAFETY?

The Australian Department of Defence (DOD), including the Royal Australian Navy (RAN), has in place tried and tested systems, process, and controls to ensure that the vehicles and equipment that it operates do not cause unwanted harm to either its personnel or the wider public, whilst also ensuring that the effectiveness of their assets is not unduly constrained. These systems and processes form an excellent base on which to build. But several hazards associated with nuclear power manifest differently to those from more conventional equipment.

As a hazard, radioactivity is not axiomatically worse or more dangerous than other industrial hazards. However, it does have unique and challenging attributes. It is invisible, transmissible over considerable distance, not signalled through other senses such as smell or sound, deadly in very large doses, and presents a stochastic risk of serious future illness in lower doses. While readily detectable, the sources of hazard are also frequently long-lasting, meaning the impacts of the worst incidents are both acute and then chronic. Collectively, these attributes naturally evoke a primal reaction of fear among many people. In risk communication terms, it evokes a sense of "dread" [9].

Due to the non-local and long-lasting impacts that can potentially occur if highly radioactive material is allowed to spread to the environment, assessment of nuclear risks do not just limit themselves to the dangers within and around the nuclear power system, but stretch to other aspects as well, such as lifting activities in the area, or other nearby sources of risk to the containment boundaries that are in place to mitigate the danger from radioactive contamination. Nuclear power is also unlike other thermal power sources (e.g. coal/gas) as heat continues to be generated (initially ~6-8% of full power, falling to ~1-2% after ~1 hour) for an extended period after operation, sufficient heat to seriously damage the reactor core and create additional risks if it is not managed. Nuclear safety for a power reactor is therefore not just concerned with what happens in the reactor during operation. It stretches to the surrounding infrastructure and hazards, and hazard management must continue long after the reactor itself is not actually operating. If cooling is lost, then as demonstrated by events at Fukushima Daiichi nuclear power station, irrecoverable damage can occur to the reactor, leading to possible loss of containment and the risk of radiation contamination over a large area. Management of this is not just a safety consideration but clear communication around the risk and management thereof is essential in ensuring the effective management of public opinion which could otherwise be set against the Commonwealth and lead to considerable difficulties. This topic of public communication is worthy of further expansion, but this is outside the scope of this paper.

The corollary of these unique hazards and operational challenge is that the global nuclear energy industry has developed a justifiably good reputation amongst safety professionals for the way in which the risks are managed, resulting in it being one of the safest producers of

large scale electricity, normalised for production (see Figure 1). There is already good Australian expertise around managing safety in a nuclear environment within the respected guidelines laid down by the IAEA. However this expertise is narrowly held, consistent with our limited sector.

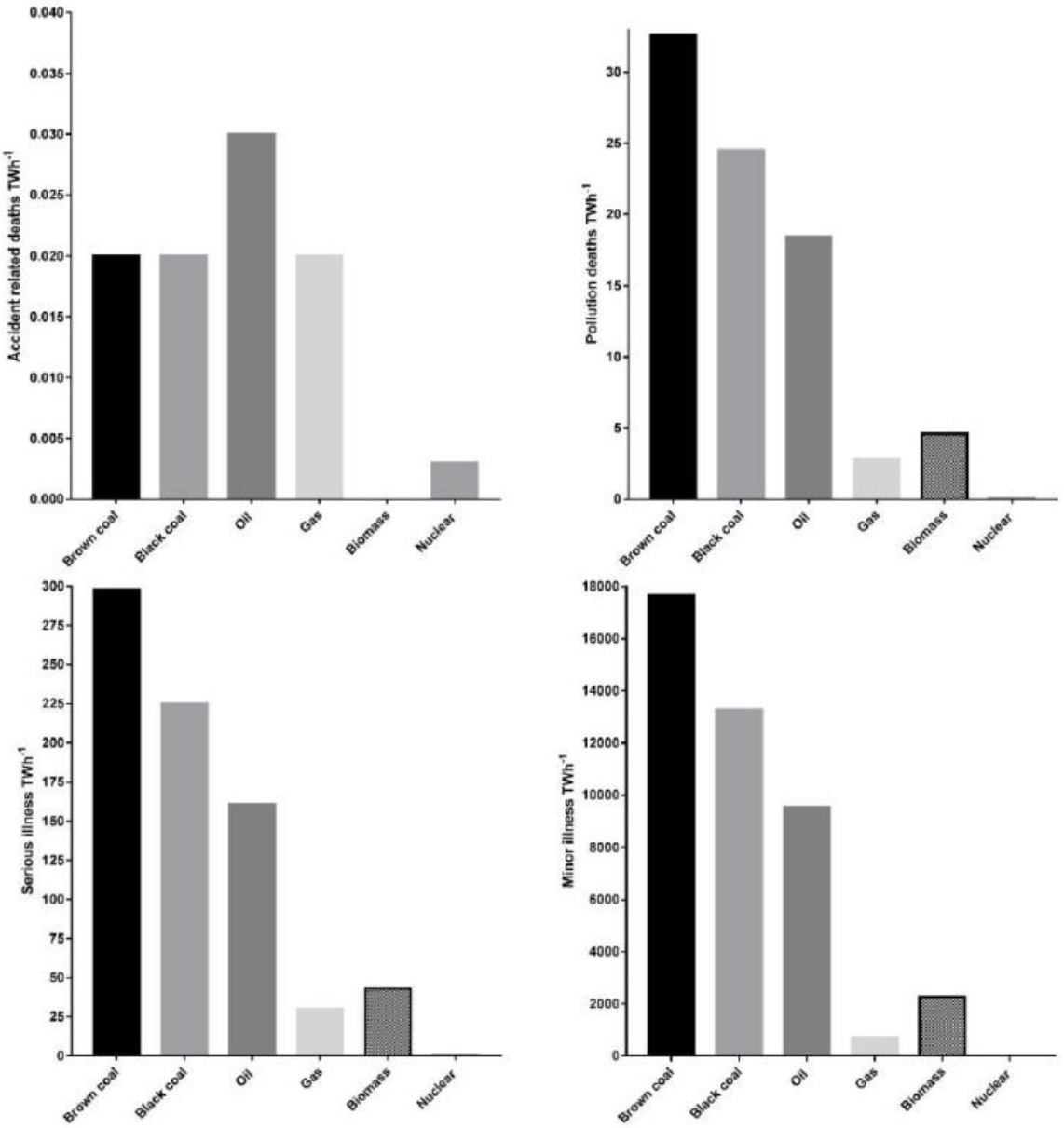


Figure 1 - Comparison of mortality and morbidity, normalised to units TWh-1, between brown coal, black coal, oil, gas and nuclear power [10].

Having established why nuclear safety is important, we can now move on to the role of nuclear safety culture within that picture. This starts with a discussion of what nuclear safety culture is and then expands that into what it looks like when applied well, and how that culture benefits the organisation.

WHAT IS NUCLEAR SAFETY CULTURE, AND HOW DID IT ARISE?

The implementation and development of strong nuclear safety and security culture[2] will provide enhanced consistency, accountability, reliability, security and, most obviously, safety for crew, employees, and the broader public. This approach, combined with effective and transparent communication on how the risks are both well understood and well managed, will also raise the prospect of broad social acceptance.

According to the International Atomic Energy Agency (IAEA), "Establishing a strong safety and security culture is one of the fundamental management principles for an organization dealing with radioactive material. Such a culture influences the organization's structure and style, as well as the attitudes, approaches and commitment of individuals at all levels in the organization." [11]. In other words, a safety culture is not just a series of regulations but is in fact a mindset that affects not just what you do, but also how you even approach it.

The term "safety culture" was first widely introduced to the nuclear industry by the International Nuclear Safety Advisory Group (INSAG), reporting to the International Atomic Energy Agency (IAEA). This was following their investigation into the 1986 Chernobyl nuclear disaster [12]. The report concluded that faults existed in safety culture within the safety management systems [13]. This conclusion was similar to that of a report commissioned by the US President on the earlier 1979 Three Mile Island (TMI) incident [14]. This report concluded that the accident was a result of "a series of human, institutional, and mechanical failures". The report notes that "the major factor that turned this incident into a serious accident was inappropriate operator action", and that this was not the fault of the operator, but instead the result of insufficient training, lack of communication (or action on known issues), and failure to learn the lessons of previous incidents. These attributes will be seen again, in reverse, when we discuss the traits of an effective nuclear safety culture.

Since the INSAG report, the term "safety culture" has been adopted across the industry. A widely used definition comes from the UK's Advisory Committee on the Safety of Nuclear Installations (ACSNI). ACSNI defined the nuclear safety culture of an organisation as "the product of individual and group values, attitudes, perceptions, competencies and patterns of behaviour that determine the commitment to, and the style and proficiency of, an organisation's health and safety management" [15]. Using this definition, safety culture is not directly linked the quality of safety management systems within an organisation, instead it is dependent on how the individuals within an organisation behave.

Whilst Australia clearly has, within the Defence industry, a well-developed safety culture, this is not a nuclear safety culture[3]. This difference is important, as within a nuclear safety culture, the importance of appropriate nuclear training is widely agreed as essential [16]. This is important for all people on site[4], or responsible for changes on site – knowledge that radiation

[2] It is worth noting that the safety and security aspects of nuclear safety should both be covered within a strong safety culture. For ease of discussion, nuclear safety, and nuclear safety culture, should (nearly) always be assumed to include nuclear security, as the two are so intricately tied.

[3] Although it should be emphasized that important and valuable nuclear and nuclear safety expertise and culture do reside in both ANSTO (Australian Nuclear Science and Technology Organisation) and ARPANSA (Australian Radiation Protection and Nuclear Safety Agency).

[4] Whether that "site" is a dockyard, or a submarine.

is not humanly detectable, or that some supplies (e.g. water, power, pressurisation, cooling) remain essential even after shutdown is important. These, and other such considerations, can and should affect decisions that people make even when their job is only related to non-nuclear plant. Recognising the nuclear aspect requires a base level of knowledge. Further, developing the culture where every question includes that nuclear aspect is something that will be new for Defence and much of its supply chain.

HOW DO YOU DEFINE AND RECOGNISE AN EFFECTIVE NUCLEAR SAFETY CULTURE?

According to the UK's Office for Nuclear Regulation (ONR), the health of the safety culture is "one of the key factors determining safety performance in organisations" [17]. In order to illustrate effective safety culture, personal examples will be discussed that highlight how it can be seen. In addition, whilst an effective nuclear safety culture will clearly help ensure safety, other benefits from the mindset are also presented.

According to many organisations (e.g. UK ONR, US Nuclear Regulatory Commission (USNRC)) there are nine key traits of a strong nuclear safety culture, specifically, from the USNRC [18]:

1) **Leadership Safety Values and Actions**: Leaders demonstrate a commitment to safety in their decisions and behaviors;
2) **Problem Identification and Resolution**: Issues potentially impacting safety are promptly identified, fully evaluated, and promptly addressed and corrected commensurate with their significance;
3) **Personal Accountability**: All individuals take personal responsibility for safety;
4) **Work Processes**: The process of planning and controlling work activities is implemented so that safety is maintained;
5) **Continuous Learning**: Opportunities to learn about ways to ensure safety are sought out and implemented;
6) **Environment for Raising Concerns**[5]: A safety conscious work environment is maintained where personnel feel free to raise safety concerns without fear of retaliation, intimidation, harassment, or discrimination;
7) **Effective Safety Communication**— Communications maintain a focus on safety;
8) **Respectful Work Environment**— Trust and respect permeate the organization; and
9) **Questioning Attitude**—Individuals avoid complacency and continuously challenge existing conditions and activities in order to identify discrepancies that might result in error or inappropriate action.

An overarching theme through these is around clear, efficient, effective, and uninhibited communication around safety, and maintaining a challenging environment to ensure that errors or inappropriate action are not accepted[6]. This general aura has been described as "chronic unease" [19] – where all that you see and do is challenged with a healthy internal scepticism.

[5] This is not exposed separately in the ONR approach, which explicitly folds this into the communication trait, and instead pulls out the importance of "Decision-making: Decisions are systematic, rigorous, thorough, and prudent" as its other trait.

[6] Returning briefly to the TMI accident discussed earlier, it is worth emphasising that TMI occurred due to many of the above traits being absent within the equipment manufacturer, the plant management, and the nuclear regulator.

WHAT DOES IT FEEL LIKE TO WORK IN AN EFFECTIVE NUCLEAR SAFETY CULTURE?

The fundamental behaviours observed in a nuclear safety culture are personal accountability and excellent safety communication (specifically the ability to raise concerns freely, openly, and without fear of reprisal). The culture is then one of shared ownership – where there are any issues, be they actual or perceived, anyone can raise them and see that their concern or query is treated with due consideration. Once this culture is embedded, safety becomes not just a consideration, and not even just the over-riding consideration, but simply part of subconscious thought – affecting all that is done both inside and outside of the nuclear environment. I believe that it is this subconscious action which differentiates a nuclear safety culture from a simple stated focus on safety.

I recall a work social event around 10 years ago. Following an enjoyable evening, a large crowd were exiting the top tier of the stadium where we had been watching the cricket. I happened to look ahead of me through the dense crowd of hundreds of people and saw our team descending the wide stairs – all at one side, all holding the handrail. They were the only people within sight to do so, despite the inconvenience of this in such a large crowd. None of these individuals had made any conscious effort to do so I later found, but the simple habit, a learned behaviour, had embedded itself so deeply that even away from a work environment where social conformity would imply otherwise, all chose to make their world just that little bit safer. Whilst this may seem "trivial", it is a sign of the general atmosphere throughout the UK nuclear industry where all sites are (justifiably) proud of their record since their last lost time accident – for some of the power station sites, this record stretched over a decade [20], despite part-time contractors, high-activity around-the-clock outage periods every couple of years, and various other significant industrial risks associated with high-speed rotating machinery, heavy plant, dangerous chemicals, and superheated steam. This example therefore demonstrates both the personal responsibility and also the avoidance of complacency that are inherent in effective nuclear safety culture.

A second example comes from one of the Magnox nuclear power stations – one of the longest running nuclear power stations in the UK (now in decommissioning). To simplify both safety compliance and clarity, all industrial areas of the site (where hazards exist from large/heavy/overhead objects and/or excessive noise) are demarcated by a blue line. Within the "blue line area", all people must wear steel toecaps, a safety helmet, and have hearing protection (with them, not necessarily worn). A station director (the most senior member of the site management team) was doing a tour of the site, when he crossed this line – whilst it's not possible to tell whether someone is wearing protective footwear, or carrying hearing protection (e.g. ear-plugs), the absence of a hard hat is plain to see. This director was immediately confronted by a junior member of staff who asked him to immediately leave the area. This the station director did, whilst also thanking the person and calling out to all both his own lapse and the excellent behaviour of that person in later communications. This simple example is a clear demonstration of many of the positive traits listed: leadership actions; personal accountability; work process; continuous learning; "safe" environment for raising issues; respectful work environment; and, importantly, but maybe not obviously, a questioning attitude. The station director is the person responsible, to the regulator, in demonstrating that the station is operating safely. As such, they have ultimate power on the site – be that implementing or changing rules, or even initiating an emergency reactor shutdown. This position of ultimate power could mean that the rules don't apply – they set

the rules – but the actions of the station team member demonstrate that a blind assumption that "it must be OK" is neither correct nor valid – this is core to not only the safety, but also the efficiency and effectiveness of the site. A culture that lets junior team members challenge senior team members on whether or not the action is correct allows improvements to the process that drive effectiveness and efficiency, as well as ensuring the safety of all involved.

As hinted in the historical reflections of the development of nuclear safety culture, the on-site culture was not always this way – nuclear safety culture had to be created. The early days of the UK nuclear industry are full of various incidents that show a sea change in the way in which risk was approached from that today. The health and safety chief (at the same station as the second example above) told me that when he was an apprentice (back in the early '70s), they used to race around the top of the railings at the edge of the cooling water inlet – a structure that is over 5m above the ground below, making this "bit of fun" a potentially deadly activity. The process of change that has taken place in the UK (and exemplified by the change in culture at this station) was driven across the industry, and covered all aspects from regulators to senior management and from reactor desk operators to temporary on-site contractors. Without question, the modern Australian Defence Force is in a significantly better position on safety than '70s Britain. However, the importance of maintaining strong, values-driven improvement is essential to the successful adoption of a strong nuclear culture within the Royal Australian Navy and its supply chain, and should see additional benefits in operational efficiency and effectiveness.

WHAT'S THE IMPORTANCE OF THE NUCLEAR SAFETY CULTURE AT THIS EARLY STAGE?

This early period in the life of the submarine task force will inevitably set the values that will be inherited by a later operating organisation. This operating organisation will be ultimately responsible for designing and building maintenance facilities, operating those facilities, maintaining the operability, effectiveness, and safety of the submarine fleet, and also decommissioning that fleet at the end of its operating life. Ensuring that all staff making decisions are suitably knowledgeable to make those decisions, as well as ensuring that all supporting staff have an environment where valid concerns can be raised and managed without fear of reprisal are the types of behaviours that can be easily set now, but would be hard to change in the future.

In addition to this, the behaviours that form a strong nuclear safety culture (such as a questioning attitude, willingness to learn, and personal accountability), are also self-evidently behaviours that will lead any enterprise to a journey of continuous improvement. This journey will not just evidence itself in a justifiably good reputation for safety, but will also lead to improvement in all areas of operational effectiveness and efficiency.

The first stage in embedding a strong nuclear safety culture is ensuring that the management of an organisation buy-in to all aspects of that culture. As the submarine task force is currently a very thin organisation, this makes it significantly easier to set a tone that enhances this. Communicating clearly, openly, and honestly about safety, and the opportunities for learning, will foster that culture. Equally important is a willingness to be challenged on whether or not actions are "right" – not just accepting that "we've always done it that way". The culture also needs to be embedded in all related activities, whether they are elsewhere within the Commonwealth (e.g. RAN development activities), or devolved down to third-party suppliers

(such as dockyard activities). If the entire supply chain is not onboard, then opportunity will quickly be lost.

CONCLUSION

Effectively applying the nine listed inherent traits of an effective nuclear safety culture to a wider organisation and the way in which it thinks and acts clearly ensures that the safety retains the necessary priority, and also provide greater opportunities for efficient and effective use of available resources.

The open and questioning attitude that this culture entails will, when correctly implemented, stretch to all aspects of work – bringing together the whole organisation in a continual journey of constant self-improvement that will affect everything from requirements definition at the start of the process, through to the correct, timely, and, efficient application of maintenance activities.

This paper has looked at where Australia currently is on its journey to nuclear-powered submarines, and where there will work will be required to develop existing practices. This led to examining the role that safety culture will play, and to that end, looked at what safety culture is, why it is needed, and what it looks like once embedded.

A safety culture can be also described as "how things are done around here." This latter description, whilst casual, is I believe, one of the best guides to knowing that the culture is truly embedded – as discussed, the reduction of risk is second nature to all involved, and this leads to more productive and engaged crews, enhanced public safety and perception, and the best possible outcome for Defence. An apocryphal Chinese proverb states: "The best time to plant a tree is 20 years ago. The second-best time is now." – as there is no earlier time to embed a nuclear safety culture for the Australian Department of Defence, now is surely the best time?

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FIN

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SUBMARINES: CONSTRAINTS AND OPPORTUNITIES

Synergy Consulting Group

Mick Mahy (Partner, Synergy: MMahy@synergygroup.net.au),
Anne Edwards (Executive Director, Synergy: AEdwards@synergygroup.net.au),
Dr. Jiao Wang (Executive Director, Synergy: JWang@synergygroup.net.au),
Dr. Jan Drienko (Senior Manager, Synergy: JDrienko@synergygroup.net.au),
Sian Phillips (Senior Manager, Synergy: SPhillips@synergygroup.net.au).

INTRODUCTION

The announcement of the AUKUS trilateral partnership between Australia, the United States and the United Kingdom is significant for its explicit focus on cooperation in the Indo-Pacific region. Its first initiative, to support Australia to acquire nuclear-powered submarines and infrastructure – while maintaining commitments to the *Non-Proliferation Treaty* and International Atomic Energy Agency safeguards regimes – challenges Australia's strategic, socio-political, economic, and legislative environment. Among this set of challenges, workforce sustainment and supply chains are sources of extant risk to national security outcomes. When the Department of Defence acquires major capital equipment, it faces an array of internal and external forces and influences that create significant difficulties to navigate. They include comprehensive planning and scoping; risk management (from beginning to end); integration complexity; good project management; industry capability and capacity; an increasing lack of skilled workforce; complex contracting arrangements; through-life support considerations. The most important conduit between these forces and influences is the ubiquitous relationship between the capability manager, the delivery group, the receiving service, and industry that is essential during every stage of the capability lifecycle. The sheer size of the program to acquire and sustain nuclear-powered submarines (SSN) should not be underestimated. But will the organisation learn from past experiences to address the constraints and opportunities that acquisition of a nuclear-powered submarine fleet presents?

Defence has extensive experience in the development of large-scale platforms. For example, the Joint Strike Fighter (JSF) known as *AIR 6000—New Air Combat Capability* (NACC) in procurement nomenclature, was conceived as replacement for five types of aircraft (the F-16 Falcon, F-15E Eagle, A-10 Warthog, F/A-18 Hornet and AV-8B Harrier). The Program is a coalition of eight partner nations who joined to fly, produce, and maintain the JSF. Its success is contingent on a common design (with three variants) and the requirement to share 80 per cent of JSF parts. The undertaking has been so complex that it has been plagued by numerous delays and cost increases. We now know this was because of unrealistic cost estimates, an aggressive program schedule, immature technology and an insufficient budget to integrate the technology. In short, the complexity of the project was so immense that trying to gain commonality from disparate partner needs meant that the cost and schedule slippage was suffusive. For the Hunter class Frigates, the aggressive timeline is likely to be the infractor. Production is expected to start in 2024; but, this will be tight due in no small part to the requirement to include design aspects from the British Royal Navy. Add to this, Australia's preference to use the Aegis (US Combat System) and CEA radars (a Sovereign Industrial Capability Priority) and already the vessel will be heavier with a decrease in range. To this end, a schedule delay of 18-months was accepted by the Defence Minister in July 2021[1]. Lessons may also be learned from a more traditional large-scale construction project such as the Collins Class Submarine in the 1980s[2]. We know that the Collins submarines were plagued by technical problems from its original design and throughout its early life. But the *Coles Review* did not find these technical issues fundamental to the Program's broader issues[3]. Rather, it found management and the inability of the Royal Australian Navy (RAN) to retain sufficient personnel to operate the submarines were the problem and by 2008, only three vessels could be crewed.

The AUKUS agreement is not settled and the terms of an agreed capability transfer for Australian purposes are still unknown. However, there are some conclusions that may be drawn from examination of what may be needed to develop a supporting construction and infrastructure strategy to enable the nuclear submarine capability. The development of solutions requires new ways of thinking to maximise opportunities and leverage capabilities in Australian interests. This paper identifies opportunities to strengthen outcomes for maritime security. It draws on large-scale platform design and expertise in nuclear, maritime,

and infrastructure to demonstrate divergent thinking on some of the fundamental inputs to capability to maximise efficiency in a new naval, defence, and foreign policy environment. The new maritime capability also requires whole of government effort extending far beyond that of build choice and delivery. It must be informed on a broader scale to maximise solutions and outcomes. This requires a shift in foreign, defence, and national security policy to shepherd it to completion. Even with the support of the United States and United Kingdom, plans for eight nuclear-powered submarines are already under intense scrutiny. The challenges include where to build, who will develop, sustain and maintain them, and how will they be crewed. Thinking beyond traditional processes for capability acquisition may alleviate pressure on key decisions: particularly if we examine how to build and sustain the infrastructure workforce. This should be done in parallel with Navy recruitment and crewing options.

Defence infrastructure contains assets in the military domain that support the effective functioning of the Australian Defence Force (ADF). The Civilian Critical Infrastructure (CCI) sectors represent a significant part of the production, supporting effective and interconnected industrial functioning of the Australian economy. Critical infrastructure assets are shared resources: where the Department of Defence priorities are geared towards operability: civilian assets are driven by economic objectives. We will examine the intersection between defence and civilian infrastructure and the services that can support this shift in Australian defence capability. To that end, this paper positions Department of Defence and CCI services as critical to raising and maintaining the nuclear-powered submarine capability. Key to success will be reconciliation of efforts to integrate defence and civilian workforces and capabilities, while adhering to some of the strictest regulations an ADF platform has ever been developed under. This is the overwhelming issue our modelling identifies – it is the “Achilles Heel” for the development of ANY defence infrastructure asset. Workforce constraints and supply constraints across all facets of development, deployment, sustainment and infrastructure are the defining challenges of securing this capability.

The paper provides an overview of the extant shipyard infrastructure and considers the development opportunities and constraints that may arise if these bases were used as interim, primary, or additional shipyards for the nuclear-powered capability. This is followed

by detailed workforce analysis for the submarine infrastructure based on one of these shipyards – demonstrating the value of the site location of the future east coast base when announced. We conclude with an examination of what persistent risks and opportunities may mean for the future supply chain – through the development, use, sustainment, and maintenance of the new submarine fleet. This paper does not draw any definitive conclusions given ongoing trilateral efforts to establish AUKUS capability transfer. Instead, workforce modelling is used to explore critical success factors, from which to meet some of the criteria the government may need to realise its strategic objectives.

CRITICAL INFRASTRUCTURE

On the 7th of March 2022, Prime Minister Morrison announced that three sites on the Australian eastern seaboard were being considered to develop a deep-water submarine base that would complement Fleet Base West.[4] This is reminiscent of the long-standing strategic objective of the Defence White Paper's *Two Ocean Navy* policy of 1987;[5] which initiated a period of unprecedented infrastructure, force structure recapitalisation, and redeployment of the RAN (when HMAS *Stirling* becoming the home of the Navy's Collins class submarines). An east coast base supports naval recruitment and retention strategies and provides a degree of redundancy in capability that acknowledges geo-strategic shifts in Australia's regional security environment.[6] Build choice and strategy will have considerable impact on the critical infrastructure needed for the new submarine capability.

The new development, "supports basing and disposition of the future nuclear-powered submarines… [This base] would provide homeported submarines with specialised wharfs, maintenance facilities, administrative and logistics support, personnel amenities, and suitable accommodation for submarine crews and support staff. It would also enable the regular visiting of US and UK nuclear-powered submarines."[7] The three possible base locations – Brisbane, Newcastle and Port Kembla – are sound choices due to their proximity to extant industrial infrastructure; populations centres that could grow and attract a submarine workforce (which would include uniformed and civilian crew and support); proximity to maritime training facilities; be strategically safe from potential threats.[8] While the decision to select a new naval base on the east coast is based on the need to transition away from the Collins Class, there are lessons to be learned from the extant sovereign base capability. There

are currently two major ship building yards in Australia – Osborne in Adelaide and Henderson in Perth. Currently, Osborne is Australia's largest 'naval' shipbuilding hub. It has demonstrated its success at building large naval vessels including the Collins Class Submarine, the Air Warfare Destroyer and it will soon begin to build the Hunter Class Frigate. It may also be a possible contender to build the Nuclear-Powered Submarine. Henderson is a 'commercial' Shipbuilding precinct but is positioning to become the Australian sovereign shipbuilding capability powerhouse into the future.

To determine lessons available from Australia's sovereign base capability, our economic modellers conducted a feasibility study to understand if there was a need for an interim naval base and/or a model for the new naval base. To achieve this, the current construction and (deep) maintenance infrastructure already existing at Osborne and Henderson was analysed to establish if they are both fit for purpose. Our feasibility study demonstrated that while any potential upgrade of infrastructure is dependent upon the design choice of the submarine, Osborne's submarine build history presented as a critical strength in its favour. The downside is that it is constrained by its older physical infrastructure and constant inability to maintain a skilled shipbuilding workforce for ship building and sustainment.

There are clear challenges to realising Australia's intent to maximise in-country support for submarine capability. Defence and CCI hold similar, and at times, symbiotic physical assets and systems that functionally enable the operation of critical services in Australia, see *Figure 1*. There are two key components of civilian and defence critical infrastructure inter-dependency. The first is defence critical infrastructure contains assets in the military domain critical to the effective functioning of the ADF. The second is that CCI represents a significant part of production, supporting effective and interconnected industrial functioning of the Australian economy. Therefore, efforts to prepare existing and future maintenance facilities to receive the submarine fleet should be put in place concurrently with development of a new base on the east coast. Preparing these facilities requires infrastructure upgrades and new construction irrespective of the technological design selected. Any delays to critical infrastructure preparedness will result in maintenance of the first submarines having to be undertaken outside of Australia. Significant reconstruction and upgrades of the Osborne shipyards and surrounding support facilities should be the priority among a set of projects to

enable onshore maintenance and porting capabilities. Our modelling indicates that the compounding effect of state committed infrastructure developments and associated delays creates a significant shortage of available capital assets, materials, and personnel to conduct works on infrastructure upgrades.

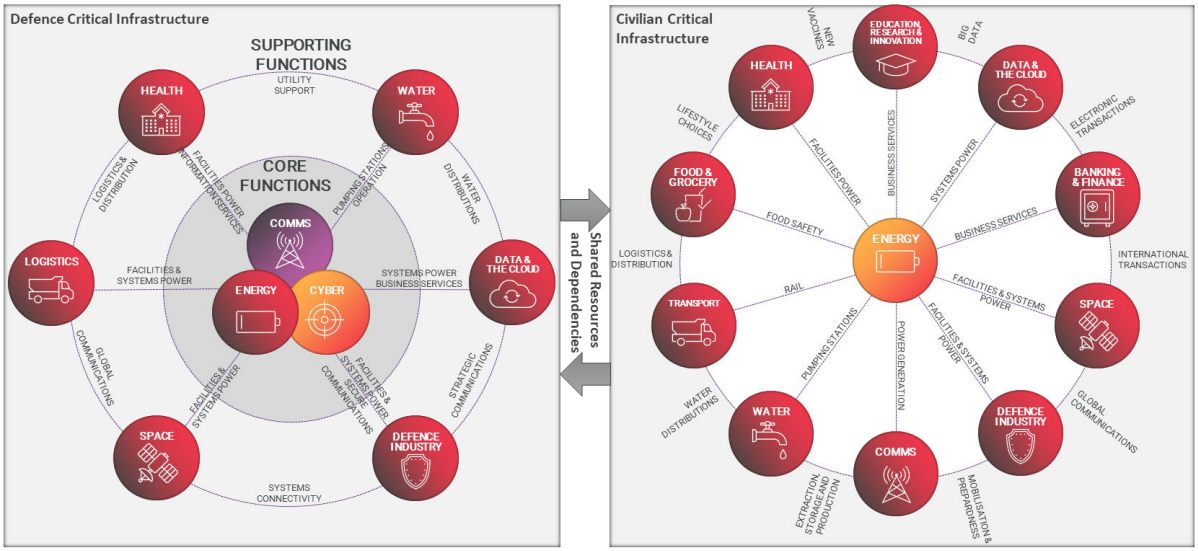


Figure 1 – Critical Infrastructure Inter-dependency – Defence vs. Industry

Tailored ecosystem modelling focuses on a system-wide approach to sector functionality and accounts for inter-dependencies between civilian and defence domains to support clearer strategic pathways to sovereign capability acquisition and sustainment. Therefore, it is essential to improve understanding of the interconnections between defence and civilian critical services such as defence key and enabling assets, CCI assets, and government as a regulator. Modelling presents the likely outcomes of external impacts to defence capabilities, industry functionality and the flow-on implications for other parts of the economy.

The scope of what is required to maintain a deep platform for the submarines is an important milestone because it informs the initial and long-term contracting arrangements required to secure these capabilities. Two adjacent priorities to scope are maturing Australian industry capability, and long-term opportunities for academic research and innovation. Both can generate the expertise required to fulfil future capability development activities. Long-term commitment to academic partnership is also critical to the success of delivering innovation, research, and development. Such partnerships can be leveraged to drive the uptake of

technology insertion; shaping and incentivising Australian industry and technology partners to build products and services that can be incorporated into the design stages of the submarine program.

WORKFORCE

Prime Minister Morrison raised an important criteria to meet the objectives for the submarine base – the ability to, "attract, recruit and retain the substantially larger uniformed submarine workforce we are building to crew and support the future submarines."[9] Skilled workforces play a critical role in the function and operation of the critical infrastructure and industry sector in terms of skill type, accessibility, and supply/demand balance. The government may seek to map the skills needed in quantity and for how long over the lifetime of the submarine fleet. We used our workforce model to indicate what this might look like. The occupation skills index is an indicator of over supply or under supply in the external labour market in the private economy. It is defined as a percentage deviation from the demand of skill requirement[a], or:

$$\boldsymbol{Skills\ Index} = \frac{\boldsymbol{Skills\ Supply} - \boldsymbol{Skills\ Demand}}{\boldsymbol{Skills\ Demand}} \times \mathbf{100}\%$$

The Australian and New Zealand Standard Classification of Occupations (ANZSCO)[b] classifies both core and non-core occupations in maintenance, training, digital support, and the associated ground infrastructure support. The availability and shortage of certain skills and occupations in the wider labour market drives the likelihood of obtaining the required skills to deliver core and non-core skills. The skill index shows the difficulty of obtaining new skills from the external labour market. Significantly large negative figures demonstrate a high-level of difficulty in obtaining workers to support specific program functions. Core occupations are closely aligned to the job families critical to the delivery of projects; often representing very specialised skills which need to be maintained over the long-term – even during periods of reduced demand. Non-core job family skills present a more generic part of the workforce with skilled labour available in the market. This modelling is based upon skills, industries, and job

[a] If the skill index is positive percentage, it means skill surplus, while vice versa.
[b] Up to 6-digit ANZSCO Occupations, ABS#1220.0

families that are currently not under the same strains and penalties as those required to work with the most sensitive of nuclear technologies. Yet, we can draw some conclusions that allow some visibility of the constraints that workforce capability may face. *Figure 2* demonstrates selected occupations at *4-digit ANZSCO* level in terms of skill index – shortfall gap vs. surplus – to present a dynamic labour market in Western Australia. The skills gap is shaped by a diverse range of global and local drivers. A highly imbalanced difference between skill supply and demand generates risks for employers presenting as a skill shortage. An ideal market environment should have a skills gap as close to zero as possible, alternatively represented as a small percentage of the workforce.

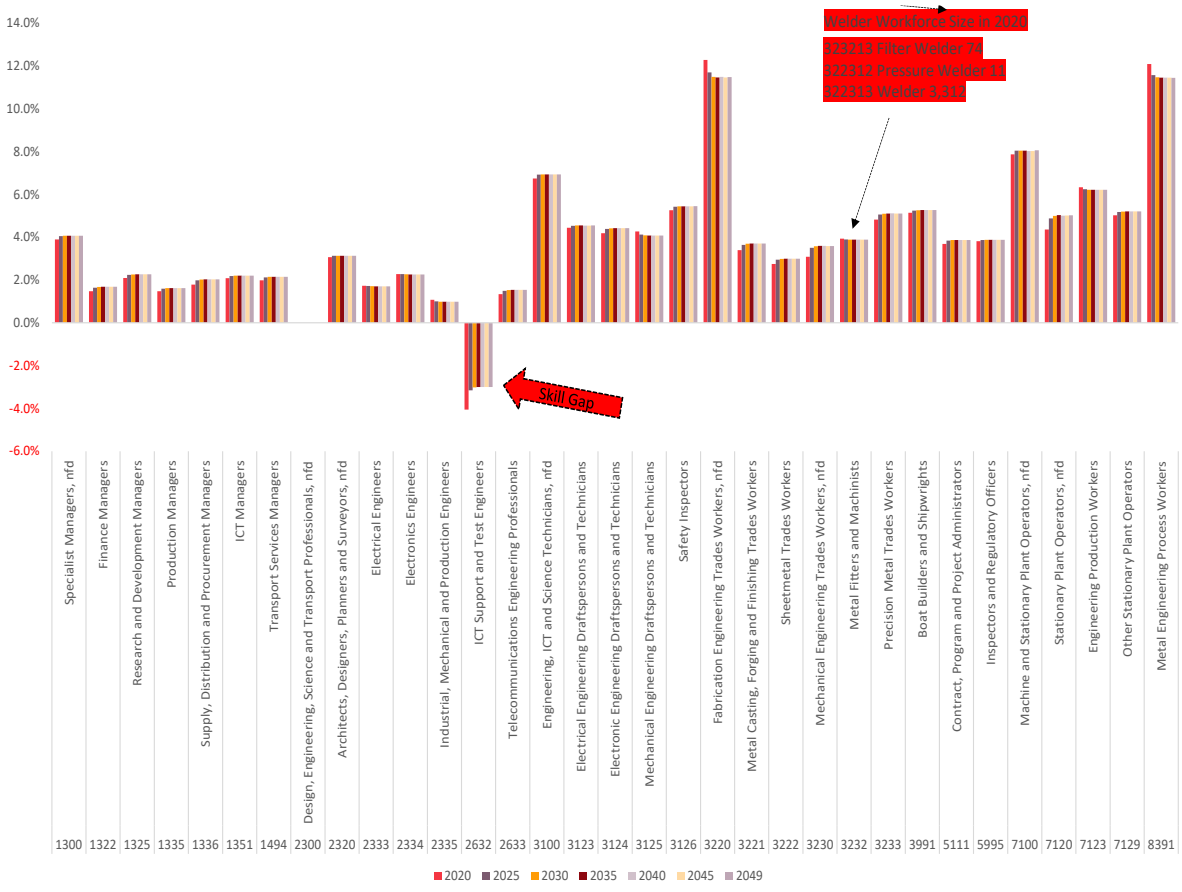


Figure 2 - Skill Gap Analysis on Selected Shipbuilding ANZSCO 4-digit Occupation in WA

Our modelling identifies that the severity of workforce shortages will impact capability readiness differently over time. This can be managed using Agile methodologies to plan, maintain and develop critical skills required over the long-term. The identification of gaps in local capabilities and skillsets as early as possible is fundamental to their resolution. It will also

be necessary to forward manage industry capability and skillsets that are essential to technology releases, intellectual property, and technical data.

Partnering with industry to deliver the submarine capability presents a broad set of challenges. An active and ongoing dialogue with Australian industries on materiel and services at every stage is crucial. Sharing sensitive nuclear technology will likely preclude many stages of the development from being discussed with the wider industry; but, early consideration should be given as to how industry partnerships can be leveraged. These partnerships can provide the space for strategic engagement to drive skills development. For example, the Defence Industry Policy Division should be working closely with the Nuclear Submarine Task Force to identify future workforce skills gaps, policy levers and incentives to mitigate these gaps. Access to a skilled Australian workforce will be essential to the success of the program's Australian industry strategy. Notwithstanding the sensitivities and the highly educated workforce needed to operate and maintain the submarines, there is a need to insert some pragmatism into policy discussions about required onshore capabilities and those supported by international partners. Workforce shortages will be directed in the short- to medium-term by a significant absence of specialist skills and knowledge within the national support base. In the longer-term, workforce shortages may be characterised by an ageing population, difficulty in incentivising the existing skilled workforce to remain, and the suitability of highly skilled personnel. A long-term view of a sustainable industrial base supported with the workforce skills and development pipeline to realise this effort is achievable. It is normal for industry to experience frequent changes in demand for skilled workers from other sectors and procurement processes cause workforce inefficiencies. Strategic defence engagement can support industry to grow beyond its current capacity by addressing these inefficiencies as part of its Nuclear Submarine Task Force.

The recent commitment of the government to increase capital investment and the advancement of nuclear technology does not change the fact that the skills required to achieve this on a sustained basis does not yet exist. There have been some attempts to address the limited number of workers in the field by releasing a significantly greater number of scholarships to develop a pool of talented and highly skilled workers in the future. But the number and the geographic concentration of learning facilities continues to significantly limit

the growth of newly available personnel. The workforce modelling identified conditions where policy levers could focus Australia's education intuitions' efforts to produce more graduates in specialised fields to address current and future skill gaps. Proactively dealing with these issues will mean Defence will have strategic relationships across Australian industry to ensure the required workforce is available to support this and future programs in public or private sectors in pursuit of defence objectives.

SUPPLY CHAINS

The Australian government has long leveraged Naval shipbuilding as a platform for a competitive local defence industry. Alongside historic support for a sovereign defence industry base, the Australian Government has centred defence industry as a critical component of Australia's COVID-19 economic recovery. This approach reflects a broader transition to reinforce economic and strategic goals as mutually dependent and builds the foundations of strengthened national resilience and preparedness for a changed geo-strategic environment. Within this context, COVID-19 has shaped a national discussion about sovereign capability – when, and in what industries should a greater degree of self-sufficiency become an explicit strategic choice in Australia's interests. Sovereign capability discussions are also inherently about the strategic shaping of supply chains to deliver in Australia's interest. Now, Australia finds itself at a critical juncture in its design of nuclear naval capability – our sovereign capability and supply chains have the highest dependency on manufactured imports and lowest levels of extant manufacturing self-sufficiency in the OECD.[10] Australia's Naval industry is exposed through its supply chains to a variety of risks that can dampen industry drivers, increase costs, cause schedule delays, and ultimately undermine Australia's national interests as capability acquisition is delayed or underperforms.

While supply chains are complex systems designed to deliver consistency and regularity as their complexity increases – their transparency decreases. The state of global supply chains, under pressure for some time, has been exacerbated by ongoing implications of the COVID-19 pandemic. In Australia, industry struggles with increasing costs, decreasing freight availability, and drastic changes to the global business environment. This is compounded by pressure within air and maritime logistics industries to manage freight movement, and significant changes in consumer behaviour. Within this framework, industry continues to

adapt – reviewing their business models to leverage specialisation and economies of scale, adopting agile ways of working, and value chain transformation to manage supply chain disruption. Differential global recovery from the pandemic within and between geo-strategic regions and the repercussions of regional conflicts, further sharpen the demand for Defence to consider the ways it can adapt capability acquisition strategies to manage risk and leverage opportunities in the 'new normal' for supply chain centrality to asset acquisition and sustainment.

We know that business supply chains that lack flexibility, demonstrate geographic clustering, and have long supply chains – are more prone to risk. For policymakers concerned with market-level supply chain risk, Australia's imports are most vulnerable to disruption in health, water, and energy industries.[11] Our model uncovered differential availability of skills, materials, and infrastructure accessible to Defence as it moves from acquisition to maintenance functions for these capability platforms. For Defence, the key to alleviating some of the now chronic challenges embedded into Australia's naval supply chain is strengthened collaboration and real-time learning between services acquisition officials and industry – built around strategic clarity outlined in the *2017 Naval Shipbuilding Plan* and expanded under the *2020 Force Structure Plan*. As the Government's new Nuclear Powered Submarine Taskforce takes shape, its recommendations should inform treatment of supply chain risks to mitigate implications for Australia's national interests, capability to support Allied activities, and lead regional response efforts.

Using detailed supply chain analysis, we can also determine not only the direct effects of supply chain shocks but also the indirect effects by tracing the interdependency of industries via their supply chains to base materials. For example, a hypothetical critical infrastructure disruption to the energy and transport sectors – where up to half of the liquid fuel supply chain is disrupted and sixty per cent of the transport sector is disrupted (operation of maritime ports) – for a period of just three weeks can generate direct GDP loss of up to one per cent, see *Figure 3.* This may cascade into other industries causing economic flow-on impacts through inter-connected supply chains which are only exposed when supply chains are impacted in this manner (such as critical infrastructure inter-dependency) potentially leading to up to two per cent loss to GDP. To put this into context, the defence budget is just

above two per cent of the national GDP per annum.[c] Should this hypothetical disruption occur, Defence can expect increased acquisition costs and schedule delays without adequate mitigation and adaptation strategies in place to dampen the negative impacts of supply chain disruption on capability acquisition targets.

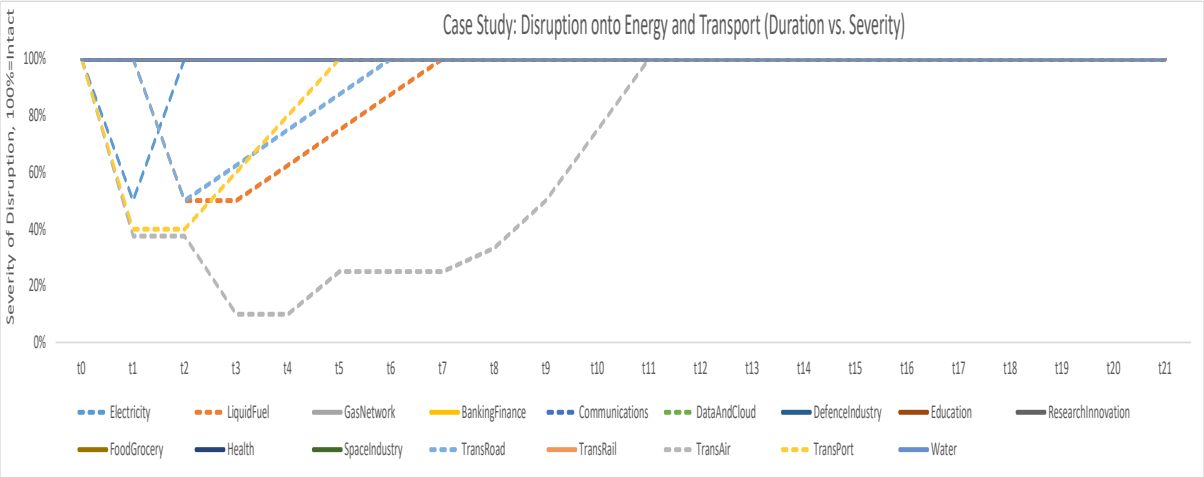


Figure 3: Direct Impact of Disruption and Recovery Profile

Source: Assumption-Driven Parametric Approach

Depending on national strategic priorities, the impacts of market disruptions and recovery profiles between defence and civilian industries may be unequally shared with direct consequences for socio-economic policy and national resilience. Large disruptive events (such as natural disasters, regional conflicts or pandemics) to the market expose these system vulnerabilities. This environment increases the likelihood of a potential market failure as physical susceptibility and economic fragility across the supply chain. A risk and vulnerability measurement can demonstrate the impact of potential disruption scenarios to defence critical infrastructure assets, including the spill-over effects and any cascading impact onto the infrastructure system. Building on the scenario outlined in *Figure 3*, should the disruption event go beyond the maximum capacity threshold of the nuclear submarine capability project to absorb material and resource scarcity, it could result in an irrecoverable situation where a complete rebuild might be required to maintain the pre-disruption level of operation and performance. Risk and Vulnerability analysis could be used to inform defence strategic

[c] Defence budget climbs to $44.6 billion in 2021/22 budget. https://www.aspistrategist.org.au/defence-budget-climbs-to-44-6-billion/ Although this may change, depending on the election outcome of 2022

engagement to strengthen the existing infrastructure system interests (such as upstream and downstream interactions); or to develop construction and infrastructure strategies as Australia's nuclear capabilities are developed.

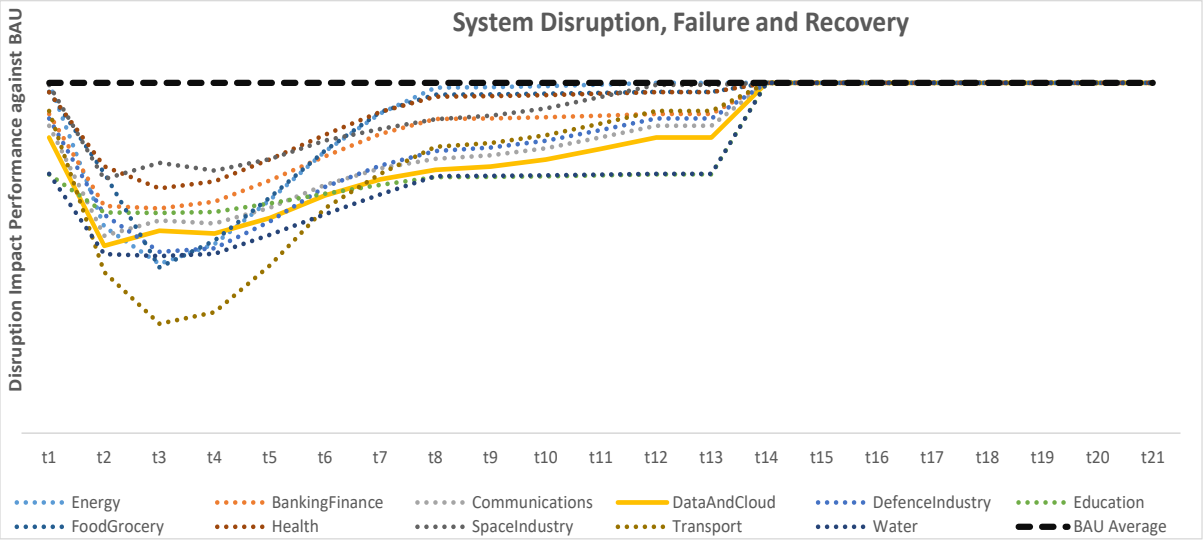


Figure 4: System-wide Impact, Performance Index against BAU

Source: Synergy's Modelling Calculation

Australia's shipbuilding and maintenance industry is import dependent. For example, in the defence sector, Australia has medium-high operation capabilities while low-medium productive capabilities.[12] Using a detailed model, our analysis demonstrates the potential impacts of a hypothetical system-wide event impacting supply chains, see *Figure 4.* Our modelling shows the significant and relative exposure of defence industry to disruption. While the industry has high barriers to entry due to significant capital investment requirements in facilities, the consolidation of talent is less centralised than across industries relying on similar skills. This will become more of a concern when layered with a significant increase in security regulations for a nuclear skilled workforce. There are few prime providers directly involved in delivery of major supply contracts. However, there still exists a network of smaller competitors (who will still need to be aware of their commitments to nuclear regulations and oversight) that supply the primary providers which motivates the aggregate industry to continue to compete and innovate.

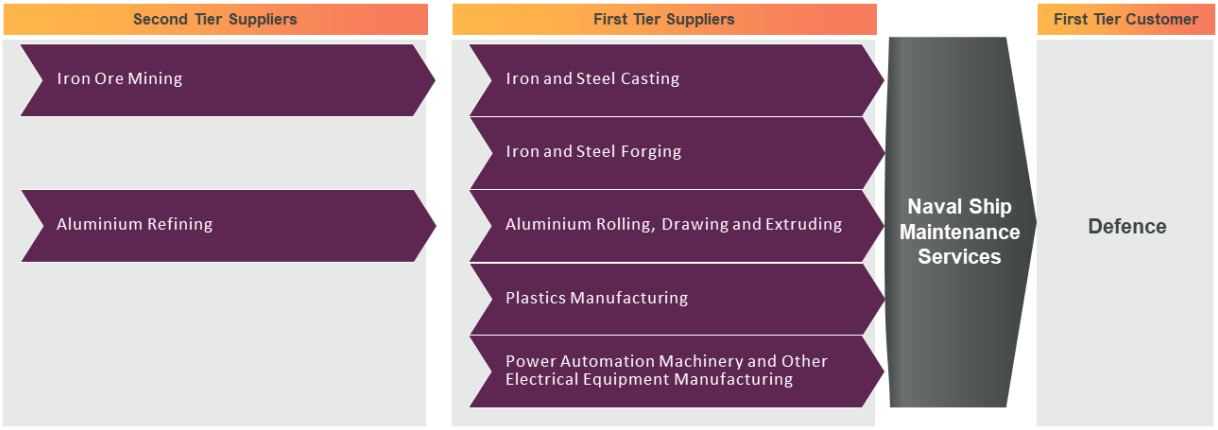


Figure 5 - Suppliers

The nuclear program is expected to operate for at least the next four decades. A priority focus of the program strategy is to deliver defence and industry benefits over the long-term. There is scope to establish an opportunity pipeline for Australian industry. The pipeline could leverage economies of scale resulting from significant optimisation and reduce the risks in supply arrangements. This approach delivers benefit to Defence by providing access to sustainable and efficient Australian industry suppliers at lower costs. Defence may further seek to develop supporting comprehensive strategies based on robust assessment of supply chain domestic industrial strengths and vulnerabilities in Australia. There is scope to inform supply chain optimisation applying scaled maturation processes by developing sector plans to secure local production and address policy challenges to Naval capability.

As Australia develops its Naval capability, effort is needed to reinforce sovereign capability and solidify Australia's commitment to be a member of the global fleet support network. Within this approach persistent risks should be addressed. These include the political inclination to support domestic shipbuilding and maintenance industry, the financial impost of education while the domestic sector builds its sovereign 'brains-trust' capability, and public awareness of the nuclear realm writ large. Further consideration should be given to assessment of the competitive and comparative advantage of Australian shipbuilding and maintenance capabilities. Given the sensitivities, global competitors for the nuclear submarines are not a factor; but they will emerge for other platforms among the defence and civilian sectors. This highlights the importance of a continuous evaluation process informing the ongoing capability development needed to secure Australian interests. With appropriate analysis informing comprehensive long-term investment plans, defence and industry have the

foundations to stabilise an increasingly uncertain environment and direct strategic production effort in Australia's strategic interests. Growing stability in the local industry and its support base to mature and provide innovation, advancement in technologies, and enhance Australia's geopolitical leverage in the region requires strengthened structures within Defence to direct industry engagement. Nuclear capability is extremely challenging to establish in Australia, and it may prove even harder to maintain and sustain efficiently and effectively.

CONCLUSION

The AUKUS announcement to build nuclear maritime capability in Australia is a strategic shift in Australia's diplomatic, strategic, and economic posturing in the Indo-Pacific region. The Prime Minister has underscored the importance of sovereign capability to this shift in posture. Any discussion of sovereign capability in Australia must be cognisant of our recent history of deindustrialisation. Our modelling demonstrates that critical infrastructure, supply chains, and the workforce to sustain the submarines will encounter significant hurdles and present challenges to realising the strategic objectives of Australia's Nuclear Submarine Program. There is significant policy opportunity to increase industry engagement, public awareness, and mature long-term strategic planning of inputs to defence capabilities. There is evidence to support thinking differently about these challenges: to not opt for well-worn processes: to apply divergent thinking to develop innovative strategies to overcome a monumental change in Australian foreign, defence, and national security policy and infrastructure.

We know that Defence will continue to face budgetary pressures over the forward years. Concurrency pressures will continue to increase; challenging defence capability to meet domestic commitments and foreign activities. While Australia's national security tasks are almost exclusively assigned to capabilities, this is unlikely to change and the pressures on Defence will continue to grow. The nuclear-powered submarine is a highly sensitive, complex and large program. It will increase capability and workforce pressures – even more so due to the need for nuclear specialised skills in the domestic workforce. This means that fundamental reform is required for Australia to achieve a higher degree of self-reliance, or sufficiency to support a nuclear-powered submarine capability and deliver its broader sovereign industry priorities. This includes supporting submarine maintenance activities,

coordination (within defence and across industry) and management approaches relating to very large and very long-term programs such as this to facilitate a more effective relationship between Defence and its suppliers. Building long-term, outcomes-focused strategic relationships between the nuclear submarine program, a sovereign capable workforce, and its many industry partners will build confidence. This can lead to the best industry and defence capability outcomes. There still remain challenges with Australia's strategic adoption of nuclear-powered submarines including the need to resolve barriers to sensitive technology sharing; the socio-political consequences to changing long-held Australian nuclear policy; legislative change in accordance with nuclear treaty agreements; and growing an educated workforce needed to design, develop, sustain and maintain the capability needed to realise our strategic maritime interests. Ultimately, no matter what submarine design or location for an East Coast Base is deemed fit for Australia's strategic objectives, thinking differently and creatively is the ONLY way to achieve the delivery of a significant part of Australia's defence and national security.

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A Training Pipeline for Nuclear Submarine Crews

Author: Roger Baker, L3Harris MAPPS Ltd, Roger.Baker@L3Harris.com

Author: David Pritchard, L3Harris MAPPS Ltd, David.Pritchard@L3Harris.com

INTRODUCTION

Generating the expertise and culture required to operate Nuclear Powered Submarines (s/m) represents a step change in the training regime and pipelines for the most competent and experienced navies. The introduction of the Astute Class s/m into service with the UK Royal Navy, with their innovative new technology, also posed a major challenge in the concurrent design, development and introduction of an equivalently innovative training solution.

This paper will outline the innovative solution adopted for the Astute Class Training Service (ACTS), as well as the state of the art technical solutions used in the production of the various training devices including propulsion and s/m control trainers. The challenges of developing the training solutions to accurately reflect the 'as built' configuration of the First of Class (FOC) s/m will also be explained.

Finally, the paper will reflect on the enterprise benefits, key risks and lessons learnt throughout the Astute Class Build Programme, and during the continuing operation of the Training Service.



Figure 1 – Astute Class s/m

BACKGROUND AND EXPERIENCE

L3Harris MAPPS Ltd (L3H) has been involved in the Astute Class s/m programme for the last 22 years, both as the Integrated Platform Management System (IPMS) provider for Astute Class Boats 1 to 3, and since 2001 as part of a joint venture consortium, for the design, development and delivery of the ACTS including all training media and courseware. For Astute Class Boats 1 to 3 L3H was responsible for the design and delivery of the s/m principal

operator workstations for platform and propulsion systems control, including responsibility for human factors, safety and operability. As the IPMS provider for Astute Boats 1 to 3 L3H was also responsible for the system design, development and delivery of a SIL 2 distributed control system including s/m vehicle control. For the latter this included development of an innovative dual redundant computer controlled Steering and Diving Control (S&DC) system, and for the development of the s/m's S&DC autopilot and hover control systems that are embedded software applications of the Astute Class IPMS.

For the ACTS L3H was responsible for the design, development and delivery of a range of training solutions used for nuclear propulsion and platform operator and maintainer training. This included the provision of full scope high fidelity operator team trainers, part task trainers, supporting courseware and Suitably Qualified and Experienced Personnel (SQEP) instructors for training delivery, integrated into the existing training pipelines. These solutions were able to draw on the extensive pedigree of L3H parent company L3Harris MAPPS Inc. as the foremost provider of training simulators for the worldwide nuclear power industry.

BUILD TRAINING REQUIREMENT

Build Programme Challenges

A major challenge in the development of the Astute training solution was the requirement for development concurrent with the boat build programme. There was no firm design baseline, which had to be iterated during the boat build process, on which to base the training solution. The requirement included the development of courseware and media, both of which had to accurately reflect the actual boat configuration.

The Astute programme training requirement also demanded that the crew of the FOC s/m be trained and qualified to the exacting standards required for Nuclear s/m propulsion and ship control operation during the s/m build and commissioning phase. This necessitated that the training media and courseware for training delivery needed to be developed in parallel with the s/m build, introducing a number of unique challenges in meeting the ACTS Ready For Training (RFT) date.

L3H designed, developed using a classic full design life-cycle, and delivered into service a full scope nuclear operator trainer (Manoeuvring Room Trainer - MRT). The MRT being similar in its functionality scope and operation to any major warship machinery ship control centre, with the addition of the nuclear steam raising plant and s/m propulsion aspects. L3H was also responsible for the development of a dynamic full mission s/m control simulator (s/m Control Trainer - SCT) based on a six (6) degrees-of-freedom motion platform system. ACTS is also responsible for provision of training to ship staff for the duration of the s/m's operational life. This includes support and upkeep of the training facility and its associated training media. To meet this requirement L3H has a through-life contract to support these key trainers for the life of the Astute-class s/m platform, which at contract award in 2001 was 37 years. The ACTS is now entering its 12th year of operations.

Development of the two key operator trainers (MRT, SCT) for the ACTS, which was a major achievement, included production of structured courseware using a recognised systems approach to training. The scope included instructor training and qualification, and the actual training delivery, using the L3H developed training media, in a customised waterfront Astute Training Facility (ATF) in the s/m operating base (Faslane). With the fourth Astute class s/m (HMS Audacious) now in service, L3H has now supplied a second full scope nuclear operator

trainer (MRT2), and an innovative soft panel SCT [see figure 2] to support additional ACTS training. This additional provision reflects an uplift in media utilisation resulting from the increase in the number of s/ms entering operational service.



Figure 2 – Astute Class s/m Control Trainer

Training Capability Timeline

A major challenge was to develop the Training Service Capability, resource this requirement, and then to sustain the service provision Delivery Capability. Growing the capability required significant investment to first attract and recruit the necessary instructors and training designers, and then to sustain this capability into the operations (delivery) phase. The ACTS pre-operational phase contract was awarded 2001. The ACTS operational contract did not commence until 2011. That said, the pre-operational contract had to manage a significant slip of the Astute Boat Programme, and subsequent major s/m design changes that impacted the development of the key high fidelity operator trainers (MRT, SCT). From this it can be seen that a least ten years should be allowed within a programme to bring the training capability to full readiness, and this is for the Royal Navy with forty years of previous nuclear s/m operating and training experience.

TRAINING COURSEWARE CAPABILITY AND DEVELOPMENT

Fundamental to the acceptance and through-life delivery of safe training is that the training courseware itself is designed, delivered and maintained to an established standard. In the UK, this standard is the Defence Systems Approach to Training (DSAT)[i]. This documentation must be reviewed and re-baselined every three years. For the fifty (50) courses within the ACTS this has represented a significant task in its own right. A major challenge for the ACTS was the requirement to meet key dates for the development of courseware without availability of mature operator and maintainer Training Needs Analysis (TNAs).

It was necessary to recruit a Training Design and Delivery team with the necessary Subject Matter Expert (SME) knowledge to develop the Training Service courseware. Then to ensure courseware integration with the training media, and then to deliver SQEP instructors to deliver the training once at RFT. For Astute Training this represented a major challenge to the Training Design (TD) enterprise, accompanying courseware development, and to eventual training delivery. It required over thirty (30) SMEs with the necessary TD competencies and

skills to support the courseware development, and deliver training as SQEP instructors. It also required the setting up of a training Quality Management System (QMS) to assure the training output and to maintain the necessary delivery standards. Recruiting and retaining SMEs, maintaining the SQEP steady state instructor cadre (24) needed, who are predominantly all ex UK submariners, remains a key risk to the training service.

SYSTEMS APPROACH TO TRAINING

Training Design Process

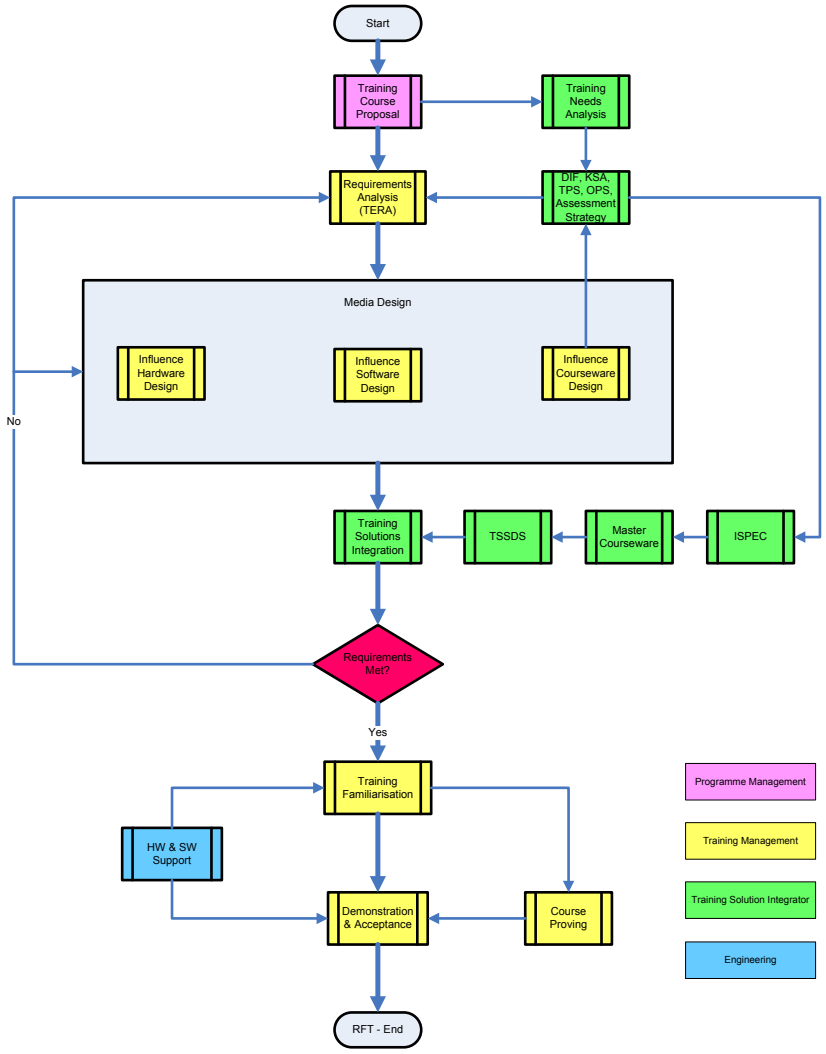


Figure 3 – ACTS Training Design Process

The TD process is defined to provide guidance on the structured steps to be followed to develop a complete training solution, including training media and environment, courseware and supporting courseware documentation. The process steps identified are broadly aligned with those found in the Royal Navy's Systems Approach to Training (RNSAT)[ii], the forerunner to DSAT, and the ACTS contracted standard. The process used by L3H is therefore primarily focused on the training media design activities. Courseware design development is closely aligned to that of the training media development, as combined they form an integral part of the overall training solution. The media and courseware design was developed concurrently using the same process to design, develop and then deliver the training solution(s).

Statement of Training Requirements (SOTR)

The overall scope of the ACTS is to provide some fifty (50) different courses to a throughput of some one thousand (1000) trainees per year in steady state delivery. The first task of the Training Service provision was to agree a Statement of Training Requirements (SOTR) with the relevant authorities. The SOTR had to consider the existing nuclear s/m Fleet training provision and identify the Astute Gap (training not covered by existing RN training) as a new class through conduct of a Training Gap Analysis. The identified Astute Gap training content had to be agreed with the overall RN Training Requirements Authorities (TRAs) and aligned and integrated with the existing RN career and nuclear training pipelines. Integration with the existing pipeline enables staged training delivery in support of the various nuclear operator watch-keeping categories (A, B, C & D). Through the use of DSAT the training courseware and delivery is aligned with the existing pipelines, thus assuring full coherency across the service.

Training Equipment Requirements Analysis

The TD process for the ACTS involved the development of a detailed Training Equipment Requirements Analysis (TERA) process. This examined the level of fidelity requirement for each training device to satisfy the training objective for each course element. For nuclear propulsion control, it is customary to provide a full scale replica of the Manoeuvring Room and the Submarine Control desks. In other areas, full physical replication has not been required. The TERA process assessed each on-board operator role, task or duty conducted by the operator at his principal operator workstation, including the undertaking and conduct of all standard and emergency procedures. The process recorded all physical, environmental, and functional requirements to carry out each operator task (Task Analysis) identified by the relevant TNA job and or role scalar. From the results of the TERA process it was then possible to determine accurately the level of fidelity and the scope required from each of the training devices, to meet the training acceptance requirement. In practice this has resulted in a full fidelity simulation model of each of the s/m's systems capable of representing both normal, abnormal and accident conditions. These models then interact with a faithful representation of each of the s/m's operator control stations, including features such as interactive internal communications, sound (collision) and environmental (ventilation) effects, and in the case of the SCT six (6) degrees-of-freedom full motion effects.

DEVELOPMENT OF TRAINING SOLUTION MEDIA

Common Simulation Models Approach – Create Once, Use Many Times

L3H developed all the simulation models deployed in its training simulators from first principles, using its Orchid® Real-time Object Oriented Simulation Environment modelling toolset. Using this highly flexible and adaptable object-oriented, graphical/icon-based suite of tools L3H has faithfully modelled all the required platform and propulsion systems. TERA was used to identify the target system fidelity level to enable the execution of the platform operator tasks identified in the operator job scalar. Orchid® Modelling Environment (ME) employs 'software through pictures' development environment for the construction of simulation systems. The tool provides libraries of component objects for the construction of Orchid® schematics; these are but not limited to, hydraulics, electrics, logic, and interfaces. The user deploys these library components to construct a schematic that exactly reflect the

system being designed, effectively copying the system layout and construction from CAD system drawings. These components can then be calibrated by adjusting the components' variables to reflect the system characteristics such as capabilities, pump outputs, pipe flows, tank sizes, generator output, breaker function etc.

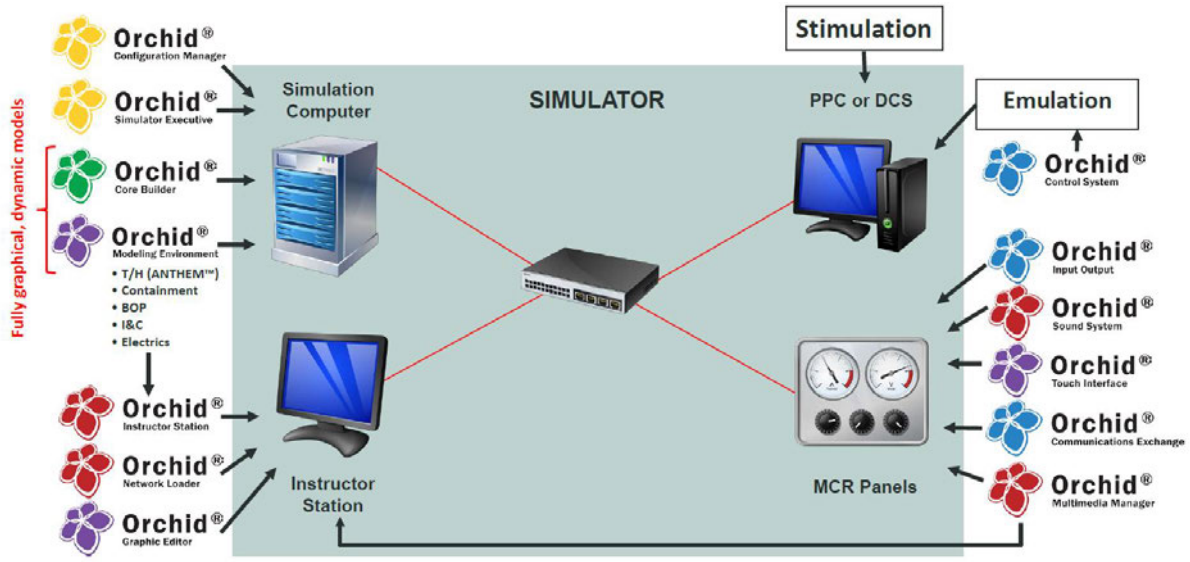


Figure 4 – Orchid® Suite of Tools

Reuse of Boat Software Code in the Training Environment

The Astute is the first UK nuclear s/m fitted with a distributed computer system (IPMS), including applications for propulsion, electrical and platform control and monitoring. Astute Class is also the first UK nuclear s/m with a dual redundant computer controlled S&DC Autopilot, being an embedded application of Astute IPMS. These IPMS software applications have been successfully integrated into the trainers.

One significant advantage of using the actual boat code in the training media is that it can be shown through Verification and Validation (V&V), that the boat control sequences and algorithms can be ported into the training media without change. This permits faithful replication of the s/m dynamic behavior for the same at-sea conditions in the training environment, thus ensuring realistic and accurate training can be delivered.

Qualification and Training Output Acceptance

Many of the courses to be designed and delivered had historically been reliant on existing custom and practice within the s/m flotilla, rather than having clear and measurable pass/fail criteria. In the contractual framework of the ACTS, this approach could no longer be maintained and a clear acceptance criteria had to be developed for each course. This required a systematic, measurable and repeatable approach to courseware and course delivery. Particular emphasis also had to be placed on the maintenance of the strong s/m and nuclear safety culture within the Service during training delivery.

For the Astute Class s/m build programme whilst the s/m was still in the shipbuilder's hands the UK MoD Submarine Delivery Agency (SDA) was responsible for the provision of the trained crew, and which were provided to support the s/m commissioning programme. For an in-build nuclear s/m, operators must be qualified in a MRT before FOC live 'critical' plant

operation is permitted. This is critically important for nuclear propulsion operators where qualification standards are independently regulated and are assumed to meet the requirement of the associated reactor plant safety justification and s/m safety cases. This ensured that nuclear operators were trained and qualified in a suitable training environment before the s/m nuclear plant initial criticality, and this is assumed to be an unchanging requirement of the nuclear s/m programme.

Training and Compliance Standards

L3H applied the ANSI/ANS 3.5 standard[iii], which is used for commercial power plant simulator acceptance, as a definitive and measurable way to assess its MRT performance. The standard was used very successfully for the acceptance of the nuclear operator trainer simulator (MRT) into operational service. The standard, which is used for commercial nuclear power plant simulator performance compliance and acceptance, specifies precisely the acceptable degree of accuracy regarding realistic operator feedback for the simulation. The standard also defines the accuracy and performance requirements for the simulator for all simulated nuclear plant steady state, transient and accident conditions. L3H having assessed the simulator performance for V&V purposes then bench-marked its performance with existing Royal Navy MRTs. This demonstrated to the Royal Navy's nuclear regulatory and s/m operating authorities that the performance of its simulator was at least equal to or indeed delivered better performance to comparable training simulators in RN service.

IN SERVICE SUPPORT

Training Service Feedback

An invaluable part in maintaining the ACTS training delivery standard to avoid negative training is the internal and external feedback it receives from the trainees passing through training systems on completion of their training courses. Feedback is collected during Post Course Discussion (PCD), from operational s/ms and the s/m flotilla, and other stakeholders (Fleet Officer Sea Training - FOST). The internal feedback (INVAL) may provide comment on instructor techniques, the difficulty of the training including any examinations and/or assessments conducted whilst under training. Feedback on provenance and appropriateness, accuracy and relevance of course content, training media performance and any identified functionality shortfalls, and of the relevance to the individual of the training imparted, can also be collected. On completion of training the students will leave the ACTS, join and or re-join their s/m and then embark on his s/m On Job Training (OJT), and subsequent on-board qualification. Again any discrepancies and or shortfalls between ACTS delivered training and the boat condition may be identified and that can then be fed back to the ACTS as external feedback (EXVAL). This includes trainee readiness and preparedness on joining the operational s/m, and where necessary feedback to improve and or change training content of the courseware and training delivery.

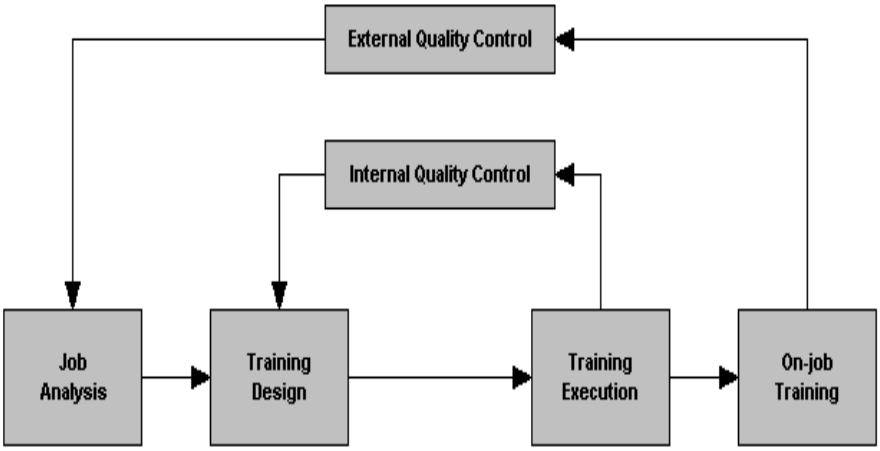


Figure 5 – Training Feedback Process

Media Availability

Continued and seamless ACTS Operations Phase training delivery requires training equipment and media availability of >98% that requires an ATF onsite support capability provided by L3H training support engineers. This arrangement is maintained during core hours of training (8am to 8pm Monday to Friday). L3H continues to maintain the equipment availability and will do for the life of the contract. L3H is also contracted to maintain equipment availability, conduct technology refreshes and manage obsolescence of the training media. Failure to maintain the equipment availability will incur penalty under the contract.

Media Updates

L3H continues to provide enhancements and additional training devices, to meet new training requirements consequent of boat changes, as more Astute Class s/ms enter service. Additionally, as ACTS expands its capacity, capability and training throughput to meet the increasing training demand, so must the level of equipment support be increased. Maintaining the s/m and training equipment baselines as near as possible, to prevent the divergence of the training media from that of boat condition, is also paramount. Regular change impact assessments are conducted, and an ACTS change process is used to assess all boat changes and operational documentation updates that may impact training to prevent divergence, and to justify the update of the training as SDA funded change.

TRAINING ENTERPRISE BENEFITS

Use of Training Service to Assist s/m Commissioning

Operations in the key training simulators (MRT, SCT) were conducted, following their entry into operational service, before the system operations were conducted in the platform. Standard and Emergency Operating Procedures were first used and verified in the simulators. Significant improvements to these procedures were made, based on the training observations made when conducting drills, and this was a major de-risking measure to the s/m build.

Use of Ship Staff SMEs

Use of Ship's Staff (SS) SMEs, during the simulator design and development phase, provided invaluable input. It also provided SS with initial visibility, familiarisation and operation of the on-board systems, through the simulation development media. This assisted in the efficient

and timely qualification of the operators, as it provided early opportunity and experience of system 'dynamic' operation greatly enhancing as it did system knowledge and understanding.

OBSERVATIONS & FINDINGS

- Dynamic testing using simulation models can and should be applied in a wider capacity in any shore based integration test facility to de-risk the on-board setting to work and commissioning of complex control systems.
- The Astute Class is the first UK nuclear s/m fitted with IPMS, including for propulsion and platform control and monitoring. It is the first UK nuclear s/m with computer controlled S&DC Autopilot control, and attack s/m with Hover capability.
- A key factor in achieving ACTS operational date to meet the s/m build requirement was that L3H was both the IPMS and Trainer provider.
- Operations in the key operator training simulators were conducted before the similar system operations were conducted in the actual s/m. Standard and Emergency Operating Procedures first use was in the trainers.
- Late platform design changes where operating procedures had to be changed in consequence were also trialed in the appropriate simulator environment including changes to the s/m S&DC control surface actuation.
- Generation of simulation model schematics identified certain discrepancies with shipbuilder supplied design information. In some cases this lead to engineering changes (ECRs) being actioned to the installed system(s), in the s/m.
- Astute Class IPMS control code is hosted directly into the trainer emulated environment without change, where it is recompiled in the simulator run-time environment, providing the pedigree and provenance evidence required for Verification and Validation (V&V).
- The first opportunity to actually test boat IPMS automated control sequences realistically was in the trainer environment. The high fidelity simulation model enabling realistic operation of all platform and propulsion systems, and the stimulation of the boat software. The trainer acted as a further shore reference test environment.
- The s/m IPMS drives the simulation modelling fidelity & functionality requirement.
- Creating high fidelity simulation models allows for use in wider system 'test' applications such as integration into the Shore Integration Facility (SIF).
- The simulation models can also be developed by system designers if provided and trained to use the simulation software tools.
- High fidelity training simulations provide opportunities for the testing, spiral development of on-board automation and complex control systems. Investment is required to build complex simulations early within the long lead time associated with a s/m build.

KEY RISKS

- Data supply, maturity, completeness (black box logic) and timeliness, mitigated by an innovative Data Exchange Framework (DEF) (MOD, Boat Builder and Training Providers).
- Development of training solutions concurrent with FOC Design and Manufacture (build) mitigated by series of customer funded workarounds including development of trainer software due to late boat software availability to maintain the training schedule.
- Maintaining a coherent training and s/m equipment baseline to mitigate any divergence and consequent introduction of negative training and emergent risk to final acceptance and Ready For Training.

- Late and/or immature TNAs mitigated by training providers developing the operator job (role) scalars to support training solution development. These were then reconciled against TNAs when issued.
- Development and integration of build, interim and steady state training solutions mitigated by very close cooperation with UK MOD, boat builder and Training Requirement Authority owners.

LESSONS LEARNT

- Speed, agility and responsiveness of the Training Service, in the development and delivery phases, is fundamental and requires early engagement with the training provider.
- Simulation modelling fidelity using a full scope, physics based simulation including proven Reactor Physics models will be required to meet training requirements.
- Introduction into the s/m platform of complex systems such as IPMS, determined the fidelity and functionality requirements for the simulation modelling.
- The challenge of obtaining Boat Data and corresponding Data Maturity Requirements is fundamental. The Training Devices requiring the same or more data (black box logic, etc.) than the s/m construction programme.
- The key simulators (MRT, SCT) are vital in the development of the s/m standard and emergency operating procedures. In some areas where new technologies were being deployed, key simulators were used to formulate s/m concepts of operation.
- Training Devices should contain current versions of operational boat code from software based systems such as IPMS and S&DC to avoid the risk of introducing negative training.
- Use of SS SMEs was a key part of Training Courseware development, as in some areas of s/m operation doctrine is not formally captured.
- The use of the Training Service to assist s/m commissioning is a vital programme constraint. Qualified nuclear watch keepers will be required early in the commissioning programme, which will place training provision on the critical path to vessel delivery.

CONCLUSIONS

- ACTS trainers were delivered to meet the FOC Astute Class Training Requirement.
- ACTS experience is that at least ten years should be allowed within a complex nuclear s/m programme to bring the training capability to full readiness.
- ACTS development and maintenance through life of a cadre of several hundred trained people for the Astute s/m programme, beginning in time to support FOC build and commissioning phase, has been a major challenge.
- ACTS systematic feedback of actual seagoing experience enables the improvement of courseware and training delivery through-life.
- ACTS simulators are now a valuable tool that is used for analysis of the platform and propulsion system(s) performance whilst in service.
- ACTS continues to meet its training requirement, is rated as one of the most successful RN training organisations, returning trainee success rates consistently of 100%.

[i] JSP 822 Defence Systems Approach To Training (DSAT)
[ii] Royal Navy BR 8420 Systems Approach to Training (RNSAT)
[iii] ANSI/ANS-3.5-2009 Nuclear Power Plant Simulators for Use in Operator Training and Examination

SESSION 3

Naval Ship Technology

High-Temperature superconductors: technologies and solutions for naval applications
Refereed

Naval platform design considerations for meeting increased hotel load demand

Naval platform survivability analysis for mission capability resilience

Novel penetration equipment to optimise naval indirect firefighting attack efficacy by means of simplifying systems and training

High-Temperature Superconductors: Technologies and Solutions for Naval Applications

Jonathan C. Knott[1], Shawn Nielsen[2], Peter O'Brien[2], Rob Hickey[2], Stephen Van Duin[1,3], Andrew Bailey[4], Fabio Souto[5], Michael Newman[4] and Richard R. Taylor[2]

1: University of Wollongong, NSW, Australia
2: Queensland University of Technology, QLD, Australia
3: DMTC Ltd, NSW, Australia
4: Defence Science and Technology Group, NSW, Australia
5: Thales Australia, NSW, Australia

ABSTRACT

Superconductors are materials that can carry significant current with essentially zero resistance, making them particularly useful for applications where high currents – or the generation of large magnetic fields – is required. Practical superconducting elements – either wires or tapes – can carry currents hundreds of times larger than copper wires of the same area, meaning the devices made with superconductors can be compact (e.g. up to 90% weight reduction in degaussing applications compared to their copper-based equivalents). The increased performance of what is intrinsically a quantum technology material is achieved with the application of cryocooling technology (TRL 9), utilising highly efficient cryocoolers, for instance Stirling cycle coolers. In the future, the parallel development of quantum optical solid-state cooling will revolutionise superconductor cooling technology and accelerate the deployment of superconducting technology in a wide range of naval applications.

Recent improvements in the performance of 'Second Generation' (or 2G) High-Temperature Superconductors (HTS), coupled with enhanced simulation techniques, have opened new opportunities for HTS in naval applications.

Here we provide a review of Naval applications where high currents and/or high magnetic fields are making possible enhanced capability in naval propulsion, mine countermeasures and energy generation. We discuss the developments in producing long lengths of high-performance and high-homogeneity HTS tape, and how the maturation of these production techniques opens new opportunities for superconducting devices. We discuss the state-of-the-art and open issues associated with designing and simulating HTS-based devices and solutions. We then conclude with an outlook of how HTS-based devices can continue to play a role in enhancing the capability or reducing drawbacks present in current solutions in Naval applications.

1 INTRODUCTION

For more than 100 years, superconductivity as a fundamental physical concept has been intensely researched by the scientific community. The mechanisms and properties of loss-free transfer of energy through superconducting materials are scientifically, technically and technologically curious, and the exact mechanism of superconductivity in high-temperature superconductors (HTS) remains an area of active research and linked to manufacturing development and electrical performance improvement.

For engineers, technologists and entrepreneurs, the applications and efficiencies made possible through the application of superconductors, specifically leveraging their superior current density and efficiency characteristics, are a major drawcard.

The deployment of superconductors can offer options in both evolutionary and revolutionary solutions for high current / high field applications – either 'evolutionarily' by reducing the existing size, weight or volume (or equivalently allowing greater performance from the same profile); or 'revolutionarily' by opening up novel solutions. We focus here primarily on the evolutionary solutions, however also touch briefly on some more revolutionary solutions in the discussion section.

In this paper we first outline naval applications where high current or high magnetic fields are required, and provide discussion of the nature and scale of existing solutions. We then provide a high-level introduction to high-temperature superconductors (HTS), their present-day development status and the core supporting technologies required for the deployment of HTS. A review of existing HTS demonstrations and deployments in naval applications is then undertaken, highlighting the key outcomes and learnings from some of the demonstrations. Finally, a discussion on the open questions, challenges and opportunities – both evolutionary and revolutionary – is given.

There are other characteristics of superconductors and superconductivity that may find use in naval applications. For example, Superconducting Quantum Interference Devices (SQUIDs) have the potential to measure extremely small magnetic fields, making them attractive for measuring small magnetic changes [1]. Similarly, HTS structures can be used in filters for communications devices and ultra-selective narrow bandpass filters for use, for example, in weather radar systems [2]. These technologies – and many others – demonstrate the significant benefits superconductors can bring to naval applications generally. In this paper we focus on the high current / high field naval applications of superconductivity. Readers interested in these additional applications are directed to references [1]–[3].

2 HIGH CURRENT / HIGH FIELD NAVAL APPLICATIONS

There are many naval applications where high currents are required, including in electric propulsion, power generation, power distribution and major equipment protection. Additionally, there are more applications where very significantly large magnetic fields are required, as well as in vessel magnetic signature management and magnetic mine countermeasures.

2.1 Propulsion and Power Generation

Maritime vessels have two key energy-based requirements – propulsion and 'hotel load', i.e. lighting, sensors, communications, HVAC etc. In a typical configuration, provision of these requirements is decoupled, with separate 'prime movers' (e.g. diesel motors, gas turbines) combined with electrical generators or propulsion systems.

Fully-electric propulsion strategies for naval vessels, and maritime vessels more broadly, are becoming of increasing interest as a range of driving forces converge. One of the broader industry drivers is the movement towards 'green shipping', motivated by increasing energy prices, cost management, and increasingly stringent emission and particulate regulations [4]. From a naval perspective, there are a number of opportunities integrated electric systems provide [5], including:

- Supporting high-power mission systems as all prime mover capacity can be made available for ship service needs;
- Reducing the number of prime movers required to service propulsion and hotel loads;

- Improving efficiencies of prime movers through operating them at design/efficient speeds decoupled from propulsion speeds;
- Improving efficiencies of propulsor systems, allowing opportunities for compact and/or high-efficiency electric motors to be deployed;
- Providing general arrangement flexibility, through providing flexibility in the location and positioning of the prime mover/s – rather than requiring them to be co-located with the propulsor systems;
- Simplifying vessel construction and offline system testing;
- Facilitating future integration of novel energy supply technologies, such as fuel cells.

Power requirements for propulsion and hotel loads on naval vessels can reach into the tens of megawatts (MW) overall, for example the all-electric USS Zumwalt has two 34.6 MW propulsion motors – with a total of 78 MW of electrical generation to provide power for the combined propulsion and hotel loads of the vessel.

2.2 Power Distribution and Protection

Increasing electrical demands from sensors, mission and sustainment components, and even weapons packages, has resulted in modern vessels becoming complex electrical microgrids. Depending on their size, modern naval vessels can have multiple MW of electrical 'hotel load' (i.e. the non-propulsion loads outlined above) spread throughout the vessel [6], as depicted in Figure 1.

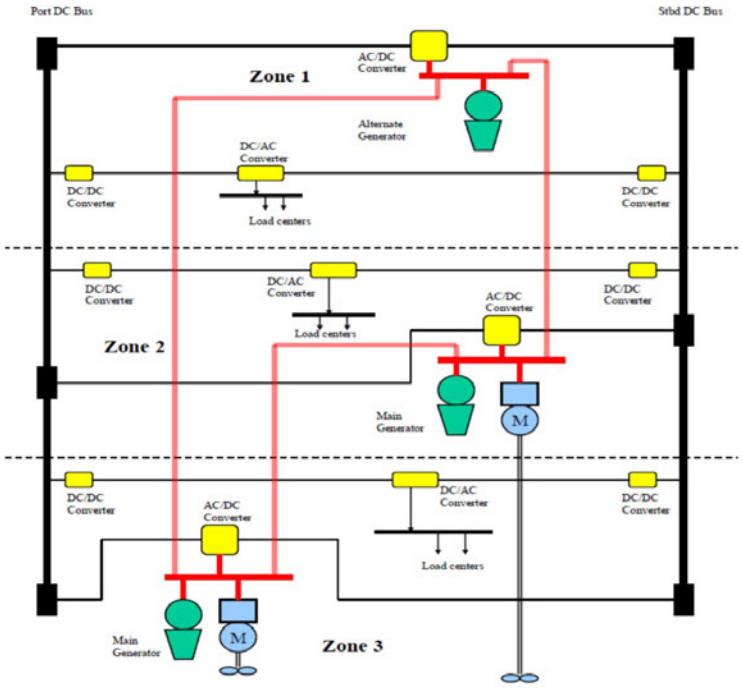


Figure 1 – Zonal distribution system architecture for naval power system applications, adapted from [7].

These microgrids come with requirements not only to produce electricity to power the loads, but also to distribute it in an efficient and resilient manner around the vessel, and protect against damage and impacts from electrical faults.

In addition, a trend to configuring a vessel electrical system into 'zones', as shown in Figure 1, for survivability and flexibility requires careful consideration of appropriate power distribution and protection technologies to facilitate these architectures. The USS Zumwalt, the US Navy's

innovative electric propulsion destroyer, uses a zonal distribution system architecture with a 1 kV DC bus system to move power within and between zones.

In addition to the addressing present power delivery requirements, power distribution and – to a lesser extent protection systems – must be designed to be appropriate for the anticipated power demand over the entire service life of the vessel. This can include additional power demand for sensors or weapons systems, and can play a role in the specification of cabling cross-sections, which for copper-based cables is typically in the range of 3 A/mm^2. HTS conductors usually operate above 25 kA/mm^2 and the most recently documented 2G HTS cables significantly greater than this magnitude.

The use of multiple MW-scale devices and kV-range distribution architectures requires appropriately specified fault management and protection solutions. This protection is particularly important where there is the potential for large fault currents – as is the case in naval operations where a small number of large loads are present and the potential for damage to power delivery infrastructure is present.

2.3 Magnetic signature management via De-perming and Degaussing

The Earth has a magnetic field that behaves as if generated from a bar magnet positioned through the centre of the planet, reaching from the magnetic north to the magnetic south pole (which, presently, is on an approximate 11-degree tilt with respect to the Earth's rotational axis). The magnetic flux density of this field ranges between 25 and 65 µT depending on the location and local geological features, which also impacts the direction of the field. As a comparison, a refrigerator magnet has a flux density approximately 100 times greater. Knowledge of the Earth's magnetic field magnitude and direction at a particular position can be used in sensing net changes or distortion in that field due to other magnetic field sources or magnetisable material nearby.

For example, the hulls of naval vessels are typically manufactured from magnetic steels, and as such have a remnant 'magnetic signature' due to the manufacturing. This magnetic signature can interact with the Earth's magnetic field and result in a detectable 'distortion', as is depicted in Figure 2, where the resultant magnetic field detected at a reference place some distance below a vessel is shown for a constant vertical (left) and constant horizontal (right) magnetic field. If the vessel was not present (or it was made of non-magnetic materials), the magnetic field on the reference plane would be constant and would be a single colour, rather than showing 'hotspots' as can be seen.

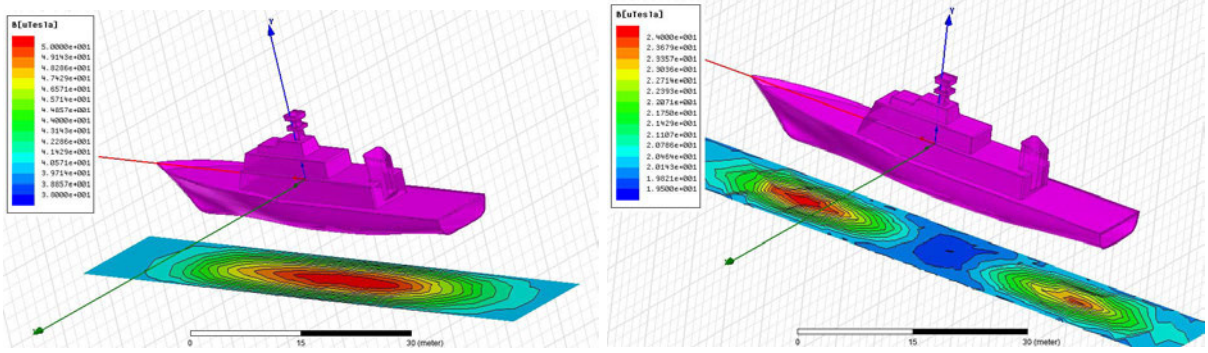


Figure 2 – simulations of the magnetic signature of a ship at a reference depth when subjected to a vertical magnetic field (left) – as would be experienced directly over the north (or south) magnetic pole; and when subjected to a horizontal magnetic field (right) – as would be experienced at the equator. Adapted from [8].

Two techniques can be employed for magnetic signature management – both of which require the significant and/or sustained magnetic field – known as de-perming and degaussing.

De-perming is a process that aims to reduce the residual magnetic signature of a vessel through applying a large but decaying alternating magnetic field (Figure 3 (left)) to the entire vessel. This can either be done through cables directly applied to the vessel – as shown in Figure 3 (right) – or via some other controllable source of substantial magnetic field. The ideal outcome of this process is a vessel with a minimal and homogenous residual magnetic signature.

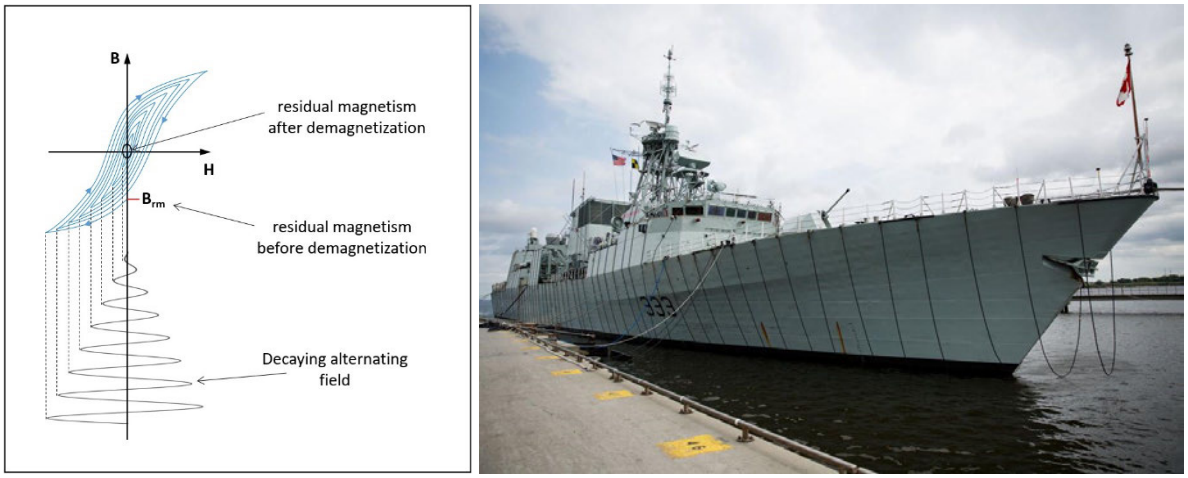


Figure 3 – graphical description of de-perming process, whereby a decaying alternating magnetic field reduces the residual magnetisation of a material (left), adapted from [9]; and de-perming coils wrapped around a naval vessel (right) [10].

De-perming is typically a static process, done at a specific 'drive in' dry-dock or when a vessel is docked.

To appropriately manage magnetic signature during operations, on-board degaussing systems can be employed to reduce the resultant impact on the background magnetic field as the vessel moves through it. Original degaussing systems consisted of a coil or series of coils positioned in the vessel in a vertical orientation to develop a vertical field that counteracted the resultant field from the interaction between the Earth's magnetic field and the vessel, as shown in Figure 4.

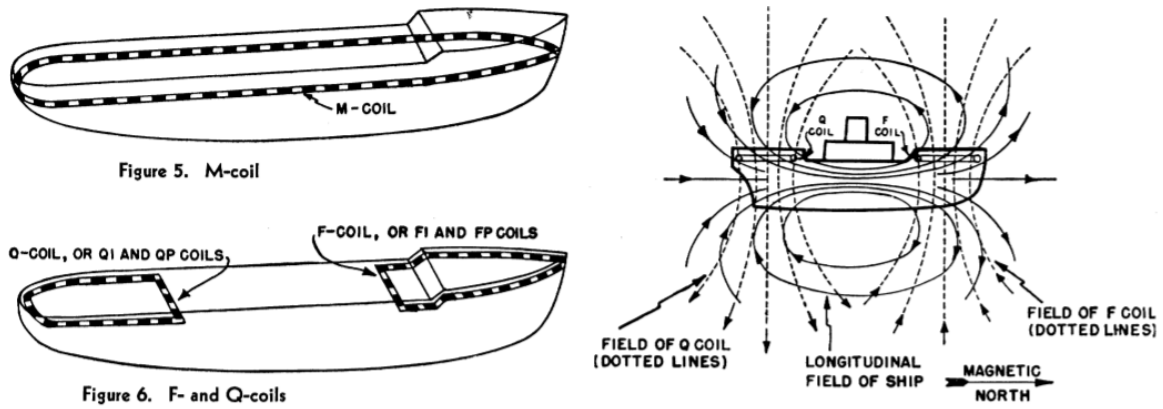


Figure 4 – WWII-era degaussing system conceptual schematic for producing a vertical magnetic field, adapted from [11].

Degaussing systems are designed not to make the vessel magnetically 'invisible', but rather to reduce the resultant impact on the Earth's magnetic field detectable by magnetic influence mines or sensors.

As magnetic detection systems have become more sensitive and sophisticated, degaussing systems have had to evolve. Two-axis systems can be used to effectively reduce a magnetic signature up to 75%. A three-axis system is able to reduce up to 95% of the magnetic signature of a vessel [12]. Modern degaussing systems typically consist of tens of coils in three axes, and can have power requirements in the hundreds of kilowatts (kW) [13].

Table 1 – Degaussing systems on naval ships, with HTS-based system included for comparison. Adapted from [13].

	M Frigate (NL)	LCF Frigate (NL)	LPD (NL)	LPD17-copper	LPD17-HTS
number of L coils	9	11	4		
number of A coils	10	10	5		
number of M coils	8	9	14		
total number of coils	27	30	23	>40	>40
weight (ton)	5	16	19	51	10
conduit (ton)				66	13
system inc. cooling (ton)				117	26

Table 1 shows a comparison between conventional copper coils and HTS conductors deployed as a degaussing system. The HTS system weight is approximately 20% of the copper system.

2.4 Magnetic mine countermeasures

Naval mines can be classified into four major groups – contact, remote control, influence and dummy mines. Influence mines detect the presence of vessels through sensor technologies, including via acoustic, pressure and/or magnetic sensors [14]. Magnetic influence mines can be configured to detect a distortion of the Earth's magnetic field due to the presence of a source of magnetic field, or a distortion in the background

There are a number of magnetic Mine Countermeasures (MCM) strategies that can be employed, however their broad focus is to produce a magnetic field mimicking that of a vessel to induce triggering of magnetic influence mines.

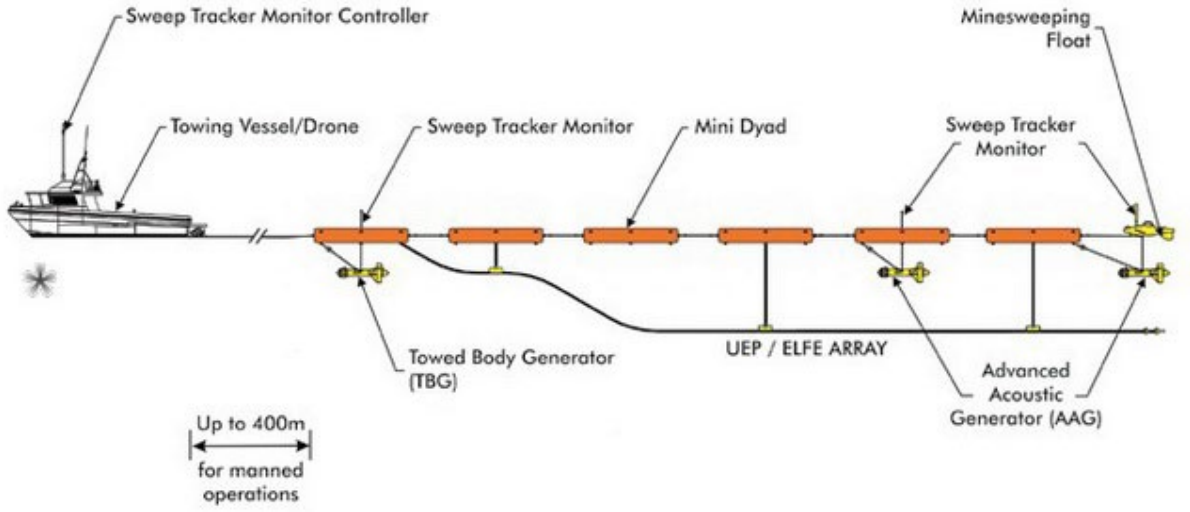


Figure 5 – schematic of towed dyad MCM apparatus, adapted from [15].

An Australian-developed 'world's first operational emulation sweep' technology – known as the Australian Minesweeping and Support System – is based on towed dyads (buoyant permanent magnet cylinders) that can be configured to emulate a variety of vessel magnetic

signatures through the configuration and spacing of the dyads, as depicted in the schematic in [16].

These dyads use rare-earth magnets, to produce magnetic field of the same order as that produced by a naval vessel.

3 SUPERCONDUCTIVITY AND SUPERCONDUCTORS

Superconductivity is a broad term that covers a wide array of distinct materials, physical principles and device architectures. For example, there are more than eighty materials, alloys and compounds that show superconducting properties – that is, under specific temperature, electric current and magnetic field conditions electrons can pass through the material with no impediment. Most of these materials, however, are not suitable for practical superconductor devices – for example mercury – the first material discovered to show superconductivity – is only superconducting when it is cooled below 4.2 K (-268.95 °C) and when the background magnetic field is below 40 mT. In contrast, bismuth strontium calcium copper oxide (known as BSCCO) is superconducting at temperatures up to 108 K, a temperature well within reach using liquid nitrogen – a cheap and easy-to-produce cryogen.

Superconductor-based devices have been developed, productised and commercialised in a number of applications – none more prevalent than in Magnetic Resonance Imaging (MRI). There are approximately 50,000 MRI machines worldwide, with a further 5,000 sold every year [17]. These devices almost exclusively employ low-temperature superconductors (LTS) and liquid helium cooling in their operation at 4.2 K (-268.95 °C), with both of these technologies mature and well understood from engineering and deployment perspectives.

There are many ways to categorise and group different classes of superconductors, however from a 'devices and applications' standpoint it is often practical to classify based on the critical temperature – i.e. the temperature at which the material transitions to a superconducting state. Using this metric, Low-Temperature Superconductors (LTS) are typically defined as materials that have a critical temperature below 30 K (-243.15 °C), and High-Temperature Superconductors (HTS) as materials that have a critical temperature above 30 K. LTS have been in commercial use since the 1960s, and – as noted above – have found particular application in MRI and Nuclear Magnetic Resonance (NMR) magnets. The first HTS material was discovered in 1986, have been of research and commercialisation interest since [18].

3.1 High-temperature superconductors

High-temperature superconductor (HTS) is a term that covers a number of classes of superconductor material as outlined in Table 2.

Table 2 – Key HTS materials and indicative properties

HTS material	HTS class	Critical temperature [K]	Current cost	Technology maturity
MgB2	-	39	$	●
BSCCO	1G-HTS	108	$$	●●
ReBCO (where "Re" is a rare earth element)	2G-HTS	~90	$$$	●

HTS materials can be produced in various forms, from 'bulk' pellets that can be magnetised and used for magnetic levitation or bearings [19], through to wires and flat 'coated conductor' tapes – as shown in Figure 6 – that can be used as cables for power delivery or wound into coils for magnetic field production.

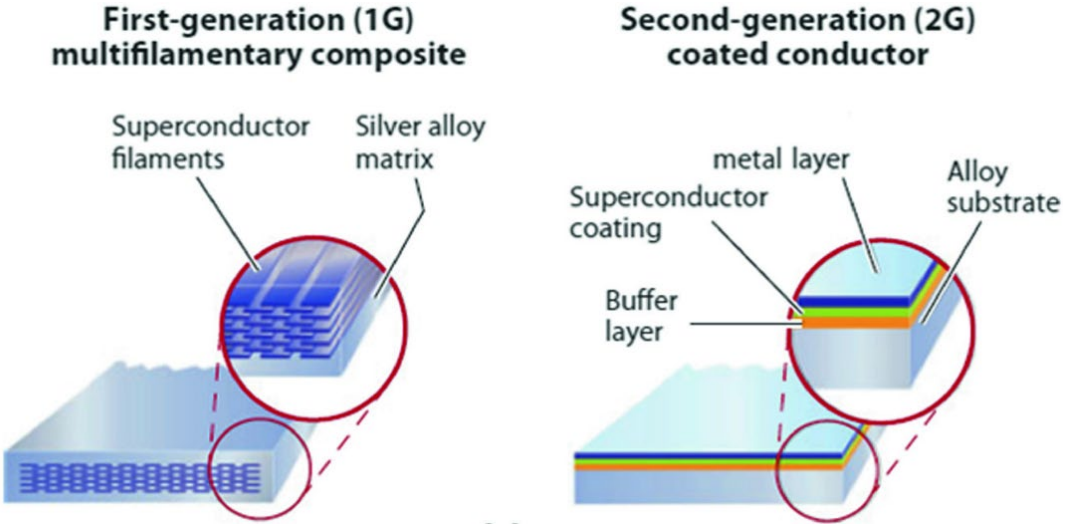


Figure 6 – Schematic of 1G-HTS (left) and 2G-HTS (right) conductors, adapted from [20].

There are more than ten 2G-HTS conductor manufacturers worldwide – more than the number of producers of the widely-deployed LTS conductor technology [21]. This diversity of producers and production routes, coupled with the relative nascence of 2G-HTS commercial production has resulted in significant and sustained increase in HTS conductor performance, which is anticipated to continue as the technology and production methods are further refined.

Table 3 – HTS manufacturers worldwide, adapted from [18], [21].

Manufacturer	**Location**	**HTS class manufactured**
American Superconductor (AMSC)	USA	2G-HTS
SuperPower	USA	2G-HTS
Superconductors Technology Inc. (STI)	USA	2G-HTS
Bruker EAS	Germany	2G-HTS, 1G-HTS
DeutscheNanoschicht	Germany	2G-HTS
THEVA	Germany	2G-HTS
Showa	Japan	2G-HTS
Fujikura	Japan	2G-HTS
SuperOx	Russia/Japan	2G-HTS
Shanghai Superconducting Technology (SST)	China	2G-HTS
SuNAM	South Korea	2G-HTS
SAMRI	China	2G-HTS

Sumitomo	Japan	1G-HTS
Innova Superconductor Technology	China	1G-HTS
Showa	Japan	1G-HTS
Oxford Superconducting Technologies	USA	1G-HTS
Alcatel/Nexans	France	1G-HTS
HyperTech Inc.	USA	MgB2
Columbus Superconductor	Italy	MgB2
Hitachi	Japan	MgB2
Sam Dong	South Korea	MgB2

In addition to this anticipated increase in 2G-HTS performance from maturing of production methodologies, HTS conductors have intrinsic unique characteristics that make them particularly suited for maritime and naval applications – including a high critical temperature, high critical current (which increases with decreasing operational temperature) and superior mechanical properties (such as bending radius of conductors and yield strength) [21].

3.2 Operating infrastructure for superconducting devices

The highest temperature commercial HTS conductors operate at is ~100 K (-173.15 °C), which necessitates the use of specialised infrastructure to reach and maintain these temperatures.

The management of heat flow from ambient surroundings into the superconductor is a critical function of the superconducting device operating infrastructure, and is achieved through the appropriate selection and design of two critical components – the cooling methodology, and the structural/containment system. In addition, the power supply and protection system also play a significant role in managing heat flow and protection under all operating conditions.

One of the key events that a cooling methodology must appropriately protect against is a 'quench', where – due to temperature, current or impinging magnetic field beyond the limit of the superconductor – the superconductor transitions from the superconducting regime back into the 'normal' conducting regime. Accompanying this transition is an increase in resistance in the quenched superconductor by many orders of magnitude, which can result in substantial local heating. Quenching is typically avoided during operation of superconducting devices through ensuring the superconducting elements are operated below their temperature, current and magnetic field limits, however it is an event that must be appropriately planned for and mitigated.

3.2.1 Cooling

The primary strategies to cool superconducting devices can be categorised into 'cryogen-based' and 'cryogen-free' strategies.

Cryogen-based cooling relies on immersing the superconducting element (and any supporting structures) in a cryogen – such as liquid helium (4.2 K) or liquid nitrogen (77 K) – and using the mass of the cryogen to maintain temperature in the superconductor and support structure, collectively known as the 'cold mass', and absorb any heat entering the system during operation. Using this strategy, as the cryogen absorbs heat it undergoes a phase transition from liquid to gaseous phase, and heat is removed from the system as the gas escapes. This

gas can be captured and recondensed using external cooling systems in a closed-loop cycle, or may be vented – thus necessitating periodic replenishment of the cryogen in the system. This is a well-understood and optimised cooling strategy, and is used in many commercial devices – for example almost all MRI machines use liquid helium cooling and are optimised to rarely require helium replenishment except after the occurrence of a quench event.

Cryogen-free cooling uses mechanical cooling devices commonly referred to as 'cryocoolers' to transfer heat from the cold mass via thermal conduction. This strategy has the advantage of not directly requiring cryogens, however relying on thermal conduction typically results in temperature gradient across the cold mass, and less thermal mass available to mitigate the impacts of heat impulses into the cold mass – as is typically the case during a quench event.

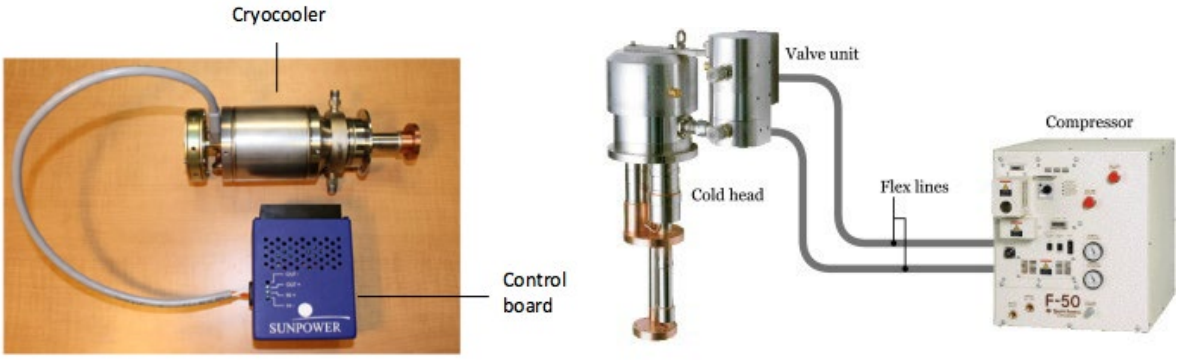


Figure 7 – Stirling-cycle cryocooler (left) and Gifford-McMahon-cycle cryocooler (right) cryogen-free solutions for superconducting device cooling.

3.2.2 Cryostat

One of the core pieces of infrastructure for a superconducting device is the cryostat – the apparatus that encapsulates the cold mass, thermal management system and structural system. A high-level schematic of a superconducting coil in a cryostat is shown in Figure 8, where an outer and inner cryostat configuration is used. This allows for the insertion of low-conductivity material (or vacuum) between the two cryostats to minimise heat transfer from the ambient temperature outer cryostat to the cold mass temperature inner cryostat.

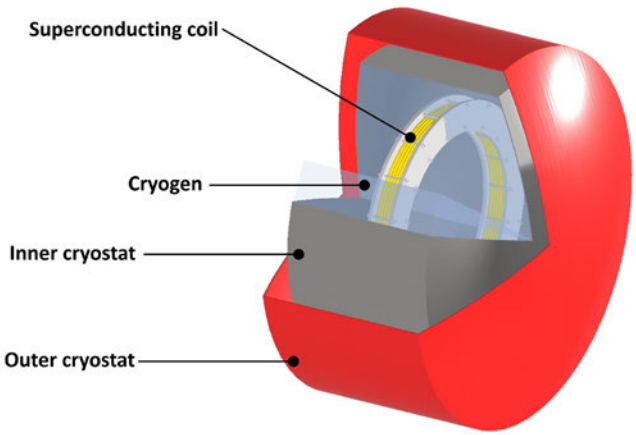


Figure 8 – Schematic representation of a superconducting coil device, including cryostats and cryogen volumes.

3.3 HTS: current state-of-the-art and challenges

1G-HTS and 2G-HTS conductors are being developed and commercially produced by manufacturers across Europe, Asia and the USA. 2G-HTS architectures are becoming more

prevalent, particularly as the technology and manufacturing capabilities are maturing. In particular, 2G-HTS conductors are being driven to higher and higher critical currents – with state-of-the-art 12 mm wide / 0.11 mm thick 2G-HTS conductors being rated for > 550 A current in liquid nitrogen [22].

Despite these advances, a number of challenges still remain for the commercial deployment of 2G-HTS conductors. A critical limiting factor is the relative cost of 2G-HTS conductors, currently in the low-hundreds of dollars per meter, as shown in .

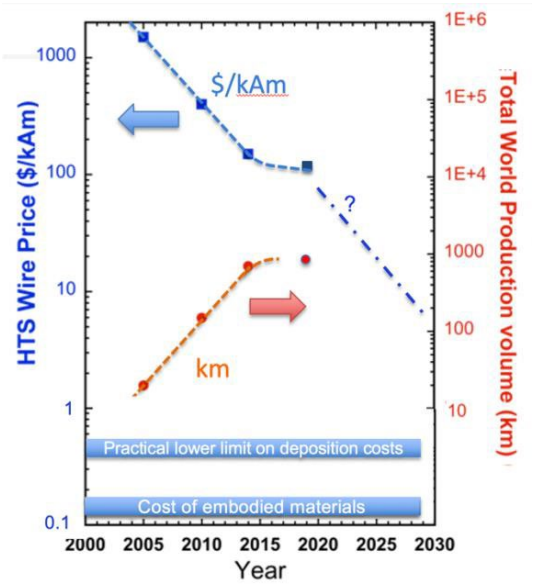


Figure 9 – Actual and predicted price of 2G HTS wire (blue) and production volume (orange) over time, adapted from [23].

This is orders of magnitude above the cost of input materials and the (complex and currently CAPEX-intensive) production costs for the 2G-HTS conductors. As such, there is well-placed confidence that 2G-HTS conductor costs will continue to fall as economies of scale and production method optimisations come in to play.

Current production methods for 2G-HTS tapes are complex and can result in inhomogeneity in performance over long lengths of conductor. As such, most 2G-HTS manufacturers limit single piece lengths available for purchase to 500 m. This presents additional challenges for some high current / high field applications. It is currently possible to join pieces of 2G-HTS tapes with resistances as low as nano-ohms, and novel techniques for optimising joints in 2G-HTS is an active and ongoing area of engineering research and development.

From an engineering design standpoint, high-fidelity modelling of 2G-HTS conductors and their behaviour under operational conditions remains an area of active research and development. As robust models and methods for characterising 2G-HTS conductor behaviour over the anticipated range of operating conditions become available, design of 2G-HTS superconducting devices will similarly become more structured and suitable for engineering design processes.

4 SUPERCONDUCTING TECHNOLOGY DEVELOPED FOR NAVAL APPLICATIONS

Since the commercialisation of LTS in the 1960s, there have been discussions on how superconductors could be developed and deployed for maritime and naval applications (e.g. [24] from 1972). As outlined in Section 2, there are many applications where the superior current densities and/or magnetic field production capabilities of superconductors can

provide significant benefits in existing applications – or even open the door to novel applications and solutions. In this section we highlight existing demonstrations of superconductors in naval applications, comparing and contrasting their performance with respect to non-superconducting solutions. We also provide an insight into potential applications for superconductors to meet the next generation of naval requirements.

4.1 Existing demonstrations/deployments

There have been a significant number and breadth of successful demonstrations of superconductor-based devices in naval applications – from lab-based demonstrations through to full deployment.

4.1.1 Propulsion and power generation

There have been several HTS propulsion motors developed and laboratory-demonstrated, including: a 5 MW 2G-HTS-based motor in South Korea [25], a 3 MW 2G-HTS-based motor in Japan [26] (depicted in Figure 10), and a 36.5 MW HTS motor in the USA [27], [28].

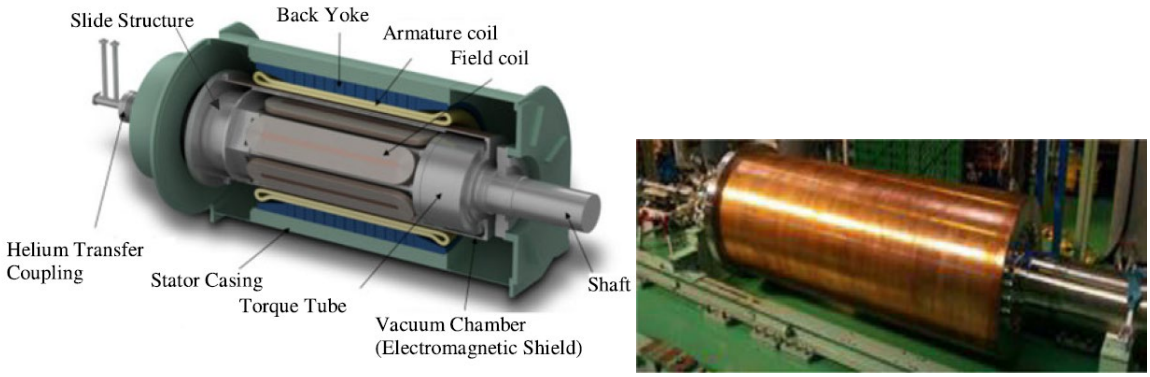


Figure 10 – schematic (left) and HTS rotor (right) from the Japanese 3 MW HTS propulsion motor, adapted from [26].

As can be seen in Figure 11 (right), the 36.5 MW motor designed, built and tested in a laboratory configuration in the USA shows substantial weight and volume reduction compared to a similar torque copper-based motor, and are also substantially lower in acoustic noise generation during operation [29].

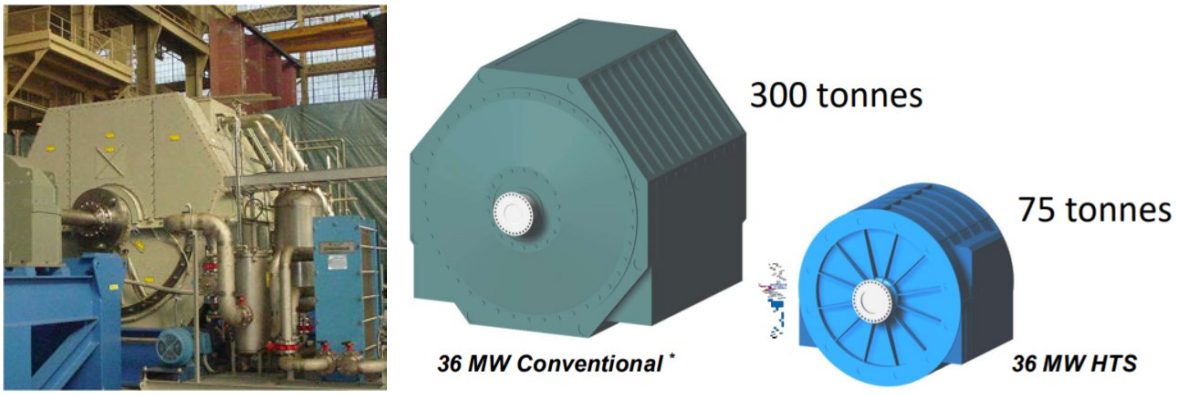


Figure 11 – 36.5 MW HTS motor in test facility (left) and size/weight comparison with a conventional motor, adapted from [27] and [28].

As noted in Section 2.1, the USS Zumwalt has two conventional 34.6 MW electric motors for propulsion, so this demonstration shows that HTS motors can be produced at torques and power outputs necessary for modern naval and maritime applications.

4.1.2 Power delivery

Superconducting power cables have been identified as a critical contributing technology for realising all-electric naval vessels, as the higher current densities possible compared to copper cables allows for up to 10x current density at one-third of the weight [30], as depicted in Figure 12. While there is significant research and scoping work presented in the literature on medium-voltage DC (MVDC) power delivery networks in naval vessels, there does not appear to be any publicly-available descriptions of large-scale laboratory or *in-situ* deployment of this technology in naval applications to date.

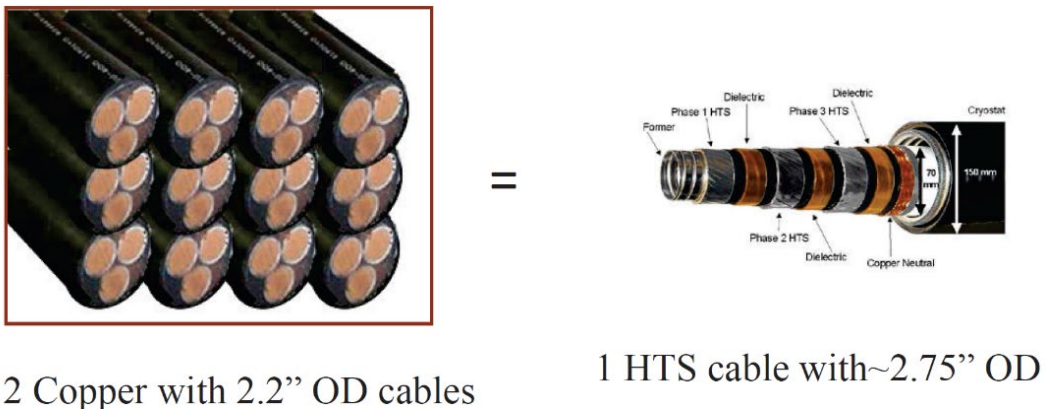


Figure 12 – Power delivery cable requirement cross-section reduction possible using HTS cables in place of traditional copper cables, adapted from [29].

4.1.3 De-perming and degaussing

One of the more technologically-advanced HTS demonstrations in naval applications was the deployment and continuous operation of a HTS-based degaussing loop (as part of a larger, primarily copper-based system) on the US Navy active combat vessel DDG-76, USS Higgins. The HTS-based cable and associated cooling system was installed in the USS Higgins in 2008 after the removal of a copper-based experimental system, and was successfully energised in April 2009. The HTS-based component of the degaussing system operated continuously from June 2009 to February 2010, during which time the USS Higgins completed a circumnavigation and travelled a total of 37,073 miles [12].

This demonstration was significant, as it is estimated that transitioning naval vessels from copper-based degaussing systems to fully-HTS systems could reduce total installed cable lengths by up to 92% and decrease overall degaussing system weight by up to 79% [31].

4.1.4 Magnetic mine countermeasures

A 1G-HTS coil was developed form magnetic mine countermeasures applications and was laboratory-tested in the early 2000s and was able to produce a maximum magnetic dipole moment of 80 kAm^2 [32]. This device provided evidence for the suitability of 1G-HTS conductor for magnetic mine countermeasures, however there do not appear to be any public-domain reports on whether this particular device – or any subsequent HTS-based devices – have been demonstrated *in-situ* in magnetic mine countermeasures applications.

4.2 Potential deployments of HTS in naval applications: opportunities and challenges

There is already significant focus on the research, development and operationalisation of an 'all-electric ship' by the US Office of Naval Research-funded Electric Ship Research and Development Consortium (ESRDC). This consortium has developed an all-electric ship baseline model, which consists of a four-zone, two-bus DC distribution system fed by two main turbine generators and two auxiliary turbine generators. In the model the load consists of propulsion,

service, radar and high-energy mission loads spatially-distributed throughout the vessel [33]. This model serves two important purposes from an 'opportunity for superconductors' standpoint – firstly it provides a clear understanding of the identified power and energy requirements for all-electric naval vessel operations; and secondly, it shows where superconducting devices can be leveraged in future naval applications.

4.2.1 Challenges for the deployment of HTS technologies on naval vessels

One of the primary operational challenges of using HTS in any application is the requirement for producing and maintaining a low temperature environment. As noted in Section 3.2.1, this is implemented through the use of cryogens or mechanical cooling systems. Each of these methods present unique challenges for naval applications.

In the case of cryogens, such as liquid nitrogen or gaseous/liquid helium, having these cryogens onboard a vessel can require careful operational and safety mitigation strategies. Both nitrogen and helium gas can displace air and create an asphyxiation risk in enclosed environments. HTS systems using cryogens for cooling will produce gas during operation, as transfer of heat from the HTS system into the cryogen, and then the warming and eventual phase change of the cryogen from liquid to solid is the mechanism for heat rejection from the system. In an appropriately designed HTS system, this gas production is minimised through minimising the heat input into the system. Unexpected events, such as a quench (where large amounts of heat are generated in the system as the superconductor transitions to normal-state operation) or damage to the system containing the cryogen, can cause significant instantaneous production of gas – requiring adequate venting to minimise the risk of asphyxiation or structural damage.

The use of cryogens in a HTS system also necessitates a method of replenishing the cryogen in the system over the operational period. Standardised processes for capturing and reliquefying helium, or extracting nitrogen from the atmosphere, have been developed – however this requires additional plant and capability to be installed along with the HTS system.

The use of cryocoolers can eliminate many of the challenges present for the use of cryogens in naval applications, however cryocoolers present their own unique challenges that require appropriate mitigation strategies. Cryocoolers still use gasses – typically helium – as a heat transfer mechanism. These volumes are substantially smaller than in cryogen cooling, however still present issues for dealing with unanticipated gas release if the cryocooler is damaged.

Cryocoolers also use mechanical processes in their operation, and the attendant noise, vibration and electromagnetic field emissions must be appropriately addressed. These emissions are comparable to those produced by standard air-conditioning equipment.

One challenge unique to the use of superconductivity is the impact of quench on operational capability. Quenching (i.e. the transition from superconducting to normal state) of a superconductor element in a system can impact the operational capability of the system – from minimal impact through to loss of operation. While not exclusive to naval applications – the reduction or loss of functionality due to quench can have a substantial impact in this context. One mitigation strategy implemented in a number of 2G HTS-based systems is 'no insulation' use of HTS conductor – where there is no electrical insulation between adjacent conductors in a cable, or adjacent turns in a coil, to provide alternate current pathways during a localised quench. This strategy provides additional protection for the HTS conductor, and

allows for continued operation of the HTS system during the quench event. Coupled with the appropriate cooling methodology, a HTS system can be designed to recover from these 'soft quench' events with minimal impact to the overall performance of the system.

4.2.2 Challenges for the development and deployment of all-electric vessels

As demonstrated in the previous sections, all-electric naval vessels are not a prerequisite for the deployment of HTS technologies in naval applications — however there are demonstrable synergies in leveraging the two in tandem.

Many of the challenges identified in the *US Naval Power and Energy Systems: Technology Development Roadmap* highlight the broader issues around developing and deploying all-electric vessels, including: the increased complexity in managing and controlling energy flows in an all-electric configuration where propulsion, communications and weapons systems may all require energy; the integration of multiple mature and emerging technologies into an integrated power system; the development of energy storage technologies; the development and thermal management of power conversion systems; and the protection of high-current DC power circuits – an application for which HTS-based Fault Current Limiters are uniquely suited [34].

These core challenges do not preclude the deployment of HTS technologies for propulsion, mine countermeasures, or other applications – however an integrated approach to addressing these challenges may enhance and accelerate the take-up of HTS technologies in naval applications.

5 DISCUSSION

Superconductors have the potential to unlock new opportunities in maritime naval applications, and to provide value in existing applications through reducing mass, volume and losses. As fleets and vessels are modernised – and in some cases fully-electrified – increasing power demands will necessitate the development and deployment of high power, robust and resilient generators. This is an area where the superior current-carrying characteristics of superconductors can be leveraged not only in power generation [35], but also in lighter-wight and lower-volume power delivery solutions.

Similarly, increasingly sophisticated requirements for magnetic mine countermeasures technologies to more accurately simulate naval vessels opens opportunities for HTS magnet-based solutions. To underscore this, the US Office of Naval Research has recently issued a Special Notice on the Magnetic and Acoustic Generation Next Unmanned Superconducting Sweep (MAGNUSS) project, inviting proposals for HTS-magnet based minesweep technologies.

American Superconductor has also recently announced a multi-million-dollar contract with the US Navy to leverage the outcomes and learnings of the HTS degaussing system described in Section 4.1.3 to supply a complete HTS degaussing system for Landing Platform Dock vessels.

There also exists 'revolutionary' opportunities for deployment of superconductors in naval applications – inspiration for which can be taken from recent developments in aerospace applications. For example, leveraging liquid hydrogen to act as a cryogen (20 K) for HTS cooling as well as a feedstock for a hydrogen fuel cell for electricity generation could be implemented in a vessel where regular replenishment of liquid hydrogen was available [36].

6 CONCLUSIONS

Here we have undertaken a conceptual review of naval applications where high currents or substantial magnetic fields are required. Highlighted were the limitations of existing solutions, particularly focusing on where emerging naval requirements are driving the need for novel solutions. We introduced High-Temperature Superconductors, highlighting the new applications this class of material facilitates through superior performance over a range of operating conditions, and introduced some contemporary 'open questions' in HTS development and deployment. A review of the demonstrations of HTS devices in naval applications gave an understanding for the breadth of suitability of this technology currently, and a brief discussion of next-generation applications provided a vision of how the superior current-carrying capabilities of superconductors can play facilitate future naval applications.

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Naval platform design considerations for meeting increased hotel load demand

Samuel Smith, Neil Patterson, Christian Rayes and Peter Hield
Defence Science and Technology Group, Department of Defence, Australia
samuel.smith12@defence.gov.au

ABSTRACT

The hotel load power and energy requirements of warships are increasing. This trend is expected to continue, driven by the introduction of directed energy weapons and ever more powerful radars. Supplying this increased hotel load while maintaining propulsion loads requires increased power generation capacity and energy storage (fuel). Due to the highly integrated nature of naval vessels the necessary changes to the power and energy systems have significant implications for other aspects of platform performance, including resistance, stability, seakeeping and operability.

DSTG has developed an integrated platform performance modelling and analysis tool, known as InteShip. InteShip features an open architecture in which various subsystem models are interlinked to capture the different aspects of platform performance using inputs from a centralised database. This allows holistic performance assessment of platform designs against objective performance measures. Optimisation and design space exploration tools integrated into InteShip allow for increased understanding of the complex and sometimes conflicting interactions between the different subsystems and performance requirements that make up a modern naval platform. InteShip supports evidence-based decision making.

This paper describes the use of InteShip to explore the effect of increasing the power generation capacity and fuel stores on the platform size for a generic naval frigate, while maintaining range as well as sufficient space and weight aboard for other uses.

INTRODUCTION

Increasing power demand

The U.S. Navy now considers that we are entering an age of electric ships [1]. The hotel load and power and energy requirements of warships are increasing. There has been a trend over the last 30 years from propulsion power dominating the total vessel power demand to directed energy weapons (DEW) and sensors being the largest power draw [2]. The Chief of US Naval Operations, Admiral J. M. Richardson is quoted in 2019 saying "*I'm going to buy as much as I can afford. As much power as I can afford. Because I know by the time I retire the ship I'll use it all"* [1].

Estimation of radar power levels range from 2.5 MW [2] to 7 MW [3] and are only going to increase in future designs [4]. Only around 20% of the energy is transferred to radiated energy with 40% attributed to signal processing, pumps and chilled water systems [3], highlighting the complexity of incorporating radar systems into future vessels and the significant impact their size, mass and power requirements will have on the vessel's conceptual design. This is highlighted in the upgrade to the ANZAC class frigate's air search radar from the AN/SPS-49(V) to the CEAFAR2 which involves a weight increase from 1.4 t to 2.4 t in the antennas alone [5].

Supporting systems can account for approximately 80-90% of the total radar system weight with 43.4 t out of 50.6 t attributed to the supporting systems of AN/SPY-1D [6]. DEW (e.g. lasers for ship defence) have emitted power levels ranging from 10 kW to a few MW [7-9] depending on the intended target and can require shipboard power levels up to 20 MW [2, 8] when efficiencies, combat system processing power and cooling are taken into account.

Supplying this increased hotel load while maintaining propulsion loads requires increased power generation capacity and energy (fuel). The increase in power loads from future weapon systems and radars will have a significant impact on many facets of ship design [8]. White and Billups suggest to achieve optimum performance and cost, radar and ship design must be integrated [3].

InteShip

Modern naval vessels are comprised of many advanced systems that are becoming ever more integrated into a unified platform, leading to key performance aspects that are significantly inter-dependent (Figure 1). This trend exposes the inadequacies of traditional point-based design methods, such as the design spiral, as they are inefficient at dealing with the growing complexity of systems integration, both physical and functional [10]. This is driven by the early commitment to a single design strategy that can lead to limited options, poorly understood assumptions and late detection of design mistakes requiring substantial rework [11].

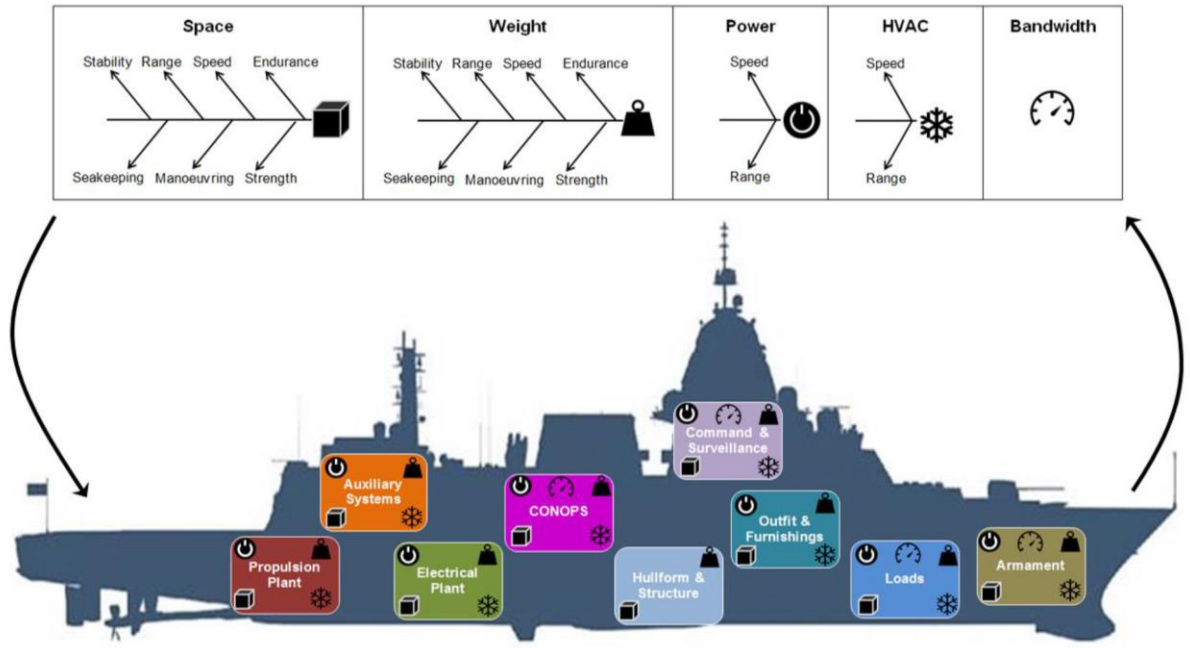


Figure 1: The extensive range of inter-dependent systems that make up a naval vessel with multiple performance aspects.

To overcome the inefficiencies of traditional methods, an integrated and holistic approach is vital to capturing the complex system integration and multi-objective performance characteristics of modern naval vessels. This approach is achieved by adopting a set-based design (SBD) strategy which is based around the principle of *assume variability; preserve options* [12]. To help meet the emerging technical challenges in the recapitalisation of Australia's fleet DSTG has developed an integrated platform modelling and analysis tool

referred to as InteShip. The software leverages advanced modelling and simulation capabilities to create an integrated framework that syntheses modelling and simulation tools, technical databases, and information exchange systems. This enables InteShip to have a modular environment in which the wide range of modelling tools can be rapidly connected to create a ship performance simulator tailored to a specific design problem (Figure 2). The integrated technical database is used to import digital representations of a ship and its various sub-systems into the simulator. The simulator is then used to explore the design space by adjusting design variables and evaluating the effect on the vessel's performance (Figure 2). InteShip has a built-in design of experiments tool which supports design space exploration and SBD by automating batch simulations which can be based on parameter scans as well as optimisation algorithms.

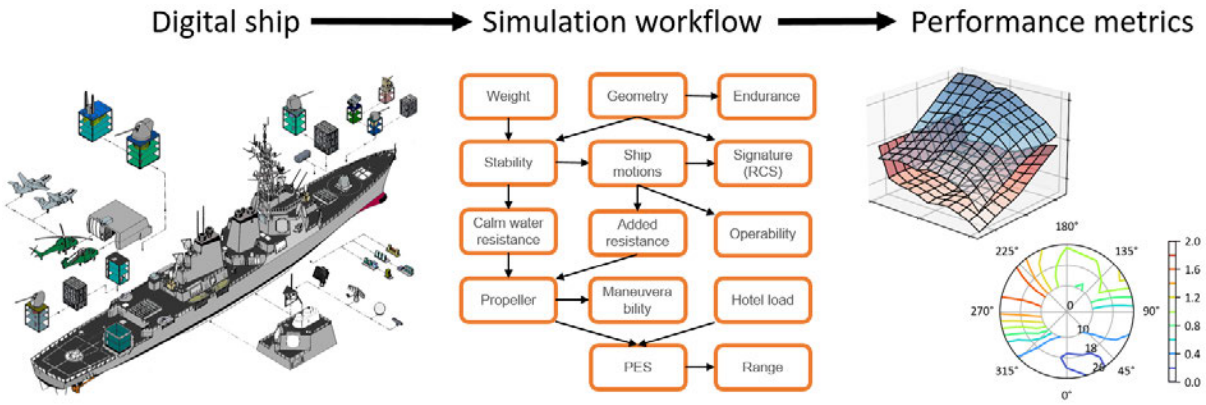


Figure 2: Destroyer design concept with multiple configuration options (left) are made into digital representations that import into an InteShip simulation workflow (middle) which produces the performance metrics (right).

In this paper, InteShip has been applied to investigate the effect that increasing power delivery, energy storage and mass to support future laser weapons and more powerful radars has on a generic frigate size and performance. The analysis investigates Power and Energy System (PES) configurations, the impact increased ship size has on available payload, ship resistance, stability, seakeeping and operability performance. The findings presented herein provide recommendations on the required size increase of a generic frigate to meet the needs of the new systems and the impact on vessel performance.

VESSEL SPECIFICATION

The investigation is centred on a baseline vessel featuring a generic frigate hullform, shown in Figure 3, with principal dimensions shown in Table 1. The hullform features a predominantly plumb bow with the stem sweeping forward above the waterline along with an integrated skeg and stern wedge. The vessel features bilge keels, fin stabilisers, a rudder and two propellers.



Figure 3: Generic frigate hullform.

Table 1: Principal dimensions of the baseline vessel.

L_{BP}	109.0 m	Δ	3662 t	C_B	0.521
B_{WL}	14.5 m	*Trim*	0.0 m	C_P	0.636
T_{MS}	4.5 m	*LCB*	50.8 m	C_M	0.806

Appendages consisted of bilge keels, 14.4 m long, along with two fin stabilisers and a rudder with planform areas of 5.6 m^2 and 13.0 m^2, respectively. The baseline vessel is propelled by two Wageningen B5.80-1.4 propellers, each with a 4.5 m diameter.

Lightship of the baseline vessel is broken up into steel, outfitting and machinery with each accounting for 50%, 35% and 15%, respectively, of the initial 2,800 t displacement. To allow the investigation of multiple engine configurations, 105 t is removed from machinery for the initial prime movers. The solid variable load (SVL) was set to 160 t with 650 t assigned to liquids, 485 t of which is diesel fuel. Additional capacity is the additional mass required to have the hull sitting at the design waterline (DWL). This is to be consumed by the prime movers, radar and laser upgrades and additional fuel to power the upgraded systems, and will be discussed further in the following sections.

Table 2: Weight breakdown of baseline vessel

Category	**Mass (t)**
Lightship	2,695
Steel	*1,400*
Outfitting	*980*
Machinery (excluding prime movers)	*315*
Liquid load	650
Solid variable load	160
Additional capacity	157
Total	3,662

The vessel has a combined diesel electric or gas (CODLOG) power and energy system architecture typical of modern frigates (e.g. [13-15]). This has a single gas turbine, which is mechanically connected to the propellers through a gearbox, and a number of diesel generators, which supply power to the on-board systems and to the propellers via main propulsion motors (see Figure 4). The system can be operated in two modes: diesel generator mode (DG mode), in which all the power is supplied by the diesel generators; and gas turbine mode (GT mode), in which power for propulsion is provided by the gas turbine and power for the on-board system is provided by the diesel generators. The baseline ship on-board systems are modelled as a hotel load with a constant power requirement. This paper investigates the effect on vessel size and performance of adding a radar and a laser to the vessel. The power requirements of these systems are modelled separately.

METHODOLOGY

Parameters/scaling approach

With naval platforms looking to integrate emerging technologies there are multiple design challenges that need to be investigated to identify viable options. Of these emerging technologies, advanced radars and lasers are of great interest but pose a major design

challenge requiring significantly more power and energy that conventional platforms cannot provide. To explore the design space of potential solutions, the baseline vessel has been used to create an array of vessel sizes which are then modelled with various engine configurations using InteShip.

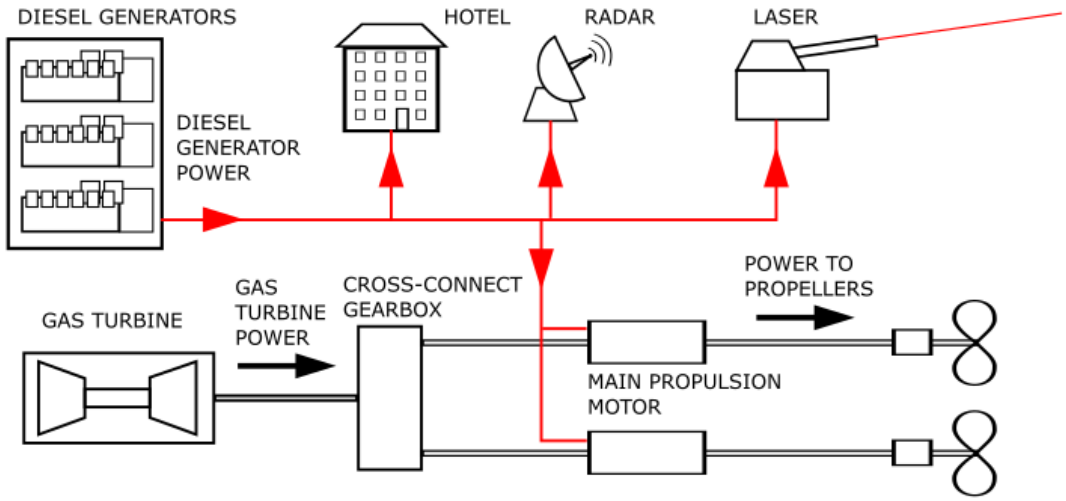


Figure 4: Schematic of the power and energy system.

The baseline vessel was scaled in three dimensions up to 110% in 2% increments (i.e. baseline vessel has a scale of 100%). Lightship mass and centre of gravity (COG) were scaled following the method outlined by Ventura [16] in which the steel, outfitting and machinery mass scale separately using knowledge of the baseline vessel's weight distribution. The COGs of the solid variable load and liquid load were scaled but the mass was kept constant.

To ensure each hullform was assessed in a state it was designed for, each vessel scale was modelled at a displacement and longitudinal centre of gravity (LCG) that had the vessel sitting on the DWL. The resulting displacement and COG was allocated to the corresponding lightship, solid variable load and liquid components with the remainder designated additional capacity. This additional capacity was then used to assess the performance and viability of various engine configurations to meet the radar, laser and extra fuel requirements. The extra fuel requirements are based on the vessel scales maintaining the 7,200 nm range of the baseline vessel with the initial 485 t fuel allocation.

Modelling

Taking advantage of InteShip's model repository, a simulation workflow was built around modelling the performance of each vessel scale and the various engine configurations to meet the increased hotel demand of the upgrades.

Stability

Stability was assessed using both an equilibrium and a large angle stability model, both of which are built upon Maxsurf Stability [17]. The equilibrium model was used to determine the equilibrium state of the vessel and subsequently the hydrostatics and initial stability of the vessel. The large angle stability model was used to produce a righting arm curve, or GZ curve, and determine the high angle stability of the vessel.

Resistance

Each vessel's resistance in a seaway was determined by calculating the various components using dedicated models. The model used to calculate calm water resistance of the bare hull was built upon Maxsurf Resistance [18] with simulations done using the Holtrop [19] empirical method. Appendage resistance comprised of rudder, fin stabiliser, propeller shaft and bilge keel components, each of which were calculated following the analytical methods developed by Peck [20]. The added resistance in waves model is built on Maxsurf Motions which utilises strip theory to predict vessel motions with the Gerritsma & Beukelman II [21] method used to calculate added resistance.

Seakeeping

The simulation workflow includes two seakeeping models both of which are based on Shipmo7 software [22] that predicts vessel motions using strip theory in the frequency domain. One of these models was used to obtain the vessel's response amplitude operators (RAOs) while the other model calculates the operability for a given seaway. The operability index is calculated following the method outlined in in DEF(AUST) 5000 [23] which is based on the vessel's motions, specified criteria limits, locations and ship speed.

Hydrodynamic coefficients

Wake fraction and thrust reduction coefficients were calculated via models that implement methods by Holtrop [24]. The coefficients were computed based on the vessel's principal dimensions.

Propeller

The propeller model consists of a database that contains thrust coefficient, torque coefficient and efficiency curves of different series of propellers. When provided with the required vessel speed, the model uses lookup tables to determine the required propeller thrust and delivered power.

Power and energy

The power and energy model is a spreadsheet-based tool which calculates the total fuel consumed during a mission for: a specified power generation system; specified on-board systems; mission parameters defining propulsion power and the usage of each of the on-board systems during that mission. Each mission was broken down into phases, where each phase has a different power requirement. For each mission phase, the duration of that phase and the power required from each the gas turbine and the diesel generators was calculated. If the diesel generators are capable of supplying the required power, the fuel consumed during each of the mission phases was then calculated and summed to obtain the total fuel consumption for the mission. Four missions were considered with different on-board systems present: hotel load only; radar and hotel load; laser and hotel load; and radar, laser and hotel load. The fuel consumption was calculated for both DG mode and GT mode, for seven different diesel generator combinations.

Simulation Settings

To generate accurate and useful results, the simulation workflow depends not entirely on the hull geometry and loading condition, but also on ancillary settings. This section briefly describes the collection of parameters used for that matter.

Environmental conditions

Simulations were conducted with a water density and kinematic viscosity set to salt water at 25°C. Added resistance in waves was calculated for a Bretschneider spectrum with a characteristic wave height, H_W, and period, T_W, of 1.88 m and 7.3 s. Wind resistance was calculated based on a head wind speed of 15 knots.

Seakeeping

The operability of each vessel was simulated for four operations with the criteria, sea states and ship speeds outlined Table 3 and corresponding locations outlined in Table 4.

Table 3: Criteria used for the calculation of the operability index as specified in DEF(AUST) 5000 [23].

Operation	Criteria	Location	Sea state	U_S (knots)
Transit	Deck wetness: 30 events/hr Motion Induced Interruptions (MII): 1 events/min	E A	Bretschneider H_W = 5 m T_W = 9.1 s	5 15 25
Helicopter	Vertical velocity: 2 m/s Vertical acceleration: 1.96 m/s^2 Lateral acceleration: 1.23 m/s^2	B B B	Bretschneider H_W = 5 m T_W = 9.1 s	5 15 25
RAS	Deck wetness: 0.5 events/hr MII: 0.5 events/min	C C	Bretschneider H_W = 5 m T_W = 9.1 s	10 15
L&R	Deck wetness: 0.5 events/hr MII: 0.5 events/min	D D	JONSWAP H_W = 5 m T_W = 9.1 s	5 10

Table 4: Operability locations.

Location name	Label	x/ L_{BP}	y/B_{WL}	z/T_{MS}	DH/ T_{MS}
Bridge	A	0.76	29.7	3.62	3.42
Flight deck	B	0.00	50.3	2.04	2.04
Replenishment at sea (RAS)	C	0.45	29.0	2.24	2.04
Launch and Recovery (L&R)	D	0.14	49.7	2.24	2.04
Forward perpendicular	E	1.00	7.6	2.33	2.33

Operation

The mission is a simplified representation of a mission a frigate may be expected to conduct, and consists of a transit to the operational area, a combat phase and a transit back to base, conducted at a constant speed of 18 knots. The propulsion and hotel loads are supplied for the entire mission. The radar operates during the combat phase and the power is supplied to the rail gun power for the time taken to consume the entire magazine.

Power and Energy System

The gas turbine was sized at 28 MW to provide a top speed of 29 knots for the baseline frigate and has a specific fuel consumption curve based on that given in Herdzik and Cwilewicz [25]. There are a limited number of marine gas turbines available, so the gas turbine was not scaled with the ship size. A fictional series of diesel generators was created, with models ranging from a 'V6' with a power output of 900 kWe to a 'V20' with a power output of 3000 kWe. Power outputs, weights and volumes were approximated based on datasheets from well known diesel generator manufacturers [26-28]. The specific fuel consumption curve was based on typical values presented in textbooks (e.g. [29, 30]). Seven different diesel generator configurations (labelled EC1 to EC7) with different power ratings were examined, ranging from four V6 diesel generators to eight V20s (see Table 5). The motor and gearbox efficiencies were held constant at 0.95 and 0.97, respectively.

Table 5: The diesel generator engine configurations investigated in this paper.

Engine combination	**EC1**	**EC2**	**EC3**	**EC4**	**EC5**	**EC6**	**EC7**
Generators	4 x V6	4 x V8	4 x V12	4 x V16	4 x V20	6 x V20	8 x V20
Total power (kWe)	3600	4800	7200	9600	12000	18000	24000
Total mass (t)	44	52	64	76	88	132	176
Total volume (m^3)	68	76	92	112	124	186	248

A hotel load was defined as a uniform 1,500 kW throughout the operation of all variants, which is within the range of values observed in similar vessels [13-15, 31]. For the analysis herein, the power and weight requirements of a future radar system and laser were estimated based on values from the open literature. For the radar, a mid-range power level of 4.0 MW was utilised with a weight increase of 10 t and 20 t to the parent ship's radar and radar system, respectively.

To remain within reasonable limits for a CODLOG system, in this paper we examine a rail gun with a power of 13.3 MW. The design intent was that a laser can fit within the approximate weight and dimension constraints of a current traditional system. For the purpose of the analysis a mass increase of 10 t was selected to account for the new laser weapon system.

An estimate of the additional power required for cooling is also included for both the radar and the rail gun, increasing the total power required for the radar to 5.1 MW and that for the rail gun to 16 MW.

RESULTS

Hydrostatics

With the loading condition of each vessel scale based on the hull sitting on the DWL sees the draught amidships increase steadily from 4.50 m to 4.95 m for the 100% and 110% scale, respectively (Figure 5). This results in a displacement of 3,662 t and 4,874 t for the 100% and 110% scales, respectively, with the increase in displacement between scales growing as the vessel grows. The waterplane area follows a similar non-linear trend ranging between 1,201 m^2 and 1,453 m^2.

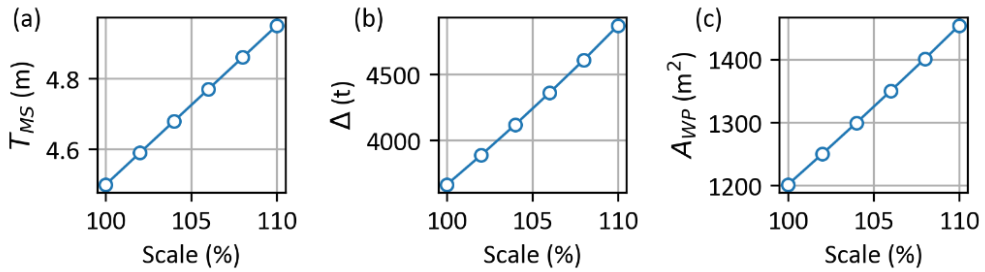


Figure 5: a) Draught amidships, b) displacement and c) waterplane area as a function of scale factor.

Stability

Assessing the stability of each vessel scale in an intact condition from the righting lever (*GZ*) at varying angles of heel (i.e. *GZ* curve) shows *GZ* increasing with vessel scale at all positive heel angles (Figure 6). This *GZ* behaviour translates to an improved initial stability with metacentric height (*GM*) increasing linearly with vessel scale for the range of scales modelled. This results in the area under the *GZ* curve, between 0° and 30°, growing at the same rate as the scale factor (i.e. 2% increments).

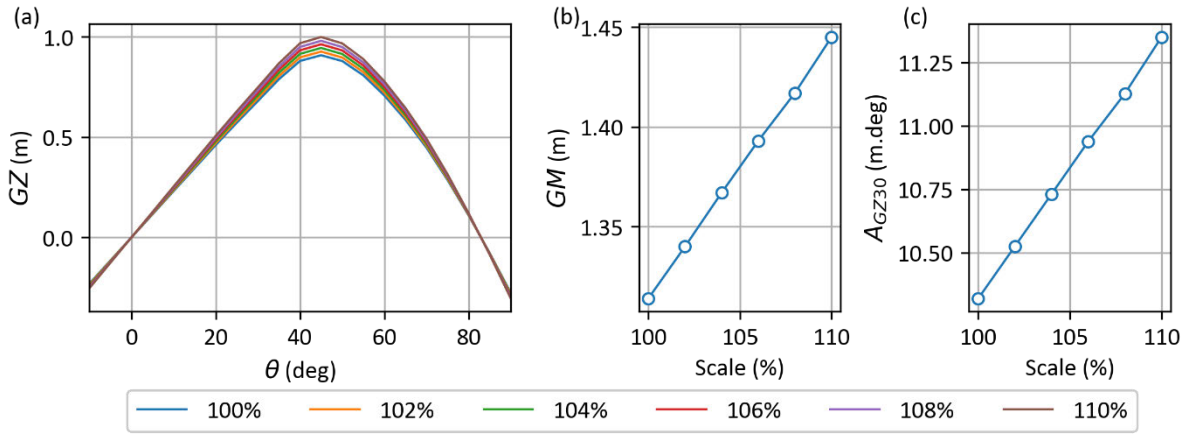


Figure 6: Stability metrics of each vessel scale including: a) GZ curves; b) metacentric height; and c) area under the GZ curve up to 30° of heel.

Seakeeping

The vessel motions are shown not to vary significantly for the range of vessels scales modelled as shown in the heave, pitch and roll RAOs (Figure 7). The RAOs show typical ship motion characteristics with both heave and pitch starting at unity for low wave frequency (f_w) before rolling off sharply with increasing f_w. Both heave and pitch motions level out at a slightly lower f_w for the larger scales as the wavelength is smaller relative to the vessels length. The roll RAO shows a reduction in the resonant peak frequency as the vessel size increases. This can be attributed to the increased `momentum' of the higher roll mass moment of inertia ($I_{xx}$) of the larger vessel scales overcoming the increased `stiffness' from the increasing *GM* (Figure 6).

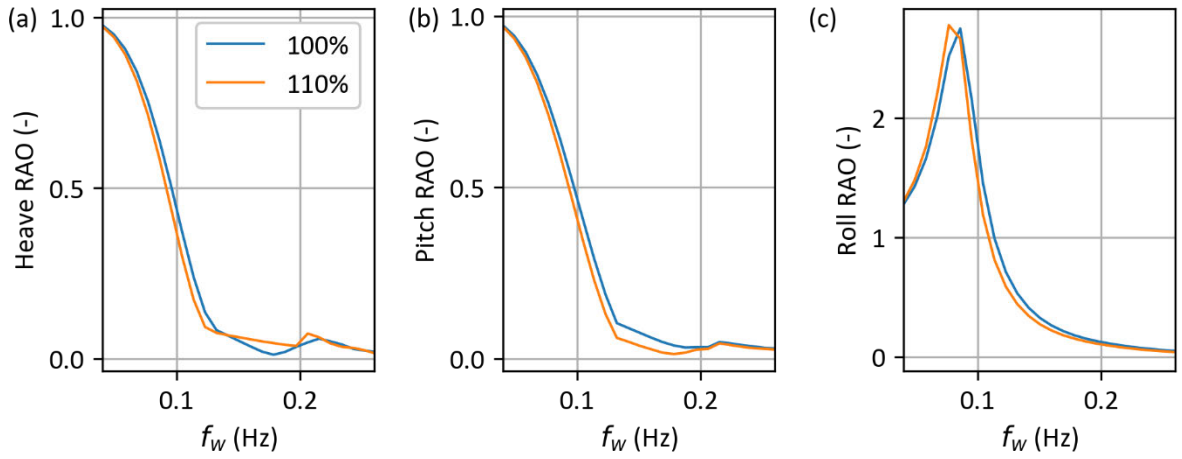


Figure 7: Non-dimensional RAOs for (a) heave and (b) pitch motions in head seas and (c) roll motions in beams seas for the 100% and 110% scales operating at 18 knots.

The operabilities for all operations are shown to improve with vessel scale with the exception of RAS operability which shows no change (Figure 8a). Transit operability was found to be hinder predominantly by deck wetness and MII in head and beam seas, respectively, both which were shown to reduce with increasing vessel scale (Figure 8b,c). Helicopter operations showed good operability overall only exceeding the 1.96 m/s^2 vertical accelerations criteria limit in head and bow quartering seas at 25 knots. The relatively low operability of L&R operations is driven solely by the high MII with the deck wetness criteria limit not being exceeded.

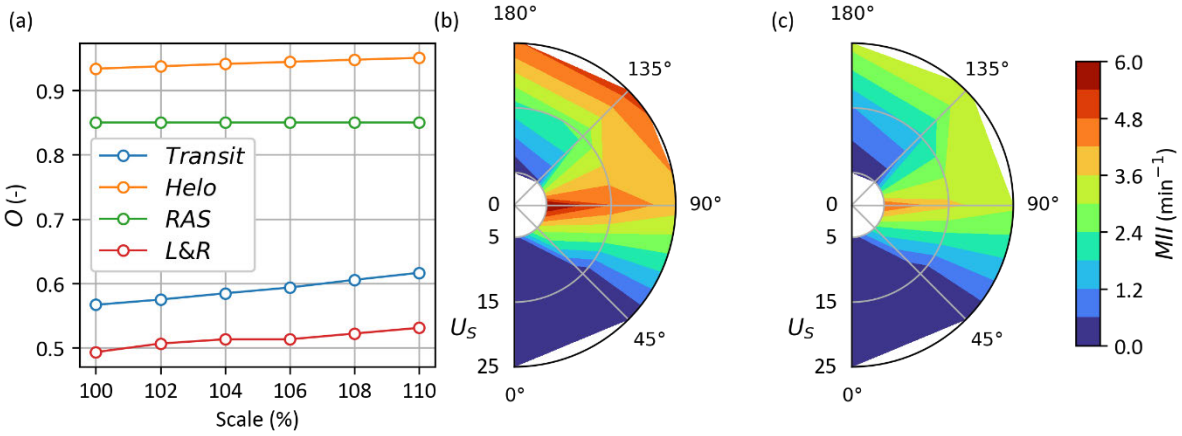


Figure 8: a) Operability of transit, helicopter, RAS and L&R operations for the varying vessel scales. Polar plots of the MII at the bridge for the b) 100% and c) 110% vessel scale.

Resistance and power

Figure 9a shows the increase in total resistance as the size of the ship increases. This requires an increase in effective power (P_{eff}) and hence power delivered to the propellers (P_{del}) (Figure 9b). The power required for the on-board systems does not change as the ship size is increased (Figure 9c). A consequence of the increasing resistance with increasing ship size but constant gas turbine power is a reduction in the top speed achievable, which reduces by 0.5 knots over the range of vessel scales considered (Figure 10).

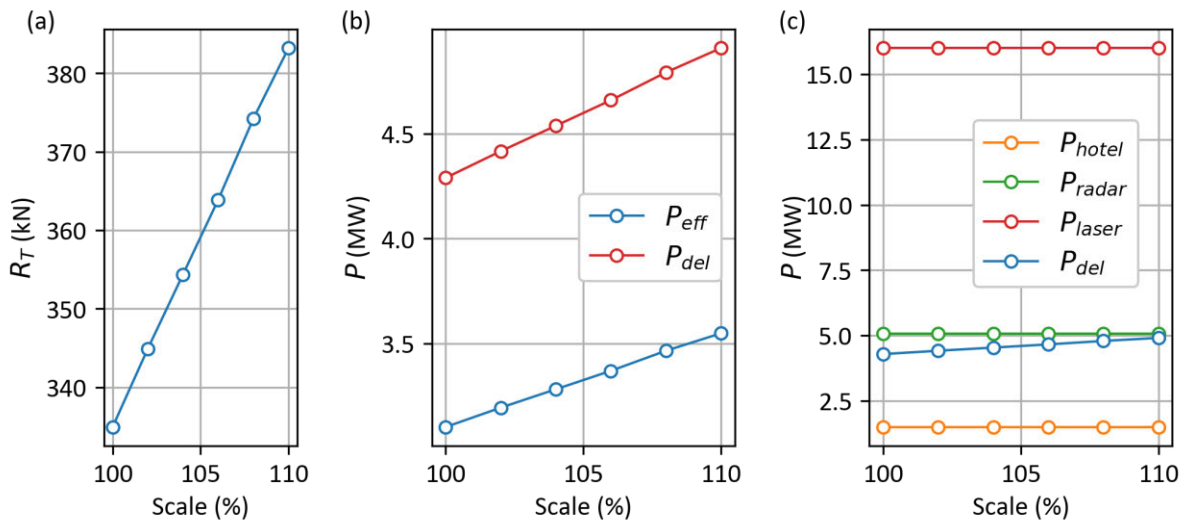


Figure 9: The effect of scale factor on: a) Total resistance (R_T); b) effective propulsion power (P_{eff}) and delivered propulsion power (P_{del}); and c) the power required for propulsion, the hotel load, the radar and the laser.

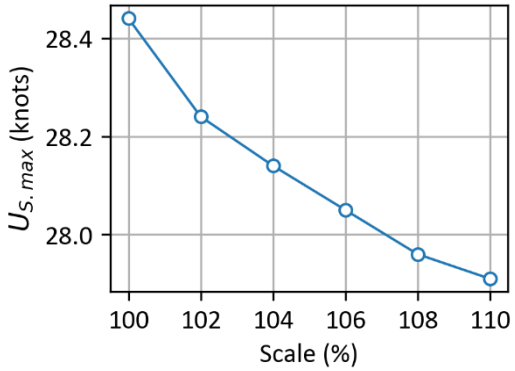


Figure 10: Top speed in GT mode for each vessel scale.

Figure 11 shows the power required from the diesel generators for all four mission variations for both diesel generator and gas turbine modes. The horizontal dashed lines show the power available from each of the diesel generator systems considered, allowing the smallest diesel generator combination needed to support each of the given missions to be determined. For example, it can be seen that none of the combinations considered can support the laser, radar and hotel load mission in diesel generator mode, but four V20 diesel generators can supply sufficient power in gas turbine mode.

Fuel consumption

Figure 12 shows the fuel consumed during each mission in both diesel generator and gas turbine modes, for the smallest diesel generator combination capable of supporting that mission. The fuel consumed increases as the on-board services power demand increases as well as with the ship size due to the extra total resistance. There is also a significant increase in fuel consumption in moving from diesel generator mode to gas turbine mode, due to the higher specific fuel consumption of the gas turbine for the same power output. In the simplified model considered here, gas turbine mode assumes the use of the gas turbine for

the entire mission and not just the portions where the extra power is required. This gives a fuel consumption estimate at the higher end of the likely range. Note, however, that no allowance was made for travelling faster than 18 knots, which would consume extra fuel.

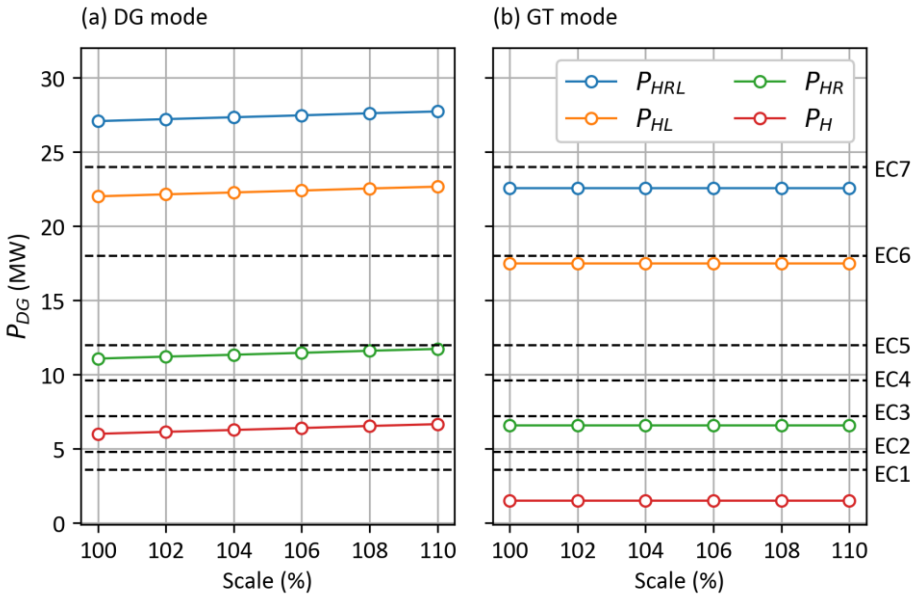


Figure 11: The effect of scale factor on the total power required and the available power from the seven different diesel generator configurations, in both a) diesel generator and b) gas turbine mode.

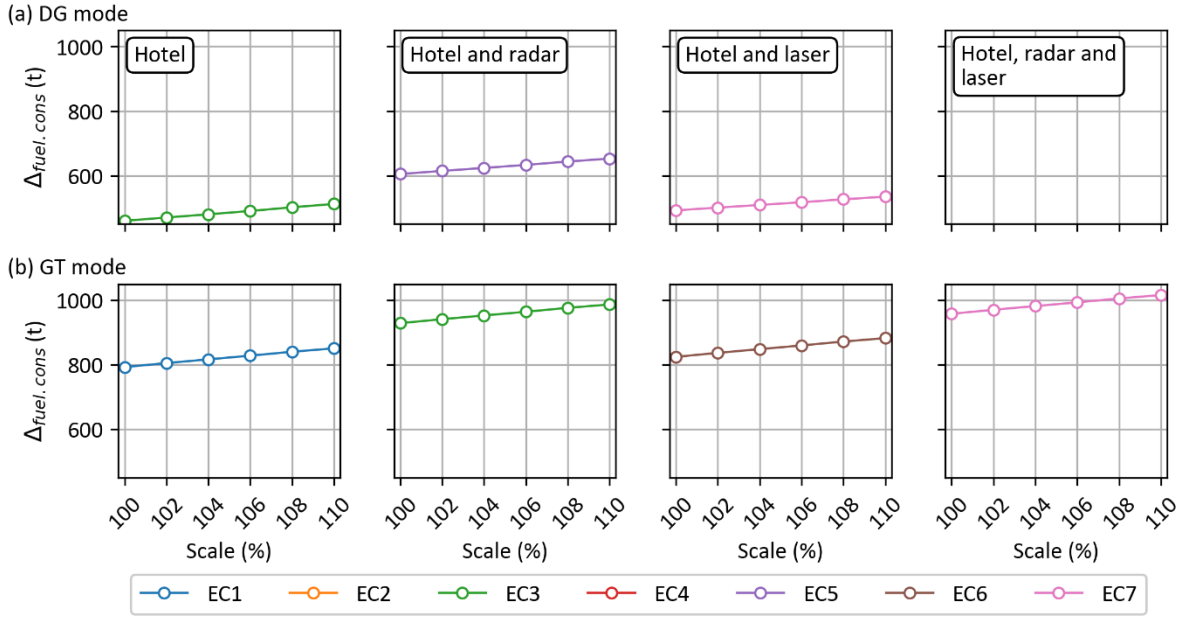


Figure 12: Fuel consumption for the smallest diesel generator combination capable of supplying sufficient power for each mission, in: a) diesel generator; and b) gas turbine mode.

Additional capacity

The additional capacity is based on the additional mass and vertical centre of gravity (VCG) required by each vessel scale to have the hull sitting at the DWL with the same relative VCG after accounting for lightship (excluding prime movers), liquids and solid variable load. Figure 13a shows the additional capacity increases from 157 t to 783 t across the vessel scales.

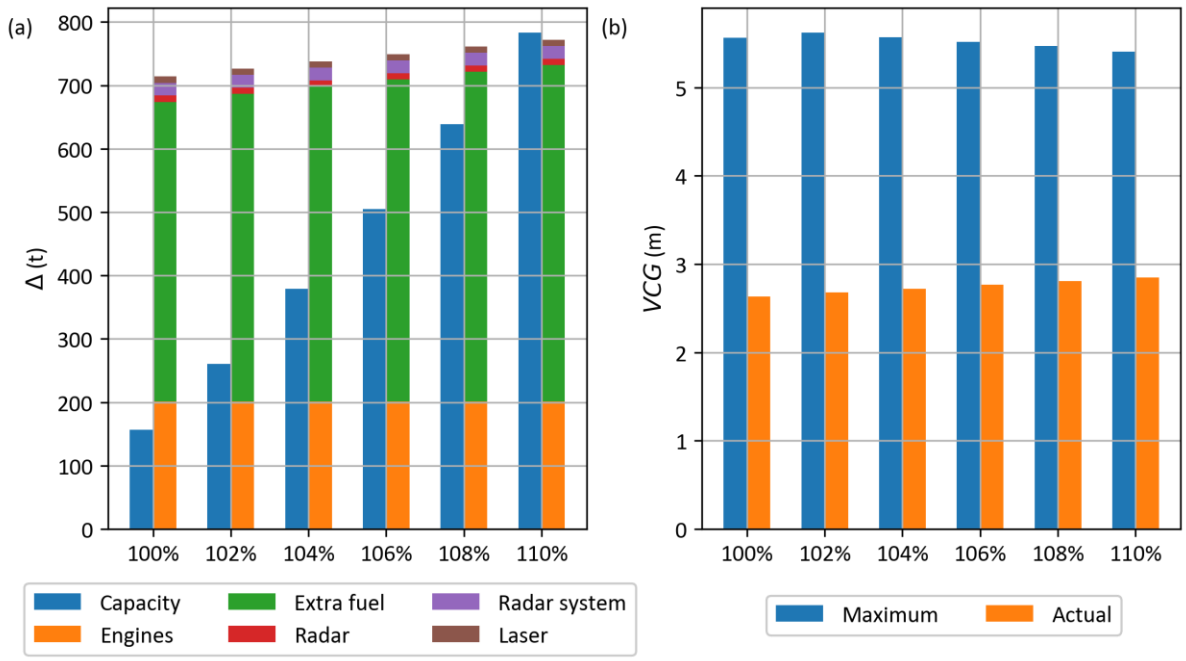


Figure 13: Breakdown of the a) additional mass and b) VCG required to install the upgrades and EC7 to each of the vessel scales. These are compared to the available capacity of each vessel scale.

The required mass to incorporate the upgrades at each vessel scale is broken down into components. This consists of the EC7 upgrade (as it is the only configuration capable of meeting the power requirements), the additional fuel required to maintain a range of 7,200 nm along with radar, radar systems and laser upgrades.

The only varying mass consumption component between vessel scales is the extra fuel due to the increased fuel consumption to meet the increasing propulsion power of the larger scales. Comparing the required mass to incorporate the upgrades with the additional capacity at each scale (Figure 13a), only the 110% scale possesses sufficient capacity.

The maximum allowable VCG of the upgrades to maintain the design VCG is compared to the actual VCG of the upgrades in (Figure 13b). The results show that despite the decline in allowable VCG and the rise in actual VCG with vessel scale, the actual VCG never exceeds the allowable VCG for the scales modelled. This is primarily driven by the engines, fuel and radar systems being located low down as well as the laser which despite being located on the main deck, the majority of the supporting systems are located low in the vessel.

DISCUSSION & CONCLUSION

Having explored the design space, an understanding of the relationship between the various systems and performance aspects has been developed. As the vessel size increases, we see improvements in the stability, with a 10% increase in the metacentric height, and seakeeping performance, with transit operability improving from 0.567 to 0.617. These gains need to be weighed up against the additional 619 kW power required to propel the 110% scale vessel at 18 knots compared to the baseline vessel (a 14% increase), as well as a 0.5 knot drop in top speed. This additional propulsion power would require up to an additional 52.2 t of fuel,

depending on the engine configuration. The larger vessel would also cost more to both build and operate.

Design space exploration of the various ECs and operating modes on each of the vessel scales enabled the identification of viable configurations for each of the upgrade options as well as the impact on the vessel's performance. None of the ECs had the capability to meet the propulsion, hotel, radar and rail gun power demands while operating in DG mode but could be met in GT mode with the largest, EC7, which features 8 V20 diesel generators. The fuel required to service the hotel, radar and rail gun loads, as well as to propel the vessel, is 958 t for the 100% scale, which is an additional 473 t in excess of the initial fuel allocation, exceeding the baseline vessel's available additional mass capacity.

The upgrades investigated here require additional mass and VCG to be accommodated on the ship. The significant majority of the extra mass is fuel to provide the required energy. The results show that all vessel scales have sufficient additional VCG capacity, however only the 110% scale vessel has sufficient additional mass capacity to accommodate the upgrades.

By using InteShip to conduct a design space exploration a deeper understanding of the relationships between vessel size, PES, increasing hotel load and the various performance aspects has been developed. This provides objective quality evidence, generated from the simulations, which can be used to fully understand the trade-offs in design decisions. It is data from investigations such as this that can be used to support evidence-based decision making by stake holders.

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NAVAL PLATFORM SURVIVABILITY ANALYSIS FOR MISSION CAPABILITY RESILIENCE

Anthony Woolley[+], Alexander Gargano[+], Serap Aksu[+], Grant Gamble[+] and Daniel Foos[++]
[+]Defence Science and Technology Group, Australia
[++]Test and Evaluation Solutions, LLC, USA
[+]anthony.woolley@dst.defence.gov.au

ABSTRACT
Battle-ready naval platforms are those with agility and resilience to endure in contested maritime environments. Contributing to platform agility and resilience are the capabilities afforded to the platform to maintain warfighting readiness and enable survivability for the achievement of the mission requirements. To maximise the probability of mission success, assessment of platform susceptibility, vulnerability and recoverability is required. Traditionally, this analysis was 'stove-piped'. That is, analysis was independently performed within each of the susceptibility, vulnerability and recoverability domains. However, such analysis only informs platform survivability with respect to each of those domains. Conversely, Integrated Survivability examines the greater survivability trade-space made available by combining susceptibility, vulnerability and recoverability into a holistic framework. Analysis of this trade-space provides a mechanism to ascertain the capability resilience of naval platforms to the threat environment, and to maximise warfighting capability. To demonstrate the application of Integrated Survivability analysis, a case study was developed in which the survivability of a generic naval platform was analysed against a weapon threat encounter. The case study included blast and fragmentation, fire and smoke, and crew damage control activities. The study highlighted the effect changes to platform configuration will have on platform survivability and mission outcomes. Output from the study included development of a workflow to perform future Integrated Survivability analysis. Presented in this paper is an overview of the case study, survivability analysis of the platform against a specific threat encounter, the outcomes, and a discussion of the implications to naval platform and mission capability resilience.

1. INTRODUCTION

Naval platform Integrated Survivability assessment is an analysis of the platform against combat and non-combat threat environments. It is a temporal, holistic consideration of the domains, susceptibility, vulnerability and recoverability. Depicted in Figure 1, the Integrated Survivability Onion highlights the high-level survivability trade-space afforded to naval platforms. Integrated Survivability assessment examines this trade-space to facilitate platform configuration design decisions; enable capability trade-off during acquisition; and provide seaworthiness and battle-readiness assurance for specified mission profiles. For the Royal Australian Navy (RAN), Integrated Survivability assessment contributes to 'maximising the likelihood of achieving the specified operational effect for the defined tasking' [1].

Currently, only a conceptual Integrated Survivability framework has been developed [2] and implementation of a suitable software environment is ongoing [3]. However, demonstrating the benefits afforded by an Integrated Survivability analysis capability can be achieved via case studies utilising available survivability modelling and simulation (M&S) software tools. For example, Piperakis and Andrews [4] analysed Integrated Survivability for five naval combatant designs and two oil replenishment platforms. However, due to the temporal nature of

recoverability and a need for human factors analysis, they derived weighted performance measures for recovery of platform functions. Consequently, crew behaviour during damage control and recoverability was not directly simulated. Liwang and Jonsson [5] derived measures of survivability with respect to vulnerability and calculated the probability of kill, P_k, for various platform functions. Using three generic frigate configurations against two threat types, they highlighted the effects of system redundancy and separation.

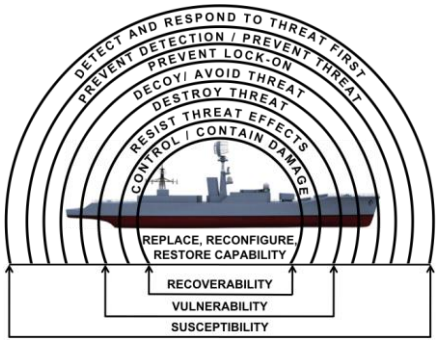


Figure 1: The Integrated Survivability Onion contributing to platform survivability

To further demonstrate the practicality of platform Integrated Survivability analysis, including crew behaviour for the achievement of mission objectives, a case study involving four generic platform configurations exposed to a weapon threat was examined. The output from the survivability analysis was a recommendation of a platform configuration suitable for the achievement of the defined mission objective. Another output from the study was the development of a workflow to perform future survivability analysis.

The remainder of the paper defines the case study (Section 2); describes the survivability scenario (Section 3); presents survivability modelling of the platform configurations against the weapon threat (Section 4) and the integrated analysis for capability resilience (Section 5); and discusses the outcomes in relation to the case study objectives (Section 6).

2. CASE STUDY DEFINITION

In this section, the objectives of the case study, constraints, and assumptions are defined. The choice of survivability M&S software tools is also described.

2.1 Case Study Objectives

Two primary objectives were defined to:

1. demonstrate integrated analysis of platform survivability for capability resilience. The aim of this objective was to highlight current capabilities supporting RAN platform survivability analysis during acquisition and upgrades to the fleet-in-being; and
2. develop a workflow to perform naval platform Integrated Survivability analysis and assessment. This output would be a ‘step-by-step’ workflow to enable development of survivability scenarios, identification of M&S software tools, and identification of inputs to the M&S software tools.

2.2 Constraints and Assumptions

To manage the scope of the study for the achievement of the objectives, constraints and assumptions were imposed to reduce the complexity of the scenario. They were:

1. no verification and validation (V&V), of the M&S software tools, to be performed;
2. platform structure material properties was mild steel with plating of 5mm thickness;
3. weapon impact location was predefined;

4. fire fuel load was concentrated to an area at the centre of the compartment of interest;
5. fire fuel load was a solid combustible materials (A Class) fire;
6. the heat release rate[1] was ramped from 0 to 600kW over one minute and then remained at 600 kW;
7. the effect of fire insulation was not considered;
8. only systems and components required for the scenario were modelled;
9. system operational specifications set to default values in the relevant M&S software tool;
10. no flooding; and
11. crew complement was limited to personnel required for the scenario.

Note, V&V of the respective survivability M&S software tools is a separate study to be performed by (susceptibility, vulnerability and recoverability) domain experts who utilise those tools. For example, a limited analysis of fire and smoke M&S software, and crew movement software has previously been performed [6, 7]. V&V of survivability software was outside the scope of the study documented herein.

2.4 Survivability Software Tools

Three M&S software tools were selected to demonstrate naval platform survivability:

1. *Unity based Vulnerability Assessment Model* (*UVAM*) - developed by Defence Science and Technology Group (DSTG), to calculate P_k for system components and platform structure exposed to blast and fragmentation;
2. *Fire Dynamics Simulator (FDS)* [8] - fire modelling software tool; and
3. *Integrated Recoverability Model* (*IRM*) [9] - a time-based simulation used to evaluate naval platform systems, mission capability, and recoverability after damage. *IRM* was coupled with the fire modelling software *Fire and Smoke Simulator* (*FSSIM*) [10].

3. THE SURVIVABILITY SCENARIO

The scenario examined four platform configurations, involving technology insertion and reconfiguration of platform general arrangement, exposed to a weapon threat. The aim was to identify a platform configuration to achieve a defined mission objective. The platform model was the Virtual Survivability Research Ship (VSRS) *Arion* [11, 12], derived from ex-HMAS *Derwent* [13].

3.1 Scenario Synopsis

VSRS *Arion* is escorting a high valued asset (HVA) transiting a contested passage of water with a large volume of commercial shipping. Enemy combatants operating in the area use the commercial shipping as cover. VSRS *Arion* detects high-speed water-borne craft approaching but is unable to engage (due to commercial shipping). The enemy combatant launches a rocket-propelled grenade (RPG) that impacts the starboard, stern of VSRS *Arion* – depicted in Figures 2 and 3. The RPG hit location (x, y, z) = (100, 3.5, 5.0) is measured in metres from a global datum at the bow [11]. Here, the hit location is 100.0 m aft of frame 0; 5.0 m vertical from the keel; and 5.0 m starboard of the centre-line. Figure 4 depicts VSRS *Arion* 3 Deck stern general arrangement, showing the weapon detonation inboard of Compartment 3P. The detonation damages the fire main in Compartment 3P, resulting in a loss of water pressure to the fixed firefighting system. Consequently, there is no firefighting capability within the compartment. Blast fragmentation penetrates the bulkhead between Compartments 3P and 5Q, damaging equipment in Compartment 5Q and resulting in the loss of manoeuvring

[1] That is, the rate at which a fire releases energy.

capability. Hot fragmentation initiates a fire in Compartment 3P, impeding the only access to Compartment 5Q. Without firefighting capability, the fire cannot be extinguished and manoeuvring cannot be recovered. VSRS *Arion* is susceptible to further attack and unable to protect the HVA. The first objective in the process to recover manoeuvring capability is to task a Blanket Search Team to identify the cause of the failure to the fixed firefighting system.



Figure 2: Plan-view of VSRS Arion showing weapon launch and platform hit locations

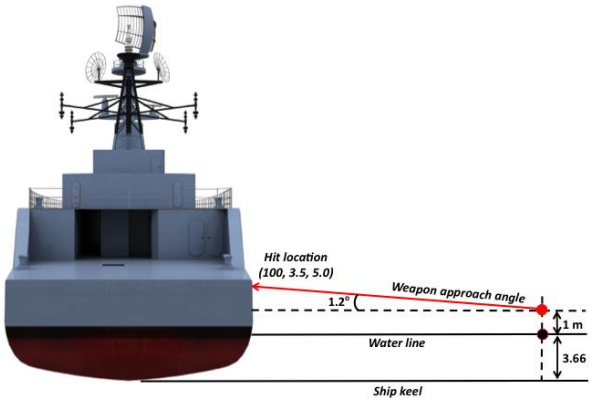


Figure 3: Stern-view of VSRS Arion depicting weapon launch and platform hit locations

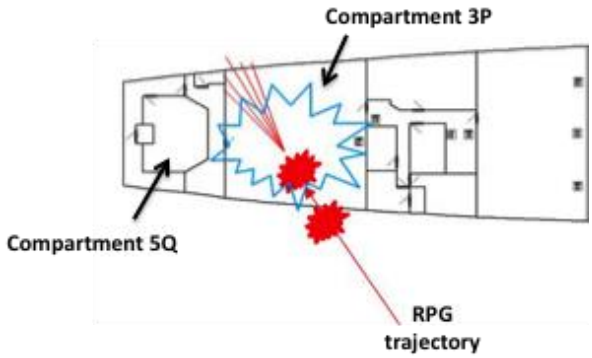


Figure 4: Compartment 3P depicting the location of the RPG detonation on 3 Deck

3.2 Weapon Description

The weapon threat is an RPG with two explosive charges. The inclusion of two charges enabled the first charge to breach the hull and create a path for the second charge to detonate within Compartment 3P. The RPG specification used in this scenario is presented in Table 1.

Table 1: RPG specification used in the scenario



Length	618 mm
Diameter	72.5 mm
Wingspan	~218 mm
Weight	1.48 kg
Warhead	0.36kg HMX

Propulsion	Rocket
Maximum Speed	133 ms^{-1}
Maximum Range	250 m
Minimum Range	50 m
Damage Radii	3.2m

3.3 VSRS *Arion* Mission Objective

VSRS *Arion* must restore manoeuvring within five minutes to maximise protection of the HVA. Between five and ten minutes, the ability to protect the HVA diminishes. If manoeuvring is not recovered after ten minutes, the HVA becomes a combat casualty.

3.4 VSRS *Arion* Platform Configurations

Four platform configurations were considered for assessment:

Configuration 1 (Baseline): crew must manually operate valves to divert fire main water to the fixed firefighting system;

Configuration 2 (Remotely Operated Valves): valves diverting fire main water to the fixed firefighting system are remotely operated;

Configuration 3 (Autonomic Valves): valves diverting fire main water to the fixed firefighting system are operated by a computer control system upon detecting a system fault; and

Configuration 4 (Configuration 1 plus access hatch): a hatch is included on 2 Deck, giving direct access to Compartment 5Q. The crew must manually operate valves to divert fire main water to the fixed firefighting system.

In Configurations 1, 2 and 3, the only access route to Compartment 5Q is obstructed by fire. The blue solid and dashed lines in Figure 5 highlights this path. In Configuration 4, a hatch is included in the deckhead connecting 2 Deck to Compartment 5Q on 3 Deck. The blue and green solid lines in Figure 5 highlights the revised access route.

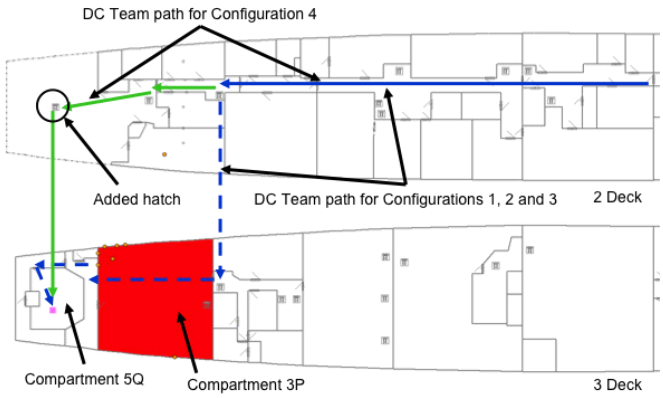


Figure 5: Access paths to Compartment 5Q in Configurations 1, 2, 3 (blue lines) and 4 (blue and green solid lines)

4. SURVIVABILITY MODELLING AND SIMULATION

Prior to any M&S, pre-processing of the VSRS *Arion* model was performed, suiting the requirements of the individual M&S software tools. Relevant aspects of the scenario were then defined within the respective software tools. That is, for example, the RPG-VSRS *Arion* explosive scenario was defined in *UVAM*; and the fire scenario was defined in *FDS*. When the respective scenarios were defined, M&S was performed and the output collated. Presented in this section is an overview of the M&S and output for the respective M&S software tools.

4.1 Blast and Fragmentation Vulnerability Analysis

The aim of vulnerability modelling and analysis is to maximise platform, systems and crew resilience to the threat effects. This is achieved by examining the zoning, separation and redundancy of platform general arrangement and system configuration. Vulnerability analysis of VSRS *Arion* utilised the bespoke software, *UVAM*, to calculate P_k for systems and platform structure damaged by blast and fragmentation. Development of the *UVAM* vulnerability model required information pertaining to:

- platform geometry data including size, shape and spatial arrangement of the internal platform structure and systems;
- material data, such as material type and structural thickness for the geometry data;
- weapon composition, such as explosive type, charge weight, and casing and fragmentation information (material type, number of fragments and fragment distribution);
- weapon impact velocity and fuse delay options.

UVAM uses empirical algorithms to calculate P_k for structural elements and systems. Here, P_k is a fraction of 1, where a value of 1 represents a 100% probability that the structure or system was damaged such that it no longer provides the intended functionality. Due to the security sensitivity of vulnerability algorithms, generic algorithms were used in this case study. The

blast algorithm, equation (1), was used to calculate the probability of kill due to blast, *BlastHit*.P_k, for hull structure and systems based on proximity of the explosive charge:

$$BlastHit.P_k = 1 - (R_O / R_D) \quad (1)$$

where

- R_O is the distance between the detonation point and the closest point of the object; and
- R_D is the blast radius in which damage is likely to occur (3.2m for the RPG, Table 1).

Visual output from *UVAM* is presented in Figure 6, showing the RPG detonation in Compartment 3P. The red circle represents the effective blast radius; and vectors originating from the blast centre represent the ejected fragment distribution. Here, the vectors only represent fragmentation direction. Objects affected by blast and fragmentation are colour coded, representing the total P_k for each object, as detailed by the legend in Figure 6. The fire main within Compartment 3P is shaded red, indicating a P_k of 80% to 100%.

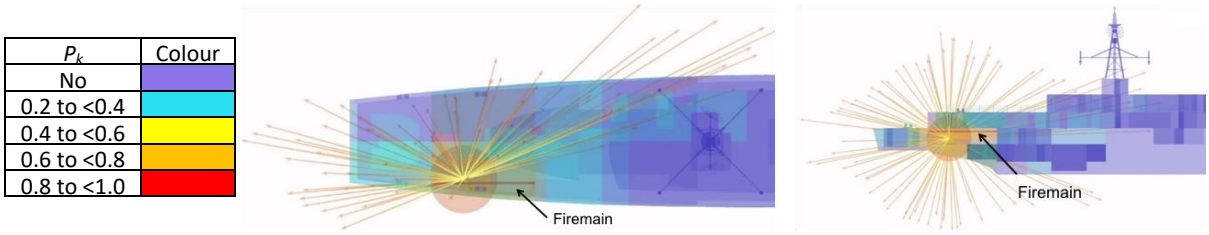


Figure 6: Top and starboard views of weapon detonation inboard of Compartment 3P modelled in UVAM

The P_k for individual objects within the damage zone can be output in numerical form via *UVAM*. For example, Table 2 documents P_k for several structural objects and the fire main. Even though only one fragment impacted the fire main, the fire main was also within 1m of the detonation. Consequently, with a P_k of 0.819, the fire main in Compartment 3P was severely damaged in this scenario. Therefore, the fire main is unable to supply the fixed firefighting system and VSRS *Arion* has no firefighting capability in Compartment 3P. The watertight bulkhead between Compartments 3P and 5Q received 12 fragment impacts, all penetrating the bulkhead. No components were modelled in Compartment 5Q; however, due to the 12 high speed fragments penetrating into Compartment 5Q, there is a high probability the steering equipment was damaged by the event.

Table 2: Number of fragment hits and probability of kill, P_k, for selected components of interest

Part Description	Distance from blast (m)	#Fragments	P_k (total)
Water-tight bulkhead between Compartments 3P and 5Q	2.95	12	0.437
Water-tight door on 2 Deck above Compartment 3P	1.70	0	0.462
Fire main located in Compartment 3P	0.95	1	0.819

4.2 Fire and Smoke Vulnerability Modelling

Fire and smoke modelling also contributes to platform vulnerability analysis with the aim of minimising threat effects. For this case study, fire progression and smoke density was modeled using *FDS* and *FSSIM*. *FDS* was selected for the purpose of understanding the capabilities of the software tool. Prior work examined other fire modeling software in support of naval platform survivability analysis [3, 6]. *FSSIM* was also selected due to its ability to directly couple with *IRM*. The coupling of *FSSIM* and *IRM* enabled firefighting analysis in support of platform recoverability. This section only examines *FDS* modelling of the RPG initiated fire, to understand the use of *FDS* in naval platform survivability analysis. *IRM-FSSIM* coupled fire modelling is documented in Section 4.3.

Hot fragmentation from the RPG detonation initiated a fire only within Compartment 3P. Figure 7 presents an *FDS* wireframe starboard stern perspective of VSRS *Arion* depicting the venting of smoke from the RPG entry hole. The dark shaded, rectangular area is Compartment 3P. In Figure 8, a cut plane through Compartment 3P shows the temperature distribution within the compartment at a specific time during the simulation. The colour coding represents red as the highest temperature through to blue as ambient temperature.

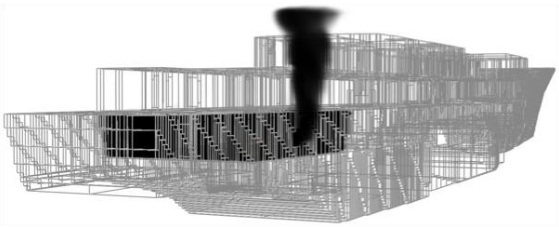


Figure 7: FDS wireframe model depicting venting from the weapon entry hole

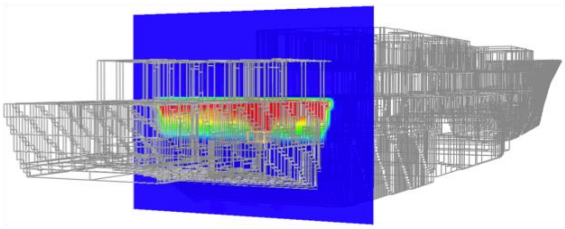
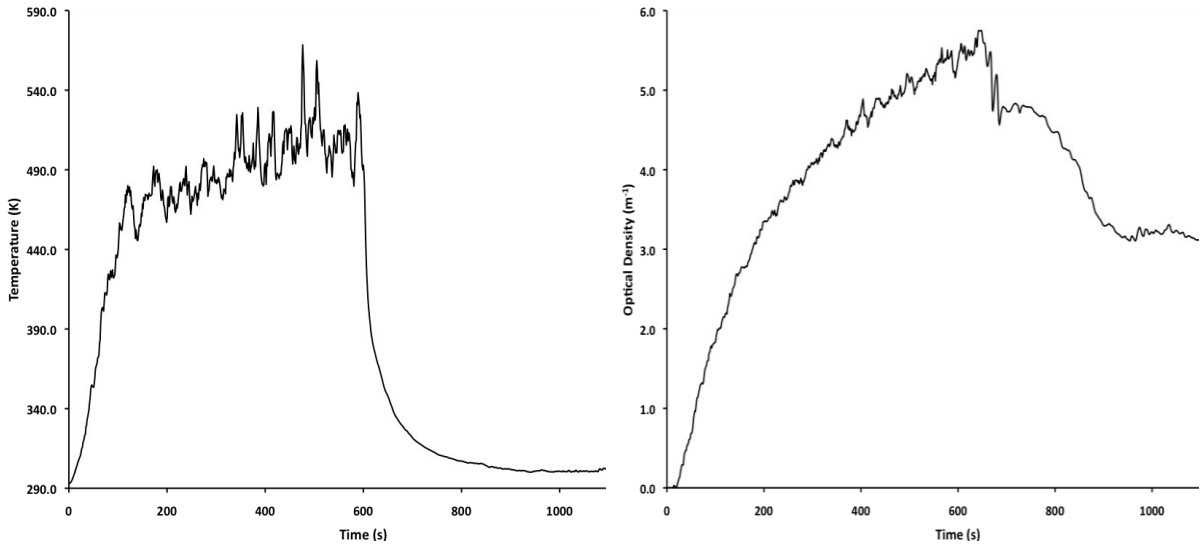


Figure 8: FDS cut plane of temperature for the fire in Compartment 3P

Another output from *FDS* for the VSRS *Arion* scenario was the temporal temperature measurement within Compartment 3P if no firefighting occurred. Figure 9 depicts the temperature increase within the compartment through to approximately 1000 seconds after fire initiation. Approximately 600 seconds after the initiation of the fire, the fuel load within the compartment was consumed and the fire temperature decreases. Also shown is an example of the smoke density within Compartment 3P. The decrease in density is a result of venting. The effect of firefighting can be modeled in *FDS* but this requires knowledge of the commencement time for firefighting activities. For this case study, the effect of firefighting on fire behaviour was modeled in *IRM* coupled with *FSSIM*, as described in Section 4.3.



(a) (b)

Figure 9: Fire temperature (a) and smoke density (b) in Compartment 3P modelled in FDS, with no firefighting

4.3 Platform Recoverability Modelling

Platform recoverability was performed using *IRM*. A typical *IRM* model includes platform structure, general arrangement, and systems and system functionality. Threat-based assessment, such as output from *UVAM*, can be used to provide the initial damage input(s) for an *IRM* scenario. Shown in Figure 10 is the VSRS *Arion* system configuration modelled in

IRM for this case study. The implemented system functionalities were: seawater chests and pumps to collect and distribute seawater through the fire main; a fire main and fixed fire fighting (sprinkler) system; and generators and power distribution switchboards to power the respective systems. Not shown are sensors to detect the presence of fire and smoke. Configurations 1, 2, 3 and 4 were modelled in IRM, similar to that shown in Figure 10, with different system activation logic according to the requirements of each configuration.

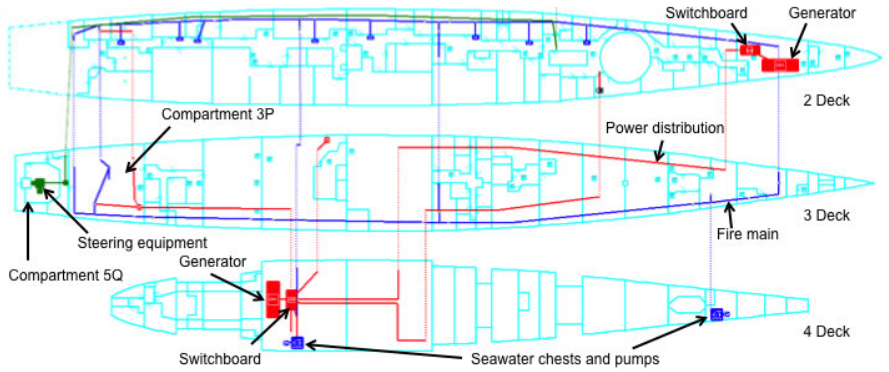


Figure 10: VSRS Arion system representation modelled in IRM

Crew behaviour can also be modelled in *IRM*. For this case study, implemented crew billets were: Damage Control (DC) In-charge (IC), stationed in the Repair Base on 2 Deck; a Blanket Search Team of two crew; two Firefighting Teams of four crew each; a Boundary Team of four crew, to establish fire and smoke containment boundaries; and a DC Team of four crew to recover system functionality. Each team performed duties according to activation logic informed by generalised DC Standard Operating Procedures (SOPs) (example DC SOPS are documented in [2]). Figure 11 shows the initial crew locations on 2 Deck. Simulation is exemplified using Configuration 1 in Figure 12 (a, b, c, and d) at various times after RPG detonation.

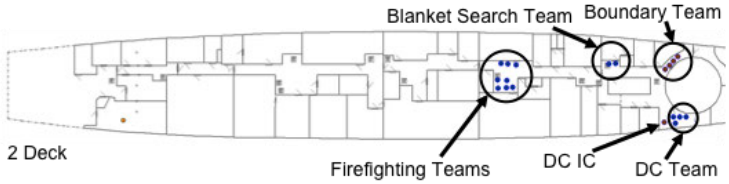
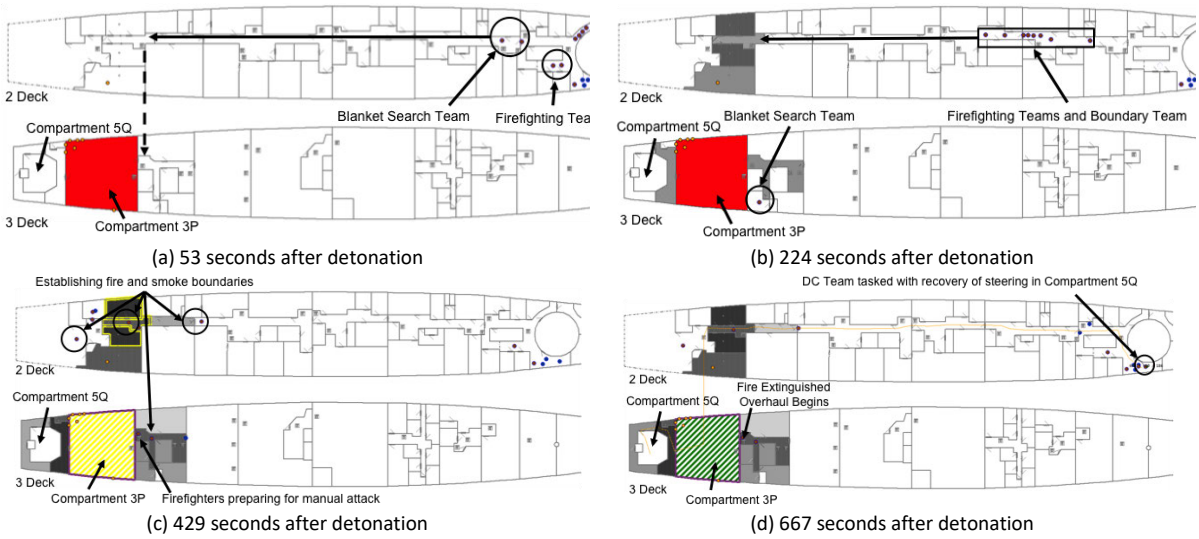


Figure 11: Initial crew locations on VSRS Arion 2 Deck

At 53 seconds after RPG detonation (Figure 12a), Firefighting Teams mustered in the Repair Base. The Blanket Search Team follows the black line to investigate the damaged fire main. Approximately 180 seconds after RPG detonation (not shown), the Blanket Search Team arrived at Compartment 3P and reported the presence of fire and smoke to DC IC. A Firefighting Team was tasked with extinguishing the fire and the Boundary Team tasked with establishing fire and smoke containment boundaries. At 224 seconds after detonation (Figure 12b), the Blanket Search Team notified DC IC the cause for the loss of fixed firefighting functionality. DC IC tasked a DC Team to isolate the ruptured fire main and restore functionality to the fixed firefighting system. Grey shaded areas represent smoke distribution; darker shades represent increased smoke density levels. Yellow borders around compartments represent the established containment boundaries. At 429 seconds after detonation (Figure 12c) the DC Team isolated the fire main and opened a supply valve to restore fire main water pressure. The fixed firefighting system was activated, represented by yellow shading. After 481 seconds (not shown), manual firefighting with hoses commenced.

The fire was extinguished after 667 seconds (Figure 12d) and the DC Team commenced recovery of manoeuvring capability. Full functionality was recovered 882 seconds after detonation.



(a) 53 seconds after detonation

(b) 224 seconds after detonation

(c) 429 seconds after detonation

(d) 667 seconds after detonation

Figure 12: State of the fire and crew at specific times after detonation

The time to activate the fixed firefighting system and time to recover steering for the four platform configurations are presented in Table 3. Fire temperature distributions for the four configurations are presented in Figure 13 with highlights indicating when the: fixed firefighting system activated; Firefighting Teams commenced the manual attack; and fire is extinguished. The temperature distribution for Configuration 4 is similar to Configuration 1; however, the hatch gives the DC Team direct access to steering equipment without the need to extinguish the fire.

Table 3: Time to activate firefighting system and time to access steering compartment

Configuration	Configuration details	Activate firefighting system, Time (s)	Manual attack, Time (s)	Fire extinguishment, Time (s)	Recover steering, Time (s)
1	Baseline	429	481	663	882
2	Remotely Operated Valves	239	390	423	654
3	Autonomic Valves	63	304	336	576
4	Added crew access hatch	405	455	637	168

The effect of technology insertion is of interest, even though it did not affect the outcome of this scenario. The scenario examined three system configurations for the recovery of fire main water pressure and activation of the fixed firefighting system. Recovery of fire main water pressure was performed manually (Configuration 1), remotely operated (Configuration 2), and via autonomous control (Configuration 3). Each subsequent configuration improved the response time to activate the fixed firefighting system. Improved response times can provide assurance a fire can be contained and is not an ongoing threat to the platform. In critical situations, such as the risk of heat transfer causing spontaneous cook-off for any explosive ordnance, guaranteed fire main water pressure will enable the crew to perform boundary cooling to reduce heat transfer. In this case study, autonomic system recovery provided the fastest response time. This would facilitate compartment recovery in a timely manner and conserve resources.

Finally, comparison of the *FDS* fire temperature distribution in Figure 9(a) and the *FSSIM* distributions in Figure 13 reveal obvious differences. The case study was used as an

opportunity to gain experience with *FDS* to understand the associated modelling requirements, and demonstrate the use of VSRS *Arion* in *FDS*. However, for the purpose of the case study's integrated analysis, the fire modeling capability provided by *FSSIM* was utilised. Future work will utilise the VSRS *Arion* model to compare and validate different survivability M&S software tools (similar to that documented in [6]). The comparative study would utilise data collected from the Ship Survivability Enhance Program (SSEP) in which a series of blast, fire, and smoke trials were performed on ex-HMAS *Derwent* [14] (the platform from which VSRS *Arion* is derived).

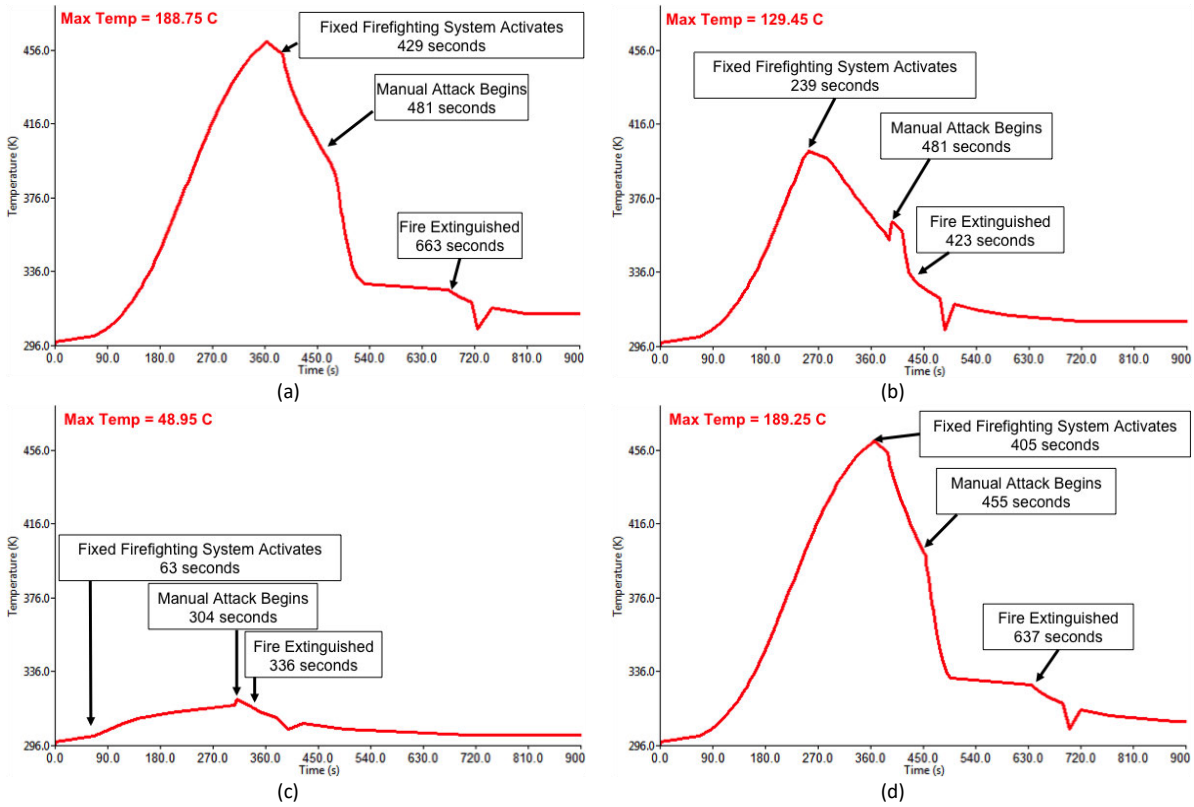


Figure 13: Fire temperature distributions representing (a) Configuration 1; (b) Configuration 2; (c) Configuration 3; and (d) Configuration 4 (Configuration 1 with a new access hatch)

5. INTEGRATED ANALYSIS

In this case study, VSRS *Arion* experienced an asymmetric threat, in the form of an RPG launched from a high-speed water-borne craft. Due to the use of commercial shipping as cover, the threat engagement compromised VSRS *Arion* susceptibility defences (such as a close-in weapon system). Subsequent vulnerability events that occurred were:

- RPG penetration of the hull and detonation within Compartment 3P;
- blast and fragmentation rupturing the fire main;
- hot fragmentation initiating a fire in Compartment 3P;
- fragments penetrating the watertight bulkhead between Compartments 3P and 5Q; and
- fragmentation damage to the manoeuvring capability in Compartment 5Q.

The time to extinguish the fire, gain access to Compartment 5Q and recover manoeuvring capability is presented in Table 3. The objective was restoration of manoeuvring capability within five minutes of weapon detonation. For this scenario, the maximum allowable time to extinguish the fire and recover manoeuvring was ten minutes, after which, the HVA would become a combat casualty. In Configurations 1 and 2, the threshold of ten minutes was not

achieved. In Configuration 3 restoration of manoeuvring was achieved within ten minutes but not within the objective of five minutes. Consequently, the risk remained that the HVA would become a combat casualty. Only Configuration 4 gave assurance to protect the HVA in this scenario. The analysis identified platform criticality attributable to a single access route to effect repairs. Therefore, to maximise protection of the HVA the recommendation is to:

1. incorporate a hatch in 2 Deck, above Compartment 5Q, for rapid access to critical equipment in Compartment 5Q.

A naval platform will need to be survivable for many different scenarios and a configuration change suiting one scenario might not suit another scenario. Consequently, configuration changes will require validation against each scenario to minimise (or avoid) adverse effects to platform survivability and/or capability. Upgrading to, for example, a laser weapon system [15, 16] for self-defence against agile, asymmetric threats will require evaluation of availability of space onboard the platform, and energy requirements for power and cooling. Increasing bulkhead thickness and/or the inclusion of armour plating may require evaluation of consequences to platform speed, weight margins, stability, and acoustic and non-acoustic signatures. Therefore, further survivability analysis would be recommended to assess other configurations to ensure capability resilience and survivability for this and other scenarios. Consequently, for VSRS *Arion,* additional recommendations include assessment of:

1. technology upgrades to the self-defence system to enable engagement of the threats in the operating environments;
2. system criticality, redundancy and accessibility for single point of entry compartments;
3. armour plating surrounding critical equipment in Compartment 5Q; and
4. autonomous control of actuating valves in the fire main to ensure boundary cooling for the platform's magazine and other critical compartments.

6. DISCUSSION

A case study, such as that documented herein, had not previously been demonstrated for the RAN. Consequently, the case study has shown that Integrated Survivability analysis in support of RAN mission resilience is achievable with current M&S capabilities. Resulting from defining and performing the study, a workflow was developed that will enable similar analysis to be performed in the future. These achievements, relating to the two study objectives, are discussed further in this section.

6.1 Objective 1: Demonstrating Integrated Analysis

M&S identified damage sustained by the platform resulting from the detonation; demonstrated the progression of fire and smoke; and identified the time to repair damage. The location of the damage and ongoing secondary events (the fire), defined priority actions to be performed to effect repairs to platform capability. Combining blast, fire and smoke and recoverability analysis demonstrated the consequences of one domain affecting the conditions within the other domains. The combined analysis identified a general arrangement configuration change (the addition of a hatch) to minimise the time to recover mission capability. This configuration option may prove more effective than solutions identified by performing susceptibility, vulnerability and recoverability analysis in isolation.

6.2 Objective 2: Development of Workflow

Following from Sections 2 and 3, the prototype workflow in Table 4 was developed. Due to space restrictions, details within the workflow have been omitted, as indicated by ellipses ('…'). A need to clearly define the scenario and identify analysis measurement criteria will

facilitate selection of appropriate M&S software tools and generate relevant models in their respective formats. The workflow will require validation to ensure it is 'fit-for-purpose' and, consequently, there will be refinement if there are omissions or inaccuracies. The workflow will also need refinement if, for example, user requirements change; or if the threat space evolves (such as, new threat types); or if new technologies are developed to counter existing and emergent threat types.

Table 4: Description of each step in the workflow to define and perform Integrated Survivability analysis

Identifier	Title	Description
1	Define Simulation	Scenario specification and M&S requirements for survivability analysis.
1.1	Define Threat Scenario	Identify the scenario requirements.
1.1.1	Scenario Description	Detailed scenario description, including threat(s), assumptions and constraints.
1.1.2	Mission Requirement	Specification of the mission objectives and capability requirement.
…		
1.1.2.2	Success Criteria	Define success criteria for achievement of mission objectives.
1.1.2.3	Measurement Criteria	Define measures to assess the scenario.
1.1.3	Survivability Capability	Identify survivability capability available to the platform for the specified scenario.
1.1.3.1	Susceptibility	Define platform capabilities to detect and respond to the threat, prevent platform detection, prevent threat lock-on, decoy threat, avoid threat and/or destroy threat.
1.1.3.2	Vulnerability	Define the platform capabilities to resist, and control and contain damage effects.
1.1.3.3	Recoverability	Define platform capabilities to recover mission and survivability capability and preserve life.
1.1.4	Threat Types	Define the types of threats to which the platform will be exposed.
1.1.4.1	Combat Threats	Define the combat threats to which the platform will be exposed.
1.1.4.1.1	Air Explosion (AIREX)	Define AIREX threats to which the platform will be exposed.
1.1.4.1.1.1	Fly-in Threats	Define the fly-in weapon threats to which the platform will be exposed.
1.1.4.1.1.1.1	Seeker Type	Define the seeker type for the threat to locate and lock-on platform.
1.1.4.1.1.1.2	Yield	Define the explosive yield of the threat.
…		
1.1.4.2	Non-combat Threats	Define threats that do not originated from combat.
…		
1.1.4.3	Secondary Effects	Define secondary events that may result from the primary event.
…		
1.2	Define Threat Model	The threat(s) to which the platform will be exposed in the scenario.
1.3	Modelling Tools	Identify the M&S and analysis tools that will be utilised to examine the scenario.
1.4	Material Properties	Define material properties for the platform.
1.5	Generate Models	M&S software tools may require platform, system and crew models in specific formats. Identify requirements for the tools and generate platform, system and crew models.
1.5.1	System Models	Identify and generate system models required for the scenario.
1.5.2	Crew Models	Define crewing requirements and generate crew and behaviour models.
1.5.3	Susceptibility Models	Identify geometry format and generate models required for susceptibility analysis.
…		
1.5.4	Vulnerability Models	Identify geometry format and generate models for vulnerability analysis.
…		
1.5.5	Recoverability Models	Identify geometry format and generate models for recoverability.
1.6	Build Simulation	Build requisite simulations within respective modelling tools.
1.7	Run Simulation	Run the simulation.
1.8	Simulation Analysis	Perform analysis of the simulation output.

7. CONCLUSION

Demonstrated integrated analysis of platform survivability was performed using a selection of available M&S software tools. Analysis of four platform configurations compared technology insertion and general arrangement. In this scenario, the integrated analysis identified a platform general arrangement configuration change to be more effective than technology insertion. However, a platform will need to survive multiple scenarios and retain mission capability. Configuration changes suiting one scenario might not suit another. Each scenario will need to be analysed and (general arrangement and system) configuration changes will need to be validated to ensure no adverse effects to overall safety or to platform resilience. Other capability trade-offs will likely be required, such as evaluation of crew SOPs, space and weight margins, power and cooling, and acoustic and non-acoustic signatures.

The case study enabled development of an Integrated Survivability analysis workflow. The workflow is a 'check-list' for the creation of appropriate metrics to measure survivability and capability resilience, and ensure M&S software tools are utilising consistent platform and threat specifications for the scenario. The analysis will facilitate mission planning and identify survivability requirements for anticipated threat environments. Consequently, informed scenario analysis and appropriate application of M&S software tools contributes to supporting resilient, battle-ready platforms.

8. ACKNOWLEDGEMENTS

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Novel portable penetration equipment to optimise naval indirect firefighting attack efficacy by simplifying systems and training.

Author, S.T. Battenally
Manderson Engineering Innovations Pty Ltd
Sarah@me-innovations.com.au

Abstract

We have designed a simple, safe portable penetration device and method to fight compartment fires at sea. It could be life-saving.

This novel system is designed to be utilised for indirect firefighting with gas-tight penetration into fire-affected compartments.

The accessory and method are designed to penetrate bulkheads and decks (vessel walls and floors) with a suppression capability that complements a range of sprinkling or atomiser nozzles. Once fitted the device can be operated unmanned, removing personnel from the vicinity of danger.

For the first time, instead of using prevalent naval containment methods - using either existing holes or cutting holes by exothermic methods to access fire - this system can penetrate into the fire with a gas-tight fitting. The system protects against extreme fire behaviour such as flashover, backdraft and fire gas ignition.

The system will likely reduce free surface flooding, human error and skill-atrophy. The device offers an alternative that not only simplifies procedures and training but also prevents firefighters from avoidable hazards.

A spring-loaded bias barb construction, anchors and locks device to secure the nozzle into the fireside of the compartment allowing it to be operated unmanned. The ability to apply a range of firefighting couplings or fire hose fittings on the inlet of the device supports the mariner or land-based firefighter to adapt fittings to the device as required. Providing any emergency team member with a portable compartment fire penetrator system.

This intuitive method could be life-saving and prevent future naval losses.

Keywords: Fire suppression; naval fire; fire at sea; indirect attack; human error; firefighting; novel technology; fire incidents; water mist

1) INTRODUCTION

Fires on ships can lead to the devastating loss of life, injuries, reduction in capability and loss of operational performance. As marine and naval technology evolves, damage control and safety systems also need room to adapt, to save lives, ships and bolster lethality. Accordingly, firefighting within a vessel is an area of increasing concern for mariners and people associated with maritime industries. Although various safety systems are required on most cargo vessels, commercial vessels and naval warships, there must be room for development and to address the gaps in prevalent seagoing and survivability operations. For that reason, the paper will propose a simple, safe portable penetration device and method to fight compartment fires at sea, that could assist in narrowing gaps in current fire safety procedures.

The procedural firefighting response onboard a naval ship can be separated into four phases, outlining the control and recovery defence-in-depth system that is consistent with the Royal Australian Navy Firefighting doctrine and validated by the Defence Science and Technology Group (Gamble et al., 2014).

1. *Manage* - Fire management starts from the instant smoke or fire is detected. It involves establishing a command-and-control communication line between the decision-makers and the crew, setting personnel boundaries and evacuating all other personnel from the affected area.
2. *Extinguish* - With the aim to extinguish the fire, the immediate response is to activate water mist systems where fitted or apply portable firefighting systems before persisting with direct tactics. If successful, a recovery of the affected compartment and systems will commence.
3. *Suppress* - If the fire is not extinguished, it is then managed by suppressing measures which include closing all ventilation dampeners and securing all doors and hatches. At this time, it is imperative that all personnel attacking the fire have been withdrawn.
4. *Containment* - These measures are applied once the fire is near to or has reached fully developed status within the compartment, and all fitted and direct firefighting actions have failed to control or extinguish the fire. The aim in the containment stage of a naval fire is to limit the growth of the fire within the compartment(s) and stop the fire from spreading to surrounding compartments. This requires establishing boundary cooling and smoke boundaries, with these boundary systems intended to starve the fire through a lack of oxygen.

In the containment stage, if a ship's emergency response team cannot stop the spread of the fire, heat or smoke to adjacent compartments, the fire can become uncontrollable and the crew will need to be evacuated. If uncontrolled the fire can progress and lead to extreme compartment fire behaviours such as flashover, backdraft and fire gas ignition. Such fire scenarios were examined and documented in the Command Investigation of the United States Ship (USS) Bonhomme Richard Fire (2020) and the US Navy Major Fire Review (2021).

Technologies for revised methods of indirect firefighting to regain control in the late stage of fires are very few. By proposing the novel firefighting accessory and method in offering the system as a portable sprinkling or water mist tool to optimise processes in the containment stage, it could increase fire incident management options. This is done by providing a temporary penetrator system to apply a gastight and indirect firefighting attack into a compartment from the deck above or an adjacent bulkhead.

This paper proposes a portable sprinkling/water mist penetration tool to reduce free surface flooding, human-error and aid in steaming out a fire. The methods and hardware have been initiated by two passionate maritime firefighters driven to develop firefighting accessories to increase preparedness in the naval, maritime and maintenance environments. The innovative approach could plug a gap in fire management systems and may present solutions to the options and recommendations highlighted in the USS Bonhomme Richard investigation and the US Navy Major Fire Review. Prior to this paper, the device has been referred to as Penetration Technology and identified as the Breach and Attack Tool, or BAT for short. This novel technology was reviewed by the Chief of The Royal Australian Navy, Vice Admiral Michael Noonan, and it has been recognised with the 2021 Chief of Navy Innovation Excellence Award.

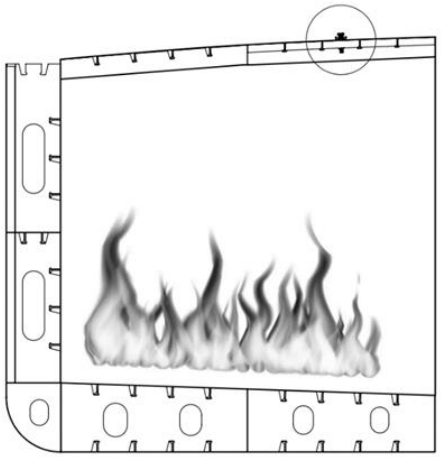


Figure 1: Cross-sectional view of a container ship with the BAT novel penetrator secured into the deckhead of a midships hull section.

Literature Review

The literature is unanimous in identifying the main cause of recent US major fire incidents as a combination of lack of preparedness and human factors. Many recommendations in the literature focus on the implementation of advanced damage control technology and training. They also highlight a need to increase training concurrency and champion a modernisation of damage control equipment to facilitate greater fire attack posture and consequently reduce major fire incidents.

The US Department of Navy held an investigation into the 12 July 2020 major fire onboard the USS Landing Helicopter Dock Bonhomme Richard (LHD 06) and found that the resultant naval loss was due to preventable causes and outlined four operational standard deficiencies leading to the result (United States Naval Institute News [USNI News], 2021).

This incident exemplifies that in maintenance environments, when at port or docking, personnel are transient between other core duties. Crew are intermittently away from the platform and fixed firefighting systems are often shut down. This increases the risk of an inefficient attack while also increasing the likelihood of fire breaking due to activities such as welding. Other factors include a lack of familiarity with platform-specific procedures with transient and new staff and procedural non-compliance which further compounds the risk of a fire.

In addition, The United States Fleet Forces Command released an Executive Summary of the Major Fire Review (2021). The (US Fleet Forces Command [USFF Command], 2021) literature presented an analysis of 15 separate major fires in the US Navy over a 12-year period from May 2008 to July 2020, not including the complete losses of USS Bonhomme Richard or USS Miami. Of the 15 major fire events investigated, 13 occurred during depot-level or unit level maintenance environments, 11 occurred outside of the normal workday, and only two incidents occurred while underway. The report concludes that the units were not fully prepared to fight fires in the maintenance environment. Major issues raised included lack of sufficient temporary systems for fire detection and suppression, lack of firefighting system redundancy, lack of knowledge of shipwide damage control conditions, and absence of a specific, detailed, and rehearsed firefighting plan for the maintenance environment including incorporation and interoperability with shore-based firefighters [USFF Command] p. 8.

Both investigations provide evidence that naval fires are more likely to occur in the maintenance environment. Vessels at sea have a higher level of readiness but need better assessments of preparedness to respond to fires while in port. This highlights the need to address non-compliance and training vulnerabilities in transient maintenance crewing. There is also an urgent necessity for incorporation planning with shore-based firefighters. Had the device and techniques offered by the BAT technology existed at the time, the device could have addressed these issues. The BAT could support a cross-platform readiness, provide a higher-level shipboard fire safety and assist in preventing such major fire incidences.

2) BREACH & ATTACK TOOL (BAT) COMPONENT DESCRIPTION

The undertaking in inventing and developing the methods involved applying learned experience, technical skill sets, and reviewing naval Incidents and command investigations. Experiencing an incongruity in the containment phase and personnel readiness inspired the development of solutions and equipment with a goal to minimise future naval damages or losses. This resulted in a Breach and Attack Tool (BAT) that is user friendly, simply instructed, and can assist in removing dangerous and complex steps in regaining tenable compartment fire access.

To assist in effective learning and reduce training shortfalls, the BAT is a one-system-fits-all approach. BAT may help in strengthening the emergency team's operational ability and efficient incident management through simple, portable and intuitive product design, and centralised training. The component-level design of BAT is unpacked below.

The inlet
On the rear of the device are fittings for connection to a source of fire extinguishing agent. This fitting can be changed to work with any required firefighting hose, or air fittings to mate with a pressurised cylinder of fire suppressing agent. For this example, a 38mm Storz fitting has been used.

The conduit
An internal passage makes up the central pipe extending between the inlet at the rear and the outlet nozzle at the fore-end. The internal pipe allows the firefighting agent to flow through the device to the nozzle.

Securing grapnel hook arrangement
The front-end incorporates a securing grapnel hook design. Acting between;

- *A retracted configuration:*
  The barbs are obtained within channels, allowing a smooth pass through the aperture.
- *A deployed configuration:*
  When the barb members fully penetrate the aperture, they are biasedly spring-loaded to the deployed configuration.

Closure and tensioning wing nut
The body has a threaded external feature complimenting the wing nut. The operation applies tension on the body between the closure and the deployed barb members. Ensuring gastight operation once the device is secured through the aperture in the bulkhead; allowing the device to be fitted in place and operated unmanned.

The outlet
For this example, the fore-end of the device is fitted with a full cone sprinkling nozzle. This nozzle can be interchanged to any design required. The components entering the affected compartment will be manufactured with considerably fire-resistant material, such as 316-grade stainless steel. Once tensioned the device is gastight, when charged it allows a fire extinguishing agent to penetrate the affected compartment to attack the fire and apply a cooling effect to the compartment.

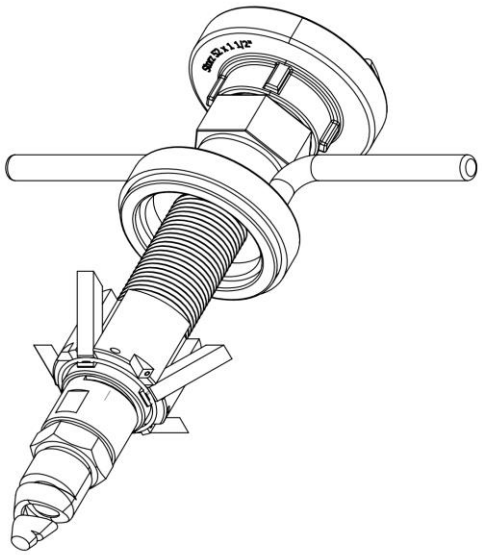


Figure 2: Spray nozzle adapted BAT.

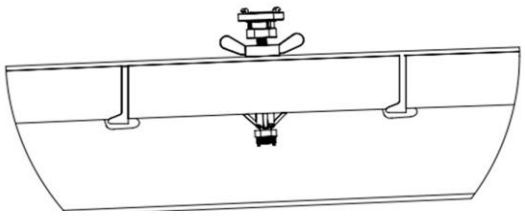


Figure 3: Water mist nozzle adapted BAT.

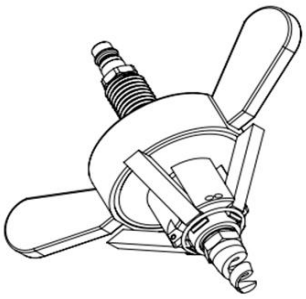


Figure 4: Shipping container adapted BAT.

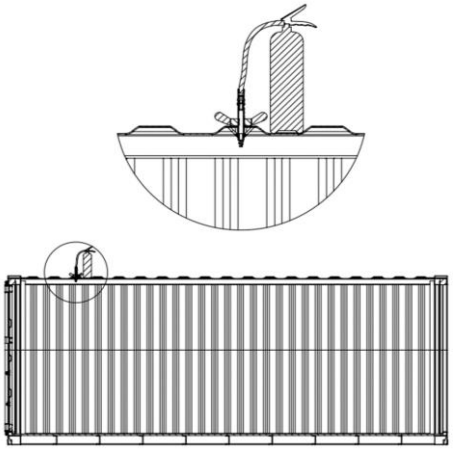


Figure 5: BAT penetrating a shipping container.

3) METHODS AND PROCEDURES

The steps in deploying the Breach and Attack Tool are:

a) Connecting the BAT device to the hydrant hose (Un-charged)
b) Preparing the aperture. - Using a high torque, low-speed cordless drill, arbor extended bar with a hole saw and nylon plug. [NOTE: A nylon disk (plug) is fitted on the extended arbor, it blocks the aperture when disconnecting the cordless drill from the hole saw, sealing the two compartments.]
c) Penetrating through the bulkhead, by drilling through the entire bulkhead/deck including any initialisation installed on the other side. [NOTE: Penetration points will be predetermined and marked-out to avoid severing electrical cabling, encountering pipework, I-beams, trunking etc.]
d) Disconnecting the drill leaving the hole saw and nylon plug within the aperture.
e) Directing the BAT towards the aperture inserting a fore-end and nozzle through the bulkhead. [NOTE: The nylon plug is tapered 1mm larger than the opening, under its own weight it will remain in the aperture. When pressure is applied both the hole saw drill bit and plug will transit through the hole and become sacrificial to the fire torn compartment.]
f) The firefighter should then attempt to retract the device to test the deployment of the barbs. In this step, a focus was placed on designing a robust and appropriate biasing operation that can support rapid incursion and securing. Its shape with the barbs encapsulated in channels mostly blocks the hole/aperture on entry. The minimalistic exposure reduces smoke, fire, or air regress on entry when married to an ideally sized penetration hole.
g) Engaging tension on the wing nut at the rear end of the device will fix the barb members against the fireside of the bulkhead. [NOTE: With bulkheads having many materials sandwiched between the inner and outer wall and of differing thicknesses, the BATs extended threaded body allows it to adapt variable penetration depths.]
h) Return to the hydrant and operate the valve at full pressure for 2 to 4-minutes.
i) Using thermal imaging or laser temperature sensors, assess the temperature of the compartment bulkheads for the desired cooling effect/ tenability before applying more cycles.

4) EXPERIMENTAL SETTING

Computational Fluid Dynamics (CFD) was conducted to understand the basic internal flow characteristics. ANSYS software supported a simple mathematical evaluation of the internal pipe designs' effect on freshwater flow velocity and pressure loss. As the device is centred around the delivery of water through a pipe the internal design could be easily tested. The CFD model supported a 38mm Storz hose connection at the inlet and compensated for the sudden contraction of a 1-inch N7 U.S Coast Guard approved nozzle at the outlet. This experiment did not include the K-factor of the nozzle as this component is interchangeable with any type of nozzle that is required to suit the fire incident and environment.

The experiment applied an assumed inlet flow rate condition of 400 litres per minute, of fresh water at 20 degrees resulting in an inlet flow velocity of 5.0352 m/s. This assumption was made considering friction losses to the point of penetration, Sydney wharf side fire hydrants and ideating the flow to volume characteristics to support a large compartment.

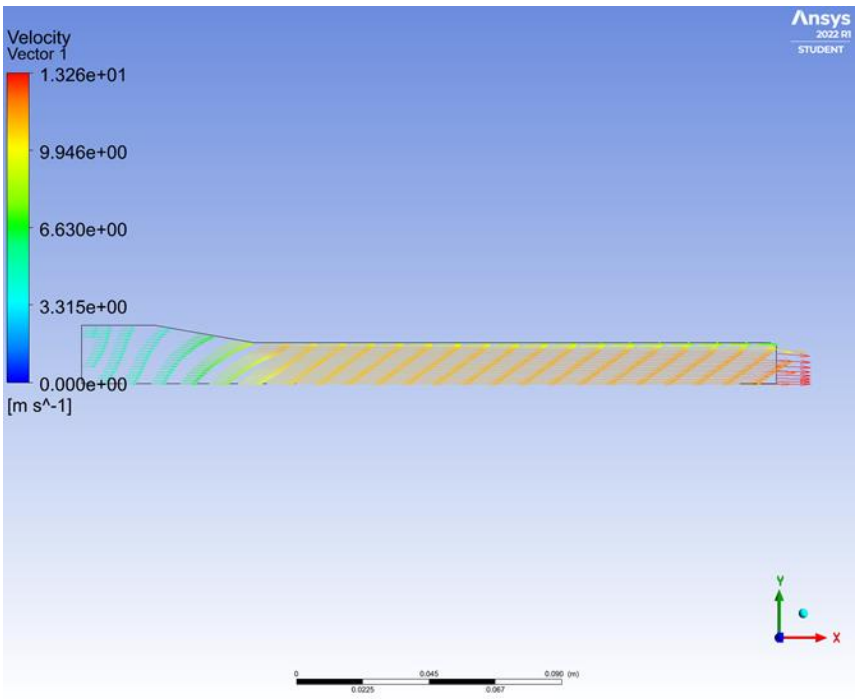


Figure 6: CFD streamline flow velocity contour with vectors.

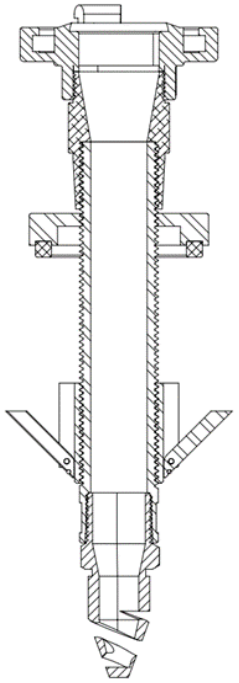


Figure 7: Sectional view.

The resultant CFD modelled the flow velocity, the vectors can be viewed by the streamline contour (left). The computational results found the velocity on the outlet of the pipe to be: 13.26 m/s equating to 47.736 km/hr. Applying a pressure and velocity coupling and defining absolute pressure on the outlet, returned a pressure differential over the pipe of 93.8 KPa or 13.6 PSI. These characteristics support the N7 nozzles manufacturers operating flow rate parameters for a 120-degree full cone fog to penetrate a fire and assist in steaming out a compartment fire. Further investigation, live testing and analysis are required to support this modelled evaluation.

To reduce the effects of free surface flooding, simulation and testing would be required to provide greater insight. A cautionary recommendation would be for the accessory to be operated in an on/off cycle of at most 2 to 4-minute intervals, with the firefighting team I/C ready with a thermal imaging camera to check for the desired cooling effect before conducting further cycles. Further CFD, platform analysis and live testing are needed to support this theory.

The accessory and method are designed to provide a through-bulkhead/ through-deck fire suppression system that can complement a range of sprinkling or atomiser nozzles. Allowing a platform engineer to model and equip the crew with a compatible firefighting nozzle for the

Platform-specific modelled fire situations. Alternately, the platform could have in emergency locations a ready use BAT as redundancy for any shipborne fire mishap.

5) PROPOSED SOLUTION AND FUNCTION

The Breach and Attack (BAT) Tool could comprehensively address the four operational challenges that led to USS Bonhomme Richard fire [USNI News]. The combination of operational factors pointed out in the report were: 1. Material Condition, 2. Training and Readiness, 3. Shore Establishment Support, and 4. Oversight. The ensuing paragraphs discuss how BAT could address these challenges.

1. Material Condition

In the USS Bonhomme Richard fire, 87% of the ship's firefighting systems were under maintenance and inactive. However, the BAT design circumnavigates the material condition of the vessel because it is completely portable and can be operated with or without the ship's fitted systems. The design will operate independently of ships' power or any external energy sources. It only requires a charged fire hose and a cordless drill fitted with an extended bar and hole saw. The system is portable and can be stored in a pelican case, meeting military shock grade. It is light, portable and transported simply by a single crew member in full firefighting attire. The BAT prototype housed within a pelican case, including the cordless drill and drill bit, weighs under 10 kilograms. Any sea fit crew member could lift and carry 10 kilograms to the scene of penetration.

Bulkhead/through-deck materials on ships vary and the BAT can accommodate for various depths and materials. The locking and securing mechanism can adapt to the varying thickness of ship bulkheads. The BAT is designed with a threaded wing nut and a hose connector at the back and expanding grapnel hook on the fore-end. BAT's design has locking strength to hold against the force of the spray and the length of the treaded body allows it to adapt to the varying thickness of bulkheads. The design considers the ability of the device to be removed after being exposed to heat. The components are made with 316-grade stainless steel with high durability in extreme temperature environments.

BAT could reduce the life-threatening issue of backdraft by having no open cavity when being used, this is achieved by simplifying the practice of rapid gas-tight procedures (as mentioned in method steps above a-i). The oversized wingnut houses a heat-resistant packing/O-ring with a larger circular footprint than the drilled hole. This material is sandwiched between the wingnut and bulkhead like a gasket creating a gastight seal. Having the single thread in the centre allows for an even crushing pressure to be applied to the sealing material, getting the full pressed capability out of the material in a single action. The circular relationship also helps to evenly control and dissipate the impulse and momentum forces when operated in cycles to discharge the firefighting agent. The ship's power was off during the initial hours of the USS Bonhomme Richard fire. It had Inactive, secured power conditions and unavailable fire-fighting systems. The BAT, if deployed, would have been totally accessible instrumental in overcoming these issues. It could have been an easy, portable, simple solution.

2. Training and Readiness

The investigation to USS Bonhomme Richard fire found major gaps in training:

"The training and readiness of Ship's Force was marked by a pattern of failed drills, minimal crew participation, an absence of basic knowledge on firefighting in an industrial environment, and unfamiliarity on how to integrate supporting civilian firefighters" [USNI News]

The BAT could address these issues. All Seafarers, Naval and Maritime personnel have to conduct training in shipboard survivability as a requirement of their duties onboard a seagoing vessel. Such training is delivered to international high standards. Mariners are instructed to perform steps and activities in relation to the lifecycle behaviours of fire. Training is proven to increase reaction timing and benefit the survival of the crew and platform.

The training and readiness of the BAT is based on natural instinctual processes and simplifies training and readiness. It leverages prior knowledge and to operate it is a right-hand thread. Like the rhyme, "righty tighty, lefty loosey" - the core operation is as simple as turning a tap. This simple survivability step could increase reaction timing. It could address the ***absence of basic knowledge***. The simplicity of operation, training and readiness could benefit the survival of crew and platform.

The basic familiarities to maintain human skill currency are a necessity to react swiftly and appropriately in these emergency situations. It could be said, current complicated processes need vast amounts of focus and bravery, intensifying the human factors that contribute to an inefficient attack, loss of compartment, or even loss of life and ship. If training is simplified, it is easier to practice and perform. The self-locking feature allows unmanned operations, removing crew from the scene and ***addresses the need to increase participation***. It takes one or two people to operate and they may feel safer knowing they can leave the scene of the hot spot.

Another hurdle for ***firefighting in an industrial environment*** is navigating the available fitted systems and containment of the fire. The BAT is a novel approach. Detailed cut marking could reduce human error when penetrating and could be clearly marked and learned. Personnel can clearly understand where to drill. These location markings could be marked onto the deck and bulkheads to locate ideal penetration points for all compartments. Drafted by a suitably qualified engineering naval architect to avoid the nozzle operation from being impeded by cabling, trunking or pipework etc. Also, ensuring minimal structural damage is incurred by the cut.

The Bonhomme fire found there were 14 consecutive ***failed drills*.** The BAT addresses this by providing an opportunity to build confidence for personnel in the attack party. The BAT can be inserted into the entry and could create a cooling effect when fire teams re-enter the fire impacted compartment. When applied to or adjacent to a scuttle, door or hatch with a water mist nozzle, the atomised mist can create a cooling wall effect, preventing a heatwave from exiting upon opening a compartment and assisting the fireteams' re-entry. The BAT could address the second issue of training and readiness in the USS Bonhomme Richard fire.

3. Shore Establishment Support

The BAT could address the third issue of shore establishment support in the USS Bonhomme Richard fire, by providing Interchangeable fittings for familiarity and sacrificial components. It's almost a set and forget device, similar to operating ships fitted system however it is independent portable and can be an integrated mutual aid asset. The device can be easily integrated to fit all maritime fire hoses or shore-based fire hose fittings.

''Of note, FEDFIRE hose fittings are not compatible with hoses and fittings aboard Navy ships. Both FEDFIRE and BONHOMME RICHARD personnel noted the differences in threading prevented FEDFIRE and BONHOMME RICHARD hoses from being connected." [USNI News]

Having the fire hose connector fitting interchangeable by a threaded connector by intermediate fitting rather than welded or swaged on the rear of the device gives an opportunity to support interoperability with civilian firefighting equipment. In supporting an interchangeable fitting on the conduit body, the device can be easily changed to comply with all hose fittings. The BAT supports the mariner or land-based firefighter to adapt fittings to the device as required. Providing any emergency team member with the complementary mechanisms of a portable penetrator to perform indirect firefighting tasks in a time-sensitive and critical environment, for any ship's staff or external firefighters.

The rear application of fittings creates a simple process of removing the device from its fixed position when reclaiming the compartment. By removing the hose connector on the rear and fully untightening the wingnut off the rear end, the firefighter can push the body of the device through the hole/aperture. It can be assumed the nozzle and fore-end components may become brittle after exposure to extreme heat and are sacrificial to fall into the compartment. This design not only addresses unfamiliarity with Navy vessels for shore-based and civilian fire crews but also readiness as explained in point 2 above. The USS Bonhomme Richard fire and structure of the response was unfamiliar to crews. The BAT on any ship is a mutual asset that can overcome the typography and mapping of complex onboard systems to better support shore-based firefighters.

4. Oversight

It could be said it is difficult to have oversight control in critical thinking emergency response environments. However, emergency drills are continually practised alongside and underway to ensure mariners conduct firefighting procedural competency. Ships' staff are encouraged to apply critical thinking within their ability to improve efficiency. Commanding Officers (CO) and Captains cannot always control critical thinking as firefighting is not the focused expertise of crew members. Therefore, oversight execution in fire emergencies is regularly managed by the categorisation of set roles and responsibilities.

In addition, firefighting drills are mostly designed and validated experimentally through CFD fire modelling of the platform configuration and crew reaction times. This evaluates the crews' ability to meet the fire challenges and employs event tree analysts to predict the suppression or spread of the fire, calculated on the crew's actions. The event tree analysis collates

optimised crewing and procedural approaches to successfully attack a fire and builds on a culture of managed crew roles and responsibilities in fire emergencies. Maritime and naval oversight employee training programs advise the crew to follow these steps and procedures.

However, domestic firefighters encourage and prefer critical thinking by applying their extensive training and understanding of fire behaviour, COs and Captains of seagoing vessels cannot control or access the same aptitude standards and experience of their crew. The BAT is not aimed at changing current procedures but to provide an access route to an extra layer of protection in management options and could complement fire protection defence-in-depth architecture. Implementation of the BAT can support an access route to a level of critical thinking, as it can be adapted to any compartment. It could function as redundancy, or it can be applied as a directed manual firefighting tactic. The versatility to changing applications allows the BAT to adapt to different suppressant agents and compartments like switchboards, ammunition lockers, battery storage, hazardous chemical, paint storage, or warehouse doors. This could also support warfighting and damage control management in resource critical environments. The BAT could offer an increase in incident management options to the CO and command teams.

Oversight could be complemented by applying pre-set incursion mechanisms. For large machinery compartments with high fire risk equipment and storage, there may be a necessity for multiple penetration location markings. These markings can identify the equipment or machinery it is designed to protect. This would allow greater control to give crew specific commands.

On the fourth day of the USS Bonhomme Richard fire, the ship's stability was heavily impacted by free surface water. The warship gradually developed a starboard list after the introduction of firefighting water accumulated high in the structure. This required brave personnel to conduct active ballasting and dewatering techniques. As the fire raged, numerous parallel dewatering and stability actions were taken to counter the list to prevent the longitudinal bending stress and unstable conditions of the warship. The BAT operating methods could protect vessels from issues of free surface flooding by providing oversight control through the procedure to reduce the volumes of water in either a water mist or sprinkling and operating the system in short time intervals. The time intervals allow water droplets to displace oxygen by evaporating and creating a thermal management capability, assisting in suffocating the fire and reducing the temperature within the compartment. The stop interval provides an opportunity to inspect the bulkhead temperatures and assess if the cooling is effective. This approach can reduce free surface water, minimise overall water damage and reduce the risk of unstable conditions. The BAT could have been a solution to address components of the fourth issue of oversight in the USS Bonhomme Richard fire.

6) CURRENT STATE OF SOLUTION AND FUTURE RESEARCH

The current prototype could benefit from prototype testing and trials through engaging academic, naval, civil or industry collaboration to substantiate the discussed BAT potential solutions. This could be achieved through a collaborative, systems engineering approach. The possible testing may include a further spectrum of CFD fire and flowrate modelling,

investigations into kinematics, mechanics of solids and would likely need to be supported by controlled fire tests and evaluations. To move the technology forward, focused academic, naval, civil or industrial relationships could benefit the BATs implementation through meeting applicable standards defined by legislation or client performance specifications. Planning thorough design analysis and functional testing could complement the BATs validation and assist in the processes of obtaining a certification baseline in Australia or internationally. The photos below (Figures 8 and 9) are examples of early prototype development. The following intentions are to draft a test and evaluation plan however, collaborative research and diligence would ultimately be required for the BAT to be employed in any engineering shifts to fire risk management.

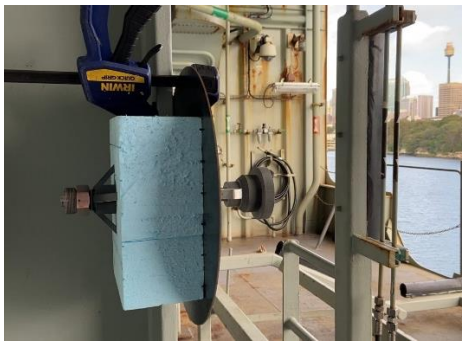


Figure 8: HP Jet Fusion 4200 3D printed BAT prototype to suit 3/8-inch atomising nozzle, penetrating a simulated bulkhead.



Figure 9: 316-grade Stainless Steel BAT prototype to suit 3/8-inch nozzle (nozzle not included) with drilling equipment in portable shockproof case.

There also needs to be research on current solutions such as US Navy Portable Exothermic Cutting compared to BAT drilling operations. The below photos (Figures 8 and 9) show the hot spots where exothermic hull cuts were made on the third day of the fire – requiring personnel to be sent in to make hull cuts [USNI News] p. 66. BAT drilling operations by design could be a safer alternative to hull cuts by exothermic processes at areas of extreme heat. The BAT design attempts to avoid opportunities for backdraft, flashover, fire gas ignition and escalation of fire which could happen in situations with exothermic cutting. The effects of exothermic cutting into hot spots are not divulged in detail in the reviewed literature.



Figure 10: "A standard photograph was taken by the drone." [USNI News] p. 65

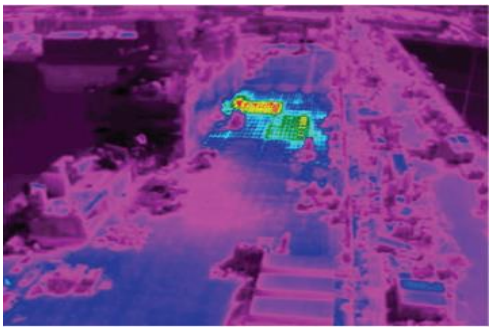


Figure 11: "Simultaneously by the same drone, a forward-looking infrared (FLIR) photograph was taken to identify hot spots for the targeted indirect attack via exothermic hull cutting." [USNI News] p. 65

7) CONCLUSION

This review has recognised the human factors related to an efficient attack on maritime fires specifically in the USS Bonhomme Richard fire. This case study highlights a need to reduce skill atrophy, improve preparedness and provide modernised penetration procedures. The BAT offers functional solutions and methods aimed to increase training readiness posture and provide a new level of individual preparedness. This proposed novel firefighting accessory could be held in emergency stations on every ship.

The BAT design is a novel technology inspired by preventing naval and maritime losses. It is a unique tool in the modernisation of damage control equipment with the aim to help combat preventable losses on vessels. It offers an alternative that simplifies procedures and training and prevents firefighters from avoidable hazards. It could save lives, ships and capability.

The method could improve emergency access to all compartment fires while increasing capability and speed in attacking any fire at sea, alongside or during maintenance. The system can work independently of the ship's power. It is portable, simple to use, requires basic training with previous common knowledge and is less than 10 kgs. Implementing the BAT procedure could provide more clarity around indirect attack methods and potentially increase survivability.

This new procedure with its optimised training practices to compliment survivability and ship safety is user friendly and training could be undertaken with ease. It adds a new layer of defence in fire safety that may give equivalent protection to mitigate those systems frequently shutdown or tagged out during maintenance. Penetrating compartment boundaries to attack a fire is imperative to keeping the crew safe and reducing the likelihood of fires in adjacent compartments. However, maritime firefighting practices as applied in the USS Bonhomme Richards fire use processes and equipment that exposed a high risk of human error and skill-atrophy that reduced the overall effectiveness of the response.

This paper proposes a better method of fighting a fire through indirect attack by identifying key points of failure. The BAT is a portable, rapid, and gastight penetration device and its various unmanned applications could improve practices in pre-set incursion mechanisms and extinguishing abilities by an interchangeable nozzle and hose fittings.

This is a basic technology to combat human error and explores methods to enhance usability, systems, and preparedness. Further investment and collaboration are needed to support the proposed novel firefighting accessory and its optimised training practices to complement survivability and ship safety.

8) REFERENCES

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SESSION 4

Commercial Ships

Maritime cyber safety - results of real-world application on ship systems

Influence of water depth on roll natural period and damping coefficient of large commercial ships in shallow water regions

Digitally enabled smart port and ship ecosystems and synthetic training using the new IHO S-100 framework model

The environmental and economic assessment of using liquefied natural gas as a fuel onboard bulk carrier ships

Maritime Cyber Safety – Results of application to real-world systems

Application of an integrated assurance approach to safety and security (surety)

Beckett LeClair & Mick Warren
Frazer-Nash Consultancy
b.leclair@fnc.co.uk m.warren@fnc.co.uk

Abstract— We face a new paradigm in maritime safety – cyber-security threats to the safe operation of vessels. Gone are the days of isolated on-and-off-board systems – focus is upon Integrated Modular Architectures, being added as modifications to new and legacy systems alike. These developments mean that we must consider new threat-vectors: inadvertent user actions, on-board connected devices such as mobile phones, and the potential for cyber-attacks to be carried out before a device even goes into production. New standards in maritime cyber-security require that the safety impacts of potential cyber-security threats be demonstrated. There is a need to ensure that these are adhered to - but how?

At SubSTEC 6 we introduced our four-step approach that focuses on those cyber-related hazards which could affect the seaworthiness of vessels. We proposed a new, pragmatic approach to satisfying the requirements for Cyber Security for Seaworthiness. This combines knowledge from multiple standards and regulations, including IMO MSC.428(98), DSwMS, and MIL-STD-882. Our method included a suite of tools, processes, and templates which eased the application of constantly developing cyber-security concepts to maritime contexts. This paper covers the application and results of that approach to a real-world scenario. This allowed stakeholders to quickly focus in on the key issues, leading to increased confidence and painless integration into existing processes – balancing cost and scarce resources. These results have significant implications for how we manage and assess the potential safety impacts of cyber-threats – especially given the increased potential for costly accidents involving interconnected systems, and ever-evolving sophisticated cyber-attacks.

I. INTRODUCTION

The relationship between cyber security and systems safety continues to be a significant area of research and development [1]. Over the last three decades, development of processors has moved defence electronics away from the traditional, isolated sets of on- and off-board systems, and towards complex interconnected system networks such as Integrated Modular Architectures (IMA). IMA replaces numerous separate processors and line replaceable units (LRU) with fewer and more centralized processing units. This, when considered in tandem with more recent developments of highly integrated systems-of-systems, machine learning (ML) models, and on-board network access (via either wireless or interface connector ports) presents significant potential security issues which stakeholders must consider.

Most electronic systems design projects in the defence domain are design modifications. Furthermore, these projects have a tendency to update designs via 'technology refresh' in a cyclic fashion spanning ten years or more. Cyber security issues found with new equipment also pose potential threats to the legacy

systems they interact with. It is both time-consuming and costly to design, manufacture, and test new designs to achieve required certification and demonstrate the appropriate safety (including best practice where possible) in operating alongside legacy systems. Thus, any ability to respond to identified security flaws is limited. In addition to this, much of the equipment currently in active use is not considered protected from potential cyber-security threats that may have entered the operating environment after design, certification and commissioning.

Mobile phones, set-to-work diagnostics PCs and other USB/Wi-Fi capable devices are now permitted to be brought aboard submarines. Protective operational protocols and procedures are in place; however, inadvertent actions may compromise cyber security (e.g. plugging into a USB port to charge a mobile device without realising the potential dangers this poses). No longer can a naval vessel be considered a fully isolated system.

In the world of civil maritime, cyber security for ship safety is generally approached via application of pre-existing techniques for safety management. This paper recaps an approach developed by Frazer-Nash Consultancy to apply cyber surety practices to surface craft and submarines, then discusses the application of this approach to a real-world context. Its application reduces the level of Suitably Qualified and Experienced Personnel (SQEP) required to undertake the work – making best use of scarce resource; it facilitates consistent and coherent application and achievement of results thus allowing different organizations to undertake the process and can help delivery of Cyber Security for Seaworthiness (CSFS) within time and cost constraints.

II. Literature Review

In this section we shall reiterate the sources reviewed in the production of our four-step process for CSFS introduced at SubSTEC 6.

A. International Maritime Organization (IMO)

The IMO maintains the International Safety Management (ISM) Code, an international standard governing ship owners and operators for the safe management and operation of ships. When required, the IMO's Maritime Safety Committee (MSC) introduces amendments which subsequently become mandatory via resolutions.

On 16 June 2017, Resolution MSC.428(98) [2] was adopted to require cyber risk management to be incorporated into the ship owner/operator's Document of Compliance (DOC). This Resolution encourages owners/operators to include cyber safety provisions into the ship safety management systems no later than the first verification of the DOC after 1 January 2021.

The resolution does not provide any specific guidance about **how** owners/operators should account for cyber safety, however.

B. MIL-STD-882 Standard Practice of System Safety

MIL-STD-882C was used on the SEA4000 Hobart Class Destroyer program [3]. Being issued in 1993, it predated many cyber concerns.

The draft version of MIL-STD-882F was open for review and comment until March 2021 [4]. The draft includes a new section 4.5.10 specifically devoted to Cyber Safety and mandates that the contractor shall address how cyber networks are accounted for in hazard analysis tasks and 'level of rigour' activities. One of the challenges of cyber hazard analysis is that the probability of occurrence is usually very difficult to predict. Our solution – outlined later – mitigates this issue.

C. Defence Seaworthiness Management System (DSwMS)

According to the Royal Australian Navy (RAN):

"*The focus of DSwMS is to support Defence to achieve operational effectiveness. It does this by integrating hazards and risk considerations into all aspects of decision making. DSwMS embodies Defence's due diligence requirements through a framework of regulation and assurance, providing Defence with a robust maritime capability. […] It also provides senior leaders with confidence that decisions are being made with a commitment to maximising operational effectiveness with a sound understanding of the hazards and risks [5].*"

This definition suggests that the safety impact of emerging cyber related hazards and risks will need to be considered to ensure the resilience of the RAN's maritime capability.

D. Implications of the emerging standards

Multiple challenges arise from the incorporation of new and emerging standards. These include:

- Understanding – by both the regulator and the regulated. Regulators must be kept informed and agree with the regulated community's process(es) to deliver a product to be assessed. This partially forms a socio-technical system.
- SQEP – there is a distinct need to ensure that personnel implementing standard requirements are suitably qualified and experienced for the task. At the inception of a standard, however, there is generally little to no experience in implementing it or similar processes. This brings additional challenges in understanding implementation methods and associated potential issues.
- Legacy equipment – implementing the new standard for changes to Type Certification is mandatory. While legacy clearances are not usually invalidated by future requirements changes, additional hazards will likely be exposed due to a lack of existing cyber-resilience. Owing to the nature of cyber security, legacy equipment changes are generally unable to be assessed in full as there may be no 'baseline' assessment in place.
- Contracts – there may be a need to update contracts to ensure that the new standard is included; this will have cost and time considerations.
- Interrelationships – standards must capture the interactions of security engineering and safety engineering. While cyber regulations link closely with safety at the outset, they do not feed any potential risks back to certification in the safety domain (specifically, due to the inability to determine concrete probabilities of occurrence).

Cyber security practitioners and safety practitioners both need to be aware of interactions between these elements and make sufficient, relevant process adjustments.

III. Cyber Security For Seaworthiness (CSFS)

Cyber security standards are concerned with protecting services, networks, devices, and data – predominantly from **intentional** theft or damage.

Safety standards seek to ensure that equipment is free from unacceptable or intolerable level of harm, by making risks 'as low as reasonably practicable' (ALARP). In contrast to those concerning cyber security, these standards generally assume that the hazards are **unintentional**.

Seaworthiness is the ability for a marine vessel to operate in the water without presenting significant hazard. Seaworthiness is a subset of marine safety because not all ship-borne equipment is critical to vessel operations (e.g. a flooring surface preventing slips/trips/falls affects safety without affecting seaworthiness).

Cyber Security for Seaworthiness is the intersection of all three of these disciplines, as shown below in Figure 1.

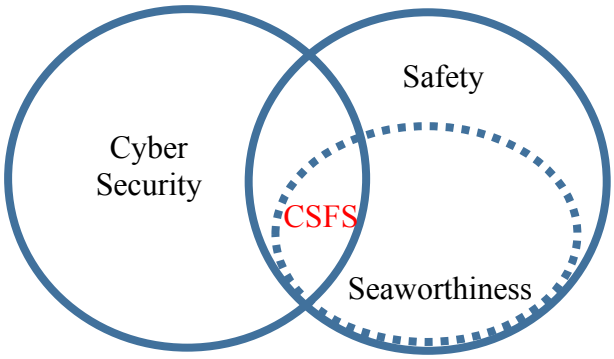


Figure 1 – Cyber Security for Seaworthiness (CSFS)

The CSFS concept gives rise to some interesting considerations. Consider, for example, a cyber-attack incident that forces a particular ship system to shut down. The system notices the error condition and good safety practice causes it to fail safely. Ship safety has been preserved without compromising seaworthiness, but the attacker's intention to compromise availability has been successful.

IV. Methodology

We will first briefly cover Frazer-Nash's process for incorporating contemporary cyber security considerations when developing the safety cases for naval vessels. The iterative, four-step process focuses on cyber-hazards that could impact vessel seaworthiness and addresses both **intentional** and **unintentional** behaviours.

This process was adapted from a successful aerospace program [6] [7] that sought to address cyber security challenges for an existing class of aircraft. It aims to triage the Line Replaceable Units (LRUs) assessed as having the highest potential safety impact from a cyber security threat perspective and then to categorize threats, mitigations and any residual risk(s) to allow the stakeholders to then make more informed decisions about potential next actions. There are four steps. These are:

Step 1 – List the LRUs onboard the vessel. This includes legacy units, units being upgraded and intended new units. This will then provide a master view of items containing a potential cyber vulnerability, namely those systems containing software and / or complex programmable hardware.

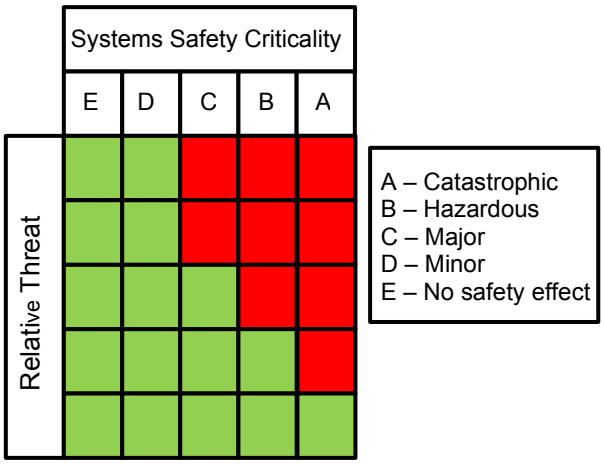


Figure 2 – Threat vs Criticality Risk Matrix

Step 2 – Baseline vulnerability assessment – Using a team of safety, security and subject matter SQEP, analyse each legacy LRU to determine security exposure, identifying which units are of concern and will need a subsequent deeper dive. This is done by studying available design information and/or maintenance manuals to understand the potential access points and threat vectors (to be covered in more detail later in this paper). An initial questions checklist is used to ensure coverage of all envisaged vulnerabilities. The result will be an LRU rating within the Relative Threat vs Safety Criticality matrix shown in Figure 2. The Relative Threat comes from the qualitative analysis of each LRU based on pre-determined questions to identify risk exposure; the Safety Criticality is derived from the systems safety process. This "triage" process will eliminate units for which the threat risk is found to be acceptable – assessed in the Green area in Figure 2 – at that time. The boundary between acceptable and unacceptable is from standards but can be altered depending on the organisations risk tolerance.

Step 3 – 'Deeper dive'. The reduced set of legacy units with an (initial) unacceptable threat risk level – assessed in the Red area in Figure 2 – are then analysed more intensely using a comprehensive security questionnaire. This assesses each residual LRU and any current associated security measures and threat paths relating to it. This assessment is undertaken for 6 condition states / categories for the status of the unit: on-board the vessel, transit and transport, navy maintenance, navy storage, design and manufacture, and repair at supplier. The results are then fed back into the risk class matrix, thus describing the *residual* risk as either acceptable or unacceptable. This allows any corrective recommendations for action to be prioritised according to their associated threat; this has clear benefits for balancing costs and resource use.

Step 4 – Assessment of new and/or heavily modified LRUs. For the remaining units which are undergoing full development, the process returns to the traditional engineering "V" life cycle. Questions are asked at critical steps in the life cycle and answered via a required document set, capturing the outcomes of Step 3 in detail. Depending on vessel structure or the library of class documentation, the necessary documents either stand alone or must be incorporated as new sections into the appropriate pre-existing class documents. New documentation is preferably kept to a minimum by enhancing the appropriate documents in the existing data library.

As part of the baseline test application of Frazer-Nash's process, the following documents are produced as output evidence:

1. **Certification Level Activity documents:** This includes a Plan for Security Aspects of Certification (PSecAC) which is produced at the outset explaining what we are going to do and then a PSecAC Summary explaining what we have done.
2. **System Level Activity Documents for Security Risk Assessment:** This includes a Preliminary System Security Risk Assessment (PSSRA), which details what our CSFS risks are and whether they are acceptable / unacceptable from a system perspective and then a System Security Risk Assessment (SSRA) which is a final assessment of the CSFS risks at the system level.
3. **Vessel / Platform Activity Documents for Security Assessment:** This includes: a Vessel Security Scope Definition (VSSD) which details what is in and out of scope of the assessment at the vessel level; a Preliminary Vessel Security Risk Assessment (PVSRA) which details what our CSFS risks are and whether they are acceptable / unacceptable from a vessel perspective and then a Vessel Security Risk Assessment (VSRA) which is a final assessment of the CSFS risks at the vessel level.

We sought to apply our methodology to a real-world scenario in order to determine the relative strength of our approach. We were mainly seeking to test our primary assumption that this approach would lower the SQEP barrier for analysing CSFS; SQEP is a key issue, as discussed previously in Section II.D. Previously, the vessel in question was being assessed purely in terms of the security of its Information Technology (IT) – where IT manages data – with little consideration or focus on OT (Operational Technology) – where OT manages interactions with the physical world. Assessment work was being carried out at the individual LRU level. Furthermore, cyber security was only being considered in terms of impacts on confidentiality which forms one aspect of the Confidentiality, Integrity and Availability (CIA) triad – which acts as the model used to develop security systems and policies – whilst neglecting considerations for integrity and availability.

PVSRA - In applying our approach, each LRU was assessed in different 'conditions': on the vessel, undergoing maintenance and repair with the owner, during storage, during transit and transport, during design and manufacture, and undergoing repair with the supplier – these total six conditions. Considering an LRU at the multiple stages of its physical existence gives a robust understanding of the potential different threat-initiating scenarios. For example, considering 50 LRUs in each condition gives a total of 300 unique 'states' that are assessed. The analysis at this stage determined the states to be at either a preliminary 'unacceptable' or 'acceptable' level (in terms of the risk from a certification perspective). The 'unacceptable' states were then taken through to the SSRA stage for further consideration.

SSRA – The objective of the SSRA phase is to explore in more depth those states which were initially revealed to have potentially unacceptable levels of risk. It requires identification of security measures, consideration of risk acceptability, and allocation of any residual risk that remains following an assessment of the current protective measures being applied. To undertake this exploration is it necessary to think about threat scenarios (see Figure 3).

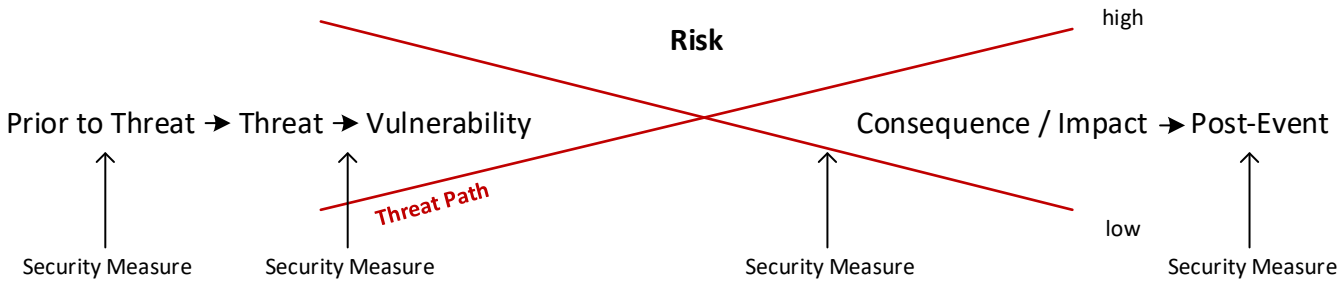


Figure 3 – Determining threat scenarios

Threat scenarios can be considered similarly to safety accident sequences. In other words, how might we get from a threat to a vulnerability, then to a risk, then to a separation of risk and residual risk with the associated mitigating security measures implemented?

In this case, the security measures had been developed from standards in terms of both exposure reduction (e.g. use of appropriate Cyber Security Management Systems, resilient network connections and security training) and protection (e.g. controlled access to assets, start-up tests, cryptography and device authentication). The process was used to assess these measures, and the results were split into three categories:

1. Preparation means (knowledge and equipment to develop the attack) – with a maximum score of 6. For instance, the equipment needed to execute an attack could be COTS (Commercial-Off-The-Shelf), bespoke tools, or nothing at all. Likewise, the knowledge required could be uncontrolled information or insider-only.
2. The 'window of opportunity' (time available to mount the attack) – with a maximum score of 8. This could be in terms of hours, minutes, days and so on.
3. Means of execution (the knowledge and experience required to actually mount the attack) – with a maximum score of 18. For example, one scenario might require bespoke equipment and high-level expertise.

The scoring above comes from the standard [8] and seemingly places a disproportionate score on the means of execution. This approach is taken as an attacker may be able to prep the attack and have a window of opportunity to mount it but the necessary equipment and knowledge to mount the attack tends to be more challenging than the other two. In the application of our designed approach to this real-world vessel context, we have completed the evaluation at this stage as there were no new or heavily modified LRUs to consider further for this vessel.

The US Department of Defense has a Cyber Table Top Guidebook [9] which aims to describe methods for "*the early identification and categorization of cyber vulnerabilities, as well as identification of associated critical mission and system failures*". It is recognized that – at face value – this is similar to our approach. However, by its own admission the US approach is an "*intellectually intensive exercise*" involving a significant amount of differing personnel across an extended time – typically a minimum of 90 days before any reports are generated. Whilst not decrying their approach, ours provides a consistent, repeatable approach minimizing the level of SQEP required and should deliver results in a more timely fashion.

V. RESULTS

The application of the PVSRA stage uncovered a number of items (30%) for which the risk was assessed as initially being unacceptable. The exact number of items is classified due to the sensitivity of the project. Hence, an approximation is shown for illustrative purposes. This comes from 50 items applied across 6 categories each to give a total of 300 item 'states'. This triage to just a subset of the original total presented a significant advantage for allocation of time and cost for the remainder of the process focusing on those assessed as most important.

Figure 4 shows how the approach was able to triage the most important LRUs in terms of CSFS criticality.

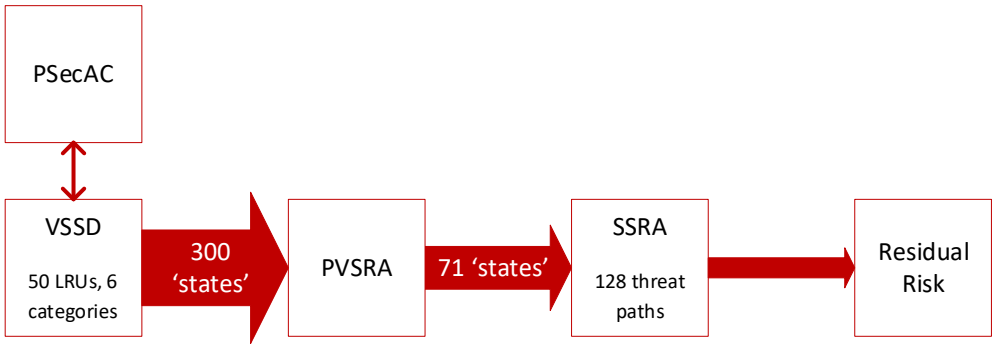


Figure 4 – The condensing of focus areas afforded by use of the approach

Following this was the application of the SSRA stage (see Figure 5). Some of the systems safety analysis had not been completed for some of the LRUs. Thus, for those items, the severity in Figure 2 was assessed as Catastrophic until we had evidence to demonstrate that it wasn't.

Once the SSRA process was applied, the majority of the initially unacceptable assessments changed to being acceptable. Of note, is that the states were subject to multiple potential threat paths hence, there is more than 100% in total.

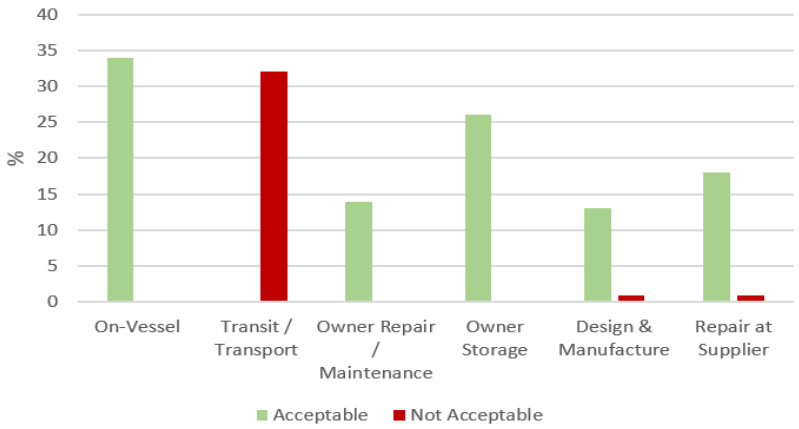


Figure 5 – Types of risk output from SSRA stage

In applying this method, we used SQEP Engineering judgement – that is, we looked at the results to see if they were believable rather than blindly accepting them. If an area was assessed as 'green' in the PVSRA but was still concerning to us because of other connecting threat paths we had found, we chose to raise it for deeper analysis anyway. An example of where we did this is in cases where units had open network connections, as we believed the risk of external connectivity warranted further investigation.

All risks assessed as being 'unacceptable' were found to be inherent to transit and transport condition – less that risk associated with the LRU which had not had the system safety analysis completed (discussed previously). A panel was held with a number of personnel experienced in safety for this particular vessel, in order to verify whether or not these results were congruent with current safety assessments. This skew of potential risks in transit and transport was noted as surprising them, as nobody within the organisation had previously considered these risks (due to a relative lack of experience in the cyber security domain), though they did agree that these concerns were valid and should be investigated further. This highlights an area

where our approach may be useful in aiding those who do not necessarily have high amounts of experience working with cyber-related risk analysis.

It must be noted that this SSRA stage involved over 126 assessments on the states brought forward from the PVSRA. As some of the security measures will cover more than one threat path, they will address both relative high- and low-risk threats paths. This reduces the amount of assessments necessary and the associated time and cost.

Current proposed recommendations raised from application of our processes are as follows:

- Consider procedural measures which could be applied to all LRUs currently in the condition. Appropriate cyber security controls should be set out in contracts, with the possibility of obtaining evidence ensuring that they are met. These could include, for example, secure freight transit or reducing time spent in transit by using air freight. An effective mitigating measure is not always the most expensive one – for example, how far could the risk be lowered by using anti-tamper seals? This is something worth potential investigation.
- Consider the associated technical measures. For example, could authenticity and integrity checking mechanisms be used to verify software, firmware, information and hardware integrity on receipt from the supply chain, prior to being fitted in their operational configurations?
- Consider measures which may be LRU-specific. For example, an LRU might be encrypted whilst in transit or transport, or access ports might be physically locked or disabled. Potential LRU encryption also has additional non-cyber benefits such as protecting exported systems and also preventing reverse engineering of an LRU.

The proposed CSFS documentation suite has been designed to be familiar and consistent with much of the existing safety, security and systems engineering documentation normally developed for defence programs. This will aid in the continued swift integration with existing processes and program knowledge. They reuse as much information generated from those sources as possible and integrate and feed back into them.

The primary advantage of application was the generation of pragmatic outputs that would not be time- or cost-intensive. The approach was particularly helpful to those personnel who were already versed in safety but had not had prior experience with the deep connectivity of different threat paths in cyber security (as highlighted in our transit and transport findings). This validated our belief that the approach lowered the SQEP barrier (and thus the effort barrier) and can therefore be useful in a context where there is a current lack of cyber experience. A subsequent benefit of finding interconnected threat paths is that the solutions can also be made to interconnect – i.e., one security measure implemented at a high level can decrease the risk for many lower-level threats, having clear implications for reducing costs of compliance. This is shown in Figure 6.

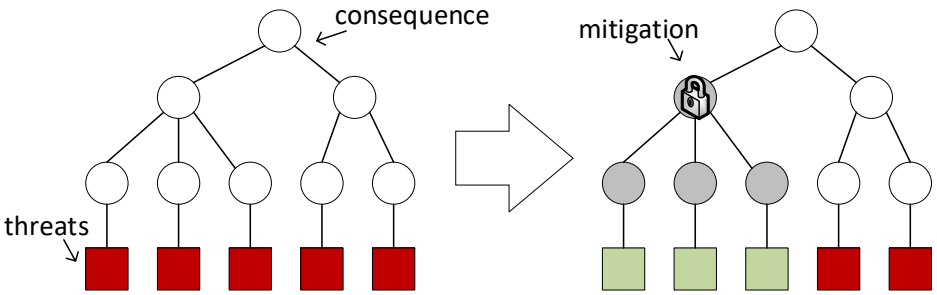


Figure 6 – One mitigation at a high level can lower the risk of many lower-level threats

Another significant benefit of this approach is that it allowed for efficient use of time and other resources; the key areas requiring action were quickly distilled from the larger list of unit states. Application made the cyber security problem less 'nebulous' and raised points which could be actioned for a relatively low cost in comparison to their protective benefit. It is expected that the entire process of this pilot application has taken slightly longer than an equivalent would take in subsequent scenarios. This is because of the test nature of the exercise which required us to ensure that we validated with different stakeholder groups that our outputs were as expected. This adds credibility to the process and ensures stakeholder buy in.

It is important to use a degree of proportionality in actioning this approach in terms of understanding when it is reasonable to stop further decomposing threats, otherwise there is a risk of diminishing the benefits to efficiency. This approach is an aid to knowledge where experience is lacking and not a total replacement for knowledge.

Another key thing to be cognizant of is that stakeholders may be introduced to new threat paths which had not been previously considered, and may then be hesitant to take action, or may seek to 'redo' analyses. It is critical that CSFS risks are actioned upon – the goalposts should not be changed because of an 'undesirable' outcome. This was not an issue in our application, but is something to be aware of.

Overall, we consider the approach thus far a success and will continue to investigate its future cyclic application to this vessel.

The challenge of maintaining cyber security in new and legacy systems, with lifespans of decades, will remain prominent in years to come. Fortunately, existing knowledge, practices and processes can bound these challenges effectively and direct resources and efforts efficiently to deliver the ongoing achievement of CSFS goals.

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INFLUENCE OF WATER DEPTH ON ROLL NATURAL PERIOD AND ADDED MASS MOMENT OF INERTIA OF LARGE COMMERCIAL SHIPS IN SHALLOW WATER REGIONS

Javad A. Mehr
Australian Maritime College
Launceston, Australia
javad.mehr@utas.edu.au

Mohammadreza Javanmardi
OMC International, Australia

Shin Wei Tham
Australian Maritime College
Launceston, Australia

Yun Yin
Australian Maritime College
Launceston, Australia

ABSTRACT

Roll stability is the dominant factor in ship stability in order to ensure safety, comfort, and vessel and goods survivability. The popularization of seakeeping software based on strip theory resulted in high prediction accuracy of heave and pitch motion. However, some commercial software neglected the effect of change in water depth on the added mass moment of inertia which lowered the accuracy in roll motion prediction.

This study aims to investigate the effect of water depth on the added mass moment of inertia in vessel roll motion, to improve the accuracy in roll period prediction under various water depths. Roll decay tests were conducted to obtain the roll period of bulk carrier model (C_B:0.85) and container ship model (C_B:0.69) at different water depths. The added mass moment of inertia increased exponentially with the decrease in water depth within the shallow water region; no significant influence was observed in the deep-water region. The ratio of added mass to the models' displacement were found to be 125.7% and 146.8% greater at d/T of 1.16$\dot{6}$ than that in deep-water which has resulted in an increment of 7.6% and 16.3% in the roll natural period of the container ship and bulk carrier model respectively. The experimental results helped in understanding the effect of water depth on the roll added mass moment of inertia and the natural period, and also served as base data for validation and comparison in accuracy of numerical simulations.

Keywords: Added Mass Moment of Inertia, Roll Period, Shallow Water

NOMENCLATURE

b	Damping coefficient
B	Beam
C_B	Block coefficient
C_{ladd}	Added mass coefficient
d	Water depth
d/T	Water Depth to Draft Ratio
g	Gravitational acceleration
GM_T	Transverse metacentric height from centre of gravity
$\overline{GZ}(\emptyset)$	Righting arm function

h_f	Distance moved on pendulum weight
I_{xxtot}	Mass moment of inertia
I_{add}	Added mass moment of inertia
I_{hull}	Hull's in-air mass moment of inertia
KG	Distance of centre of gravity from keel
KM_T	Transverse metacentric height from keel
k_{xxhull}	Roll gyradius
L_{BP}	Length between perpendicular
LCG	Longitudinal centre of gravity
m_f	Roll frame pendulum weight
M_φ	External moment
T	Draft
T_1	Oscillation period of empty dynamic frame
T_2	Oscillation period of dynamic frame with model
T_n	Natural period
$T_{\varphi Ave}$	Averaged natural period from roll decay test
$\delta\Delta$	Added mass
Δ	Displacement
$\Delta_{maxsurf}$	Aimed displacement obtained from Maxsurf
ω_n	Natural frequency
$\ddot{\emptyset}$	Roll angular acceleration
$\dot{\emptyset}$	Roll angular speed
ρ	Density
$\bigtriangledown$	Volumetric displacement

1 INTRODUCTION

As a result of increased demand in global logistics, notable size growth in bulk carriers and container ships, and new ship design such as the introduction of large bow flare have been observed. Ship stability is dominated by rolling motion, these new hull shapes might lead to large roll amplitudes [1] and larger roll period. Due to tremendous amount of capital investment required, modifying existing port infrastructure or even developing new ports to accommodate larger vessels are deemed to be economically unpractical. However, sailing larger vessel (greater draft) into these shallow regions could be extremely hazardous without knowing the change in roll period due to the change in water depth. Therefore, it is important to accurately estimate the roll natural period for safe passage of larger vessels in existing ports or canals with shallower water.

The roll motion of a ship, a dynamic system, could be defined using Newton's law of motion. This relates the roll motion of a surface vessel to a system of second ordinary differential equation, (1) [1, 2].

$$I\ddot{\emptyset} + b\dot{\emptyset} + \rho g \nabla \overline{GZ}(\emptyset) = M_\emptyset \qquad (1)$$

where $\emptyset$ is the roll angle of the vessel, I is the roll moment of inertia, b is the damping coefficient, ρ is the water density, g is the gravitational acceleration, ∇ is the volumetric displacement and

$\overline{GZ}(\emptyset)$ is the righting arm function. A dot over the variable $\emptyset$ indicates differentiation with respect to time.

The roll motion equation is defined by the inertia coefficient, damping coefficient and restoring moment. These properties of the roll behaviour are influenced by the hull shape, mass distribution and the fluid motion surrounding the vessel. As an oscillating system, the roll amplitude increases when energy is fed into the system. Vice versa, the loss of energy from the system decreases the roll amplitude, which is referred as damping. Roll damping, specifically, is mainly brought by the flow effects of the surrounding water: wave radiation, skin friction, viscous/ eddy separation, lift effects and others. In particular the inertia coefficient of the roll equation is governed by two factors, the mass moment of inertia of the hull without hydrodynamics interference and the added mass induced due to acceleration in a medium (water for a ship) [1]. To predict and avoid large roll amplitude, it is important to develop knowledge on the physics of roll motion. Therefore, it is crucial to accurately assess the dynamic stability of ships during the design phase.

The inertia coefficient in the roll motion has a direct effect on the roll behaviour as it governs the roll angular acceleration beside damping moment and restoring moment. The inertia coefficient is related to the hull coefficients, the more the hull shape deviates from a cylinder, the greater the portion of added mass moment of inertia in the total mass moment of inertia and therefore greater the influence on the roll motion. Previous studies such as those by Biran [3] and Molland [4] have estimated the added mass component empirically [5, 6]. However, Piehl [1] argued that these empirical approaches are inaccurate as they were derived from fine hull shapes which diverges from modern complex hull shapes. Nonetheless, the difference in water depth has been proven by Inglis and Price [7] to have an influence on the added mass of a floating structure; the decrease in water depth results in an increase of added mass. This is most likely the fundamental cause of incorrect prier side sally test data which led to bad roll motion on the USS Midway in head seas [8]. Nonetheless, the difference in water depth has been proven by Inglis and Price [7] to have an influence on the added mass of a floating structure; the decrease in water depth results in an increase of added mass. This is most likely the fundamental cause of incorrect prier side sally test data which led to bad roll motion on the USS Midway in head seas [8].

Although roll motion has been previously studied in many research projects [1-6, 9-13], little to none has investigated and drew conclusion on the effect of water depth on the added mass moment of inertia component in the roll equation [8]. This project, which is a research collaboration between OMC International and Australian Maritime College (AMC) aims to investigate the effect of water depth, especially at shallow waters, on the added mass component of roll behaviour.

2 MATERIALS AND METHODS

2.1 General

A set of model tests were conducted in the Model Test Basin at AMC, Launceston, Tasmania. A Midi Mak Marad F bulk carrier model and a P&O Nedlloyd Hoorn container ship model were put into roll decay tests with initial heel angles of 5, 10 and 13 degrees at five different water depths

to investigate rolling of merchant ships. Table 1 and 2 show the model particulars and the depth conditions, respectively, while Figure 1 shows the physical models.

Table 1: Model Particulars

Model	L_{BP} [m]	B [m]	T [m]	C_B
Marad F	2	0.364	0.12	0.85
Hoorn	2.47	0.32	0.12	0.69

Table 2: Experimental Water Depths and Corresponding Depth to Draught Ratio

Water Depth [m]	d/T
0.60	5.000
0.30	2.500
0.24	2.000
0.18	1.500
0.14	1.167



Figure 1: Left: Container Ship Model (Hoorn). Right: Bulk Carrier Model (Marad F)

Prior to any physical preparation, *Rhino* 3dm models were created and then exported to *MAXSURF* to carry out hydrostatic calculations for both models. Table 3 shows the hydrostatic parameters obtained from *MAXSURF*.

Table 3: Models' Hydrostatics Data

Model	KM_T [m]	$\Delta_{maxsurf}$ [kg]	LCG from stern @ even Keel [m]
Marad F	0.160	74.1	1.150
Hoorn	0.152	62.1	1.220

2.2 Pre-Experiment Preparation

The models were ballasted by fitting weights transversely to achieve the desired draft, vertical centre of gravity (KG) and roll gyradius (k_{xxhull}) obtained from *MAXSURF*. It was aimed to ballast the models' KG to 0.9m and 0.135m, and the in-air roll gyradius (k_{xxhull}) to 35-38% and 33-35% of

beam for the Marad F and Hoorn, respectively. During the ballasting procedures, the models were inspected, and the position of weights were adjusted to ensure zero heeling angle and level trim as shown in Figure 2. The value of KG was obtained through an inclining experiment. By determining the models' GM_T, the models' KG was calculated using Equation 2.

$$KG = KM_T - GM_T \quad (2)$$

where the *KG* is the distance of centre of gravity from keel, KM_T is the transverse metacentric height from keel and GM_T is the transverse metacentric height from centre of gravity.

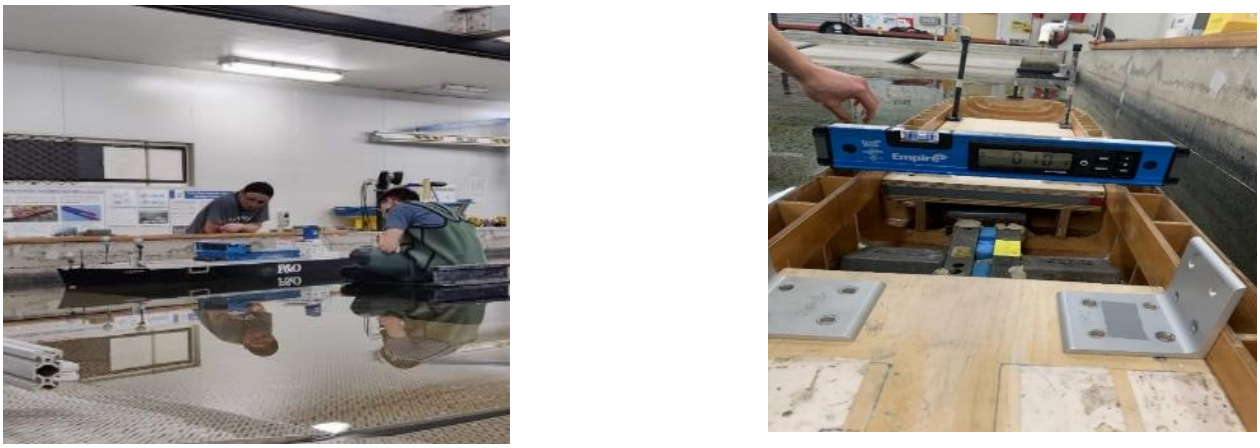


Figure 2: Left: Hoorn model under Ballasting Procedures. Right: Marad F under Inclining Test

The roll frame was then used to determine the k_{xxhull} in term of percentage of the models' beam. The under-slung supports were adjusted to accompany and allow the balancing of models at the calculated KG from. Having the ballasted model transferred onto the roll frame, several adjustments were done to bring the frame with model on to balance including:

1. Adjustment of model's alignment on the frame.
2. Adjustment of under-slung supports' length below the centroid.
3. Adjustment of vertical distance between the pendulum weight and the frame's centroid.

All the listed adjustments ensured that the models' KG came in line with the dynamic frame's centroid. The pendulum weight was then shifted to position with a known distance below the frame's centroid. The dynamic frame was then brought to an initial angle of 20 degrees and released for oscillations. The time taken for 5 oscillations was observed and measured by two experimenters at two different positions using stopwatches. In order to eliminate the irregularities due to release, the first peak and trough was disregarded. The two readings obtained were compared, and the oscillation period of the frame with model was then calculated by averaging the time taken for 1 cycle out of the 5-cycle measurement. The model was then removed, and the oscillation period of the empty frame was measured, again using the same methodology. The k_{xxhull} value was then calculated using Equation 3 [11, 14].

$$k_{xxhull} = \sqrt{\frac{g \cdot m_f \cdot h_f \cdot ({T_2}^2 - {T_1}^2)}{4\pi^2 \Delta}} \quad (3)$$

where k_{xxhull} is the roll gyradius, g is the gravitational acceleration, m_f is the roll frame pendulum weight, h_f is the distance moved on pendulum weight, T_1 is the oscillation period of empty dynamic frame, T_2 is the oscillation period of dynamic frame with model and Δ is the displacement.

The entire ballasting, inclining test, and roll frame test was repeated until the desired Δ, KG and k_{xxhull} were all achieved. This process follows a flowchart as shown in Figure 3. Table 4 shows the models' parameters after ballasting.

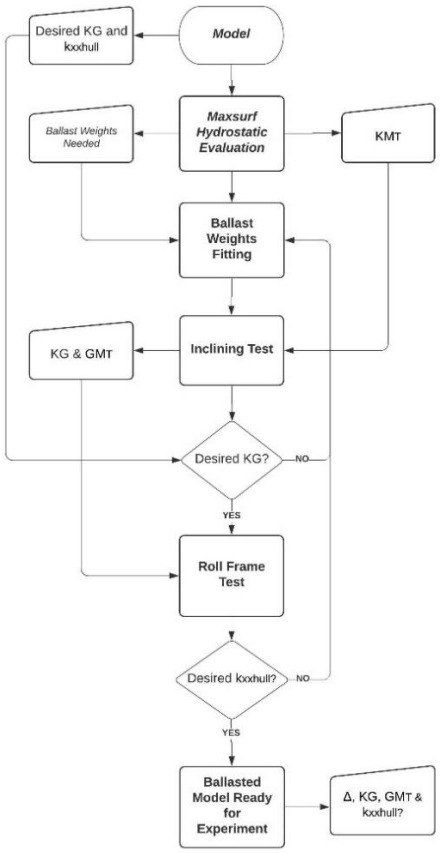


Figure 3: Pre-experiment Preparation Flowchart

Table 4: Models' Parameters After Ballasting

Model	**Δ [kg]**	**KG-Inclining Test [m]**	**KG- Roll Frame Test [m]**	**k_{xxhull} [% of B]**
Marad F	73.68	0.0902	0.0980	36.72
Hoorn	61.37	0.1185	0.1240	34.75

2.3 Roll Decay Test

The AMC model test basin (MTB) has been used widely in simulating maritime operations in shallow water environments including ship-to-ship interaction in harbour, performance analysis of wave energy converter and others. The MTB has a length of 35m and width of 12m, capable of holding 0-900m water depth. An artificial beach was installed at one end of the basin to mitigate large wave reflection from the basin walls. Besides that, wave absorbing floaters such as those used as swimming lane dividers were deployed at the other three sides of the basin to further compensate wave reflection during the testings at d/T of 1.16$\dot{6}$, 1.5 and 2.0.

The models' motion was measured and recorded using *QUALYSIS* 3-D optical motion tacking system, which was calibrated using 16 fixed reference markers and cameras. Having 5 visual trackers attached on both the models, the cameras measured the real-time 6DOF motions which could be monitored through real-time recording computer. Figure 4 shows the MTB and QUALYSIS program.

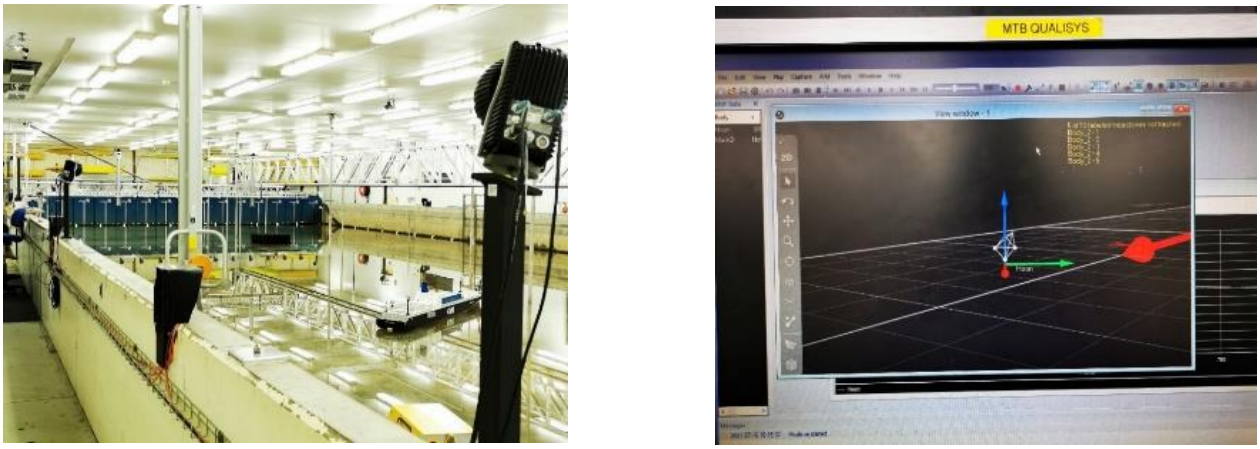


Figure 4: Left: Model Test Basin and QUALYSIS Tracking Camera. Right: QUALYSIS Tracked 3D Vector Field

During the experiment, each model was manually tilted to the designated initial angle (monitored through computer) then released. The models were allowed to roll freely until the oscillation was visually unobservable through the computer screen. From the preliminary numerical simulation done in the partner project using *AQWA* seakeeping software, it was found that the deep-water boundary for both models occurred at around d/T of 2.0. Therefore, beside d/T of 1.16$\dot{6}$, 1.5 and 2.0 which were used to investigate the effect of shallow water on the added mass, additional tests were conducted at d/T of 2.5 to verify the deep-water boundary at d/T of 2.0. In order to observe the similarity and eliminate uncertainties due to asymmetry, the models were tilted at two different sides and three different initial angles (5˚,10˚,13˚) during the experiment.

The experiment procedure for the roll decay test follows a protocol established before the commission of the experiment campaign as shown in Figure 5. The models were normally positioned to a location closest possible to the *QUALYSIS* tracked 3D field's origin for the greatest tracking quality. A platform was setup in the water as the workstation for the person who was responsible for tilting the model as shown in Figure 6. A second person who was responsible for

controlling the computer programs stayed out of water and gave command for proceeding through the procedures shown in Figure 5.

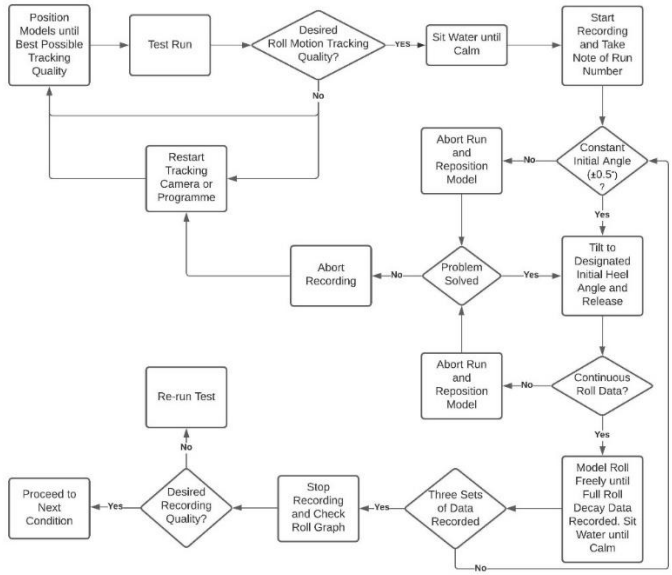


Figure 5: Experiment Procedure Flowchart



Figure 6: Hoorn being tilted for Roll Decay Test

The *QUALYSIS* data logging programme recorded and saved the 6DOF motion data from each run into a TSV format file which was exported to *MATLAB* for data processing and analysis. Interested in the roll motion, the column consists rotational motion data around x-axis in the 6DOF data file was extracted, trimmed and filtered in *MATLAB*; the natural periods of the models at each condition were then determined using Fast Fourier Transform (FFT).

2.4 Added Mass Moment of Inertia

In naval architecture, a vessel will be subjected to two types of reaction forces when accelerating in a fluid. These forces include the inertia force from the vessel's own mass and a fluid force acting on the hull surface due to the acceleration of surrounding fluid. The fluid force is widely referred as added mass due to its addition on the total mass inertia of the vessel. The total mass moment of inertia for rotational motion around the x-axis (rolling), hence, is defined as the sum of hull's mass inertia and the added mass, as described in Equation 4 [1].

$$I_{xxtot} = I_{hull} + I_{add} \quad (4)$$

where I_{xxtot} is the mass moment of inertia, I_{hull} is the hull's in-air mass moment of inertia and I_{add} is the added mass moment of inertia.

The added mass moment of inertia at certain depth is hence the difference between the experimental obtained total mass moment of inertia and the naked hull mass moment of inertia in air,(5).

$$I_{add} = \Delta\left\{\left[\frac{T_{\emptyset Ave}\sqrt{g \cdot GM_T}}{2\pi}\right]^2 - {k_{xxhull}}^2\right\} \quad (5)$$

where I_{add} is the added mass moment of inertia, Δ is the displacement, $T_{\emptyset Ave}$ is the averaged natural period from roll decay test, g is the gravitational acceleration, GM_T is the transverse metacentric height from centre of gravity and k_{xxhull} is the roll gyradius.

As mentioned, the averaged neutral period $T_{\varphi Ave}$ is obtained from roll decay test data using FFT. The transverse metacentric height GM_T, however, is obtained through inclining test. The naked hull mass moment is dependent on the radius of gyration was measured using a roll frame.

The calculated added mass moment of inertia was then converted into the dimensionless parameter added mass coefficient, Equation 6, [5, 6] to compare the effect of water depth on the added mass component of models with different hull shape by eliminating the dimensional effect.

$$C_{Iadd} = \frac{\delta\Delta}{\Delta} = \frac{\frac{I_{add}}{{k_{xxhull}}^2}}{\Delta} \quad (6)$$

Where C_{Iadd} is the added mass coefficient, $\delta\Delta$ is the added mass, Δ is the displacement, I_{add} is the added mass moment of inertia and k_{xxhull} is the roll gyradius.

3 RESULTS AND DISCUSSION

3.1 Data Processing and Analysis

After the roll decay tests were conducted, the raw recorded data from *QUALYSIS* had to be post-processed to obtain the row natural period of the models at different depths. *QUALYSIS* cameras captured the 6DOF motion discretely at 200Hz. Particularly for roll motion, the instantaneous roll angle in degree at each frame was captured, recorded and logged by *QUALYSIS*.

The logged time domain motion data was output from *QUALYSIS* in TSV format then imported into *MATLAB* for post data process. Three roll decay tests were conducted for each condition, a customized *MATLAB* data processing code allows trimming of the roll decay trace. Figure 7 shows the decay trace of an individual roll decay.

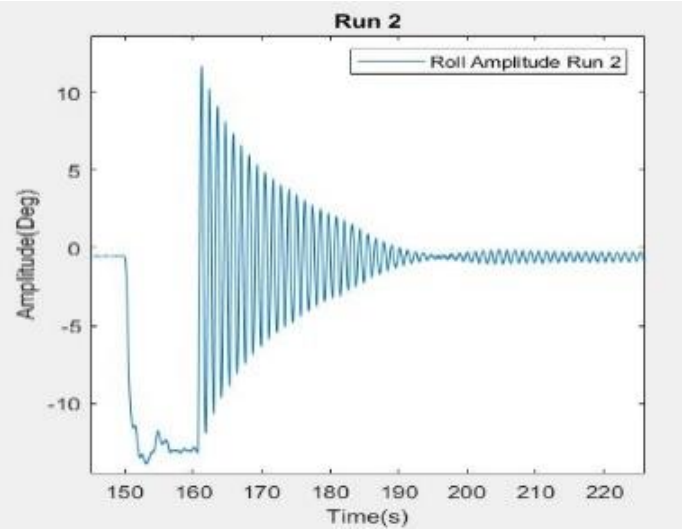


Figure 7: Sample of plotted roll decay test in MATLAB for Marad F, Run 0064, d/T: 6, 13˚, Portside Heel.

The trimmed curve demonstrated typical roll decay trace, the model was tilted manually to the designated initial angle and therefore fluctuation was seen in the trace right before the model was released and the formation of roll damping envelop. Once released, the model rolled freely and damp naturally from the initial angle to approximately 0 roll degree. However, as shown in the plot, the model resumed rolling shortly after achieving 0 roll degree due to reflected wave in the basin. Therefore, to damp and mitigate the effect of such reflected waves on the model, the water has been sat for at least couple of minutes before the next roll decay run of the same condition.

Fast Fourier Transform was applied to transform the time domain data to frequency domain; the frequency with maximum amplitude in the frequency domain curve was taken as the dominated frequency from the particular FFT and converted to period using Equation 7 [6]. Similar to measuring oscillation period from roll frame test, the first peak and trough were always

excluded from the trim to eliminate uncertainties due to manual releasing of the tilted model. Six different parts of each roll decay test were trimmed and put into FFT, the mean value of the dominated periods (excluding outliner, >1% difference from mean) was taken as the averaged natural period from the roll decay test. The natural period of a model at certain condition is hence the mean value of the averaged natural period from each of three roll decay tests at such condition.

$$T_n = \frac{2\pi}{\omega_n} \qquad (7)$$

Knowing that the change in initial heel angle would not affect the natural period of a simple harmonic motion; to investigate the effect of water depths on the roll added mass moment of inertia, the mean of all recorded FFT dominated period is taken as the averaged roll natural period of a model at certain water depth disregarding the difference in initial angle and heel side.

3.2 Rolling of Container Ship Model (Hoorn)

The container ship model, Hoorn, rolled at relatively larger period. This was expected due to the higher centre of gravity, shorter metacentric height and smaller roll gyradius in term of percentage of beam [8]. The change in heel side and initial heel angle did not induce significant effect on the FFT roll period of the model at certain water depth. Despite increased slightly with the decrease in water depth from d/T of 5 to 2, the change in period was insignificant compared to that at d/T of 1.5 and 1.16ȯ which indicated the deep-water boundary of Hoorn occurred at d/T of 2 as shown in Figure 8.

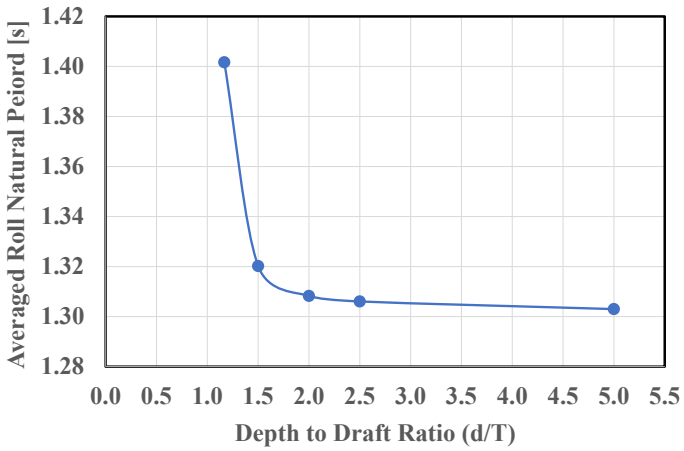


Figure 8: Roll Natural Period of Hoorn at Different d/T

3.3 Rolling of Bulk Carrier Model (Marad F)

Having larger C_B, lower centre of gravity and larger roll gyradius, the bulk carrier model, as expected, rolled with smaller natural period relative to the Hoorn. Similarly, changing in heel side and initial angle was not observed to affect the roll period of the Marad F at certain water depth obtained through FFT. As shown in

Figure **9**, the averaged roll period of Marad F did not alter significantly between d/T of 5 to 2 however increased exponentially as the water depth decreased below d/T of 2. It was observed that the deep-water boundary for Marad F occurred at d/T of 2.

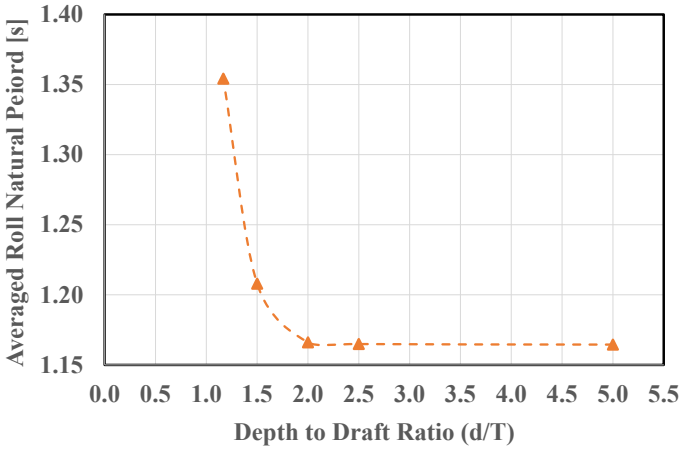


Figure 9: Roll Natural Period of Marad F at Different d/T

3.4 Roll Added Mass Moment of Inertia and Comparison

As shown in Figure 10, the roll natural period for both models remained approximately unchanged at water depth greater than d/T of 2, however, they increased exponentially with the decrease in water depth below the deep-water boundary. The roll natural period of Marad F, with greater C_B, recorded 3.7% increment at d/T of 1.5 and further increased to 16.3% at d/T of 1.16ȯ, the shallowest tested water depth. For Hoorn, with smaller C_B, the recorded increment was much lower. The roll natural period of Hoorn increased about 1.5% at d/T of 1.5, and approximately 7.6% at d/T of 1.16ȯ.

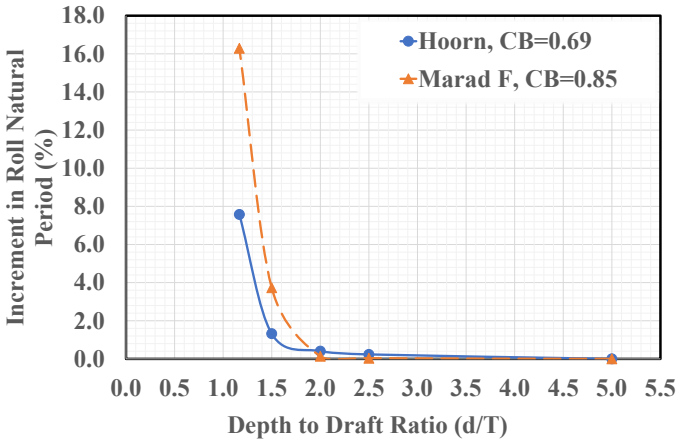


Figure 10: Comparison of % increment in roll natural period of models at different d/T

Added mass coefficient (C_{ladd}) is the ratio of added mass moment of inertia to the in-air mass moment of inertia of the vessel. As can be seen in Figure 11, the results on Marad F, with C_B about 1.23 times larger than Hoorn, showed C_{ladd} of 2.5 to 2.9 times larger than that of Hoorn. For Hoorn,

the added mass coefficient increased more than 20% at d/T of 1.5 and 125% at d/T of 1.16̀ compared to that at the deepest tested water depth of d/T=5. In the other hand, for Marad F, the added mass coefficient was 31.7% and 146.8% larger at d/T of 1.5 and d/T of 1.16̀ with respect to d/T of 5. No significant changes on added mass coefficient have been observed at water depths greater than d/T of 2. The result for Hoorn showed excellent agreement with the empirical conclusion by Schneekluth at deep-water region which states that the C_{ladd} of a merchant vessel without bilge keel could be assumed as 0.15 [3]. However, this was not the case once the water depth decreased below the deep-water boundary. On the other hand, the experiment results for Marad F disagreed with the Schneekluth estimation.

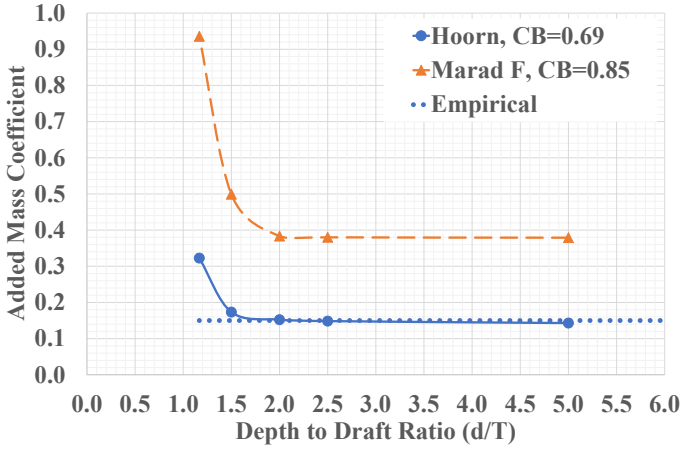


Figure 11: Comparison of added mass coefficient of models at different d/T

4 UNCERTAINTIES ANALYSIS

4.1 Inclining Test and Roll Frame Test

As discussed, *MAXSURF* was used to determine the required hydrostatic data, including displacement of the models at draft mark, LCG and KM_T, prior to the pre-experiment preparation. Of all the parameters, the KM_T value, which was used in the inclining test to work out the KG of the ballasted model, could greatly affect the experimental results since the error in KG and GM_T obtained from the inclining test were directly proportional to the error arose from Maxsurf hydrostatics evaluation. Therefore, as shown in Table 4, two sets of KG values for the models were obtained in the pre-experiment preparation, one being from inclining test and another from roll frame test.

Of all the adjustments needed during the roll frame test, listed in Section 2.2, items 1 and 2 gave the most significant effect on the balancing of the frame. Through the experiment, it was found that the under-slung supports length below the centroid is often 5-8mm greater than the obtained KG. This deviation was suggested due to the longitudinal beam deflection under load in the roll frame. As Dawson suggested [14], the deflection could be as high as 3.64mm when an 80kg load was applied on the frame. Furthermore, the KM_T value from *MAXSURF* could contain a level error due to the small difference in hull thickness between the physical models and the 3dm models. In the partner project of this study, through numerical simulation, it was proven that more

accurate results (upon validated to the results from this study) were produced using the KG from inclining test.

4.2 Roll Decay Test

The uncertainties in the obtained results were analysed using standard deviation of $T_{\varphi Ave}$ at different d/T and plotted for both models in Figure 12. As shown, the standard deviation in the data ranged from ±0.007s to ±0.013s which is insignificant comparing with the values of $T_{\varphi Ave}$ plotted in Figures 8 and 9. The highest deviation happened at the shallowest water depth tested which could be due to the higher influence from random external factors such as reflected vortex from the basin's bottom, underwater current and difference in reflected wave characteristics due to change in water depth. Generally, the deviation increased with the decrease of water depth except at d/T of 5.0. The shallow water region tests were carried out separately during the test campaign, wave absorbing floater were only deployed during these testings. The absence of the floaters might be a factor which caused a slightly higher deviation in the experimental data obtained at d/T of 5.0 despite little influence by the basin bottom.

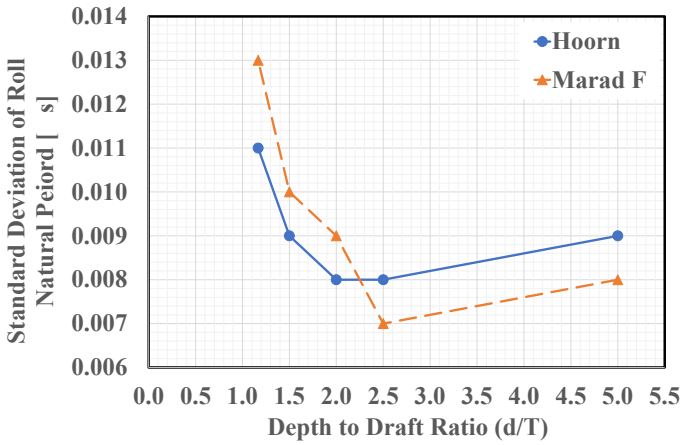


Figure 12: Standard Deviation of $T_{\varphi Ave}$ for both models at different d/T

5 CONCLUSION

As seen from the results, the added mass of a vessel with greater C_B is more prompt to changes due to the change in water depth. The increase in added mass coefficient and hence roll natural period is less observable in water depths within the deep-water region, however, that change is extremely significant in the shallow water region. The rate of change of the added mass coefficient shows an exponential growth with respect of linear decrement of water depth in the shallow water region.

ACKNOWLEDGEMENTS

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Digitally enabled smart port and ship ecosystems and synthetic training using the new IHO S-100 framework model

Phil Thompson
BMT, London, United Kingdom; phil.thompson@bmtglobal.com

Abstract
This paper describes the integration of a field-proven on-board and shore-based 3D ship navigation simulator with a leading 3D port hydraulics simulator, for the purpose of creating a precise e-navigation digital twin platform. This new data fusion platform is based on the new International Hydrographic Office (IHO) Universal Hydrographic Data Model (S-100) and uses ultra-high-resolution S-100 bathymetry and S-100 dynamic water level and current data, along with other environmental data including seabed composition, automatic identification system (AIS) feeds and weather data. The fusion and processing of S-100 data within an advanced ship navigation simulator offers the potential for more precise e-navigation, a more effective ship and shore-based navigation training platform capable of exploiting higher levels of situational awareness and a capability to assess port operability windows more accurately.

The paper also describes the successful application of this S-100 data fusion platform to the simulation of cruise, naval and LNG ships and ferries in several UK ports and terminals. The platform is suitable for both onshore and on-board use and its development secured the winning prize in the 2020 UK Admiralty International Marine Innovation Challenge.

1. Introduction

The shipping sector has come to terms with electronic chart display and information systems (ECDIS) compliance and are seeing the benefits of improvements in navigation safety and more effective voyage planning from using up-to-date electronic navigation charts (ENC). By using ENCs in an ECDIS, seafarers can easily plot routes and automatically check them for dangers such as rocks, wrecks and obstructions, or other related navigational hazards. An ECDIS has three basic components: hardware, software and data. As an ECDIS often functions as the primary means of navigation, each of its components needs to be kept safe, secure, and well-maintained.

As e-Navigation becomes more embedded, mariners are provided with streams of maritime data from multiple sources that allow them to navigate the seas more safely and efficiently. However, as the amount of information and number of sources grows, there will be a need for improved data fusion and standardisation that allows easy integrated and seamless displays on navigation systems.

Part of the solution will come from more data dense machine-readable electronic navigation charts (ENC's). These will need to incorporate new geospatial and time-variant data layers, such as ultra-granular bathymetry, dynamic water levels and current data [5], [6]. The current S-57 IHO standard for electronic hydrographic data has been used since 1992 with the last revision being in 2020. Current electronic navigational charts (ENC's) are fundamentally designed to be viewed and interpreted by a human in conjunction with pre-acquired

knowledge, experience and what the mariner can see and hear around him/her to enhance situational awareness. As smart bridge systems evolve, in some cases towards ultimately being unmanned, the enriched data fusion landscape will ultimately need to be machine readable by computers able to offer by orders of magnitude faster processing capability [7].

2. The IHO Universal Hydrographic Data Framework (S-100)

In terms of future standards, the Universal Hydrographic Data Model (UHDM S-100), introduced by the International Hydrographic Office in 2018, is inherently more flexible [3], offering provision for such things as more granular gridded data and imagery, time varying data, enhanced metadata and multiple coding formats. S-100 is the framework for the future standardisation of maritime data products and new standards for ENC's.

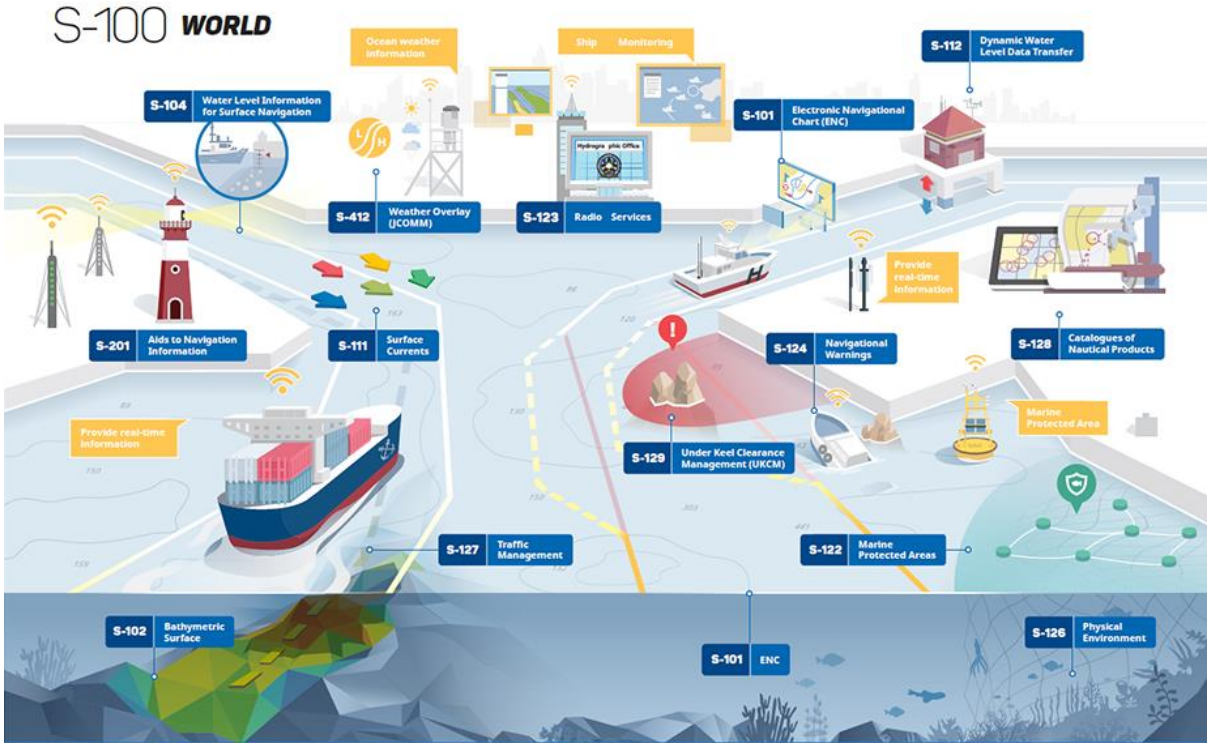


Figure 1 The IHO UHDM S-100 infographic [3]. Note the IHO Hydrographic Services and Standards Committee (HSSC) allocates S-1XX numbers to be used for the development of S-100 dependent products developed by the IHO. Courtesy of International Hydrographic Office.

At its foundation, the S-100 framework uses machine readable catalogues that will lead to plug and play systems and allow for easier updating of data standards and ECDIS systems. This will enable both mariners and other maritime stakeholders including ports, to have more information integrated within navigation systems. This will help to plan optimal routes and make critical decisions in restricted waterways. The IHO released the product specifications for S-102 edition 2.0.0 in October 2019 – high resolution bathymetry, and the following first editions are to be used for system implementation:

- S-101 – Electronic Navigation Charting (Edition 1.0.0 December 2018);
- S-102 – Bathymetric Surfaces (Edition 2.0.0 October 2019);
- S-104 – Water level Information for surface navigation;

- S-111 – Surface Currents (Edition 1.0.0 December 2018);
- S-122 – Maritime Limits & Boundaries (Edition 1.0.0 October 2019);
- S -127 – Marine Traffic Management (Edition 1.0.0 December 2018); and
- S -129 – Under Keel Clearance Management (Edition 1.0.0 June 2019).

Whilst S-57 data as carriage compliant information is not expected to be replaced for some time, new IHO standards for ENC specifications will see S-57 eventually be replaced by S-101, with specific requirements for, and data conversion between, S-57 and S-101. This will allow ECDIS manufacturers to build testbeds for trialling S-101 and overlays. Having testbeds for S-100-based product specifications is important as it ensures interoperability of additional layers when displayed in the same operating systems. Both S-57 and S-101 standards will run in parallel with two data services as there will be a mixture of bridges, some running S-57 and some with S-101. There will be a gradual adoption of the new standards.

So, what does this mean for shipping and e-navigation? With increasing levels of smart bridge automation, and the long-term trajectory likely to include progressive levels of autonomy in navigation channels, coastal zones, ports and inland waterways, the shipping and port industries and suppliers of systems supporting navigation are likely to rely more and more on a full digital world model, with IHO S-100 Universal Hydrographic Model as part of its core. This will facilitate the highest requirements for maritime situational awareness, collision and contact avoidance, system assurance, and cyber security.

2.1 S-102 High Resolution Bathymetry

The S-102 High Resolution Bathymetry specification is one of the maturing S-100 products and we can look in further detail at some of the benefits of richer, more granular bathymetric data. Preparing bathymetric data for charts typically involves taking survey data and using it to generate areas in range bands and separated by contours. This is then augmented by a scattering of spot depths, obstructions, and wreck locations.

To keep the volume of data down and to keep the presentation uncluttered to the human eye, the band ranges and contours in S57 formats are fairly coarse: ordinarily at 2, 5, 10, 15, and 20 m. Unfortunately, this can render large navigable regions outside the safety area if the safety depth does not correspond to one of the contour levels. For example, a safety depth of 11 m would place the whole of the 10 - 15 m area out of bounds.

The introduction of S-102 data facilitates more accurate passage planning by preserving a lot more of the survey data, with depth information available to the order of centimetres placed on a grid with a spacing in the order of metres. With such fine resolution data available the depth band restriction is removed allowing particularly precise plans to be prepared customised to the vessel's draught and the tidal height at the time of passage. Figure 2 illustrates this, contrasting ENC displays of identical channel locations for both S-57 and S-102 data sets using BMT's onboard and shore-based real-time manoeuvring, berthing, and training (REMBRANDT) simulator [7]. REMBRANDT, which is both S-57 and S-100 platform-enabled and is covered in more detail later in the paper, was used here to investigate the suitability of an existing approach channel for a proposed new LNG berth.

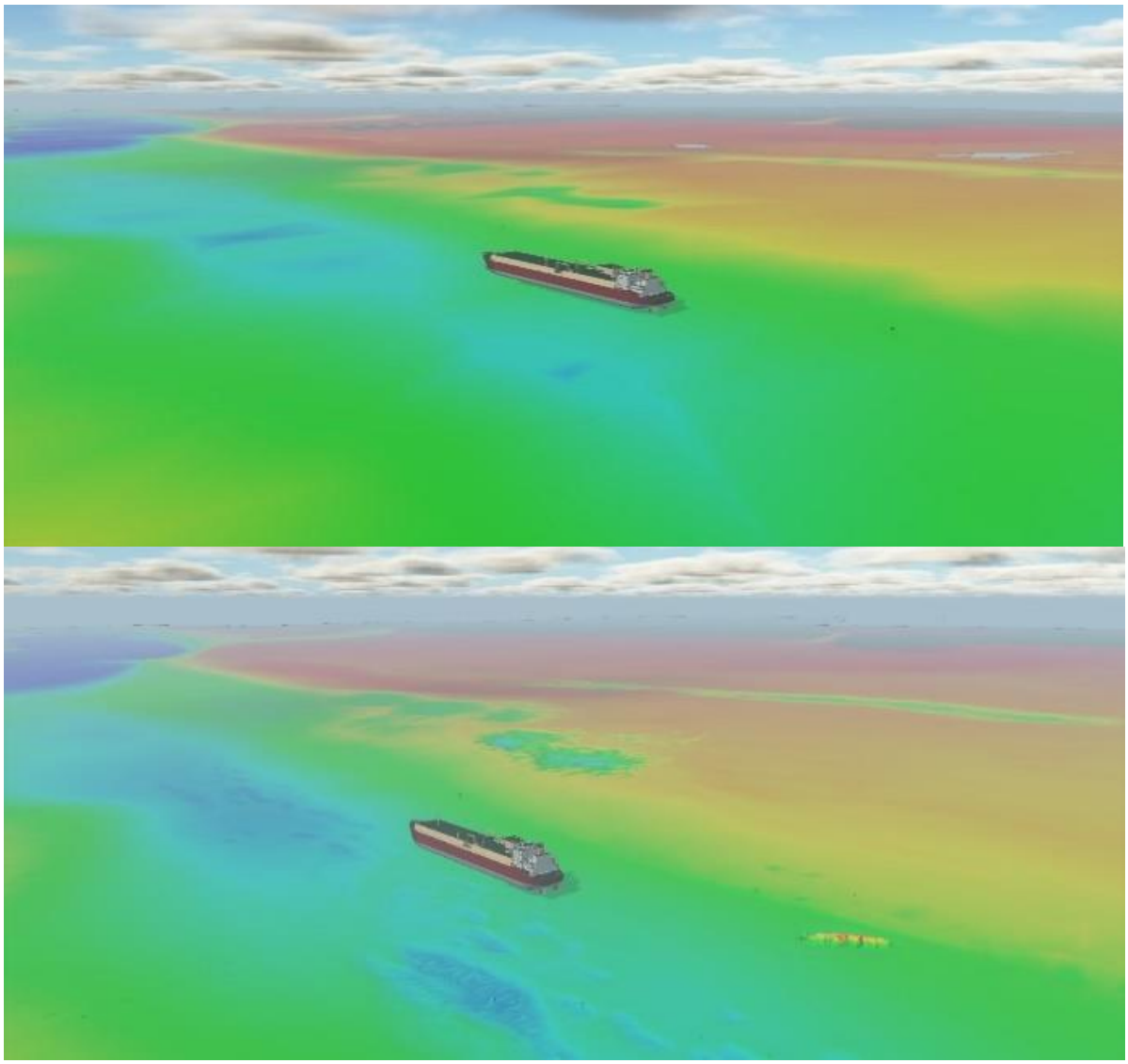


Figure 2 REMBRANDT navigation simulator contrasting S-57 (above) and S-100 (below) ENC bathymetry display formats

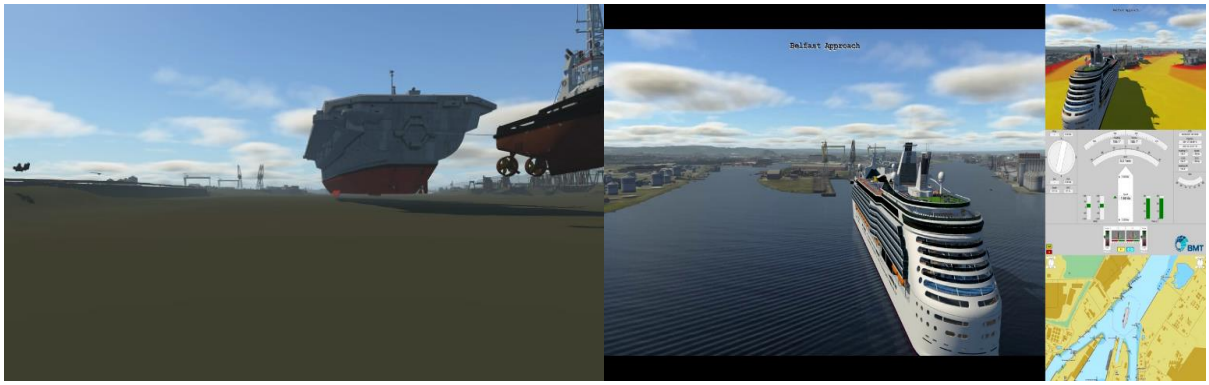


Figure 3 REMBRANDT navigation simulator displaying and processing S-100 bathymetry data to assess Belfast navigation channel, under keel clearance and drydock approach for several vessels. This example shows the S-100 navigation simulation and pilot training for the Queen Elizabeth aircraft carrier and a large cruise ship.

3. An S-100 Ship Navigation and Port/Coastal Hydraulic Data Fusion Model

The new modelling approach was developed as part of BMT's entry in the 2020 UK Admiralty International Marine Innovation Challenge, led and managed by the UK Hydrographic Office (UKHO). The aim was to demonstrate the feasibility of using a S-100 digital "wet twin" of the port and surrounding coastal areas around Plymouth in the UK to significantly enhance situational awareness and demonstrate the precision e-navigation of a ferry using a conventional man-in-the-loop simulation run and also in an "autonomous autopilot" mode of navigation. To achieve this, two separate BMT field-tested simulators were combined into an integrated S-100 dynamic data fusion platform capable of generating and processing hydraulic and other environmental data within a 3D ship response navigation simulator.

High-level overviews of the component simulators are provided below.

3.1 REMBRANT 3D Navigation Simulator

BMT's **REMBRANDT** (Real Time Manoeuvring Berthing and Training) is a 3D time domain, navigation and seakeeping simulation software application [4]. It is used onboard and ashore by multiple maritime stakeholders (e.g., operators of manned vessel fleets, port authorities, pilots, training schools and, more recently, operators of vessels with varying levels of autonomy. REMBRANDT is a scalable platform, certified as a DnV Class A 360 ^{O} full bridge mission simulator and also a DnV Class S (special task) simulator intended for both ship-based and shore-based installation. A wide range of user configurable controls allow for a variety of environmental conditions. These include reduced visibility, day/night settings, wind and current shielding, multi-directional swells and complex current fields. The software supports S-57 ENC's and has been upgraded to include ENC's displaying S-100 data sets. Visual topography includes bathymetric representation automatically generated from the ENC chart, as shown in Figure 4. It is also enabled for live AIS feeds and VDR interfaces for live interactive traffic simulations and navigation training. It also incorporates advanced digital forensics and accident reconstruction functionality and is licenced to statutory marine accident investigation authorities including the US National Transportation Safety Board, the Australian Transport Safety Bureau and counterparts in the UK and elsewhere in Europe.

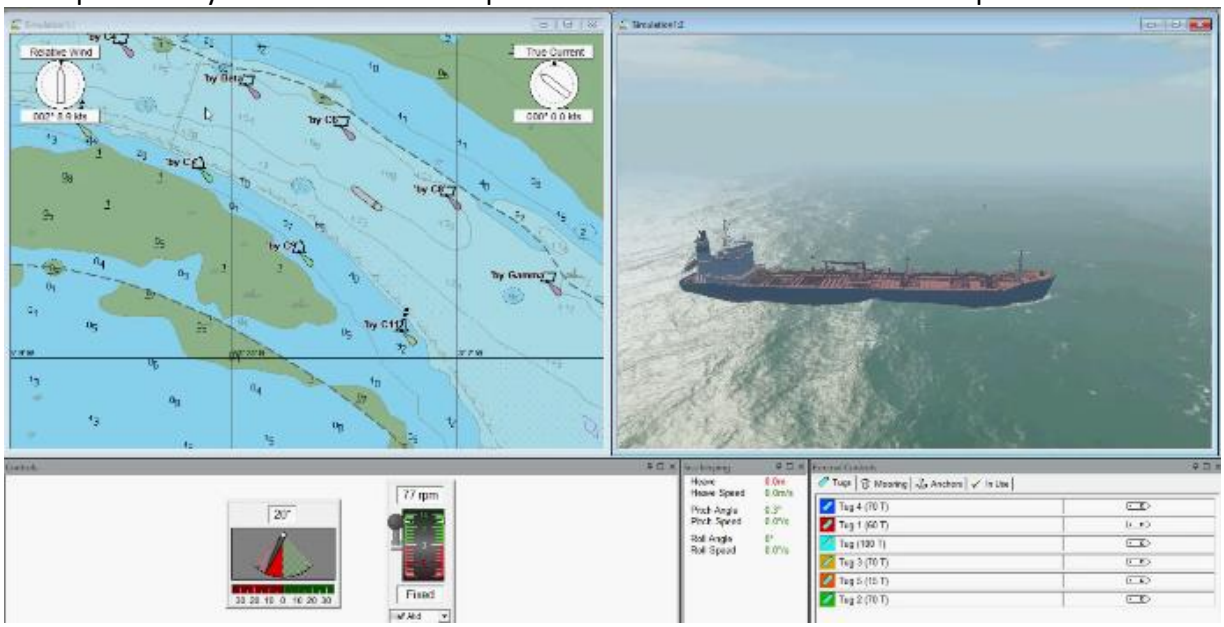


Figure 4 REMBRANDT simulator 2D / 3D split screen display of a ship navigating in a channel.

3.2 TUFLOW Hydraulic Model

BMT's TUFLOW is a three-dimensional numerical hydrodynamic engine suitable for rapidly modelling the hydraulic behaviour of channels, ports, harbours, estuaries, open coasts, and oceans [1]. The engine is designed to integrate with various oceanographic and meteorological input datasets, can be coupled with spectral wave models to assess hydraulic/surface wave interaction and is used extensively to assess environmental processes such as advection dispersion/diffusion, sediment transport and morphology, particle tracking and water quality.

Importantly, for the purposes of ship navigation, TUFLOW can be run together dynamically with REMBRANDT, allowing modelled S-100 hydraulic data to be directly fed to the navigation simulation in either hindcast, nowcast or forecast modes. Key data feeds include time and space varying two-dimensional data (water levels, depths and wave conditions) and three-dimensional, depth varying current speeds.

4. The Plymouth S-100 Data Fusion

Plymouth in the UK was used as the S-100 digital twin as part of BMT's winning entry for the UK Admiralty Marine Innovation Competition. The port of Plymouth offered several advantages in this context. Extensive UK Hydrographic Office (UKHO) S-102 data was readily available; moreover, large numbers of in-situ tidal sensors allowed BMT to fully validate its TUFLOW hydraulic simulations for S-104 dynamic data for water heights and S -102 currents. The port also has a relatively rich mix of commercial, and recreational, marine traffic, which provided a good test for REMBRANDT's simulations.

For Plymouth, a hydraulic model domain spanning 110km east to west, 50km offshore to a depth of approximately 80m and inshore inclusive of the Plymouth sound and estuaries was developed (refer Figures 5 & Figure 6). The hydraulic mesh ranged from 10m to 2000m in spatial resolution, moving from coarser resolution offshore to finer scale in the REMBRANDT navigation simulation zone in the port. Available UKHO S-57 and S-102 bathymetric data, port geometry and monitoring data was incorporated into a detailed TUFLOW hydraulic model of Plymouth port and then used to generate dynamic S-111 and S-104 equivalent data.

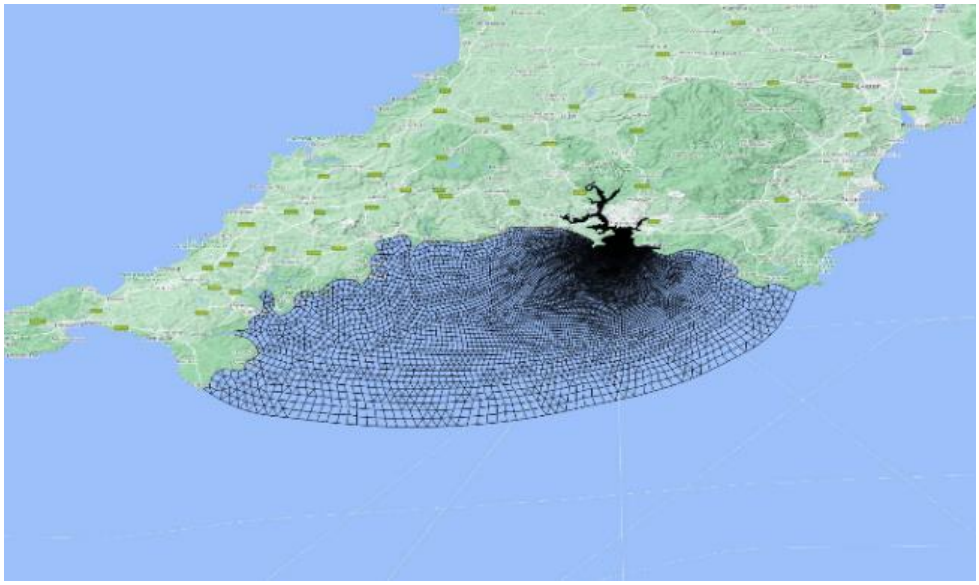


Figure 5. The TUFLOW hydraulic model mesh for Plymouth and wider SW UK coastline showing the finer modelling needed in the REMBRANDT navigation zone

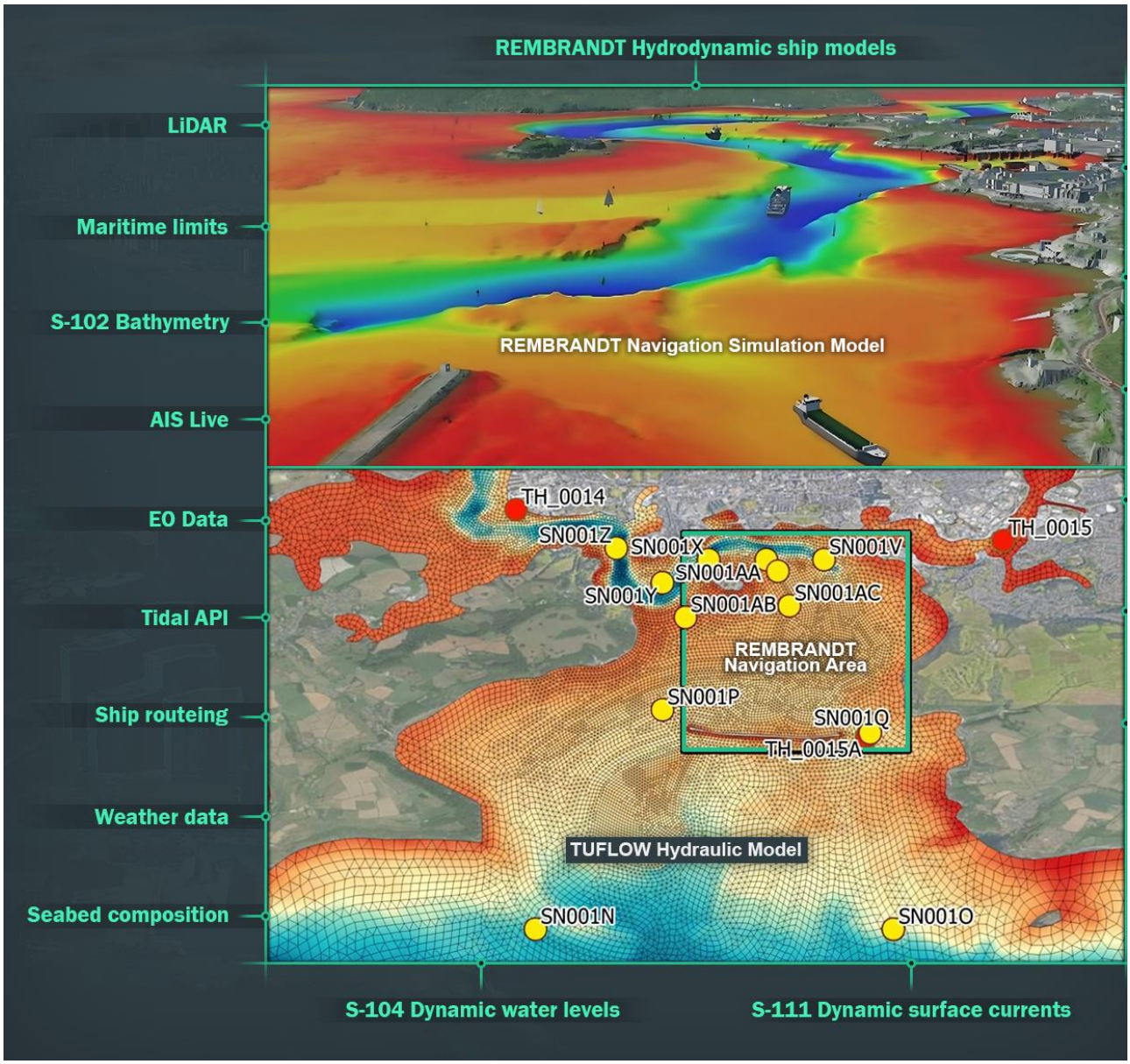


Figure 6 An overview of the REMBRANDT-TUFLOW data fusion navigation software platform. The dark green box outline represents the REMBRANDT navigational study area.

The data sets used in the S-100 Plymouth digital twin platform included:

- Bathymetry (UKHO S57; UKHO S-102) – shown in Figure 7;
  12 UKHO tidal height discrete data points (red) and tidal stream data points (yellow) shown in Fig 6 above. Used by BMT to calibrate a hi-res 10m spatial and 15min temporal gridded TUFLOW hydraulic model which generates S-104 equivalent dynamic tidal height and S-111 equivalent surface current velocities and directions shown in Figure 8;
- UKHO Seabed Composition (used by the autonomous navigation autopilot mode of operation to identify locations safe for grounding).
- LiDAR terrain data (to fill in the bathymetric data in intertidal areas and provide terrain for rain flow into tributaries);
- UKHO Vertical Offshore Frame Referencing;
- e-Notes to Mariners;
- Maritime Limits; Ships Routeing data and AIS.

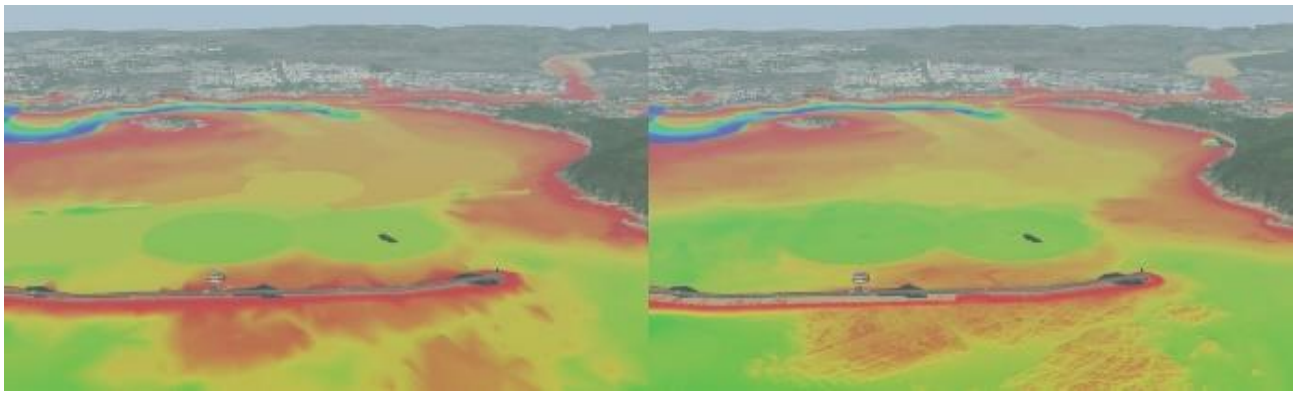


Figure 7 The REMBRANDT Plymouth port bathymetry data visualisation using S-57 (left) and S-102 (right)

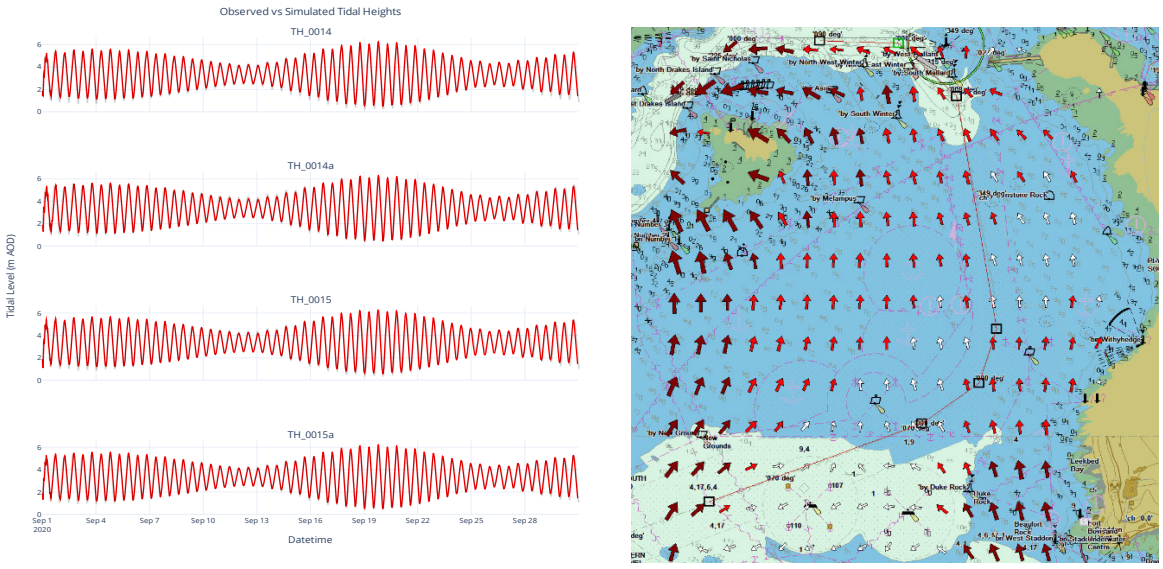


Figure 8 Calibration of the TUFLOW hydraulic model for dynamic water levels and generated surface current data for feeding into REMBRANDT S-104 and S-111 displays

Astronomical tidal predictions were compared at four tidal height and twelve tidal stream data sensors (refer Figure 6 for locations). Good correlation was achieved for water level and current velocity respectively. Zooming in on the spring tide period used for the subsequent navigation analysis, water level results indicate that whilst the overall tidal phase is well represented the model tends to over-estimate tidal amplitudes by approximately 6-8% (refer Figure 11). This was deemed an acceptable level of error for the purposes of the UK Admiralty challenge competition timescales (5 days duration). Having more time available to refine and recalibrate the TUFLOW model would likely give a marked improvement to both modeled water level and current accuracy.

4.1 The S-100 Navigation & Hydraulic Fused Data Fusion Simulation of Plymouth

The S-100 data fusion navigation simulation of Plymouth used a 3D hydrodynamic maneuvering and seakeeping model of a 140m ferry, which had been previously calibrated against pilot cards and sea trials data. The combined REMBRANDT-TUFLOW model simulated the vessel navigating on a flood tide while reading and processing S-102 (bathymetry), S-104 (10m gridded dynamic water level) and S-111 (10m gridded dynamic surface current) data. Other data feeds included were outlined earlier in Section 4. Under the manned ferry

simulation, REMBRANDT was run by manual user interaction of all ship engine and rudder controls. Under the autonomous ferry simulation, REMBRANDT operated using its autonomous autopilot mode.

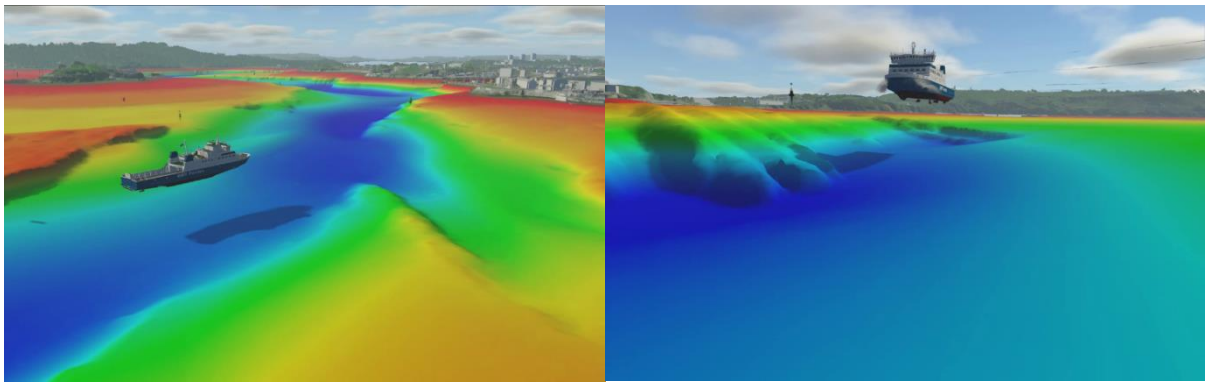


Figure 9. S-100 Plymouth Navigation simulation of 140m ferry (in both manned and autonomous mode)

A series of REMBRANDT runs were performed concentrating on the challenging navigation area in the vicinity of Smeaton Pass, Plymouth Sound. Some commercial and recreational traffic was in the vicinity. The strongest predicted period of flood tidal-flow was chosen for the exercises (circa HW-3) with a nominal 15kt South-westerly wind. Maximum tidal current experienced was about 1.5 knots, similar to that for a Spring-tide cycle in the area.

As a control exercise, the vessel was put into REMBRANDT's standard track-mode autopilot. As can be seen from the 2D track plot in Figure 10, when negotiating the alteration off S. Mallard, the swept path brought the starboard quarter of the ship close to the S. Mallard buoy and well to the NE of the charted track.

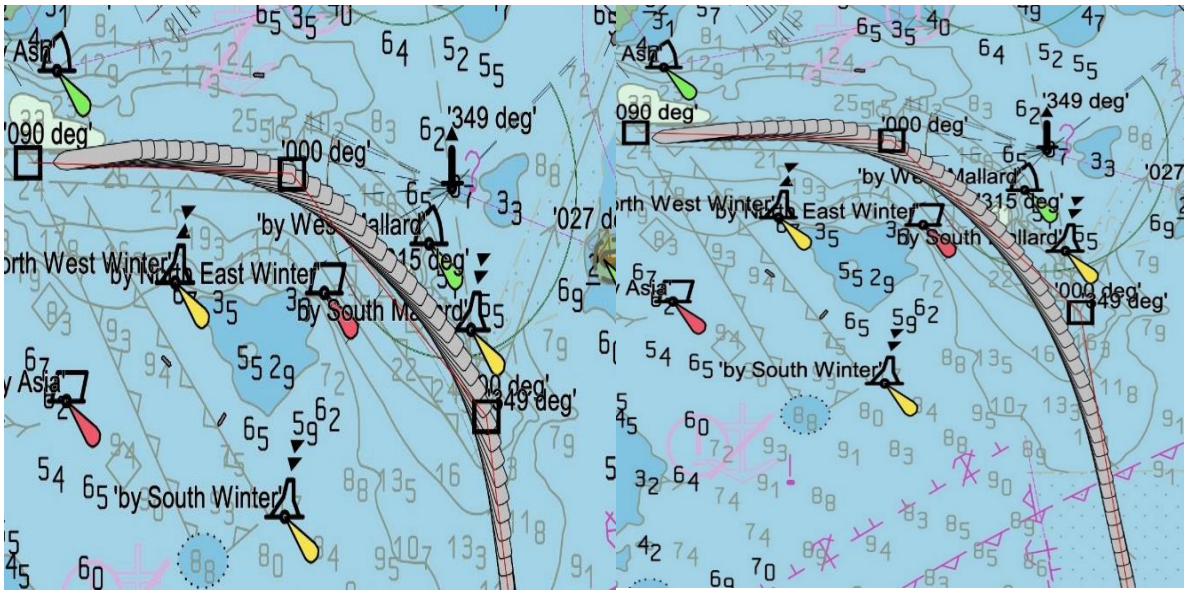


Figure 10 REMBRANDT track plots -standard auto pilot (left); autonomous autopilot mode (right)

The 2nd run employed REMBRANDT's autonomous autopilot mode. REMBRANDT interrogated and processed the S-100 bathymetric, tidal, current and seabed composition data concurrently with the prevailing meteorological and other environmental data, including

AIS, to follow the charted track. REMBRANDT also monitored precise under keel clearance (UKC) margins, as well as forecast margins ahead, by continual interrogation of S-102 bathymetry and S-104 dynamic water levels. The system also interrogated available maritime safety e-information and, in this instance, noted a machine-readable Temporary Notice to Mariners warning of an unreliable light sector from Mallard Beacon. The autonomous autopilot track plot run is shown in shown on the right in Fig 10.

Whilst on the northerly leg of the run and processing S-100 dynamic tidal stream, current data and external wind data, REMBRANDT instigated a real time calculation of the wheel-over point for the turn onto the brief 315 leg, and again to estimate a course to steer for that leg. Pilots attended the synthetic trial and noted the timing and extent of helm applied and confirmed the much finer adherence to the required track by way of forward determination of the influential hydrodynamic elements. It is worth noting that in an earlier autopilot run which tested only S-57 data set feeds, the adherence to the pilots' required track was much less satisfactory, demonstrating the value of accessing dynamic and more granular S-100 hydrographic data sets in both manned and autonomous ship navigation.

5. Further Applications in Ports and Shipping

The development of an S-100 integrated navigation and hydraulic simulator has highlighted the potential application more widely across the shipping and ports sector. Some of the potential applications are summarised below:

- Using the integrated Rembrandt -TUFLOW 3D platform in a navigation-hydraulic S-100 digital twin for both onboard and shore-based training exploiting significantly higher levels of situational awareness representations. This supports more precise e-navigation, under keel clearance management and improved mariner and pilot training.
- Using the S-100 digital twin approach to assess port operability windows more accurately.
- Supporting major ports on a pathway to become progressively autonomy enabled.
- Linking the S-100 hybrid navigation- hydraulic digital twin with other compliance-driven requirements, e.g., port Environmental Impact Assessments (EIA's).

6. Summary

This paper has demonstrated the feasibility of coupling a 3D hybrid navigation-hydraulic simulator with the evolving IHO S-100 data framework model. The author has demonstrated the utility of this approach in several aspects of port operations and manned and autonomous ship e-navigation. More applications are expected to open as the IHO S-100 data framework model matures. It should be noted that the utility of the hybrid simulator is not restricted by access to S-100 data and is designed to utilise hydrographic data of mixed levels of granularity.

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The Environmental and Economic Assessment of using Liquefied Natural Gas as a Fuel Onboard Bulk Carrier Ships

Ibrahim S. Seddiek[1], Mohamed M. Elgohary[2]and Ahmed Anwar[2]

[1]Department of Marine Engineering Technology, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

[2]Department of Marine Engineering and Naval Architecture, Faculty of Engineering, Alexandria University, Alexandria, Egypt

Abstract

As International Maritime Organization emission regulations become more rigorous, the marine industry is submitting to transformation to green shipping. Clean air and human beings health concerns during this pandemic (COVID-19) gained renovated interest and continues to be a key determinant of renewable port activity. The alternative fuels′ debate has been dominated by the potential of liquefied natural gas. LNG-fuelled vessels count to approximately 13% of the running new build order book and estimates for 2021 and demonstrates continue growth in many classifications of society of vessels. This paper studies the environmental and economic assessment of using liquefied natural gas liquefied natural gas as a fuel onboard bulk carrier ships. Environmentally, the research reveals that there is a possibility of achieve a reduction of air pollutant emissions, of nitrogen oxides , sulfur oxides, particulate matter and carbon dioxide by 80.7%, 98.5%, 97.6% and 21.8% , respectively, at annual saving damage due to atmospheric emissions per year of 2.27, 11.97, 0.82 and 0.18 million dollars, respectively. Moreover, it is predicted that an annual fuel saving cost of 2.5 million US dollar, compared to heavy-fuel oil for marine shipping could be achieved.

Key words: air emissions reduction, environmental and economic benefits, dual fuel engine, IMO, natural gas, and ship emissions

Abbreviations

CNG	Compressed Natural Gas	LF	load factor
CO2	Carbon Dioxide	LNG	liquefied natural gas
CRS	Selective Catalytic Reduction.	LPDF	low pressure dual fuel
EGR	Exhaust Gas Recirculation	NG	Natural gas
DF	Dual Fuel	NOx	nitrogen oxides
E	Emissions	P	power rating

EPA	Environmental Protection Agency	PM	particulate matter
GE	Gas Engine	SOx	sulphur oxides
HC	Hydrocarbon	T	number of engine running hours (h)
IMO	International Maritime Organization		

1- Introduction

The greenhouse gas emissions, which are announced from IMO, are coming more and more into common focus [Ibrahim and Mohamed, 2020; Elkafas et al., 2020; Elkafas et al., 2021], with growing the international seaborne trade , which is considered the back-bone of world trade around 90% between 2000 and 2018 [UNCTAD, 2018], representing 2.5%–3.5% of global CO2 emissions; [Seddiek and Ammar, 2021; UNCTAD, 2019], because of COVID-19, global maritime trade immersed by 4.1% in 2020, as shown in Fig. 1; with expectations of trade growth to return to a positive range by 4.8% in 2021; [UNCTAD 2020].

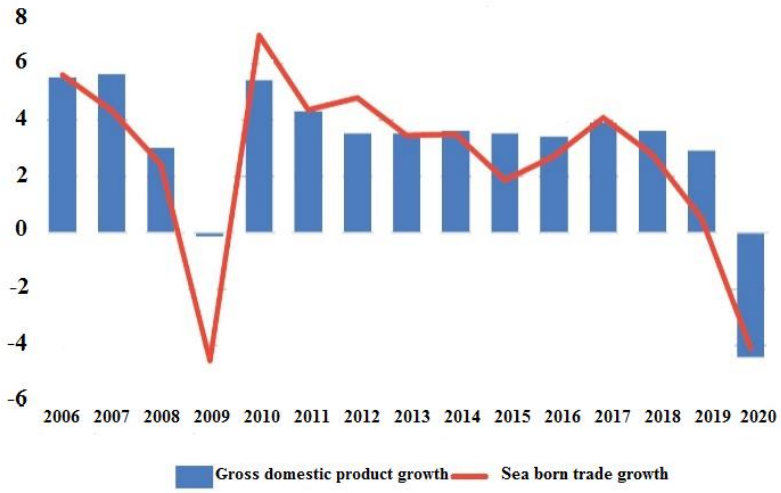


Fig. 1 Global seaborne trade, 2006-2020

Moreover, ships are responsible for global air pollutant emissions, such as oxides of nitrogen (NOx) and oxides of sulphur (SOx) of 6.6% and 4%, respectively [Ammar and Seddiek 2020]. With IMO expectations, GHG emissions from shipping industry will grow up to 250% by 2050. [Smith et al., 2014, and Salem et al., 2014]. A large number of ships go through in environmentally sensitive locations. To do so, their engines must fulfill extremely rigorous emission standards. The restrictions for all vessels traveling in international waters are defined by the Tier III, Emission Control Area and Energy Efficiency Design Index standards define. To meet IMO objectives

of decreasing carbon emission by 40% by 2030 and 70% by 2050, in comparison with 2008 levels, the international reaction to the detrimental polluted impacts on marine environment are to enforce stricter emission limits. [IMO 2018]. Fig.2 presents annual carbon-dioxide emissions per vessel; by vessel type [UNCTAD 2019] recently there are numerous technologies that have been implemented to reduce emissions [Salem et al. 2014, Banawan et al. 2010, Seddiek and Elgohary 2014] such as selective catalytic reduction, exhaust gas re-circulation to reduce NO_X, Sea water scrubbing, exhaust below water line to reduce SO_X, electrostatic filters to reduce particulates and closed crankcase ventilation.

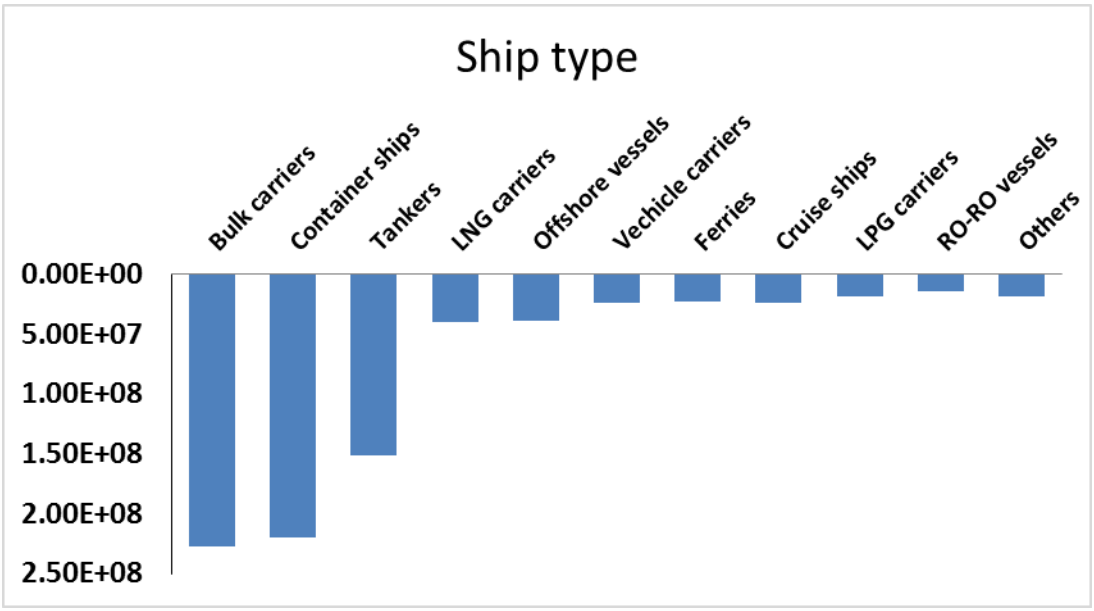


Fig. 2 carbon-dioxide emissions per vessel type, 2019

2- Alternative Marine Fuel Overview

According to recent studies, a variety of alternative fuels can be employed in seaborne trade. Liquefied natural gas, methanol and hydrogen. Have been highlighted as the top of the list as potential alternative fuels for shipping [Ibrahim and Elgohary, 204; Engineering, 2013]. All these types are essentially zero-sulfur and could be utilized to comply with sulfur content restrictions, which is regarded as shipping's most pressing issue. They can be utilized in conjunction with regular oil-based marine fuels to meet only a portion of vessel's energy requirements, or they can be used to totally replace traditional fuels for specialized ships. In spite of their low sulfur content, several of them have major problems; for instance, biodiesel has difficult time starting in cold weather increases in NOx emissions [Salem et al. 2014, Ammar 2019]; other research showed the possibility of using methanol and the emission of aldehyde, vapor lock, cold starting, and cost-effectiveness [Salem et al. 2014 , Elkafas et al., 2020]. In addition to these disadvantages, there are many basis act of making a choice of the

suitable substitutional fuel, like how is it adaptable, available, safe, lower cost, renewable, promising in performance, and friendly environmentally impacted [Elkafas et al., 2020, Banawan et al. 2010, Seddiek and Elgohary 2014] which favor hydrogen and natural gas as shown in Fig.3.

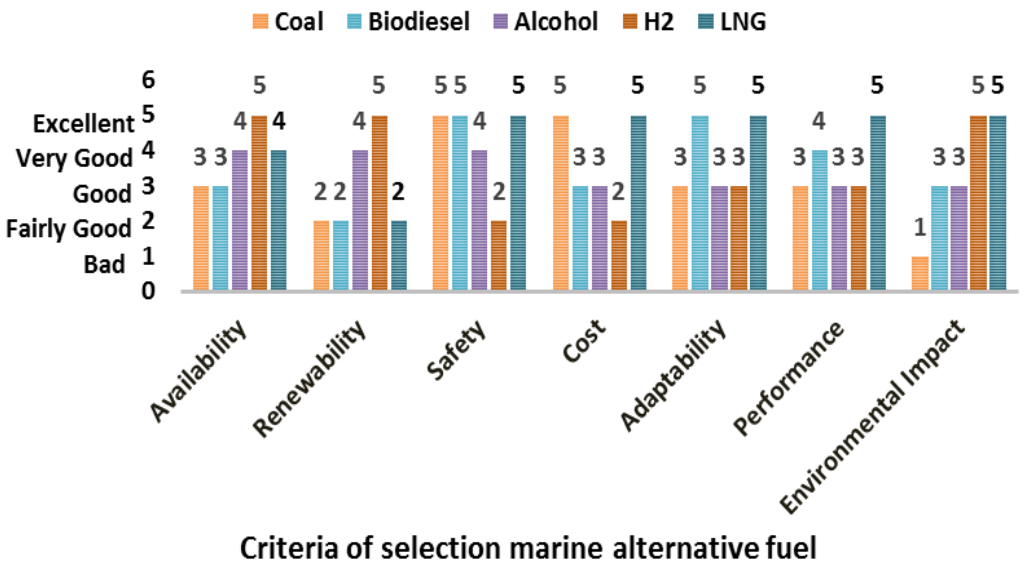


Fig. 3 weighting matrix chart of alternative marine fuels

Unfortunately, hydrogen has some safety issues that need resolution; it has a low energy density and needs a supply infra-structure to be sustainable marine environment [Elgohary et al., 2015]. Furthermore, many scientists showed the potential of utilizing natural gas for marine implementation, either for ship's powering system [Banawan et al. 2010, Seddiek and Elgohary 2014, El-Gohary 2012] or for electric generation, using fuel cells [Ammar, 2019]. This means that it is highly likely that natural gas comes at the top of list as an alternative marine fuel in the near future.

3- Natural Gas Characteristics

Natural gas consumption increased by 2%, well below the exceptional growth seen in 2018 (5.3%). Nevertheless, the share of gas in primary energy rose to a record high of 24.2%. Fig.4 shows the distribution of proved reserves in 2019. From the graph, Africa shares with 7.0% from total distribution and Egypt with 1.1% (2.1 Trillion cubic meter) [BP, 2020].

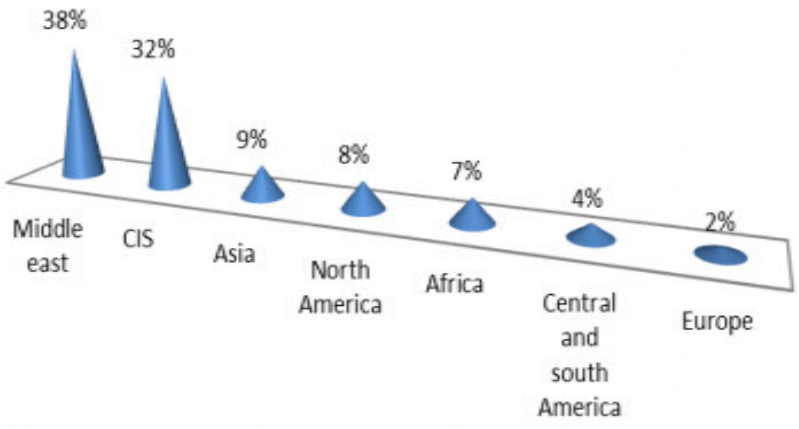


Fig. 4 Global liquefied natural gas distribution in 2019

4- Marine LNG Fuelled Engine

It is a double fuel engine that uses natural gas and liquid fuel. Due to natural gas's detergent combustion features, the use of natural gas in commercial ships' power plants is becoming a cucumber for companies in order to be interrogated with IMO and MARPOL environmental rules. Natural gas is stocked in liquid state (LNG), and the boil-off gas is routed to and burned in dual fuel engines. When running in gas mode, the engine works according to the Otto process, where the lean air-fuel combination is delivered to cylinders during the suction stroke. When in diesel mode, it works follows diesel process, which involves feeding diesel to cylinders at the end of compression stroke. The engine can be operated on natural gas, light fuel oil or HFO. Thanks to its dual fuel technology. It is possible to switch fuels in the middle of an operation without sacrificing power or speed. It is designed to generate the same level of power in any case of the fuel used. Another LNG application is to generate electricity using gas turbine technology or a combination of a gas-steam turbines running on the flue gases (COSAG) which result in more electrically and thermally efficiency, diesel engines (CODAG), and diesel generators are also used to widen the developing power curve (CODLAG) [Salem et al. 2014, Elgohary and Seddiek, 2013; and Engineering, 2013]; there are a few things to take into account: knocking can be avoided by carefully controlling injection timing.

4.1- LNG Investment

As the business case rationale for LNG as a marine fuel becomes more widely recognized, so does the order book for LNG-fuelled ships in all sectors. As on May 1, 2018, there were 122 LNG-fuelled ships in service and 132 in construction or

confirmed orders According to DNV statistics (Source DNV, 2018) as shown in Fig. 5.

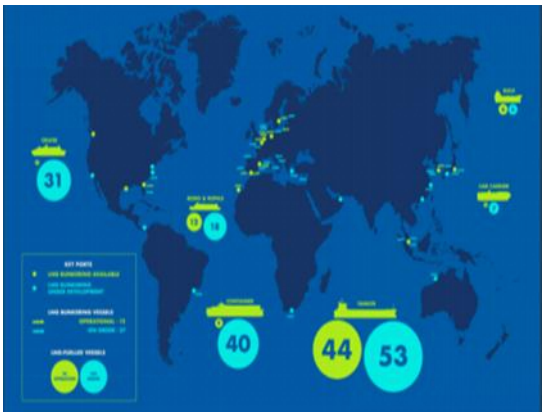


Fig. 5 global growth in LNG use and infrastructure

There were 163 LNG-fuelled ships in service In June 2019 (excluding over 500 LNG carriers) with another 155 ships on order as shown in Fig. 6 there are now 175 LNG-fuelled ships in service, 203 on order, in addition, 141 LNG-ready vessels in service and on the order books as of February 2020 [Keller 2019].

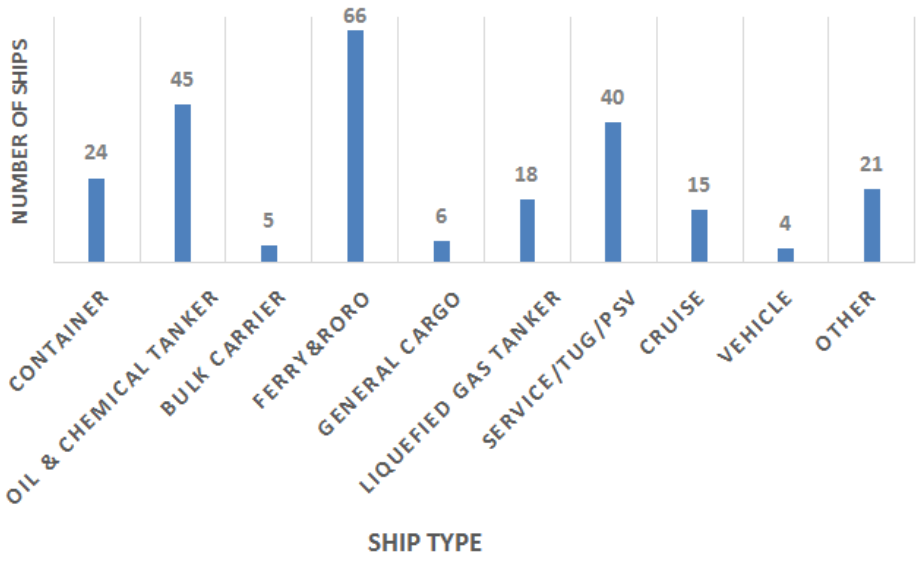


Fig 6. LNG-fuelled ships in use or under construction

5- Case Study

This study discusses both the environmental and economic assessment of using liquefied natural gas (LNG) as a fuel; the chosen bulk carrier ship is Wadi Safaga, as shown in Fig 7 that belongs to a national navigation company, which is considered the

largest shipping Egyptian company specialized in shipping dry cargo among the world's largest ports.

Table 1. Ship principals

Ship name	WADI SAFAGA
Flag	EGYPT
IMO NO.	9460734
L.P.P.	229 m
Molded Breadth	32 m
Fuel consumption per year	11579.3 ton
Main engine	STX-MAN B&W 7S50MC-C, 11060 KW @ 127 RPM
Build	2010
Gross tonnage	43736
Port of registry	Alexandria

6- LNG Fuelled Ships environmental and economic assessment

This section explains the methodology for assessing the ship's environmental effectiveness, besides focusing on the most major pollutants including CO_2, NOx, SOx, and PM with an emphasis on the calculations, as well as the methodology used to evaluate the economic benefits of switching from diesel to dual-fuel engine.

6.1 Environmental Assessment

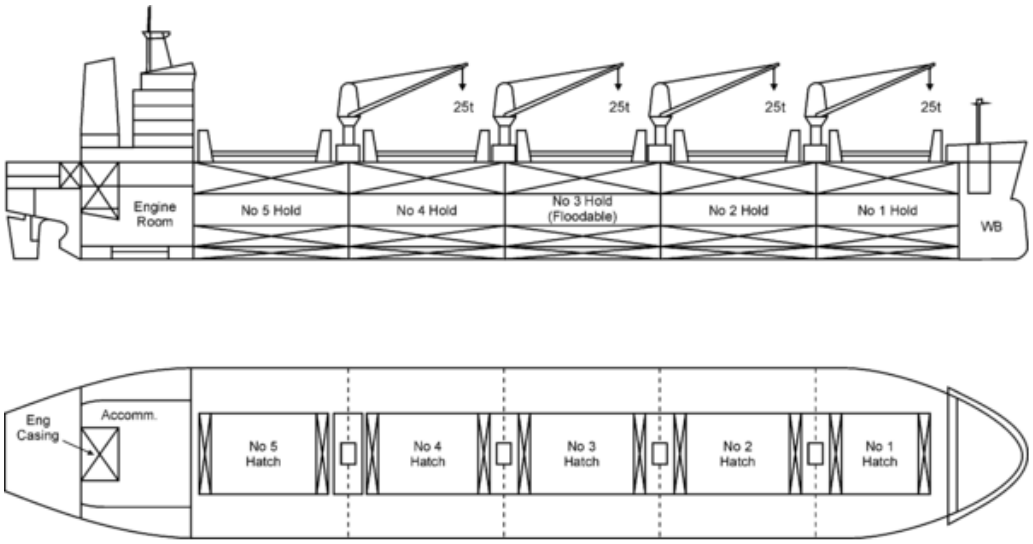


Figure 7 M/V WADI SAFAGA General Arrangement

Calculating quantity of gassy releases from diesel and dual fuel engines is considered the main crucial factor for environmental benefits evaluation. Calculating the quantity

of gassy releases from The Environmental Protection Agency (EPA) inventory method thereby includes defining the input parameters related to the vessel's type, the fuel's consumption and the operation's mood. Consequently, the emission quantity can be estimated using the following formula [Seddiek and Elgohary 2014]:

$$E = P \times LF \times efd \times t \qquad \text{equ.1}$$

where ''E'' is the emission quantity (g), ''P'' is the engine power at MCR (kW), ''LF'' is the load factor (85%), ''efd'' is the emission factor (g/kWh) in diesel mode and ''t'' is the engine running time (hr). By substituting the average HFO and LNG for two stroke diesel engines [Keller 2019, Side-effects 2015] provided equally power and running hours, by this way and conditions we can deduce the environmental benefits due to conversion from heavy fuel oil or diesel oil to liquefied natural gas (in case of dual-fuel engine) The chosen dual fuel engine is WinGD RT-flex50DF .

Table 2 Emission factors g/kwh

Emission g/kwh	Diesel	Dual fuel
CO2	549	412
NOx	14.5	2.68
Particulates	0.44	0.01
SO2	11.73	0.17

The results of this estimation are shown in Figure 8. According to these findings, switching from HFO to LNG has caused reduction in (NOx), (SOx), (PM) and (CO2) by 81.5%, 98.6%, 97.7% and 25%, respectively.

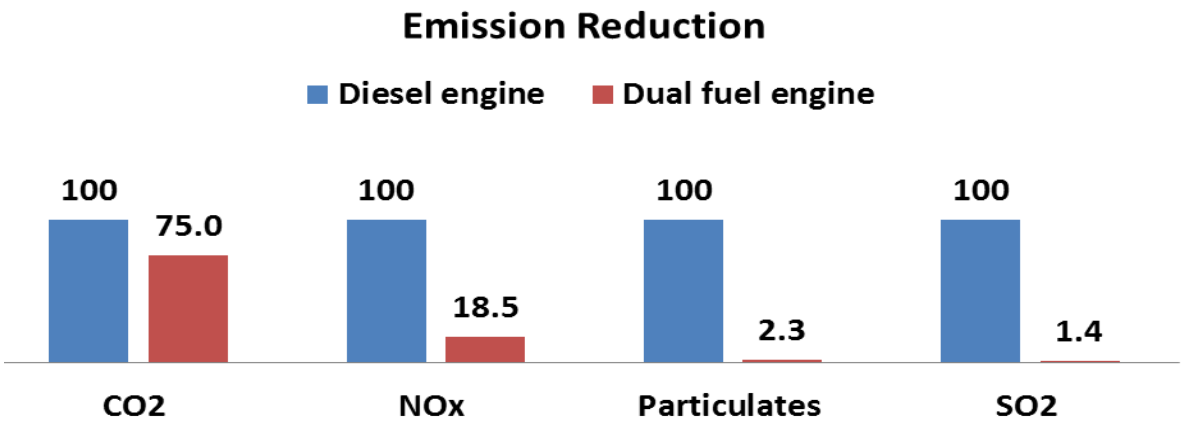


Fig. 8 Emissions reduction due to dual fuel engine.

Because the ship does not have a regular line, it sails among the world's largest ports almost all the year. From the ship owning company, the total days at sea are 250 days

a year. Table 3 shows the environmental advantages of the switching from diesel to dual fuel engine, lower emissions of CO_2 (24.95 per cent), NOX (81.5 per cent), PM (97.7 per cent) and SO2 (98.55 per cent). These results match the ones that are reported in reference [Ammar and Seddiek 2020, Banawan et al. 2010].

Table 3 the environmental benefits due to conversion process

Pollutant	Engine mode	Emission per trip (ton)	Emissions per year (ton)	Reduction ton/year
CO2	diesel	6384.34	30966.89	7727.62
	NG	4990.43	23239.27	
NOx	diesel	168.62	817.89	666.72
	NG	32.46	151.17	
PM	diesel	5.12	24.82	24.25
	NG	0.12	0.56	
SO2	diesel	136.41	661.64	652.05
	NG	2.06	9.59	

6.2 The progress in Analysis of Environmental Damage

There has been great development in the analysis of environmental damages over the last two decades; the findings show that the typical air pollutants (CO_2, particulates, NO_X and SO_2) produced by combustion of fossil fuels cause large damage costs. The costs of global warming caused by greenhouse gas emissions are also significant. The damage costs per ton of emitted pollutants are presented for typical UK settings. [Rabl et al., 2020, Cannon 2019]. Table 4 the cost of damage due to atmospheric emissions (million dollar /year) and the reduction due to the conversion process.

Pollutant	Engine mode	Cost of damage in MUSD	Reduction in MUSD
CO2	diesel	1.47	0.18
	NG	1.29	
NOx	diesel	2.79	2.27
	NG	0.52	
PM	diesel	0.84	0.82
	NG	0.02	
SO2	diesel	12.15	11.97
	NG	0.18	

From table 4, we can deduce that the reduction cost of damage due to atmospheric emissions percentage in CO2, NOx, SO2 and particulates is as follows: 12.34%, 81.52%, 97.73% and 98.55%, respectively.

6.3- Economic Assessment

Recent researches claim that natural gas can be stocked onboard, either compressed with density 0.19 ton/m^3 at 250 bar in steel bottles or liquefied temperature -162C^o with density 0.45 ton/m^3 at 1 bar, in a cylindrical cryogenic vessel that is made from arm-reinforced plastic, which typically sustains pressure from 0.3 to 10 bar. However, due to the increased volume of NG required throughout this case study's trip, it will be unable to save in compressed form. This means that using liquefied natural gas is a top priority. [Elkafas et al., 2020, Ammar and Seddiek 2020, Banawan et al. 2010]. From our case study, the ship has not got a regular line so it is prepared for 1262 hours of sailing that needs 2127.4 m^3 of LNG during this period, so we need two tanks, each with 20m length x8.25m diameter and 5mm wall thickness, which was obtained from formula:

$$T = \frac{E \cdot r \cdot p}{F} \quad \text{equ.2}$$

Where r is the tank radius, P is the operating pressure 4.14 bar, F is the tensile strength 1029 MPa and E is the safety factor taken to be 3. To convert from diesel to dual fuel engine, diesel fuel and LNG consumption per year will be 105.73 and 10317.9 ton respectively, so we can deduce that LNG offers a lower energy cost per ton, against heavy fuel oil by nearly 40% because it contains more energy for the same power. Table 5 displays operational costs of diesel engine, average price of diesel in the end of 2020 was 349.5$/ton [shipandbunker 2021]. More over diesel fuel bunkering is 9$/ton; we get oil lubrication quantity for system and cylinder from reference [IEEE 2004], whereas the cost of maintenance, repair and oil lubrication cost from the company that owns the ship.

Table 5. Diesel engine economy

Operational costs/trip				Operational costs per year in (M$)
	Ton	$/ton	M$	
Diesel fuel bunkering	2339.2	9	0.021	0.1
Diesel fuel	2339.2	349.5	0.818	3.887
Oil	12.41	2203.50	0.027	0.130
Maintenance & repair (M&R) cost			0.05	0.250
Total			0.906	4.37

Table 6 explains operational costs of Dual fuel engine, average price of LNG in the end of 2020 was 304$/ton [shipandbunker 2021], price of Main engine, Gen-sets, LNG tanks, Gas system , maintenance & repair (M&R) cost and gas storage & vaporization (M&R) cost were obtained from Wartisla company and[Aonami 2019]. Design price was obtained from reference [Washington State 2011], shipyard installation, the information was obtained from Alexandria Shipyard-Egypt (around 10000hrs with labor cost 25$/hr).

Table 6 Dual Fuel engine economy

capital costs in MUSD				
Supply	10.45			
Design	1			
Shipyard installation	0.25			
Total capital costs	11.7			
Operational costs/trip				Operational costs/year
	Ton	$/ton	M$	
Gas fuel	957.34	304	0.291	1.3836
Gas fuel bunkering	957.34	13.1	0.0125	0.0596
Diesel fuel	21.8	349.5	0.0076	0.0362
Diesel fuel bunkering	21.8	9	0.000196	0.0009
Oil	9.928	2203.50	0.022	0.1040
Maintenance & Repair			0.05125	0.2
Gas storage & vaporization			0.00236	0.0112
Total operational			0.38	1.7955
Total annual Savings operational costs				2.57 M$

From Tables 5 and 6, we get total annual savings operational costs million USD, with

reduction 59%, as shown in Fig.9.

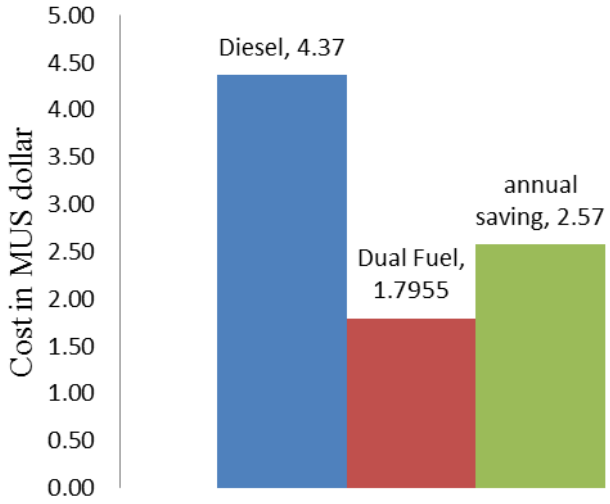


Fig. 9 Annual Saving operational Cost in MUSD

The total annual fuel cost for diesel and dual-fuel engines are US$ 3.987 million and 1.48 million US$, respectively; therefore, the annual fuel saving cost equals 2.5 million US$, as shown in Fig.10.

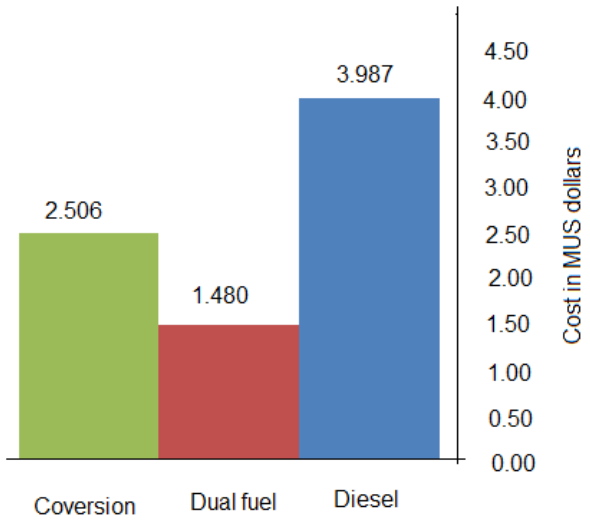


Fig. 10 Annual fuel Saving Cost in MUSD

For the supposition that the average maximum ship age is 28 years and that it was launched ten years ago, so the expected reaming 18 years, ship saving after conversion for the expected remaining ship life with different value of interests (MUSD/year), the yearly capital cost recovery is 2.57 million dollar per year at an interest rate of 3%. At the end of the ship life cycle, the total annual saving for using

DF engine equal 40.4 M dollar. Moreover, Fig.11 portrays the annual fuel saving cost due conversion from traditional diesel fuel engines to the proposed dual fuel concept for the selected case study at various interest rates.

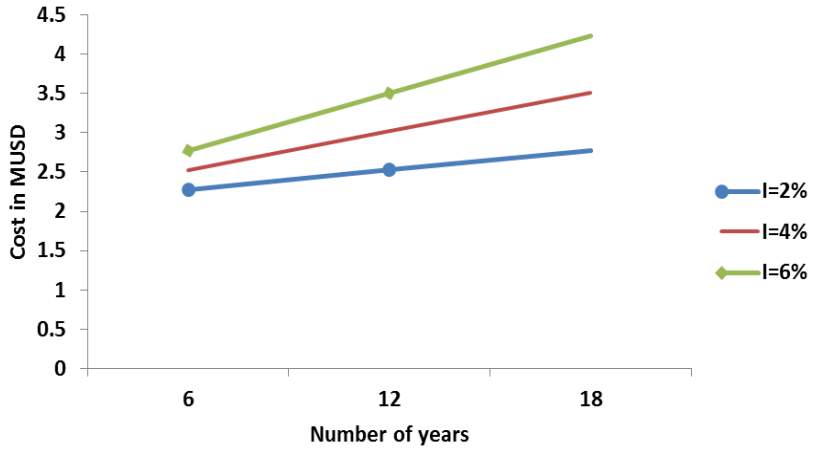


Fig. 11 Annual fuel saving after conversion for the expected remaining ship life with different value of interests (MUSD/year).

By supposing that the remaining ship age is 18 years, assuming 3% fuel price increment. From equations: CA= Ci CRF, where CA is the annual cost and Ci is the capital cost. CRF is given by,

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad \text{Equ.3}$$

Where N is the expected ship working year after conversion. Figure 12 shows the link between annual cost conversion and predicted reaming ship life.

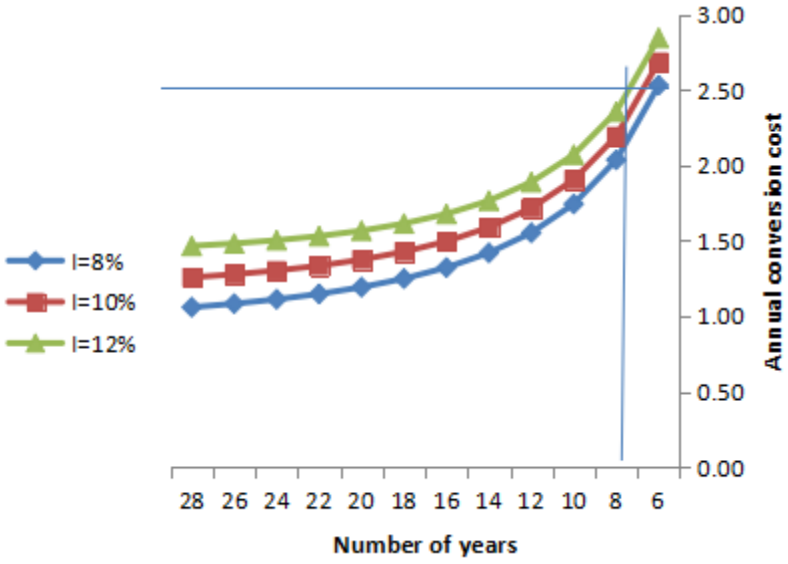


Fig. 12 the relation between annual cost conversions and expected reaming ship life

From the Fig. it is clear that with 12% interest, the minimum working years to retrieve the conversion cost is close to 8 years, at annual transmutation cost of 2.57 MUS dollars. However, this value will show a considerable reduction at 8% of interest to reach only 1.75 MUS dollars. The Figure indicate the possibility of achieve the required target of the international maritime regulations with an expected economic benefits in case of shifting from diesel power ships to LNG powered ships.

Conclusion

With demonstrating liquefied natural gas and its ability as an alternative fuel to reduce environmental emissions such as oxides of nitrogen (NOx), oxides of sulphur (SOx) , particulate matter (PM) and carbon dioxide (CO2) by 80.7%, 98.5%, 97.6% and 21.8%, respectively, and annual saving damage due to atmospheric emissions per year of 2.27, 11.97, 0.82 and 0.18 million dollars respectively as well as saving annual fuel cost and saving annual cost of 2.5 million US dollar, 2.57 million US dollar respectively, compared to heavy-fuel oil (HFO) for marine shipping, there is no wonder to take on liquefied natural gas as a top of the list fuel in marine shipping.

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SESSION 5

Autonomous Vessels

Accelerating maritime trusted autonomous systems

Introducing Autonomous Systems into Tropical Marine Operations - a Case Study into AIMS Journey

Australian defence opportunities for un-crewed vessels

Accelerating Maritime Trusted Autonomous Systems

Prof Jason Scholz
CEO, Trusted Autonomous Systems Defence CRC
Jason.scholz@tasdcrc.com.au

ABSTRACT
The trusted autonomous systems defence cooperative research centre (TAS) was established by Defence, for Defence, to develop game-changing technologies through industry-led, research-enabled projects. These technologies aim to confer asymmetric advantage for Navy to fight and win at sea, aligned with the Navy's RAS-AI Strategy. This asymmetry requires the introduction of new 'capabilities which can be produced in bulk, more quickly and cheaply' according to MINDEF. In the maritime domain the employment of 'smart, small and many systems' will enhance the capability 'complex, large and few' crewed platforms.

The foundations of TAS to accelerate delivery of RAS-AI for Navy and Defence is explained. Our vision for smart, small and many systems is based on consideration of armed conflict in an age of free silicon, and DSTGs ubiquitous command and control to achieve robustness and decentralised orchestration of the many. While laying the foundations for Navy to fight and win using these technical systems, we explore strategies to build sovereign industry and 'land' innovations through acquisition.

Without trust, Naval systems won't reach the water line. Achieving trust for these systems includes consideration of assurance, law and ethics. TAS is developing: new means for verification of AI; technologies which embed legal protocols and compliance; an Australian Code of Practice for the design, construction, survey and operation of autonomous and remotely operated vessels; a maritime COLREGS framework for RAS-AI; an airspace Detect And Avoid framework for RAS-AI; and has delivered a Method for AI Ethics in Defence with DSTG as a practical guide for industry.

BACKGROUND
Australia's current strategic position has been shaped by the 2021 announcement of AUKUS [1] and recent public commitment to NATO and AUKUS allies through sanctions, supply of humanitarian support and lethal weapons to the Ukraine to defend against the invasion of Russia [2]. Robotics, autonomous systems and artificial intelligence (RAS-AI) have been identified as an Australian Sovereign Industry Capability Priority [3], supporting recommendations from the 2016 Defence White Paper and the 2020 Strategic Update and the establishment of Trusted Autonomous Systems (TAS) in 2017.

TAS was created to address Defence mission challenges of: operation in anti-access and area denial (A2/AD) environments, reducing human exposure to risk, and achieving a force multiplier. TAS, as Australia's first Defence Cooperative Research Centre is uniquely equipped to deliver world-leading RAS-AI technologies to enable trusted and effective cooperation between humans and machines. The objective of the Centre is to improve the competitiveness, productivity, and sustainability of Australian industry by:

- developing highly self-sufficient and survivable systems
- developing highly self-determining and self-aware systems
- developing human-autonomy systems that are human and context aware
- increasing the speed to reach a deployable state for trusted autonomous systems
- increasing the scalability and reduce the cost of autonomous systems technology solutions
- educating in the ethics and legal aspects of autonomous systems
- advocating and shape national policy and regulations.

The Defence CRC Program was announced by the Australian Government as part of the Defence Industry Policy Statement in March 2016. The program forms a key element of the $730 million Next Generation Technologies Fund (NGTF) by establishing Defence CRCs to support Defence capabilities which align with NGTF priorities, and which are critical to Australia's defence and national security. TAS was launched on 6 July 2017 by the Hon Christopher Pyne MP, the former Minister for Defence Industry, and established operations as a not-for-profit public company in April 2018.

The Defence CRC program and its guidelines [4] were created by Defence, through lessons learned from the First Principles Review [5], the Miles Review [6], ACOLA report [7] into research translation, and the extensive business and legal experiences of key founders with respect to 'standard' CRCs. A few examples of differences with respect to 'standard' CRCs include:

- the Defence CRC program asserts ownership of IP to industry, rather than being held by the CRC, to facilitate transition while maintaining Defence use rights in all projects;
- foreground Intellectual Property (IP) arrangements are established for every project at formation and prior to approval, thereby avoiding the often complex and bitter negotiations at the end of a CRC project to decide who owns what IP;
- Defence CRCs offer the opportunity for Commonwealth-developed IP to transition into sovereign industry capability through every one of its projects;
- Being cognisant of the limitations of the traditional ASDEFCON contracting methodology (currently the subject of a Ministerial Review Process [8]), TAS has created a flexible, simple contracting methodology referred to as Master Funding Agreements (MFA) and related documents. This suite of documents allows an agile procurement and collaborative contracting process with Defence, industry and academia. Supported by TAS research guidance, industry lead(s) are empowered in their decision-making and may adapt arrangements so that occasional failure of a high-risk technical element does not drag down the whole project. Joint ventures arrangements, and other legal constructs are typically unsuited to achieve this.
- Defence CRCs are set up with the Commonwealth NGTF Grant managed by DISER [9] for DSTG, mirroring well-established CRC grant management practices and alleviating Defence from this burden [10].

The decision for a CRC-like model rather than some other arrangement, was based on the strong commercial and external technology drivers in RAS-AI and in acknowledgment of the long-term challenges experienced by the Department to deliver targeted, agile, risk-taking, non-competitive, fast engagement with a strategic view to pull forward game-changing technologies needed by the ADF. Defence's choice in creating an external entity to capture

external driving forces raised questions about how it should best be governed. The Department of Finance was clear on this point, mandating Defence CRC's be governed by their own board of directors, on the principle that it not gravitate towards a culture driven by Defence requirements; and focus on needs, maintain an appetite risk, and present to Defence never before conceived force structure opportunities. A similar decision to separate influences was enacted in the creation of US DARPA, and innovation is kept fresh through the assignment of DARPA leads on short-term loan from US industry, similar to industry leads for TAS projects. Yet, Defence retains significant influence over TAS, with the Chair appointed by the Minister for Defence Industry; an ex-CN on the board; multiple ex-DSTG employees in the Centre; quarterly and annual reporting of progress to DSTG; and many DSTG scientists and engineers actively engaged in projects.

The Centre continues to develop new projects today. All projects must offer real potential to be a "game-changer" in the areas covered by TAS for Defence and timed to inform critical decision points for major Defence projects. More than just a technological leap, TAS project proposals must offer the potential to "change the way the ADF fight". Finding such impact, as in all disruptive innovations is difficult, yet "you know a winner when you see it". A proposal may appear simple in retrospect once found, but this belies the complexity of reaching that point as is the case for most high-impact innovations. A key question that must be answered in the affirmative by senior ADF personnel before entering into a project is, "if we can do this and demonstrate it, would you buy it? (in principle)". The issue of how Defence can actually come good on that promise is discussed in a later section. Generating high impact requires taking risks, so we use the DARPA Heilmeier criteria [11] to assess what risks are worth taking in a project. To date, almost half of our project proposals have failed to progress past this stage for one reason or another, and that is a statistic to be expected. It is better to fail early as many of these proposals have done, rather than persist because of sunk costs.

An extensive external review of the Centre was called by DSTG in October 2019, 18 months after TAS had registered as a public company. The review was led by the ex-Chief Scientist of Australia, Prof Ian Chubb and conducted in February 2020. The report proposed two options and fifteen recommendations. The two options were for the Centre to: "deliver the existing work program and wind up"; or, "deliver enduring value to Defence and build sovereign capability". The panel's stated preference was for the second option, and this was accepted by Defence. The fifteen recommendations were made to support realization of the second option. The fulfillment of these recommendations is now materially complete. Further, noting "Robotics, Autonomous Systems and Artificial Intelligence" (RAS-AI) was announced [12] as a new sovereign industry capability priority (SICP) by the Defence Industry Minister in Aug 2021, the TAS position is further strengthened to support Australian industry in realising this challenge.

For researchers, TAS offers an avenue for successful transition of innovation IP and personnel into sovereign industry, to see their dream or star shot through to ADF impact. For industry, TAS offers simplified contractual instruments suited to innovation, speed to contract, builds credibility and ADF relationships. TAS imparts vision, demands ambition and maintains those expectations in delivery. TAS also provides a trusted technical advisory for

Defence, and champions the ethics, law, and regulation of RAS-AI through research, and support to industry.

VISION

Considering the need to continue to operate in A2/AD environments (such as underwater minefields) and achieve force multipliers, inspiration was found in Martin Libicki's notion of the 'the small and the many' [13],

> "Today, platforms rule the battlefield. In time, however, the large, the complex and the few, will have to yield to the small and the many. Systems composed of millions of sensors, emitters, microbots and miniprojectiles, will, in concert, be able to detect, track, target and land a weapon on any military object large enough to carry a human."

The TAS vision for 'smart, small and many RAS-AI', extends this by recognising the primacy of AI and was first presented publicly by Prof Jason Scholz at the December 2020 Australian Naval Institute's Goldrick Seminar [14]. Subsequently the US Chief of Naval Research, RADM Lorin Selby vision for 'smart, agile and many systems' was expressed by the in Nov 2021 [15]. The strength of this alignment is encouraging.

The smart, small and many exploits commercial advances in the Internet of Things (IoT), and includes: AI machine learning and agent systems; miniaturisation, in silicon of computing, sensors and communications; advanced manufacturing underpinned by digital engineering; new materials; and advances in power and energy. Minister for Defence, the Hon Peter Dutton in addressing the US chamber of commerce stated [16],

> "we need to pool our know-how and resources …" and that includes "capabilities which can be produced in bulk, more quickly and cheaply, and where their loss would be more tolerable, without significantly impacting our force posture. Here, I am referring to assets like autonomous craft and remotely piloted drones. Assets which can undertake multifaceted missions, be used in a swarm capacity, or teamed with traditional manned capabilities for force multiplier effects."

The 'smart and many', is addressed in the Australian concept for ubiquitous command and control (UC2) [17], which calls for "a similar and significant C2 capability on *every* platform" through decision software. That software supplies the individual 'cognitive' capabilities in each robot, the decision aids for human interaction, the social coordination, and management of these systems. This is necessary to achieve the "concert" of mass-scale extreme manoeuvre and robustness through humans and machines. This has been reinforced by the US more recently in their Mosaic Warfare concept [18]. A 'mosaic' is another term for social coordination and clipping together multiple simultaneous kill chains of robotic and human systems. UC2 offers the "agility" sought by the US CNO through the option of lesser or greater decentralization to empower those at 'the edge'.

The TAS vision is illustrated in figure 1 with a Naval emphasis. Potent crewed platforms capabilities are augmented through layers of RAS-AI. The number of layers shown is indicative only and relates to the 'logistics of autonomy' in recognition of the fact that to deploy low size, weight and power (SWaP) of the smallest systems at range requires they be carried by something larger, crewed or otherwise, or pre-deployed in advance of an operation as pop-up options. Small systems have the advantage of being able to hide and

avoid detection, and can possess surprising range and endurance, delivering significant effects both individually, and as organised collectives – achieving more than the sum of their parts. These won't always be swarms of identical systems, as diversity brings robustness and more manoeuvre options. Smaller systems may stand-in with larger platforms (crewed or uncrewed), providing deployed autonomous recharging, resupply, data exchange, etc. There are massive engineering cost savings to be had when crew are no longer required onboard, and entirely new concepts of operation possible. Not only will they be attritable, they may be cost effectively acquired in hundreds to tens of thousands.

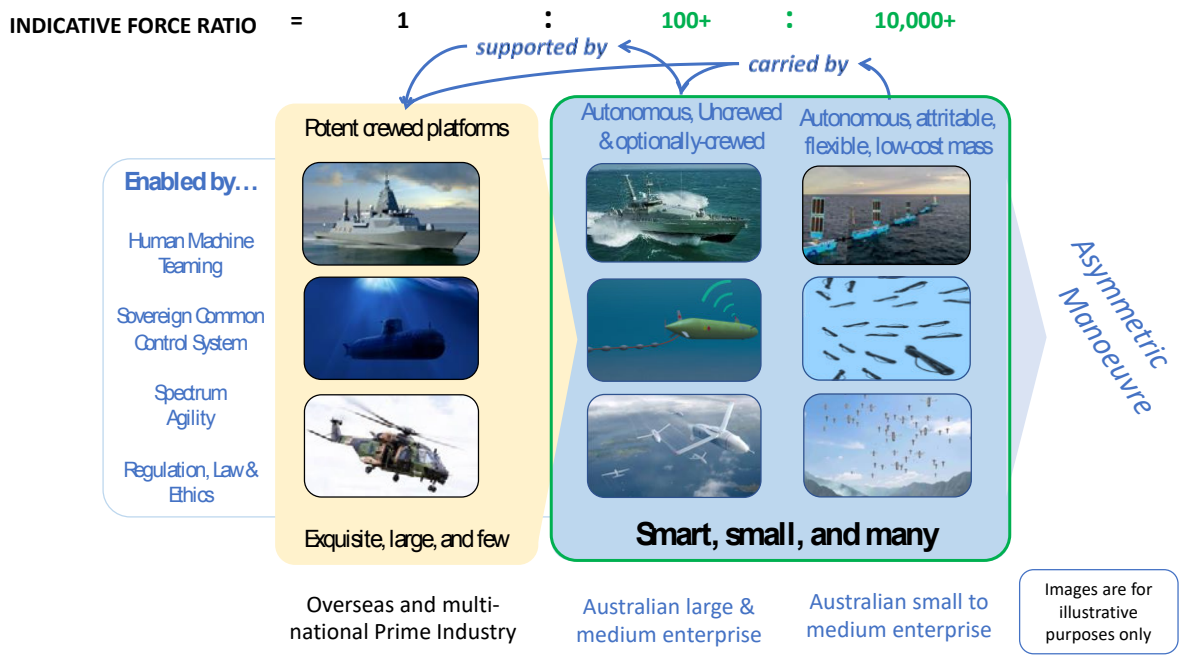


Figure 1. TAS-DCRC vision for smart, small and many RAS-AI systems.

ACHIEVING TRUST

Developing a technology 'agnostic' architecture to guide industry solutions will not guarantee a system can be deployed in Australia or overseas. Some potential technology solutions are simply not going to be trusted and thus certifiable by regulators, whereas others are inherently certifiable within given constraints, and it should be industry's problem to pose appropriate solutions. TAS has been assisting Australian industry with this through the assessment of appropriate technologies, developing new verification schemes, as well as investing in regulatory assurance, law and ethics of RAS-AI. The funding for TAS activities addressing these problems is one of the largest in the world.

In some cases, legal constraints are built into the AI. One such example is the TAS-DCRC Justified Unmanned Aerial Systems Effects project. The technologies developed in this project, have implemented the 'Minimally-just AI' or MinAI [19] concept for autonomous weapon systems, recognising protected symbols and objects in order to prevent attack, as a kind of machine-initiated 'safety catch'. Athena AI is a trusted AI product, assessed by International Weapons Review in Australia, military legal officers and military ethicists to define a suitable data assurance and test methodology for AI vision and decision support certification. The inbuilt decision support tools embody legal and rules of engagement considerations where applicable and are directly applicable to the maritime environment.

Verification of AI-based systems using formal methods, including mathematical logics, and model-based simulation using digital twins are included in the approaches taken by industry. Further complexities arise for socially coordinated systems and where more than one high trust component is added to a system. Techniques suited to certification of individual systems can lose that trust if systems interact in parallel with other systems, such as a team of autonomous mine-countermeasures vessels. TAS projects are addressing these issues.

One may ask, what does it mean to trust in smart, small and many systems? Shifting the human out of the platform and out of the piloting role reduces many of the well-known risks to human life, but it also creates new risks, and shifts other risks elsewhere. For example, small and many systems are more exposed to capture, repurposing, tamper and reverse engineering, so consideration to these security concerns must be addressed. Beyond more well understood matters of 'trust as reliability' [20] or security, what foundations do we need if we have both 'smart' and 'many' systems? We may view any form of automation to which humans attribute intent, be considered 'smart' or artificially intelligent. That is, any RAS that has a goal, or is purposeful in its actions in the mind of an observer. The engineering opportunity that this 'intentional stance' [21] presents is to extend the design of robots to include not only the physical and functional (or design / architecture) levels, but cognitive (or thinking) and social (or group) levels, making the technical system better match human psychology such as: automated object, situation and impact assessments, behavioural (cognitive) routines, language recognition and reasoning, multi-agent systems, etc. These cognitive (thinking) technical systems will contribute to the Navy RAS-AI Strategy to achieve the 'Thinking Navy' ubiquitous at the scale needed in future.

Trust viewed as integrity matters here too in engineering cognitive and social technologies, the trust humans place in RAS-AI must be warranted [22] and the 'social contract' between human and machine actors made explicit. In future, an operator may express high-level mission goals and constraints to a 'market pool' of available RAS-AI, which in turn respond with offers of courses of actions to support those goals, given situation awareness. These offers would be analysed (with AI decision aids in support) and decisions made to accept and reject various machine offers, thereby socially binding human mission command to machine control and execution [23]. If such a system faces challenges in mission execution, processes ensue locally or otherwise in an ongoing attempt to reach 'achievable intent'. So, the UC2 concept advocates social coordination as a 'contract' process [24], represented in this example using the language of 'offer', 'accept', 'reject' from legal agreements, bringing it close to common law and integrable in future with the Defence Force Discipline Act [25], though many other technical alternatives also exist. It is equally important to recognise that tight and proprietary systems integration of various RAS-AI sensors, AI-aided human decision-makers (combat and mission systems) and RAS-AI effectors that make up kill chains, *may no longer be necessary* if instead we have these loose-coupled formal electronic contract process, and common language that is human and machine understandable.

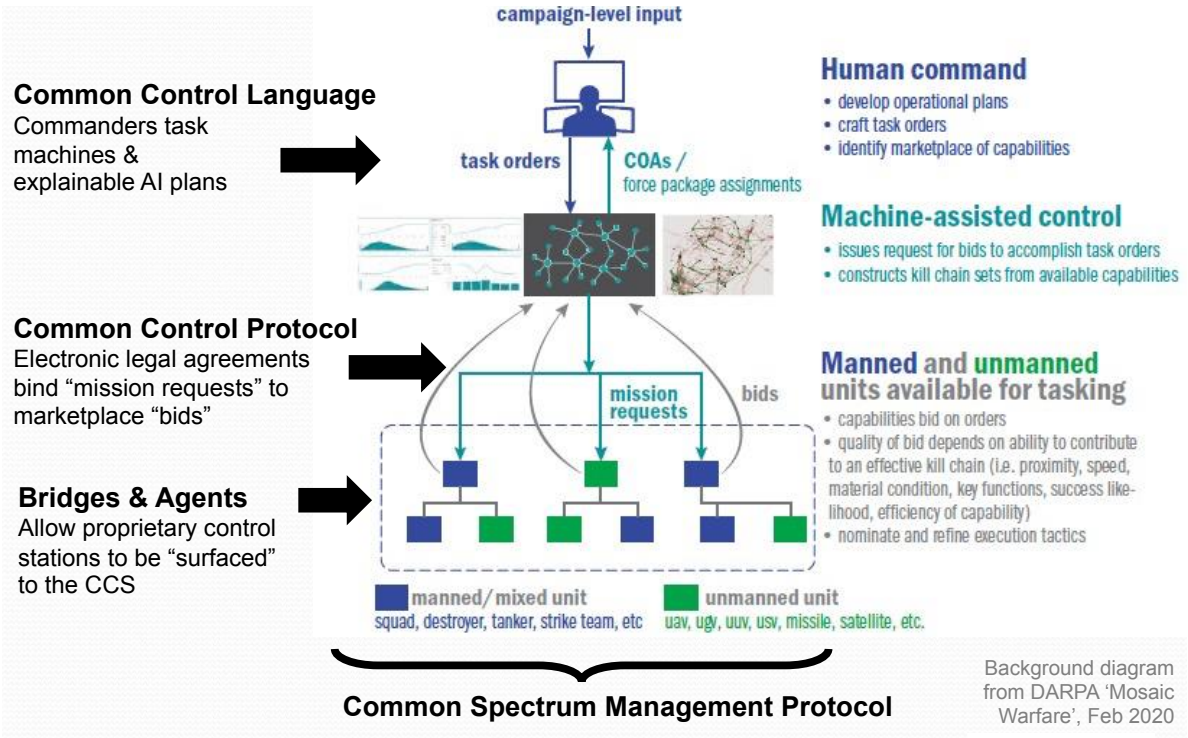


Figure 2. Mapping of sovereign CCS technological solutions (black) onto the US Mosaic Warfare concept.

The whole technical system to achieve this, was also signalled in the Navy RAS-AI Strategy, for a sovereign common control system (CCS). Given US initiatives, it will be important for a sovereign Australian CCS to operate in an AUKUS context. Fortunately, the US have embraced this thinking in their Mosaic Warfare concept [26] introduced earlier. Figure 2 illustrates how solutions developed by TAS and DSTG map to the mosaic warfare concept.

In regulatory areas, TAS led development of the Trust and Safety chapter in the 2022 Australian Robotics Roadmap [27]; drafted an Australian Code of Practice for the design, construction, survey and operation of autonomous and remotely operated vessels [28]; is developing a maritime COLREGS framework for RAS-AI; an airspace Detect and Avoid (DAA) framework for RAS-AI; and has delivered a Method for Ethical AI in Defence [29]. However, significant reform continues to be needed in the sector. Our national civil regulatory authorities are separated according to physics (i.e. AMSA for the sea surface, CASA for the air, ACMA for the electromagnetic spectrum, various for land, no-one for space, no-one for undersea, etc); each has vastly different methods and means for compliance which for RAS-AI usually requires an exemption process; and are legislatively founded on the assumption of human control of vehicles. Perhaps in future, a new domain-independent regulator, which might be called the Australian Autonomous Systems Safety Authority (AASSA), would focus on the safety of cognitive and social engineered machines, including their behavioural constraints.

The ethics and legal compliance of these systems also cannot be ignored. A Method for Ethical AI in Defence, developed by TAS with DSTG and Plan Jericho, is recognised by CASG as best practice, and provides a practical guide for industry. The framework requires developers of RAS-AI systems to identify responsibility, governance, trust, law and traceability of systems through an AI Ethics Checklist and an Ethical AI Risk Matrix to

describe identified risks and proposed treatment. For larger programs is a data item descriptor (DID) for contractors to develop a formal Legal, Ethical and Assurance Program Plan (LEAPP) to be included in project documentation for AI programs where an ethical risk assessment is above a certain threshold. The LEAPP includes legal considerations in anticipation of an Article 36 review of all new means and methods of warfare as per Australia's international commitments [30].

INDUSTRY AND ACQUISITION

To realise this vision, it is critical for Defence to find ways to better engage and intake innovative products and services from Australia's industry base. Overseas Primes are well understood by Defence, but procurement rules continue to stifle innovation with the lessons of the mid 2010's mentioned earlier still not learned, with the result that Defence struggles to exploit what SMEs have to offer. According to McCrindle [31]:

> Australia has always been an entrepreneurial nation, with small business the backbone of the economy and the labour force. The Australian spirit of independence, a DIY attitude and the courage to give things a go are strongly demonstrated in these latest business statistics.
>
> Of all Australian businesses, 88% employ 4 people or less.
>
> The tough economic times and the terrain in which small businesses operate is having an impact, however, with only half (54%) of new businesses surviving 4 years in operation. For many Australians, the entrepreneurial dream is still alive but as demonstrated by the survival rates of new businesses, without better support, only a minority will achieve success.

Figure 1 illustrates our suggested areas for overseas Prime industry, and sovereign medium and small enterprises in developing smart, small and many systems; where literally the smaller and simpler attritable systems are developed by smaller companies. Part of the help these small companies need in Australia is shared infrastructure, in effect the support of a common 'RAS-AI Factory' for hardware, firmware and software rapid development and upscaling in country. Included in this, improved access to semiconductor and packaging electronic design automation (EDA) tools to connect chip designers to chip foundries at low cost is needed for SMEs, and digital engineering infrastructure and tools to reduce the cost and time needed to become competitive. This might in future be provided by the Commonwealth NGTF program through TAS for trusted sovereign industry and academic participants to ensure defence maintains access to ready IP, realise economies of collective scale and reuse, and provide guaranteed pipeline integrity and interface standards with the Defence AI Centre.

Naval digital acquisition for RAS-AI will be necessary to transfer these innovations seamlessly into CASG. By industry employing the 'digital trinity' [32] of digital engineering, agile software development methods, and open systems standards for physical, functional, cognitive (AI) and social interfaces, digital acquisition may replace, automate, and truncate real-world activities based on authoritative virtualization or automation in the digital world. As the USAF acquisition secretary Darlene Costello says, "Digital Acquisition holds the key to unleashing the speed and agility we need to field capability at the tempo required to win in a future conflict with a peer competitor."

In a presentation to Airforce [33], we have noted that to 'land' these 'constructive disruptions' [34] as operational capability for Navy, a range of reforms relevant to industry are needed:

- CASG reward capability managers to take risks for high payoff and speed
- New "disruptive procurement" to replace ASDEFCON standard procurement for Sovereign Industry Capability Priorities (SICP)
- Prefer sole source for SICP projects in Defence
- Require that innovations that were contracted by Defence and successful, be acquired - through the firms that created them
- Encourage SME consortiums to compete with Prime system integrators (eg Army C4 Edge program)
- Plan continuous growth for chosen small firms that deliver, to become sovereign medium firms to fill the dearth of mid-sized firms in Australia
- Reward inventors for moving Commonwealth created IP to sovereign industry
- Shift to digital acquisition

At the stage of writing the results of the Defence innovation review [35] led by David Peever are yet to be announced, however, we believe the above list of reforms would be assistive.

TAS currently holds a portfolio of 21 projects [36] and has expanded to accommodate them. The first 6 were NGTF funded, the remainder are mostly directly funded by Defence, with several funded by Queensland government. Some public announced projects include: mine countermeasures in a day; long-range, low cost, autonomous and teaming station-keeping stratospheric balloons [37]; large-scale autonomous spectrum management agents; an intelligent drogue to develop and demonstrate a novel Autonomous Underwater Vessel (AUV) launch and recovery system; and a patrol boat autonomy trial. Several projects have reached completion. The technologies developed in one TAS project alone, which cannot be named publicly as yet, has successfully won a Defence tender bid worth over $35m. Several other projects have also won significant ongoing Defence funding. It is too early to realise the big outcomes expected over the next 2-3 years, but progress so far demonstrates the value of TAS and the Defence CRC model to deliver enduring value to Defence, build sovereign capability, and accelerate maritime trusted autonomous systems.

CONCLUSIONS

Disruptive innovations in the way of 'smart, small and many' (cheap) systems are coming and are set to be a game-changing opportunity for Navy. Significant technological challenges remain to realise this future, including the need for a sovereign common control system for trusted adaptation of kill chains lawfully, at scale.

But perhaps the greatest challenge of all is how Navy can land such innovations into capability development group and smooth their transition into service in the near term. We have shown why TAS is uniquely placed to support the RAS-AI Strategy for Navy, what we are doing to achieve trust in autonomous systems including assurance, law and ethics initiatives; and some strategies for industry alignment, growth and support into the future so that Navy can fight and win at sea.

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Introducing Autonomous Systems into Tropical Marine Operations: Case Study into the Australian Institute of Marine Science's Journey

Authors: Melanie Olsen, Australian Institute of Marine Science (AIMS) (m.olsen@aims.gov.au); David Mead, AIMS (d.mead@aims.gov.au); Scott Bainbridge, AIMS (s.bainbridge@aims.gov.au); and Dr. Jonathan Kok, AIMS (j.kok@aims.gov.au).

INTRODUCTION

As Australia's tropical marine research agency, the Australian Institute of Marine Science (AIMS) (Ref 1) conducts research across some of the harshest, most remote marine environments in the world. Tropical Australia is a location of amazing opportunity but also of great challenges, including that of climate change. The need to understand and respond to change is requiring AIMS to expand both the spatial and temporal scale of its monitoring and scientific work across northern Australia. This has led AIMS on a journey of augmenting our world-class diver led operations with uncrewed marine technologies to boost our range and capability.

While Australia is leading the way with small, uncrewed maritime systems development, the complexity of transitioning these systems into operational systems has been a journey of innovation and lessons learnt. From establishing tropical autonomous systems test ranges through AIMS' ReefWorks, to working with regulators and stakeholders to streamline marine autonomous systems assurance, AIMS is on a journey to establish a sustainable autonomous marine systems industry in Australia. A sovereign autonomous systems industry that can meet the diverse needs of Australian users, Government and Industry stakeholders will enable Australia to keep up with the growing world and respond to the climate and economic challenges facing tropical Australia.

In this paper we will describe AIMS' journey to date in introducing autonomous systems into our operations, and some of the lessons learnt along the way. AIMS has developed, tested and introduced several autonomous platforms and modelled how to best deploy and operationalise these systems, based on how they will contribute to AIMS science outcomes. A major focus now is on developing a marine test environment for autonomous systems as a way of evolving the regulatory framework and facilitating industry participation. While the journey is not complete, this paper will share some of the learnings so far.

TROPICAL AUSTRALIA MONITORING

Australia's tropical oceans are vast and diverse, with the Great Barrier Reef alone encompassing some 3000 reefs over an area the size of Italy. Its shorelines cover some of Australia's most remote and difficult to access country. Its low population is characterised by a rich culture of diverse First Nations people.

AIMS conducts marine monitoring and research activities throughout tropical Australia. AIMS is a Commonwealth statutory authority providing large-scale, long-term and world-class research that helps governments, industry and the wider community to make informed decisions about the management of Australia's marine estate. AIMS works across tropical

Australia from the Great Barrier Reef in the East through to the Torres Straits, across the Northern Territory, and down to Ningaloo Reef in Western Australia or some 6,000 kilometres of coastline.

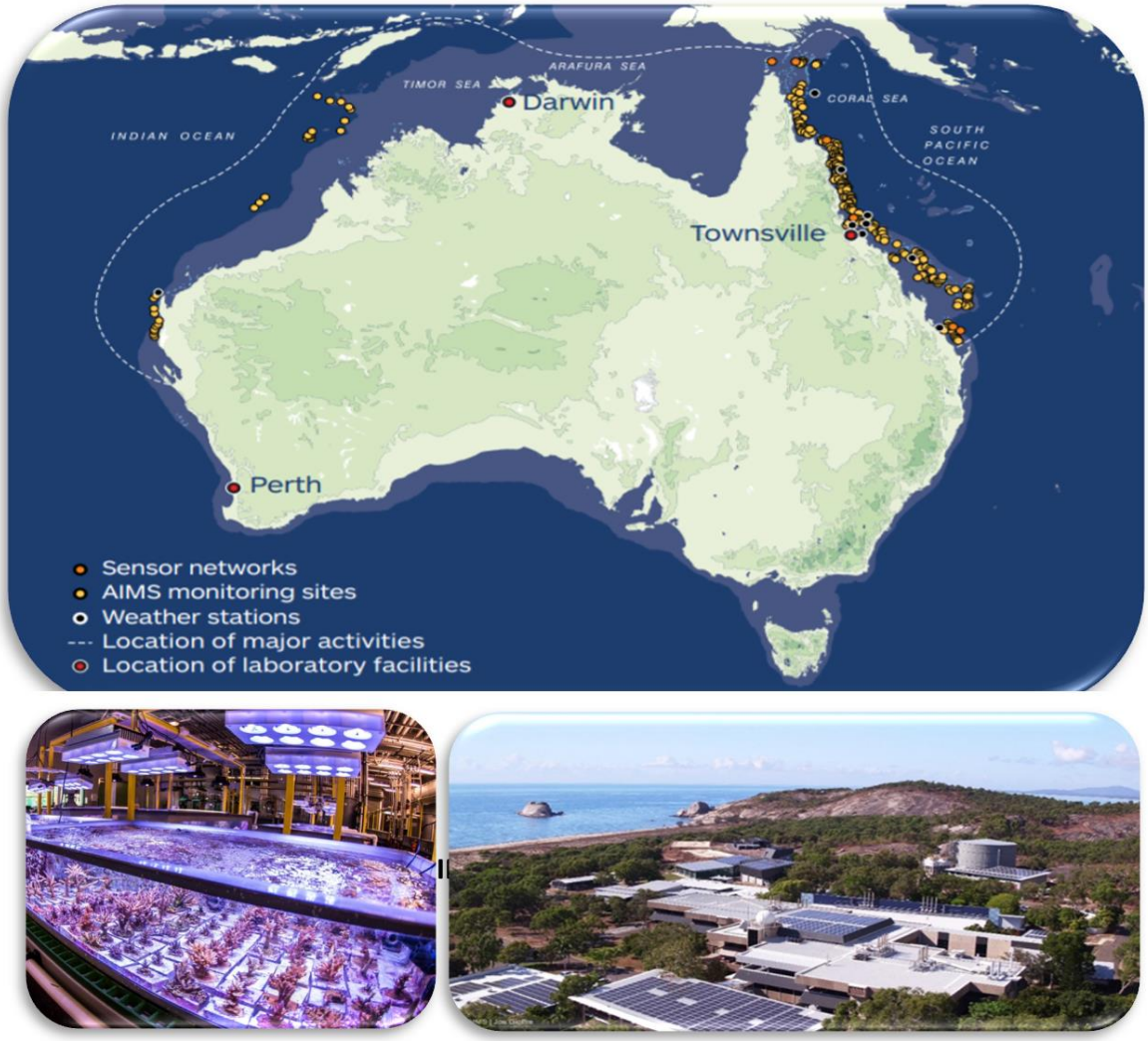


Figure 1. Australian Institute of Marine Science Monitoring Sites in Tropical Australia (Bottom Left – the National Sea Simulator, Bottom Right: AIMS HQ near Townsville Qld)

Tropical marine Australia supports a $81 billion blue economy (and 340,000 jobs) (Ref 2), yet the many of the ecosystems that support this industry are under threat from a range of stressors including climate change. AIMS has world class capability to monitor the status and trends of ecosystems (the AIMS reef monitoring program is the longest continuous monitoring program in the world (Ref 3)), with this extending to understanding and monitoring the processes that drive observed changes. Over the last 10 years, AIMS has progressively increased its R&D focus on providing solutions to opportunities and threats including climate change. The rapidly changing environment means our monitoring program needs to expand to cover more ground more efficiently, but at a price point that can scale.

Traditionally AIMS' marine monitoring methods have focused on deployed in-situ infrastructure and diver-led operations. However, marine predators such as crocodiles, jellyfish and sharks coupled with the remote, vast, harsh tropical ocean expanse means a human-machine teaming approach is essential to meet our growing monitoring demands.

AIMS has taken charge of its mission by championing technology development, building world class infrastructure in the tropics, conducting sustainable routine at-sea operations, and working with partners to develop standardised, safe approaches for marine observations in tropical Australia.

ENHANCING OUR CAPABILITY – STRATEGY 2025

In 2018, AIMS adopted *Strategy-2025* (Ref 4) which guides our research and investment in tropical marine science to inform decision-making for government and industry to 2025. AIMS set an Enhanced Capability target to employ technology to double our yearly information output at half the unit cost in half the time, an eight-fold increase in effectiveness. By deploying linked autonomous systems and automated analysis, AIMS seeks to increase the productivity of our teams and accelerate the conversion of data into information products and insights that will drive impact and keep pace with growing future needs.



The solution is to adopt more competitive methods to deliver world leading tropical coral reef research to a wider stakeholder audience. By deploying technology that others can utilise and removing the limitation that it must be collected and analysed by highly skilled specialists, others can be empowered to be part of the solution with a significant constraint removed.

SYSTEM OF SYSTEMS APPROACH

To introduce technology into operations sustainably, the entire monitoring system workflow must be addressed. Autonomous systems allow an influx of data to be collected, but the associated monitoring design strategies, data workflows, decisions support tools, products and supporting capabilities need to be revised at the same time. The purpose of introducing autonomous systems was to meet our *Strategy-2025* Capability Target while expanding to meet our growing stakeholder monitoring needs. It was not to replace our diver-based operations – both techniques need to complement each other.

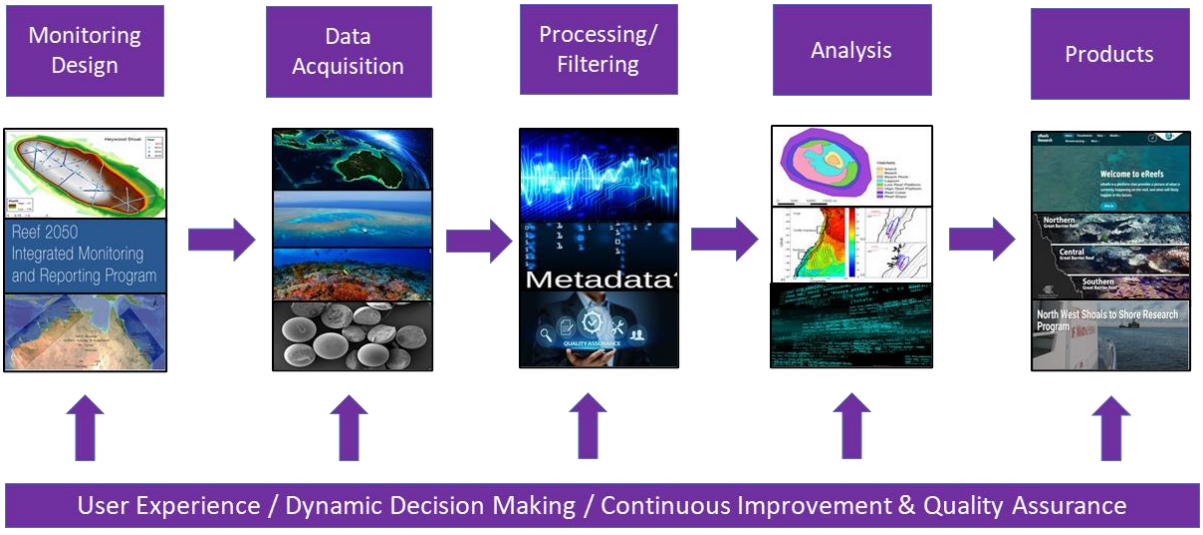


Figure 2. System of Systems Approach to Autonomous Systems Operations

AIMS invested in Operations Research with the Queensland University of Technology (QUT) (Ref 5) to create an operational configuration and costs model for our at-sea operations. This enabled AIMS to understand the overall cost implications and optimised loadouts of human and autonomous systems-based monitoring operations. Both techniques have different logistics and support needs which needed to be carefully worked through if AIMS is to improve the efficiency of its at-sea operations. There is no point replacing a team of biologists with the same sized team of programmers, any technology needs to add and create value.

In addition, a toolbox approach was taken. The vast geographical coverage needs coupled with diverse science needs meant AIMS needed a selection of autonomous tools that could adapt to answer different science questions at scale. The operations research model enabled AIMS to make informed decisions in prioritising the development and acquisition of AIMS' technology transformation program.

A LAYERED OBSERVATION SYSTEM

The three traits that underpin AIMS' autonomous systems technology program are scalability, adaptability and sustainability. These are achieved through a layered observation system approach.

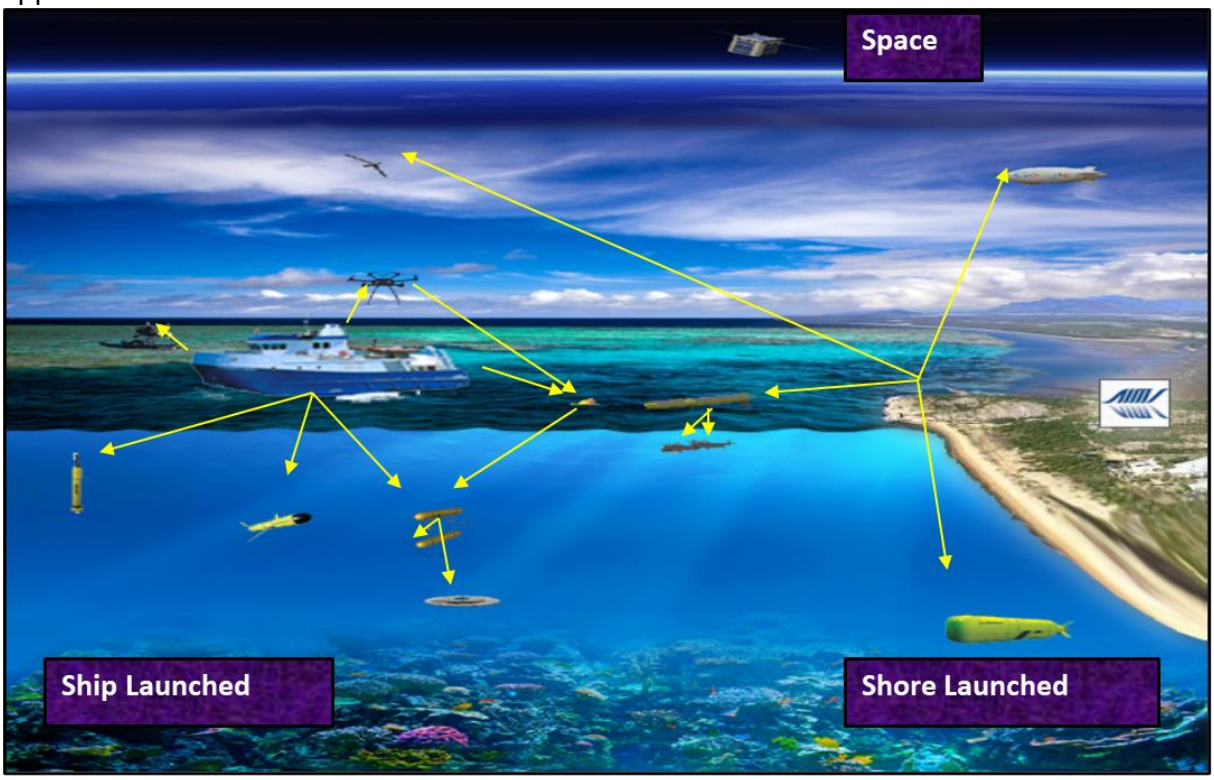


Figure 3. Layered Observation System

The ideal end-state is an efficient human-machine team working harmoniously to deliver real-time data to artificially intelligent decision support tools and information translation systems, in order to inform decision makers and researchers in a timely and accurate manner. To evolve to this end-state, AIMS has commenced a journey of trialling and integrating technologies to determine their applicability to AIMS' use cases.

High Altitude and Space Based Observations

High altitude and space based autonomous technologies provide lower resolution information at a large geographical scale. Disadvantages include the impact of atmospheric effects such as cloud cover and distortion into the water column. However, AIMS has incorporated high resolution satellite imagery into its monitoring portfolio with use cases from benthic habitat mapping through to water quality observations. AIMS also investigates new sensors as they are commissioned such as hyperspectral and synthetic aperture radar, as they have applicability to specific science questions.

At a synoptic level, high altitude and satellite data provide up to date base maps, show areas that have undergone significant change (such as from a cyclone) and are used to inform and plan more detailed on reef survey work. There is potential for new satellites, using hyperspectral or synthetic aperture radar, to provide data more akin to on-water methods.

Shore Launched Autonomous Systems Observations

The ability to acquire observations without the expense of a large research vessel greatly increases the scalability of marine autonomous systems. Long-range autonomous systems provide this capability. As an example, AIMS worked with Boeing subsidiary Liquid Robotics to evaluate the potential of a long-range autonomous surface vessel, the Wave Glider (Ref 6) in performing oceanographic monitoring across the North-West Shelf of Western Australia and on the Great Barrier Reef. Whilst the technology is clearly capable and available, the cost benefit for AIMS use cases was not viable and led AIMS to focus on ship deployed solutions.

Ship Launched Autonomous Systems Observations

AIMS' traditional monitoring methodology focuses on ship-based observations. With two large research ships (and one long term charter vessel from Riverside Marine, Ref 7) conducting 24/7 operations from Exmouth to the North-West Shelf, the Torres Strait to the Keppel Islands, and many short-range vessels, AIMS operations is built around supporting crewed in-situ observations. Therefore, AIMS' initial focus for integrating autonomous systems technologies into its observation system was on ship-launched technologies because the logistics and support infrastructure overheads are mostly already in place.

AIMS has invested in exploring a variety of ship launched capabilities from commercial-off-the-shelf drones with custom (such as hyperspectral and water sampling) payloads, to autonomous surface vessels such as the Marine Advanced Robotics WAM-V (Ref 8) with QUT, to developing its own suite of underwater coral survey capabilities through the AIMS ReefScan system (Ref 9). Below we will discuss in more detail some highlights of our ship launched/short-range autonomous systems journey.

AIMS SHIP LAUNCHED AUTONOMOUS SYSTEMS JOURNEY

AIMS' need for a layered toolbox approach coupled with a focus on short range, ship launched systems led to the design of AIMS' ReefScan coral survey technology suite. ReefScan is a modular, scalable, complete solution for tropical marine monitoring where researchers choose the sensor, the platform, the autonomy and the smarts to deliver the capability they require. Development has commenced with some aspects operational and others still requiring further investment.

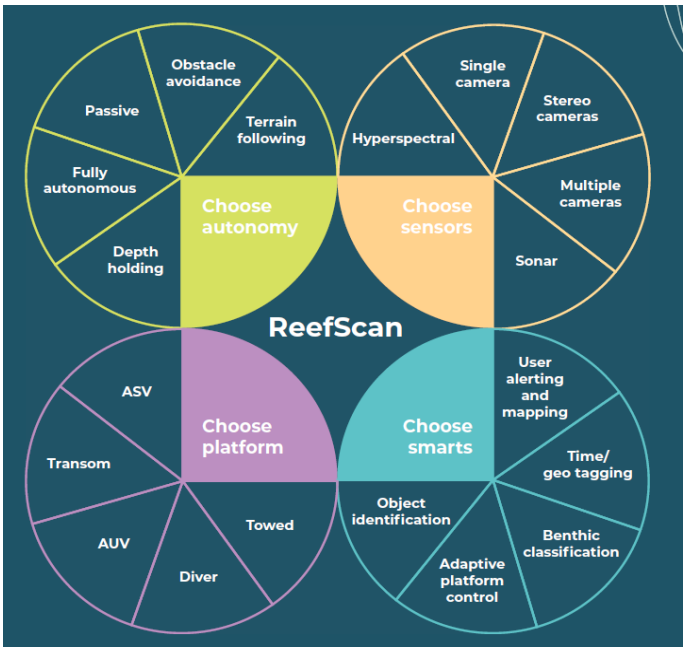


Figure 4. ReefScan Capability

Two of the more commonly deployed ReefScan configurations are aerial drones (Ref 10) and the Coral Autonomous Underwater Vehicle (CoralAUV) (Ref 11), both deployed for coral reef monitoring use cases.

ReefScan Aerial Drones

Aerial imagery (including hyperspectral imagery) coupled with machine learning enabled processing workflows is a powerful tool for understanding changes in the reef environment. To date, AIMS has focused on the 400 – 1000nm spectrum through off-the-shelf Headwall Photonics (Ref 12) hyperspectral cameras and red-green-blue cameras coupled with readily available drones. AIMS made the decision to focus its investment on applying the technology routinely in the field rather than develop new sensors or aerial platforms. Niche learnings come from applying drones at-sea, such as the relevance of "return to home" safety functions when the ship is never stationary and significant electronics interference from the vessel's infrastructure.



Figure 5. DJI M600 Drone on the *RV Cape Ferguson*

Similarly on the mission planning and data translation side, AIMS focused on developing flight parameters to get the most out of commercial tools such as DroneDeploy (Ref 13) and Agisoft Metashape (Ref 14).

Hyperspectral imagery data processing is more niche, especially with the application of hyperspectral imaging technology at a relatively close range (when compared to space-based satellite observations) being an evolving field in tropical marine science. AIMS focused on in-house developed data tools building on learnings from partners such as the Bermuda Institute of Ocean Sciences (Ref 15) and the Max Planck Institute for Marine Microbiology (Ref 16), in understanding how hyperspectral imagery can advance tropical marine research.

It is expected that hyperspectral imagery will continue to grow as a tool of choice as researchers uncover new biological and oceanographic learnings from this extended dataset, allowing for crucial applications such as coral bleaching prediction, coral health monitoring, understanding changes in water quality and harmful algal bloom detection.

ReefScan CoralAUV

The vast majority of AIMS coral reef observations have traditionally been acquired through diver-based methods. However, diver-based methods are not readily scalable, particularly to areas with marine predators and in waters below 20m depth. AIMS discussed the potential for an autonomous underwater vehicle (AUV) to meet the niche high resolution coral reef survey use case over 5 years ago with marine science technologists across Australia. The need to navigate contours in close proximity to the coral reef, at scale, was quite unique, with no obvious solution available on the market. AIMS also looked internationally and worked with Greensea Systems Incorporated (Ref 17) in the USA to develop a concept demonstrator. Subsequently, AIMS partnered with QUT and developed the ReefScan CoralAUV.



Figure 6. ReefScan CoralAUV

The CoralAUV uses adaptive navigation techniques to manoeuvre a scientific payload across a reef mission profile. Missions range from simple transects, to area mapping, to contour following. The reef is complex and fragile, leading to a strong focus on collision avoidance. However, the CoralAUV must also scale across tropical Australia. This means the on-board navigation and sensing systems must be at a scalable price point.

AIMS' CoralAUV has been a learning experience in understanding the logistics, regulatory requirements, risks, training requirements and operating procedures needed to efficiently deploy autonomous systems routinely. For example, to optimise the CoralAUV's test and evaluation program, AIMS and QUT collaborated to build a virtual environment to test the Coral AUV's guidance, navigation and control algorithms prior to at-sea testing.

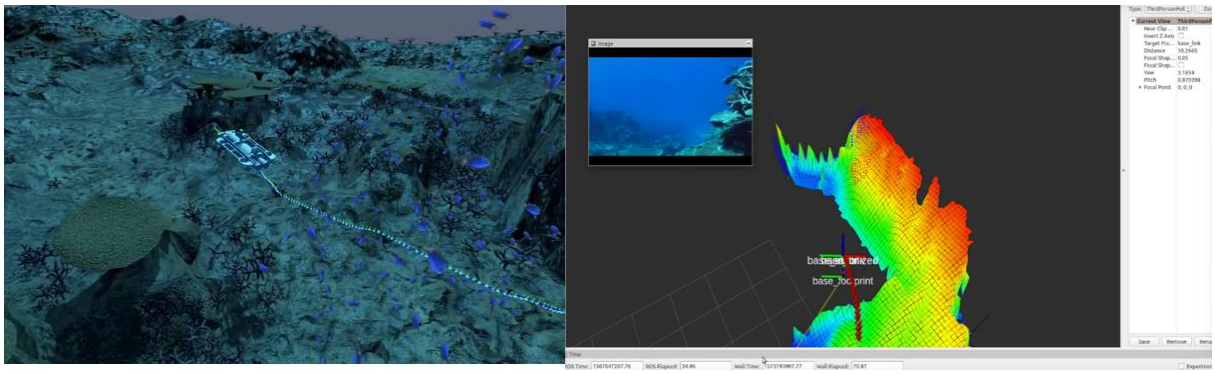


Figure 7. Coral AUV Modelling and Simulation Environment (a collaboration with QUT)

Testing autonomous systems at sea is expensive and requires a methodical approach with a skilled team. AIMS has the ideal mix of experienced marine operations personnel & infrastructure coupled with ready access to the tropical ocean. This led AIMS down a path to

open its doors to other Australian marine autonomous systems innovators through ReefWorks (Ref 18) – Australia's tropical marine technology test range.

REEFWORKS

Prior to ReefWorks, Australia did not have a capability to conduct routine, repetitive test and evaluation of marine technologies, especially autonomous systems, in a tropical marine environment. This capability is essential for the certification and commissioning of these systems into operational service.

ReefWorks will deliver development, design and testing services for technologies, especially autonomous and uncrewed systems across all technology readiness levels (concept to mature commercial systems) for civilian and Defence marine applications. ReefWorks leverages AIMS' existing infrastructures such as the National Sea Simulator (Ref 19), a world-leading experimental aquarium facility for payload testing and at-sea infrastructure to support test ranges. Test ranges represent different environments such as the turbid littoral waters adjacent from AIMS Marine Operations to on-reef ranges, linked by autonomous corridors to test the performance of longer-range vessels and vehicles. Given that much of the test and evaluation program of autonomous systems is conducted in the digital realm, ReefWorks' vision is to be underpinned by a digital twin of its test ranges, using the real-time data streams of in-situ instrumentation.

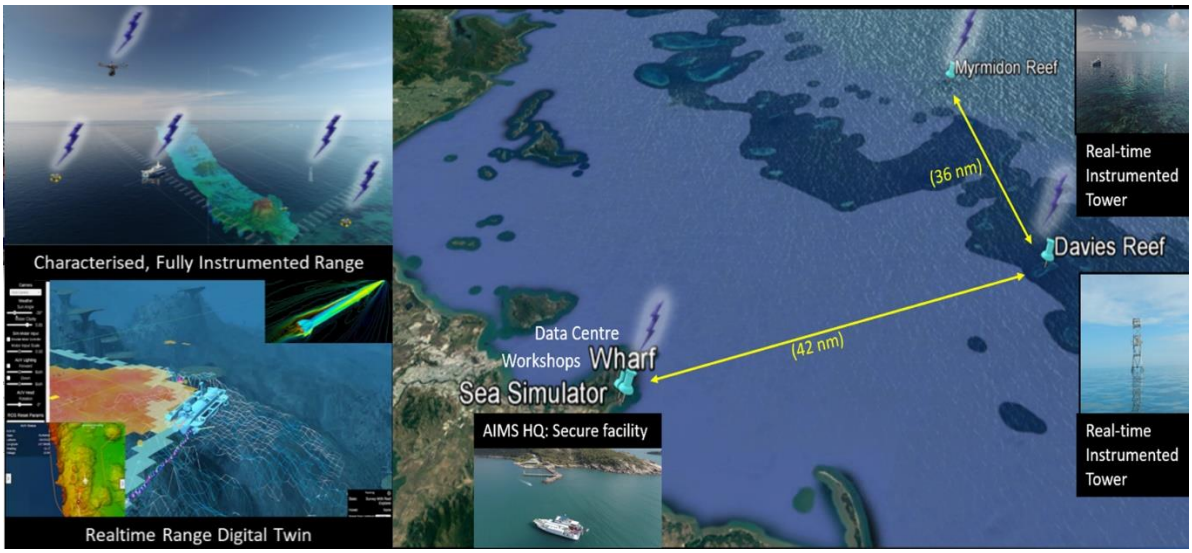


Figure 8. ReefWorks – Australia's Tropical Marine Technology Test Range

The Queensland Government and AIMS invested in launching ReefWorks' Foundation Stage in late 2021. This is a two-year work program to implement modest capital upgrades and expand AIMS' capacity to facilitate test and evaluation activities for Australia's marine technology and autonomous systems innovators.

REGULATION

There are many regulatory requirements for marine autonomous systems innovators to consider, yet legislation predates autonomous systems. In most cases, guidance is lagging and so AIMS focused on building extensive stakeholder networks with regulators including the Civil Aviation Safety Authority, Australian Maritime Safety Authority, Great Barrier Reef Marine Park Authority and Marine Safety Queensland. AIMS is also working with autonomous systems

communities including the Trusted Autonomous Systems Defence Cooperative Research Centre (TASDCRC) (Ref 20) and the Australian Association of Uncrewed Systems (AAUS) (Ref 21). AIMS also used its extensive Traditional Owner relationships through its Indigenous Partnerships Program (Ref 22) to ensure Traditional Owners needs were considered.

The TASDCRC is championing marine assurance across land, sea and air domains for autonomous systems, such as releasing a consultative Australian Code of Practice draft for the design, construction, survey, and operation for autonomous & remotely operated vessels (Ref 23). AIMS supports the TASDCRC's regulatory evolution initiatives and is also working with industry and regulators through a Business Research Innovation Initiative Challenge to streamline the assurance of marine autonomous systems (Ref 24). ReefWorks aims to provide a safe testing ground to assist innovators establish the test and evaluation evidence needed to support the regulatory process as Australia's legislation evolves to manage autonomous systems.

LESSONS LEARNT – A SUMMARY

From the journey so far, lessons learnt include:

- Think end to end – how will autonomous systems fit within existing processes, workflows and structures, what else is needed to make them work, how will their data fit into existing data systems, where is standardisation required, what skillsets and resources are needed and how do we evolve from where we are now to where we need to be.
- Think value – shiny stuff is exciting, but systems need to deliver and create value for the people involved, for the organisation and for their clients.
- What do we lose – if we take the human out of the workflow what do we lose and what can we do to compensate.
- Regulation is key – moving to operational systems means compliance with regulations, even if these are still evolving.
- Trust is everything – we need to build and demonstrate trust, trust in the function of autonomous systems, trust in their safety and fitness for purpose, trust in the data they collect and how we embed them into our human based frameworks.
- Community collaboration is key – most of the autonomous systems issues facing individual agencies are shared problems requiring interdisciplinary input and so, as a community, we need to work together to build the critical mass needed to move the marine autonomous systems industry forward.

ESTABLISHING A SUSTAINABLE MARINE AUTONOMOUS SYSTEMS SECTOR

Marine autonomous systems are a powerful enabler for addressing national tropical marine environment challenges and have the potential to boost Australia's sovereign technology development and manufacturing capability. A sustainable marine autonomous systems sector will be a transformational capability for Australia's marine domains. However, embracing these innovative technologies means organisations need to implement an acquisition cycle that allows for a tolerance of risk, and enables rapid, evolutionary change. AIMS is on this journey and is working to achieve a state where marine stakeholders from Traditional Owners to researchers can efficiently deploy marine autonomous systems at scale, to better understand our changing tropical marine environment and share these learnings nation-wide.

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AUSTRALIAN DEFENCE OPPORTUNITIES FOR UN-CREWED VESSELS

Tim Speer
Design Development Manager, Austal Ships, Australia
tims@austal.com

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OVERVIEW

1. Introduction
2. The International LUSV Landscape
3. The Australian Landscape
4. Patrol Boat Autonomy Trial
    a. Project Objectives
    b. Vessel Modifications
    c. Vessel Trials
    d. The Future
5. Conclusions
6. References

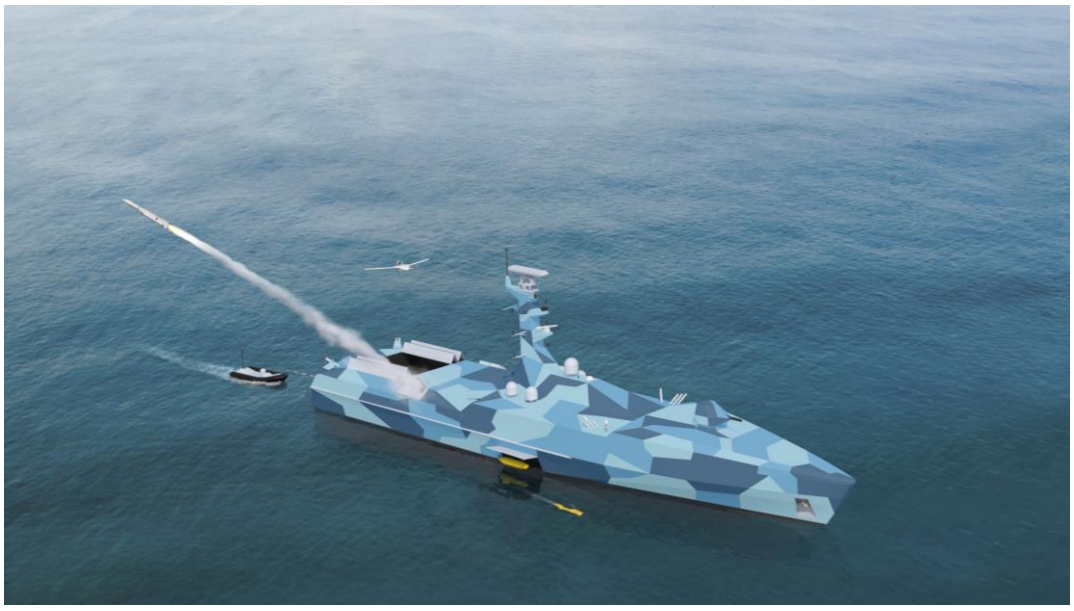


Figure 1: The potential mission capabilities of Large Autonomous Un-crewed Vessels in the near and far term are exciting for the industry and the war fighter

1. INTRODUCTION

Autonomous operation of surface vessels is developing at a rapid rate. There is a time sensitive opportunity for the Australian Defence Industry to develop world leading Large Uncrewed Surface Vessel (LUSV) solutions, before this technology leadership opportunity is lost to competing organisations outside Australia.

In the Royal Australian Navy (RAN) Robotics, Autonomous Systems and Artificial Intelligence (RAS-AI) Strategy 2040, VADM Michael Noonan states, "The race in autonomous warfare has already begun. Doing nothing, or waiting for allies to solve our requirements, is not an option." Austal sees a genuine and credible opportunity to work with the Commonwealth, Australian Industry, and Research Partners to develop Australian LUSV solutions for the RAN.

Austal has been delivering centralised and remote, monitoring and control of machinery systems for a long time. This same technology solution supports remote and autonomous control of large complex platforms in remote locations. Austal is partnered with L3HARRIS ASV in the US and Australia to support the autonomous navigation of a variety of different platforms. The focus of Austal's work in Australia is to learn by testing the remote and autonomous operation of an existing naval patrol platform, in the operating environment in which the RAN operates. Austal has already undertaken similar projects in our US business, funded by the Office of the Secretary of Defence (Project Overlord - *Figure 2*), where a 60m Offshore Crew Boat was converted to an autonomous platform.



Figure 2: Ghost Fleet vessels Nomad and Ranger are supporting USN experimentation under the Overlord USV prototype program.

2. THE INTERNATIONAL LUSV LANDSCAPE

There are a large number of USV options available in the small and medium size range. These platforms tend to have shorter range and endurance and are less capable of supporting significant mission payloads. The USN is investing in some significant MUSV and LUSV projects (*Figure 3*) including the automation of a recently completed Expeditionary Fast Transport (EPF 13 - USNS *Apalachicola*). This enhancement allows EPF 13 to operate autonomously while retaining the capability for manned operation. The work includes installation of a perception and autonomy control suite, as well as several automation enhancements to the machinery plant improving hull, mechanical, and electrical (HM&E) reliability, while reducing the number of personnel required for operations and

maintenance at sea. The vessel will undertake sea trails in the third quarter of this year. This platform will be the largest un-crewed naval vessel ever trialled.

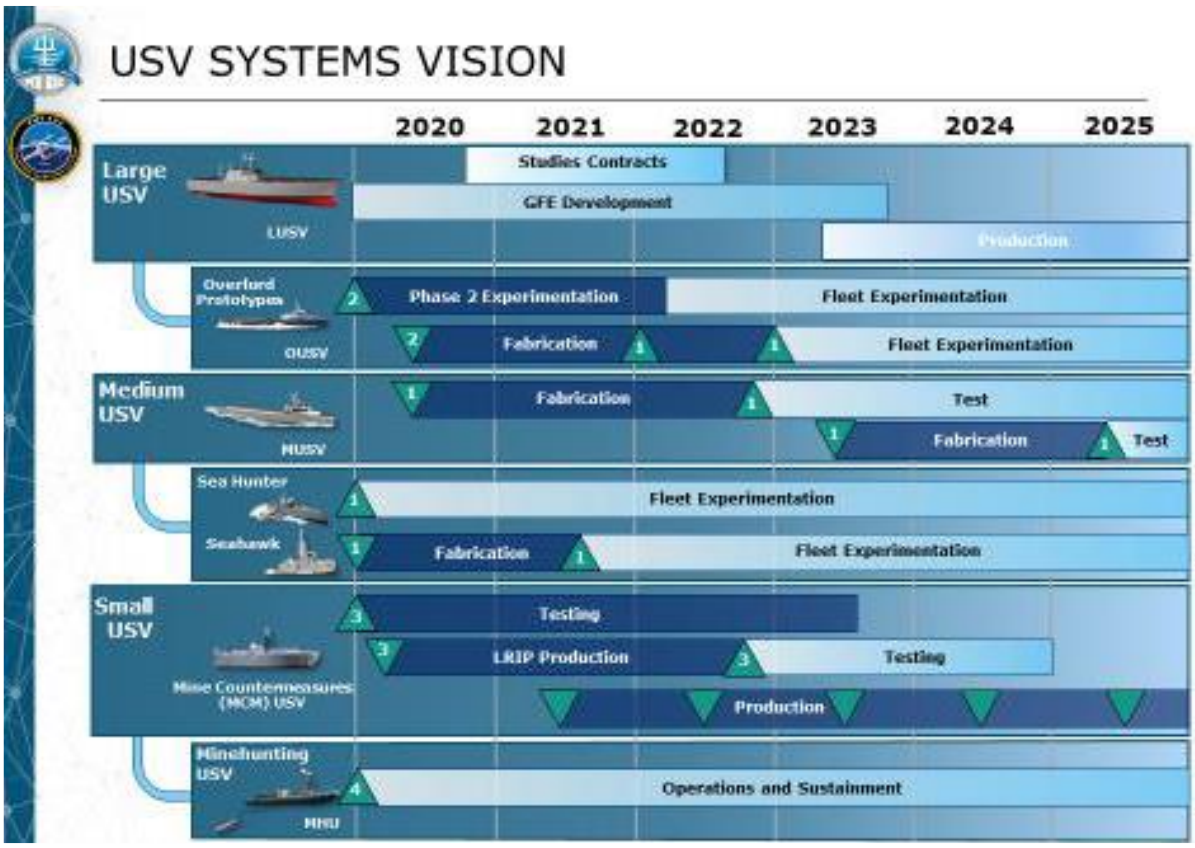


Figure 3: The USN is investing heavily in USV technology to better understand how the technology will support the future fleet mix.

This work follows on from work already completed in support of the Overlord Program and the ongoing contracted design work for the LUSV Program. Austal's Project Overlord vessel, NOMAD (formerly known as Riley Claire) (Figure 4) completed the 4,421 nautical miles from the Gulf Coast to the West Coast, moving autonomously 98 percent of the time, in May 2021.

In 2020 the US Navy also awarded USD42M in contracts for LUSV studies. Austal was one of six successful bidders for these design studies along with Huntington Ingalls Industries, Fincantieri Marinette, Bollinger Shipyards, Lockheed Martin and Gibbs & Cox.



Figure 4 Austal's NOMAD continues trials in San Diego in support of the Surface Development Squadron (SURFDEVRON) Navy experimentation

The US Navy released a long-range Navy shipbuilding document in 2021, that presents the Biden Administration's emerging successor to the 355-ship force-level goal. This document proposed a fleet architecture including 321 to 372 manned ships and 77 to 140 large UVs. It was also acknowledged that a fleet of this size would require a 43% increase in the annual $22.9 billion appropriated on average, for all Navy shipbuilding activities over the past five years.

The Royal Navy has revealed plans to develop a Future Autonomous Fleet program led by UK Naval Engineering Science and Technology (UKNEST). They claim to be on track to bring the Persistent Operational Deployment Systems (PODS) to fruition within the next ten years. PODS are interchangeable modular components that can be equipped to the surface fleet. The PODS approach creates a 'plug and play' ship concept, allowing UK naval ships of all sizes to be more adaptable during their deployment.

The British Royal Navy has also recently taken delivery of the third and final autonomous mine hunting boat. Hebe, Harrier and Hazard are major components in the future of mine hunting operations and can work in manual, remote or autonomous configurations. (UK Royal Navy)



Figure 5 Royal Navy recently took delivery of the third autonomous mine hunting boat, Hebe supporting future mine hunting operations, although the size of these platforms is modest at only 15m in length

3. THE AUSTRALIAN LANDSCAPE

The key document published by the Royal Australian Navy related to autonomy is the RAS-AI Strategy 2040. This document identifies a number of USV Missions for today, the near term and the far term which are provided in ***Table 1***.

Table 1: USV mission aspirations as identified in the RAS-AI Strategy 2040



The 2020 Force Structure Plan identifies the current maritime programs of record. The two programs in the current Force Structure Plan that identify roles for autonomy are:

- SEA1905-1: Maritime Mine Countermeasures and Military Survey mission packages including robotic and autonomous systems
- SEA5012-1: Integrated Undersea Surveillance System including investment in innovative future technologies such as autonomous vehicles, advanced acoustic data processing utilising artificial intelligence, machine learning and big data analysis

The RAS-AI Strategy highlights opportunities for USV, which are not currently reflected in the Force Structure Plan. The Patrol Boat Autonomy Trial may help to demonstrate some of the near term and far term mission capabilities which can be achieved by the Australian defence industry.

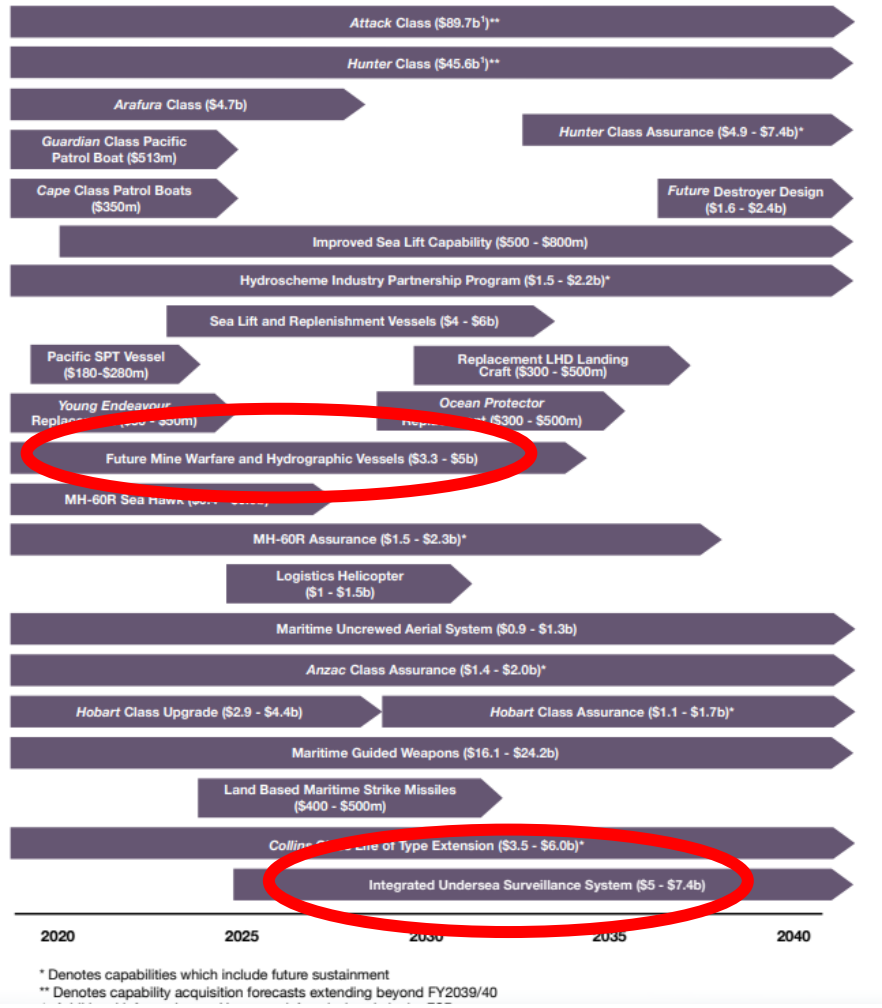


Figure 6 The Force Structure Plan identifies the programs of record currently planned between 2020 and 2040. Only SEA 1905-1 and SEA 5012-1 make reference to autonomous capability.

4. THE PATROL BOAT AUTONOMY TRIAL

Austal has been working together with the Trusted Autonomous Systems Defence Cooperative Research Centre (TAS DCRC) and L3HARRIS for over a year to develop the project scope of work and the project objectives. The project intent is to use HMAS Maitland as a vessel of opportunity (*Figure 7*) to investigate what level of remote and autonomous operation can be achieved with an existing manned patrol platform.

Similar projects have already been undertaken in Austal's US business as discussed above, however much of the learning from this work is now ITAR controlled. This local project allows an Australian LUSV Team to develop domestic capability and expertise.



Figure 7: HMAS Maitland will be used as the test platform for the Patrol Boat Autonomy Trial

A) PROJECT OBJECTIVES

HMAS Maitland is a highly capable patrol platform. The RAN has generously offered to make the vessel available to Austal following decommissioning in April 2022, to support the Patrol Boat Autonomy Trial. This trial provides an opportunity to learn by doing:

1. Sustained operation of shipboard mechanical systems without crew intervention. The design approach for crewed platforms and un-crewed platforms requires some fundamental changes in philosophy to achieve the required operational availability. The autonomous platform may require a different design approach to lubrication systems or air, fuel and oil filtration, to support the increased maintenance intervals. Strategies to reduce the need for crew inspection and maintenance may include (Chambers, Stewart, Turrens 2019):
    - Filter monitoring through the use of differential pressure gauges
    - Use of cameras for remote visual inspection of critical components
    - Installation of additional pressure and temperature sensors to replace gauge functions, as well as monitor seal integrity
    - Installation of additional level (volume) sensors for lubricating fluids
2. Establishment of a certification approach. The development of certification standards is progressing in support autonomous operations. DNV offers a Class Guideline published in September 2018 for Autonomous and remotely operated ships. Lloyds Register published the LR Code for Unmanned Marine Systems in February 2017. The IMO Maritime Safety Committee (MSC 104) agreed in October 2021, to develop a roadmap for the future plan of work for Maritime Autonomous

Surface Ships (MASS). They also agreed to develop of a goal-based instrument for MASS, with a target completion year of 2025. (IMO, 2021)

TAS DCRC is also undertaking a certification study for a minimally crewed/autonomous Armidale patrol boat in the context of AMSA and Office of Defence Seaworthiness regulations to inform future considerations for certification of large USVs for both civilian and military applications.

3. Communications requirements to support remote operation and control. The required communications data rates (Line of sight and over the horizon) depend on the situational awareness required ashore and the need for the real time transmission of optical and infrared imagery.
4. System integration challenges associated with the modification of an existing crewed platform. Existing vessels are designed to support the embarked crew with hotel services and with an expectation that the ship's crew will undertake routine maintenance tasks. Modifying an existing platform presents a greater system integration challenge in many respects than designing an autonomous platform from the outset.
5. Development of a design architecture for application on other assets. The basic system architecture will be consistent from vessel to vessel however the detailed design architecture will depend on the installed systems and sensors. The older the asset the more significant the required changes will be to achieve autonomous control.
6. Illustration of the potential for significant reductions in crewing on existing assets. Reducing the required workload of the crew through automation will allow significant reductions in operational costs. There is potential to reduce the crew focus on operational and navigation tasks and increase the focus on mission tasks. The Patrol Boat Autonomy Trial will demonstrate what is possible with an existing asset, designed almost 20 years ago.
7. The sustainment approach for a LUSV and how that approach differs from a crewed platform. The sustainment approach will not only require a change in strategies to reduce the need for crew inspection and maintenance but will also require an increase in equipment health monitoring sensors (such as vibration, pressure and temperature) to ensure the timely completion of both planned and unplanned maintenance tasks.

B) VESSEL MODIFICATIONS

The Patrol Boat Autonomy Trial is intended to demonstrate what is possible without achieving autonomy of all ship systems. This approach ensures a reasonable project cost while still satisfying the project outcomes. An overview of the system architecture is provided in *Figure 8*. The following systems are being modified to demonstrate what is possible:

- Machinery ventilation control
- Main and Auxiliary engine control
- Steering control and monitoring
- Fuel System – supply, transfer and filtration
- Bilge system monitoring and operation
- Fire system monitoring and activation
- Power management and control
- Navigation systems
- Communication systems

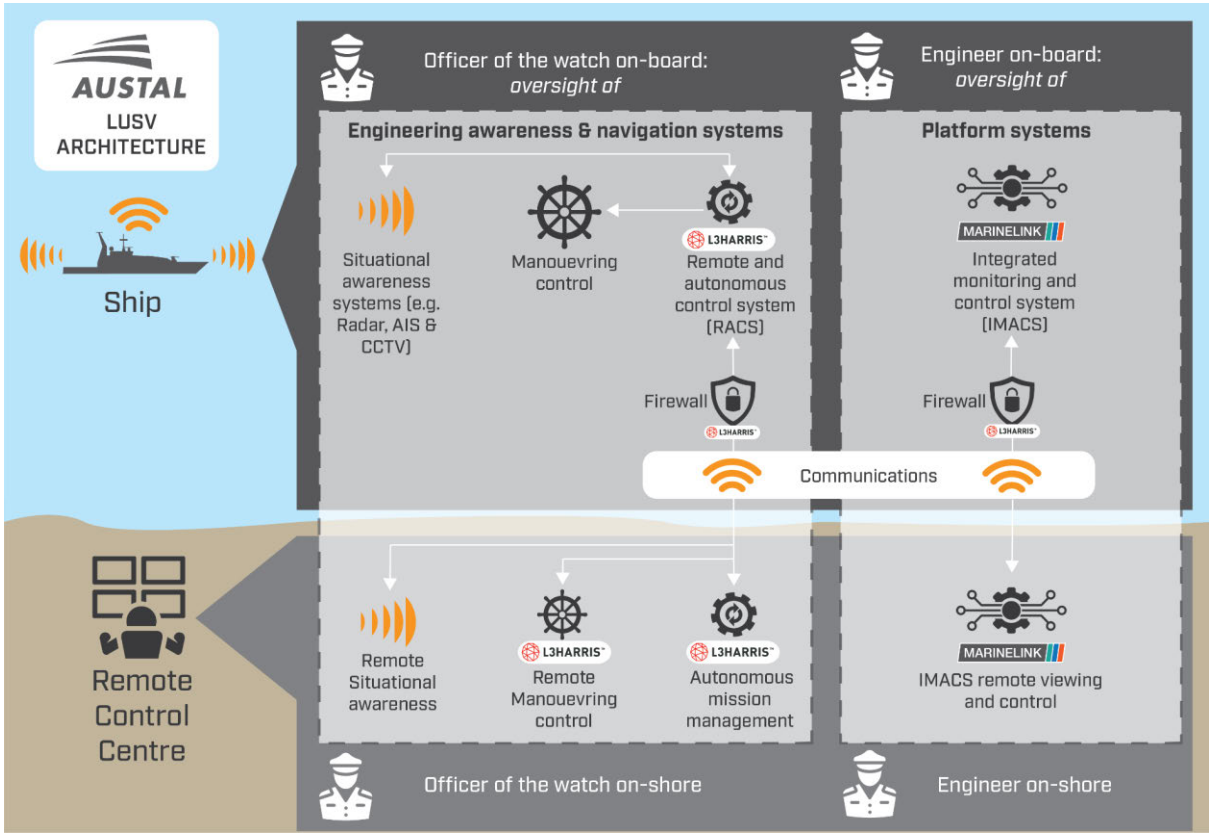


Figure 8 The system architecture includes elements on the ship and in the Remote Control Centre and addresses situational awareness, navigation control and platform systems control.

C) VESSEL TRIALS

The project will undertake three separate proof of concept demonstration trials. These trials are described as follows:

1. Remote Control Manoeuvring

2. Autonomous Manoeuvring

3. Complex Endurance for a period of 14 days

A Remote and Autonomous Vessel Test and Evaluation Plan and associated Test Procedures have been developed for the project. The project schedule makes provision for integration testing, Harbour Acceptance Testing (HAT) and Sea Acceptance Testing (SAT) prior to any demonstration trials. The nature of the three trials is illustrated in *Figure 9*.

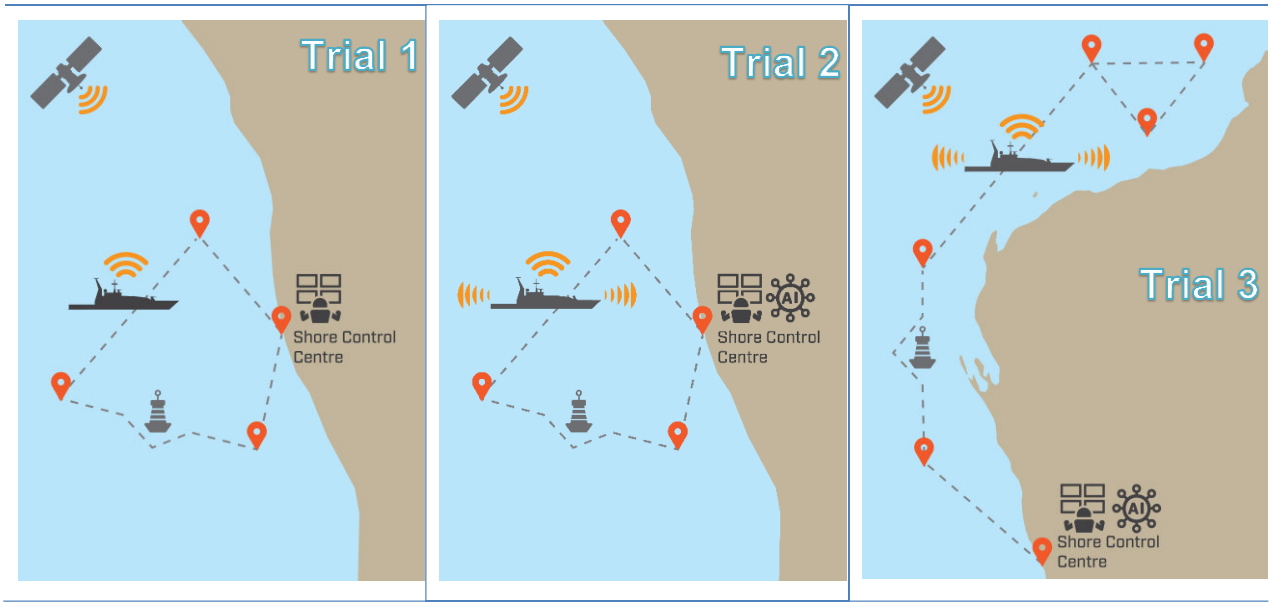


Figure 9 Three separate proof of concept demonstration trials are planned to systematically demonstrate remote and autonomous collision avoidance, command and control, manoeuvring and endurance. (From left) Trial 1 - Remote control with command off Perth trialling navigation, Trial 2: Autonomous control without command using same trial course as Trial 1, and Trial 3 – Predominately autonomous control venturing further off the Northwest of Western Australia.

D) THE FUTURE

The Patrol Boat Autonomy Trial provides an opportunity to illustrate what is possible with an existing naval platform, which has been in service for almost 20 years. Once the proposed trials are complete, the platform offers an opportunity to investigate the integration of a variety of additional capability options. This may include further ship modifications to develop mission specific launch and recovery systems (*Figure 10*).

Austal already offers technology solutions to facilitate remote and autonomous control of large complex platforms in remote locations. Austal has been delivering centralised monitoring and control of un-crewed machinery spaces for a long time. The next step to

remote and autonomous control is an incremental capability upgrade which is well aligned with the existing Marine Link monitoring and control system capability.

One of the ultimate goals of this technology is to allow flexibility in the way future platforms are crewed and ultimately to conduct missions without the need to send crewed platforms into hostile environments.

A significant portion of current platform designs, support the embarked crew with facilities such as dry and refrigerated stores, galleys, messing, cabins, hotel services and medical treatment. This point was highlighted by Hellyer (2019) where he made the point that without the need to design systems to protect the precious human cargo, the platform design can focus purely on mission success. If these crew support systems are no longer required or can be significantly reduced, there is scope for relatively smaller platforms to carry significantly larger mission payloads. The Armidale Class Patrol Boat has a significant superstructure which is almost entirely used to support crew habitability rather than mission capability.

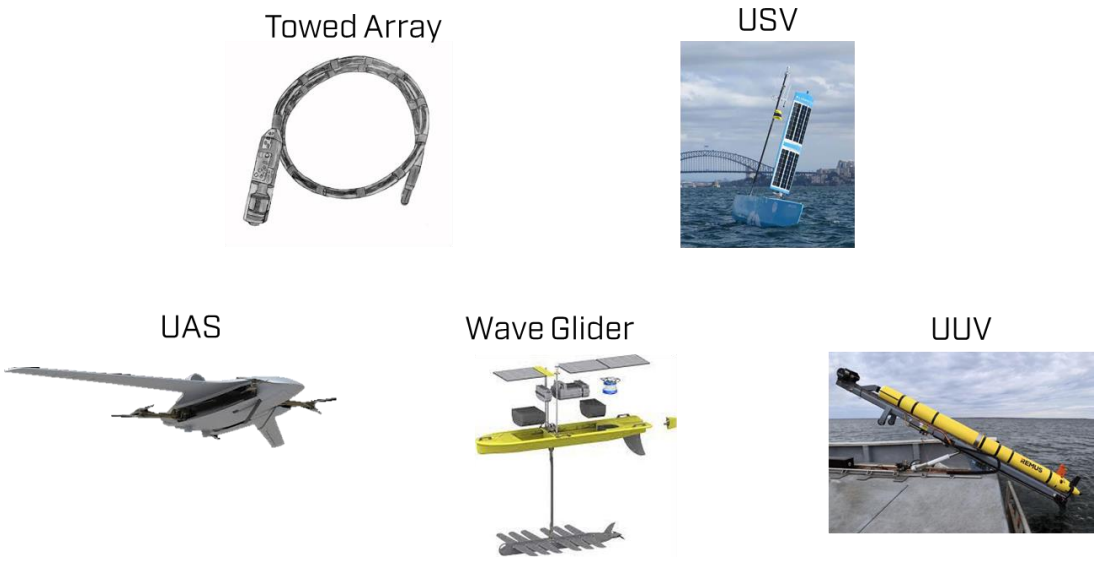


Figure 10 A LUSV platform could potentially support the delivery, launch and recovery of a variety of mission systems.

5. CONCLUSION

The International development of USV capability is proceeding at pace, however much of this progress to date has been focussed on small and medium platforms which do not offer the same mission capability as a LUSV.

While the Australian Force Structure Plan doesn't currently identify any LUSV Programs, the RAS-AI strategy is clear regarding near term and far term mission aspirations. The Australian Defence Industry can deliver this capability and the Patrol Boat Autonomy Trial will help to demonstrate the industry capability while de-risking future projects.

Crewing the RAN Fleet remains a challenge now and in the future. This work offers options to reduce future crew sizes and change the way in which future platforms are maintained. Austal, both in Australia and the USA is supporting the Navy to perform the dull, dirty, dangerous and difficult work of tomorrow, today.

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SESSION 6

Ship Design

Development of virtual ship-helicopter operational limits for a replenishment type ship

Current developments of wind turbine installation vessels

Development of Nauti-craft's 3rd generation deck pitch and roll control system

Fast generation of highly representative 3D models of large maritime platforms

Development of Virtual Ship-Helicopter Operational Limits for a Replenishment Type Ship

Nathan Humphrey[1], Hurmat Ain[1], David Boyd[1] and LCDR Viruben Watson[2]
1 Aerospace Division, Defence Science and Technology Group (DSTG), Victoria 3207, Australia
2 Aircraft Maintenance and Flight Trials Unit (AMAFTU), Nowra 2541, Australia
Email: Nathan.Humphrey@dst.defence.gov.au

INTRODUCTION

Shipboard helicopter Launch and Recovery (L&R) is one of the most challenging flight operations due to the unique and unforgiving nature of maritime environment. The job of pilots and ship crew is extremely demanding due to multitude of factors, which include unsteady ship aerodynamics, helicopter performance limits, sea state, and human factors such as pilot workload and degraded visibility. Understanding the impact of these factors is crucial to determining safe operational envelopes for rotorcraft L&R on ships.

Typically the assessment and development of Ship Helicopter Operating Limits (SHOLs) occur during First of Class Flight Trials (FoCFT). However in recent times, there has been significant interest in simulating the dynamic environment of the ship deck [1]. There are multiple approaches to deck simulation, with some groups opting for human-in-the-loop simulations, which then allows for pilot input and assessment of pilot effort through the Deck Interface Pilot Effort Scale (DIPES) [2].

To provide insight into the risks of ship-helicopter operations, Defence Science and Technology Group (DSTG) have developed a novel automated tool named the Candidate Ship Helicopter Operational Limits Tool (CSHOL). The CSHOL tool builds on previous DSTG ship-helicopter analysis [3,4,12]. This tool combines the elements of ship airwake, high fidelity helicopter flight model, and a virtual pilot to determine the Wind Over Deck (WOD) angles that are most likely to affect the controllability of the aircraft during L&R operations.

In this study, an L&R simulation of a four bladed single main rotor medium size helicopter on an exemplar supply class ship is developed. The supply class ship is intended to carry fuel, dry cargo, water, food, ammunition, equipment and spare parts to provide operational support for deployed naval or combat forces operating far from the port on the high seas for longer periods. As shown in Figure 1, the ship can support one helicopter from an aft positioned landing spot.



Figure 1 Exemplar ship model. The yellow arrow indicates helicopter landing spot.

The objective of this study is to compare control input and pilot workload limits for varying WOD angles and wind speed with and without the ship airwake. The paper builds on previous work by estimating pilot workload using the pilot cut-off frequency method and producing virtual SHOL envelopes from the predicted proximity to control limits. The results show that for smaller WOD angles, airwake turbulence has a significant impact on aircraft controls, whereas for larger WOD angles, the airwake seem to have negligible impact on helicopter controls. The outcome of this form of analysis has a potential to mitigate risks associated with FoCFT when aircraft and ship combinations are flight tested at sea. The rest of the sections in this paper describes the CSHOL methodology in detail and present the analysis for a medium sized utility helicopter during L&R on the exemplar supply ship.

CANDIDATE SHOL SIMULATION MODEL & METHODOLOGY

The CSHOL Tool methodology consisted of the following steps:

1. Computational Fluid Dynamics (CFD) is used to predict the unsteady airwake generated behind the exemplar ship superstructure at different wind over deck angles.
2. A helicopter flight dynamics model is then initialised within the resolved unsteady airwake.
3. The helicopter flight model, controlled by a virtual pilot implemented in MATLAB[1] Simulink, then flies along a predetermined recovery landing path.
4. An assessment is then conducted on the virtual pilot's control inputs and pilot workload limits to deduce if the landing was successful and feasible.
5. By considering multiple WOD angles and wind speeds a candidate SHOL can be developed for the combination of exemplar ship and helicopter.

Further insight can be gained by comparing the helicopter control inputs, torque and flight path when flying the landing procedure through the ship airwake, called herein the wake on conditions; to the same landing procedure flown without the ship airwake, that is, through a constant velocity field, called the wake off condition. The wake on/off simulations determine the effect of ship airwake on the aircraft controls during the L&R operation.

Computational Fluid Dynamics Model

The CFD unsteady simulations were performed in FLUENT[2] V17.2, using the Large Eddy Simulation (LES) method, and the dynamic Smagorinsky subgrid-scale turbulence model. The ship mesh contained approximately 55 million cells.

The CFD simulations were carried out at a wind speed of 25 knots (12.86 m/s) at a reference height of 30 m above water level (i.e. approximate ship anemometer height). An Atmospheric Boundary Layer (ABL) was also imposed based on a log-law profile assigned with typical sea surface roughness. An iso-surface of turbulent kinetic energy, coloured by velocity for the headwind 0° WOD case can be seen in Figure 2.

[1] The Math Works, Inc. MATLAB, https://www.mathworks.com/.

[2] FLUENT is a commercial CFD code developed by ANSYS Inc. Southpointe 2600 ANSYS Drive Canonsburg, Pennsylvania.

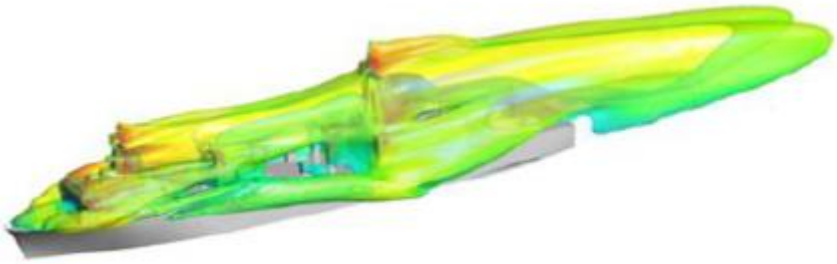


Figure 2 Iso-surfaces of turbulent kinetic energy (3 m^2/s^2) showing the wake around the vessel at 0° WOD. Surface coloured by velocity magnitude.

The unsteady simulation results were extracted for each WOD angle at 10 Hz output frequency over a 20 s transient for use with the CSHOL tool.

At wind speeds other than that simulated by the CFD, the magnitude and time of the transient data were scaled in the CSHOL tool. For the magnitude, the velocity components were scaled directly in proportion to the change in wind speed based on the argument of self-similarity. For time, the scaling is based on a Strouhal type relationship, which essentially assumes the size and distribution of the unsteady flow features remain unchanged, and are swept down by different freestream wind velocities. This results in the time being scaled inversely to the change in wind velocity, as shown in Equation 1.

$$t_2 = \frac{v_1}{v_2} \cdot t_1 \qquad 1$$

where t_1 and v_1 are the baseline case time step and freestream velocity, 0.1 seconds and 25 knots respectively, and v_2 the freestream velocity of the second case requiring temporal scaling.

Flight Model

An exemplar aircraft was assessed for recovery operations on the exemplar ship. DSTG implemented a flight model for the aircraft in the FLIGHTLAB[3] modelling software developed by Advanced Rotorcraft Technology (ART) Incorporated. FLIGHTLAB uses multi-body dynamics to simulate real-time non-linear aircraft dynamics. Flight models can therefore be built modularly, allowing for various levels of fidelity across the control system, rotor dynamics, aerodynamics and engines, amongst many other aircraft components. The aircraft was a conventional single rotor, medium sized utility helicopter. Simulations were conducted at two aircraft weights, lightly and heavily laden.

Virtual Pilot

The virtual pilot is a waypoint following system implemented through the MATLAB Simulink environment. Aircraft attitude, position and velocity are controlled via a series of proportional, derivative and integrating controllers on each of the 4 aircraft control axes. This provides an offline, closed loop control system which seeks to minimise errors in aircraft attitude, position and velocity as it proceeds through the waypoints stipulating the landing path. Control inputs

[3] Comprehensive rotorcraft software environment developed by Advanced Rotorcraft Technology (ART), 635 Vaqueros Avenue Sunnyvale, California.

required to follow the specified waypoints are logged throughout the duration of the simulation and then post-processed to determine the landing success and feasibility.

Recovery Path and Procedure

As shown in Figure 1, the landing spot was located on the aft deck of the exemplar ship. For all simulations, the aircraft was initialised one-third rotor diameter above the deck, and approximately two rotor diameters astern of the landing spot. The path consisted of a one second initialisation, then an initial hover for 30 seconds in the aircraft 'hotel' hover position. This was followed by forward flight at 5 knots to a point above the landing spot. A final hover is conducted at the landing spot for 15 seconds, which is concluded by a descent for touchdown onto the flight deck. It is important to note that the durations mentioned here for each of the flight phases are approximate as the exact value relies on the actual manoeuvre as predicted by FLIGHTLAB, and vary from case to case.

Cut-Off Frequency

To give an indication of pilot workload, the pilot cut-off frequency method was employed. This method is a measure of pilot stick activity in a single control axis during a closed loop tracking task. The cut-off frequency is where the pilot is expending half of their control power, and can be interpreted as the nominal operating frequency of the pilot. If this frequency is above the bandwidth of a given control axis, then pilot workload is likely to increase.

Bandwidth is, broadly speaking, the control input frequency above which an aircraft may be prone to pilot induced oscillation, and therefore requires increased pilot effort to maintain stability. Bandwidth is defined in ADS-33E [7] as the lesser of the gain and phase bandwidth for rate response types, and as the phase bandwidth for attitude command/attitude hold response types. The nominal bandwidth values used for the longitudinal, lateral and directional control axes were 2.4, 3.64 and 3.22 rad/s respectively. These were obtained from aircraft of a similar class and weight to the exemplar helicopter assessed herein [8,9,10].

This approach, which effectively disconnects the pilot cut-off frequency from the actual model bandwidth, is acceptable, as the virtual pilot is a PID controller tuned using optimal control theory and is not tied to task performance. In this regard, the cut-off frequency will be primarily linked to the fundamental frequency of the input command, as unlike a real pilot the virtual pilot will not adjust its control strategy to meet any task performance metrics. The cut-off frequencies presented in this report still give an indication of the relative difficulty of landing in different turbulent airwakes, but more in the sense of the changing spectral content of the airwake itself.

Simulation Limits

SHOLs are typically defined by aircraft performance considerations (e.g. control authority limits and all engine operational limits); as well as pilot assessments of workload, performance, accuracy and consistency using the DIPES, and are thus significantly complex [5]. For the current preliminary SHOL results, as presented herein, simulation limits were taken to be exceeded when any of the following conditions were reached, adapted from Reference [6]:

1. The simulation failed to land.
2. Any of the lateral, longitudinal, collective or pedal controls exceeded 90% or fell below 10%.

3. Main rotor torque exceeded 110% continuously for a duration of 20 s, or during a 20 s sliding window average.
4. Mean main rotor torque exceeded 100% for the entire duration of the simulation, or for the entire duration of the 'hotel' hover.
5. Aircraft roll angle exceeded +/- 10°.
6. Aircraft pitch up angle exceeded +10°.

Furthermore WOD speeds of greater than a gentle breeze on the Beaufort wind scale coming from astern were discarded due to the risk of the aircraft being blown forwards into the ship structure or other deck obstacles. For an aft landing position such as on the exemplar ship, tail-winds can also result in high pitch up angles which limit the pilot's field of view on aft approach landing manoeuvres [11]. For these reasons tail-wind approaches beyond 90° and a gentle breeze cannot be recommended regardless of the results of the simulation.

Finally a comparison was also made between pilot cut-off frequency and aircraft bandwidth. Any WOD speed and azimuth combination that led to the cut-off frequency being greater than or equal the aircraft bandwidth limits in any control axis was classified as a breach of pilot workload limits.

RESULTS

A total of 16 WOD angles have been examined, namely 0° (head wind), 180° (tail wind), and then 7.5°, 15°, 30°, 60°, 90°, 120° and 150° on both port and starboard sides. All results presented herein have ignored the first 5 seconds of simulation output to allow the aircraft to 'stabilise' numerically. For the sake of brevity, only the time histories of control and torque inputs for the head wind case are presented here.

To deduce the impact of ship airwake, the time histories of controls for both the light and heavy laden aircraft are presented in Figure 3. The three vertical lines represent significant waypoints, namely the time when the helicopter crosses onto the ship deck, when it reaches the landing spot and maintains hover, and when it begins decent. The solid and dashed data/vertical lines represent the 'wake on' and 'wake off' simulations respectively.

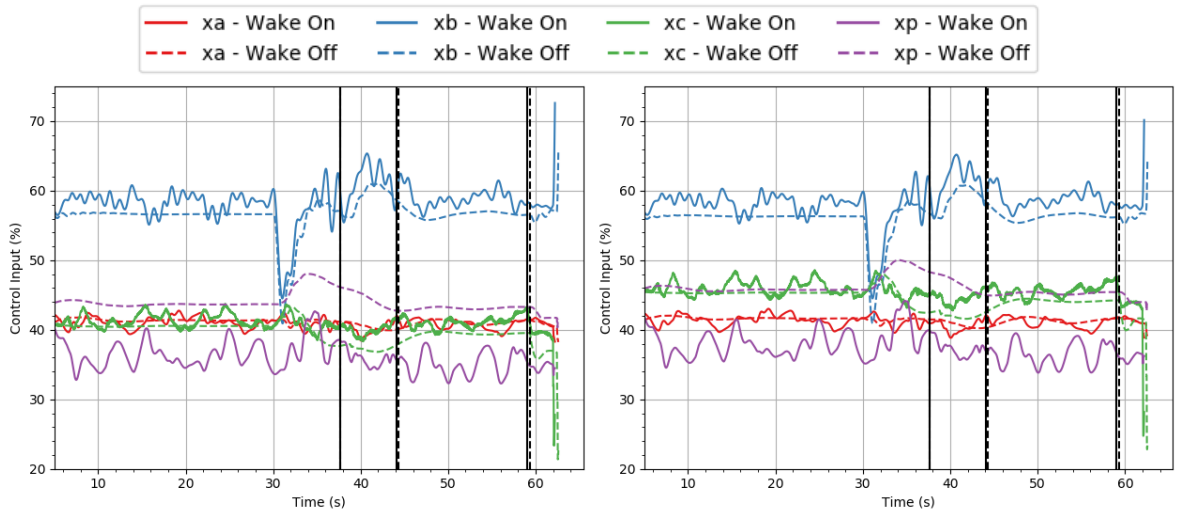


Figure 3 Control time histories for the wind from ahead (0° WOD angle) for the lightly laden aircraft (left) and heavy laden aircraft (right).

The sign convention used for helicopter controls in the simulation is such that 100% corresponds to lateral cyclic (xa) fully right, longitudinal cyclic (xb) fully aft, collective (xc) fully up and pedal (xp) full right. Control inputs of 50% are equivalent to the mid-position and 0% is the opposite of 100% position of the corresponding stick. The helicopter controls exhibit fluctuations in 'wake on' condition as compared to 'wake off' simulations, which become significantly large during final approach and hover on the landing spot. A drop in xb is noticeable after 30 s, which is due to the helicopter transitioning to forward flight from hover requiring the virtual pilot model to apply a forward cyclic stick with some positive collective input to maintain the altitude. For the heavy laden aircraft, there is approximately 5-6% increase in collective input on average as well as minor changes in pedal input made by the virtual pilot model to counter higher torque as a result of increase in collective.

The changes in torque input directly correlate with the changes in collective. This can be clearly seen in Figure 4, where the heavy aircraft appears to have 10% higher torque on average as compared to the lightly laden aircraft. Similar to Figure 3, the large fluctuations in torque input for the 'wake on' simulation are clearly evident. The description of vertical lines, dashed and solid lines are same as in Figure 3. The CFD results for the head wind case has identified an increase in turbulence intensity for small WOD angles. This ties in well with the observation of significantly higher oscillation under wake influence.

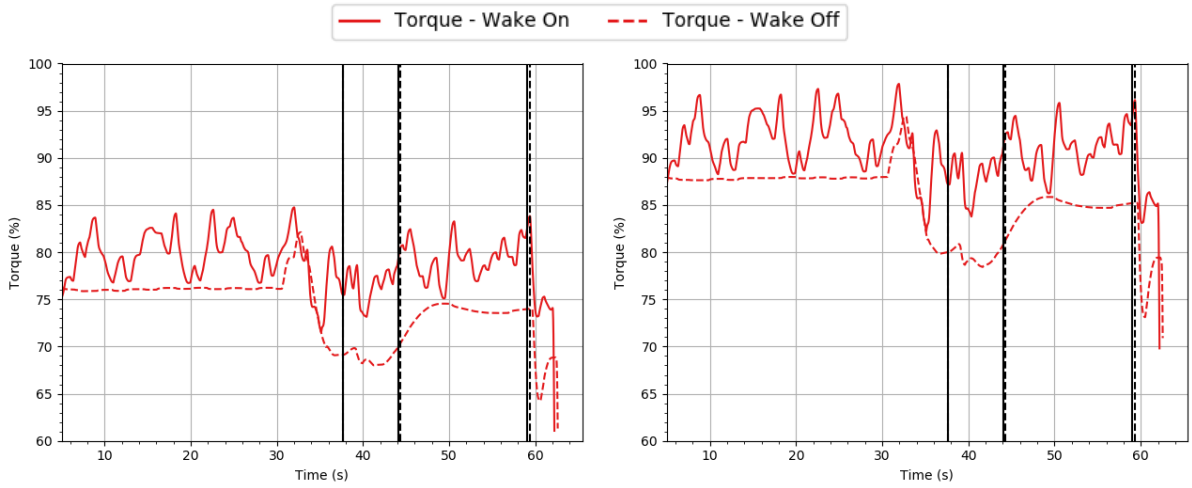


Figure 4 Torque time history for the wind from ahead (0° WOD angle) for the lightly laden aircraft (left) and heavy laden aircraft (right).

By assessing 16 wind over deck angles and scaling velocity from the CFD airwake using the frozen turbulence hypothesis of Equation 1, and considering the failure criteria previously listed under Simulation Limits, an azimuthal plot of predicted landing success or failure can be produced. These conditions and limits generate the candidate virtual SHOLs presented in Figure 5 and Figure 6. As per naval convention, red winds are winds from the port side, and green winds from the starboard. These figures indicate that the virtual SHOLs for the 'wake on' simulations are more conservative than the 'wake off' simulations. The predicted operational envelope for the heavy laden aircraft under 'wake on' conditions is the most restricted, as the increased power requirements produces more torque, which means a pilot has to work harder to balance the increased torque with tail rotor input to maintain a stable flight; leading to an increased pilot workload and saturation of control inputs.

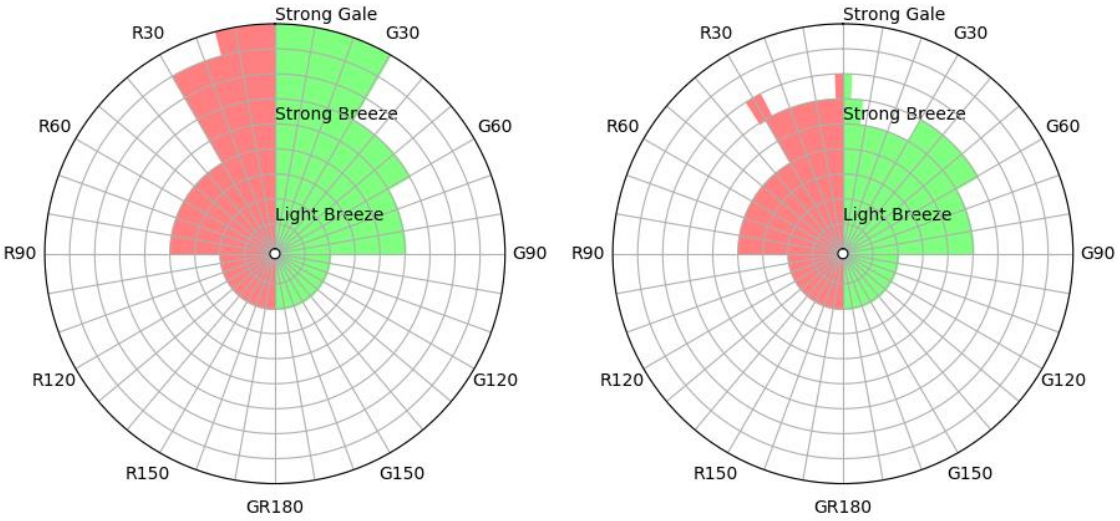


Figure 5 Light laden exemplar aircraft virtual SHOL considering control and pilot workload limits, for the wake off condition (left) and wake on condition (right). The wind description here corresponds to the Beaufort wind scale standard.

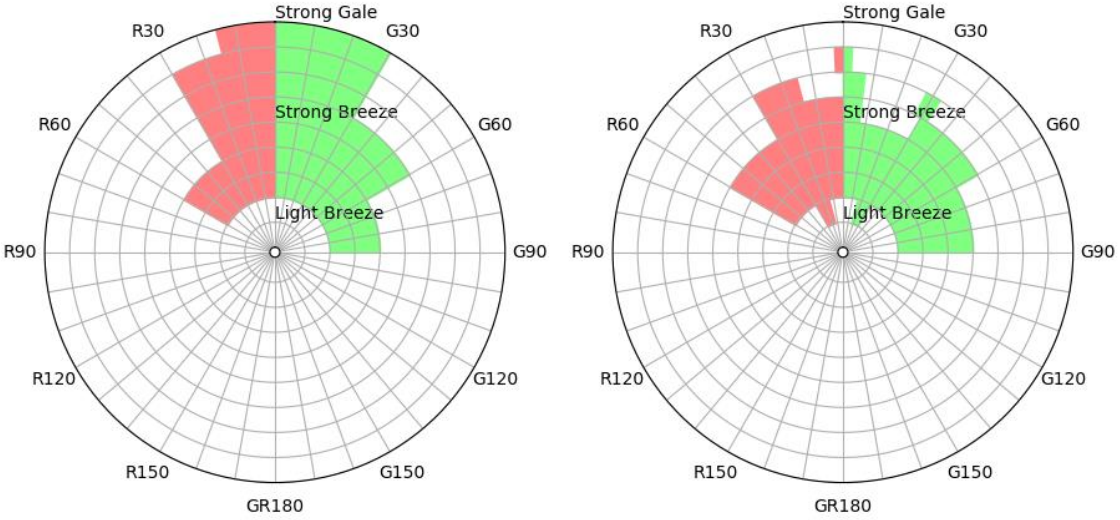


Figure 6 Heavier laden exemplar aircraft virtual SHOL considering control and pilot workload limits, for the wake off condition (left) and wake on condition (right). The wind description here corresponds to the Beaufort wind scale standard.

DISCUSSION

The results presented for the exemplar aircraft appear to conform to the expected SHOL shape. The most common failure modes are presented pictographically in Figure 7. This breakdown of failure modes can advise test pilots of what to expect during flight test trials. Note this is not an extensive indication of failure modes as some combinations of WOD angle and wind speed fail more than one criteria.

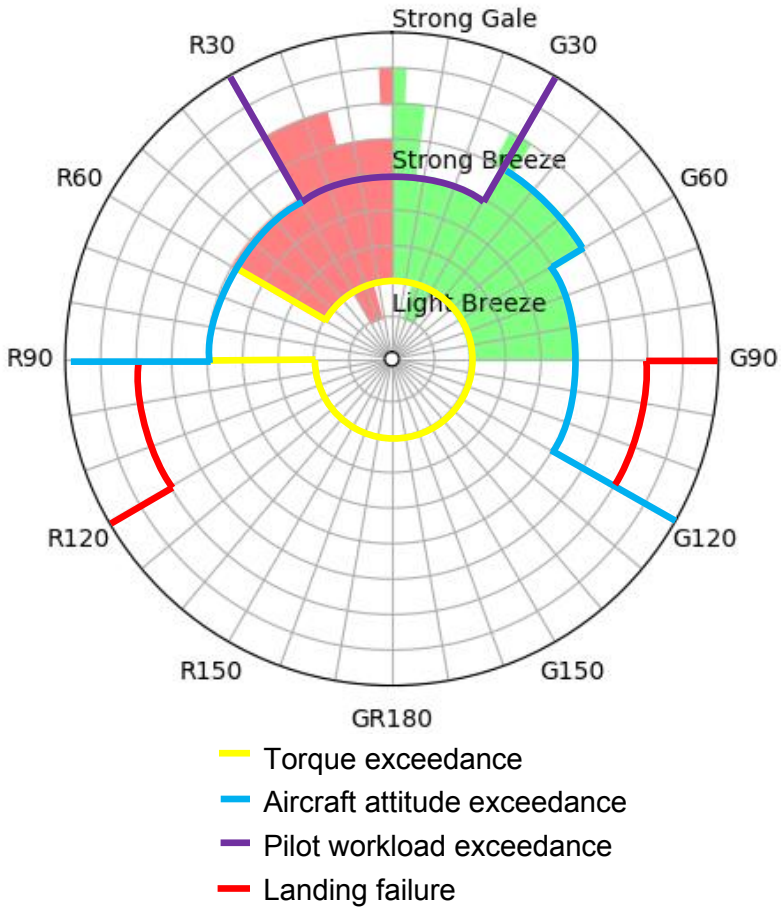


Figure 7 General failure states for the heavy laden aircraft virtual SHOL considering control and pilot workload limits.

For the lighter laden exemplar aircraft the effect of the wake is most noticeable for winds from the bow direction, as shown in Figure 5. This is due to the increased turbulence intensity and due to the large scale unsteady ship wake structures which are seen to roll down the length of the ship when visualising the CFD results. The increased turbulence intensity leads to an increase in required pilot control input, and an associated increase in pilot workload, as is noted in Figure 7 with the purple region of pilot workload exceedance.

As has been investigated previously [12], the virtual pilot does not characterize the flight environment with sufficient fidelity to exactly predict pilot actions. But considered qualitatively, regions of high virtual pilot action should correlate to regions of high human pilot workload, which is the intent of the pilot cut-off limit SHOLs. Note that where the pilot cut-off limits have been exceeded, the pilot can expect an increase in workload due to unsteady wake structures and airwake turbulence which are shed from the ship. This does not necessarily indicate the landing is unfeasible, but will be more difficult.

For the heavier laden aircraft some interesting results can be inferred from the wake on versus wake off plots shown in Figure 6. The introduction of the wake does not limit the SHOL, but further expands it in some cases. The additional case in the red portion (strong breeze from Red 60) is included as the roll exceedances encountered in the wake off case no longer occur with the wake on. It is hypothesised that the ship provides some degree of shielding against the freestream wind, so the helicopter sees a lower mean velocity wind, which reduces the induced roll angle. Similarly the two small protrusions into the light breeze region are caused

by the torque required to hover dropping below the continuous torque threshold. As this addition is symmetric on the red and green sides, and as the torque change is only minimal, it is hypothesised to be the result of the small updraft generated on the windward side of the ship.

As with the lighter aircraft the bow wind section of the plot is most heavily impacted when considering the pilot workload for the heavier aircraft. This again is due to the increase in turbulence intensity aft of the ship due to shedding of structures off the ship superstructure, which will in turn require an increase in pilot input to remain on course and land successfully.

FUTURE WORK

There are a number of regions where this process can be developed and improved. First and foremost, data from at sea flight trials including logs of actual pilot input and feedback from the pilots' experience can be used as comparison to the candidate SHOLs and predicted failure states. This will allow for tuning of the simulation limits to more accurately reflect the safe aircraft limits, and will provide invaluable data for refining the FLIGHTLAB helicopter model. This is the first step in a full end-to-end validation process which will be undertaken for the CSHOL tool.

To advance the methodology, methods for coupling the ship airwake and helicopter model are to be explored to determine feasibility and complexity involved. Integration with ship motion routines are also to be investigated as ship pitch and roll have a significant impact on landing viability. Further development of the virtual pilot system is also underway, with the implementation of a neuromuscular model, to more accurately reflect a human response and to tie the virtual pilot to task performance metrics. Future work will also involve continued verification and validation of the CSHOL tool, which will improve the confidence level of the virtual SHOLs.

CONCLUSION

DSTG have developed a novel method CSHOL to produce candidate virtual ship helicopter operational limits plots, which can be used to inform test pilots prior to at sea flight trials. The method combines a computationally resolved ship airwake, a non-linear multi-body helicopter model, and a virtual piloting system. Using CSHOL, virtual SHOLs for a medium size single main rotor helicopter on-board an exemplar supply ship for all WOD angles were developed. The airwake for smaller WOD angles wind indicated higher oscillations in aircraft controls and pilot workload. For higher WOD angles wind, the impact of the airwake on helicopter controls are considerably small. With careful interpretation and simulation uncertainties consideration, the CSHOL tool should in turn improve the safety of flight trials, by informing the pilots of potentially unsafe airwake conditions, and minimising the time and cost of such trials by reducing the amount of test points required.

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CURRENT DEVELOPMENTS OF WIND TURBINE INSTALLATION VESSELS

K. Goh, Knud E. Hansen Australia P/L

1 INTRODUCTION

The first offshore windfarms in the 1990's were constructed close to shore and in shallow waters less than 10 meters in depth. They were constructed using mobile cranes on small jack-up barges supported by tugs and barges for trans-shipping of Offshore Wind Turbine (OWT) components. These barges and construction methods were usually employed in the construction of jetties and other coastal structures.

As windfarms moved further offshore and into waters deeper than 20 meters, large floating cranes were employed, but due to the lifting precision required to construct the OWT, the construction operations were often impossible in even the slightest sea swells resulting in lengthy delays and cost over-runs. Furthermore, the components still needed to be shipped separately adding to the construction costs. Clearly a better construction method was required.

The A2SEA *Sea Energy* was a converted general cargo vessel circa year 2000. With the addition of stabilising legs and crane the vessel was also able to carry the OWT components. Although this was a step in the right direction, the vessel could not lift itself free of the sea surface and was therefore still operationally limited by wave disturbance. In 2003 KNUD E. HANSEN designed *Mayflower Resolution*, which has been recognised as the world's first purpose-built Wind Turbine Installation Vessel (WTIV). Today, the world fleet of WTIV numbers over 50 vessels and with increasing demand for offshore wind energy there is a newbuild market for about 60 vessels with an estimated value of 14 billion USD over the next 5-10 years [1].

In this paper the author investigates the current trends in WTIV capability and design to meet the demands of the increasing size OWTs and more efficient construction methodology. The paper covers some of the unique naval engineering challenges that WTIVs pose to the designer that set this type of vessel apart from others. Finally, how 3D modelling and ShipSpace™ Virtual Reality collaboration tools are being used in the development and operation of the new generation of WTIVs.

2 BACKGROUND

2.1 OFFSHORE WINDFARMS

Offshore windfarms take advantage of offshore winds that blows stronger and more consistently than onshore winds. Typically, offshore windfarms have been:

- Within 50 nautical miles from coast
- Less than 50 meters water depth
- Array of 50 to 150 wind turbines
- Peak power = 200-2000 MW
- Cost = 50-100 USD/kWh

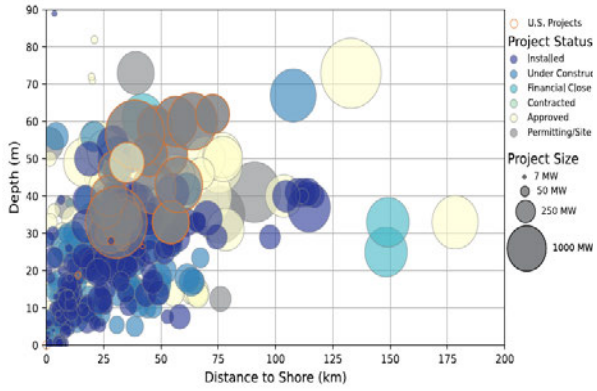


Figure 1 – Offshore windfarm principal particulars [2]

As can be seen in Figure 1, the trend is for offshore windfarms to become larger in capacity, further offshore – out to 100 nautical miles, and in deeper waters – up to 80 meters depth. These increases are mainly due to the advancement of OWT technology and the reducing availability shallow water areas with good wind resources. The maturing of construction methods and the growth of OWTs themselves have reduced the cost of installation from 200-300 USD/kWh to now less than 100 USD/kWh [1].

2.2 WIND TURBINE GENERATORS

Offshore Wind Turbines (OWT) have grown rapidly in size over the last 30 years. The first OWTs were able to generate 1000kW and had a rotor diameter of 30m. The current OWTs are able to generate 12-15MW with a rotor diameter of 220m and even larger 15-20MW OWTs are being developed. This growth trend will probably see some levelling off in the next decade as the limits of materials and economy-of-scale are reached.

Currently, almost all OWTs are of the fixed-bottom type. There are various types of foundations used including monopiles, jackets and gravity bases, depending on the water depth and seabed geology. Offshore windfarms are typically in water depths of up to 70-80m.

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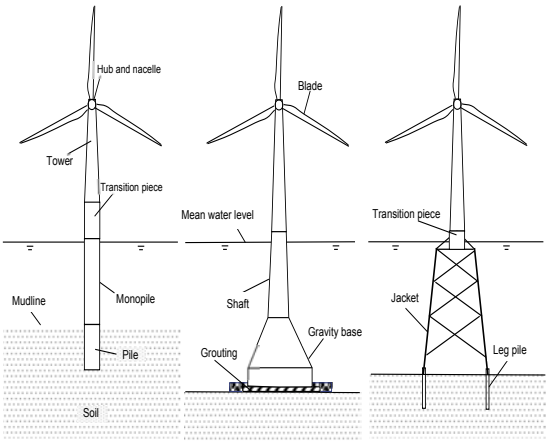


Figure 2 – Offshore wind turbine main components & foundation types [3]

Despite growing interest in Floating Wing Turbines (FWT) for waters deeper than 100 meters, there are only a couple of FWTs being tested and one pilot floating windfarm operating. All offshore windfarms in currently being planned are for fixed bottom OWTs.

2.3 WTIV CHARACTERISTICS

Although there is no formal definition of a WTIV, the main defining characteristics of a WTIVs are generally the following:

- Self-propelled & able to manoeuvre precisely
- Self-load & transport wind turbine components
- Self-install wind turbine components

It is worth noting that one of the principal operational concepts of WTIV is to be self-sufficient to eliminate the need for other support vessels. The term Jack-Up Vessel (JUV) is also used.



Figure 3 – Worlds first WTIV, MPI Resolution

The continuing growth of OWTs has also driven the growth of WTIVs. Designers at KNUD E. HANSEN Naval Architects have been at the forefront of WTIV developments. Following the first WTIV MPI Resolution, KEH developed the Pacific Orca and Pacific Osprey in 2008, which were the first WTIVs to be developed for 5-8MW size OWTs and water depths over 50m. Currently KEH is involved in the development of the next generation of WTIVs able to install the latest 12-15MW OWTs. The growth of WTIVs can be seen in the following table.

Name	Resolution	Pacific Orca	Atlas C
Year in service	2003	2013	2023
Length (LOA)	130 m	161 m	170 m
Moulded beam	38 m	49 m	60 m
Hull depth	8.0m	10.4 m	13.2m
Min. draught	3.4m	5.5 m	6.5m
Cargo area	2,800 m^2	4,500 m^2	6,800 m^2
Jack deadweight	2,000 tons	8,400 tons	18,000 tons
Crane max. load	300 t	1,200 t	3,000 t
Crane load height	100 m	140 m	160 m
Speed	10.5 kn	13.5 kn	12.0 kn
Installed Power	8,000 kWe	23,000 kWe	26,000 kWe
Typical cargo	10 x 2 MW OWTs	12 x 4 MW OWTs	6 x 15 MW OWTs

Table 1 – Principal particulars of some WTIV by KEH

One of the main problems facing owners of WTIVs is future proofing. The growth of OWTs has been so rapid that within 10 years many WTIVs have been unable to tender for construction contracts due to either water depth or crane load and height limitations. With the rapid WTIV fleet growth in the past 20 years, many owners choose to build to meet near-horizon market needs at the lowest cost and with limited ability to upgrade the vessels. Consequently, many of these WTIVs are not able to install future OWTs and will see-out their useful lives undertaking maintenance for existing wind farms.

3 OPERATIONS & LOGISTICS

3.1 TRANSPORT

Typically, a WTIV is required to transport all major components of the OWT to site and install them. This includes foundations, towers, nacelles and blades. Foundations are naturally transported and fixed in place first.

How the OWT components are transported has been the subject of much study and experimentation. It has been impractical to transport the OWT as a single unit due to the technical difficulties of lifting such a massive unit and acceleration limitations of the OWT when sea-fastened to the vessel.

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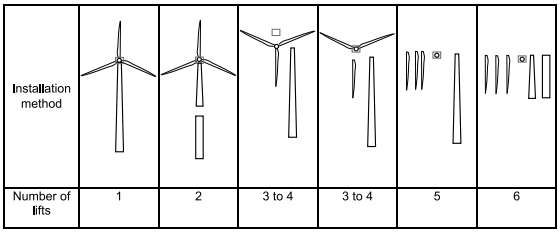


Figure 4 – Installation method & required lifts [3]

Towers were initially transported and installed in many sections, but today as a single unit. Likewise, the blades were initially been transported separate from the nacelle installed once the nacelle has been installed on top of the tower. In other OWF projects the blades have been shipped as a complete rotor assembly or as 'bunny ears' with two blades pre-assembled to the nacelle. Elaborate blade racks or rotor jigs are custom fabricated to support these delicate components.

The total number of lifts required to install a complete OWT is often used as a metric to determine installation efficiency and as a design driver for WTIVs and the OWTs themselves. For example, the WTIV is designed to take the high deck loads of a complete turbine towers, which in turn also need to be designed for the high acceleration loads of a WTIV in heavy seas. WTIVs can be quite stiff, given their wide beams compared to their draught and low GM.



Figure 5 – Nacelle being lifted onto a tower

However, reducing the number of required lifts is not necessarily a logistical benefit since the deck space required for sea fastening larger assemblies could be outweigh the benefit of requiring more lifts and on-site assembly. For example, a particular WTIV may be able to carry two 5MW OWTs each with two blades pre-assembled onto the nacelle but may be able to carry four turbines without blades attached.

The distance from the OWT staging or loadout port is another critical factor, since shorter distance may favour more pre-assembly, while a longer distance may favour carrying more OWTs even if they require more on-site assembly.

3.2 POSITIONING & JACKING

Having arrived at the windfarm construction site, the WTIV will engage its Dynamic Positioning (DP) system to manoeuvre into the desired location and position. The vessels thrusters must hold the position precisely while the legs are jacked down to the seabed.

After touch-down, the legs must be jacked down quickly to pin the vessel onto the seabed after which the DP system and thrusters can be secured. Typically, the spudcans will penetrate into the seabed by about 5 to 10 meters.

Once pinned, but before the vessel can be jacked above the sea surface, the legs will be pre-loaded one or two legs at a time to about 150% of the nominal standing load. Thereafter, if any leg experiences a seabed punch-through when the vessel is standing out of the water the remaining legs should be able to support the vessel.

The jacking height will depend on either clearing surface waves or raising the crane to increase the lifting height. Typically, a WTIV will jack at least 5 meters above the surface to ensure a rogue wave will not upset the vessel when jacked and during crane operations. Such a disturbance could result in severe damage or destruction of the legs or crane.

3.3 CRANE OPERATIONS

The WTIV can begin construction operations once securely jacked into position. When installing foundations piles, the main crane will lift the piles into a hull mounted pile gripper and then hammer the piles into the seabed with a hydraulic hammer.

More massive gravity and jacket foundations with suction buckets are lowered into position on the seabed. Other vessels may be used to pump water out of the suction buckets and laydown rock beds for scouring protection.

After the pile has been hammered into the seabed, the transition piece will be lifted and lowered over the pile and grouted into place. Gravity bases and jackets generally do not require a separate transition piece for attachment of the turbine tower.

The OWT topside construction can start after the foundations have been installed. This will usually involve the deck of the WTIV being stripped of foundation construction equipment and sea-fastenings and refitted for carrying OWT topside components – the towers, nacelles and blades.

Once jacked in position, the WTIV main crane will typically only require between 3 and 5 lifts to install the topside components and this is normally accomplished in a 24 hour day.

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Custom lifting yokes for each component are used. The blade yoke has become increasingly complex to enable remote adjustment of blade tilt and rotation in many axes to compensate for wind loads and precise alignment with the hub fittings. A single blade for a 6 MW turbine is about 75 meters in length and weighs 25 tons.

3.4 UNJACKING

Once the cranes are parked in the boom rests and secured, un-jacking can begin. This process involves not just lowering the vessel back into the sea, but also extracting the legs out of the seabed which they may have penetrated up to a depth of 10 meters. See Section 4.2(c) for further discussion of spudcan design.

When the vessel is un-jacked and being supported by the sea, if leg extraction is difficult, legs may be partially extracted one or two at a time to ensure that the transition from pinned to thruster control can be achieved quickly. Often, an unjacked vessel will start moving to the next site with legs not fully retracted. This is to save time and use the motion of the vessel to clean away any seabed that may be covering the leg or spudcan.

4 SPECIAL DESIGN ASPECTS

4.1 DESIGN DRIVERS

The design of WTIVs is highly complex, due to the demanding operational requirements and the unusual necessity as a ship to function out of the sea. When trying to breakdown a complex problem, it is instructive to understand the primary requirements and how they relate to the main systems of the vessel. For a WTIV the main systems that effect the capability of the vessel are the hull, legs, crane and propulsion system. The importance and interdependencies of these systems to the WTIV capability can be seen in the following table.

	Design Drivers vs System	Hull	Legs	Crane	Propulsion
Cargo	Deck area	H	H	M	-
	Deadweight	H	H	M	M
	Lift load	M	H	H	-
	Lift height	-	H	H	-
Environment	Min. water depth (Navigating)	H	L	-	H
	Max. water depth (Jacking)	-	H	-	-
	Water current	M	L	-	H
	Wind speed	L	M	M	H
	Air draught	-	H	M	-
Performance	Vessel speed	H	L	-	H
	Jacking speed	-	H	L	L
	Maneuvering redundancy	L	-	-	H
	Punch-through redundancy	M	H	-	-
TOTAL	Design Dependencies	20	29	15	18
TOTAL	System Interdependencies	96	107	74	71

Table 2 – WTIV design dependencies

When the system interdependencies are tabulated and then expressed graphically, it becomes clear that the legs are the most important WTIV system in terms of both the vessels capability and also the effect on the other system.

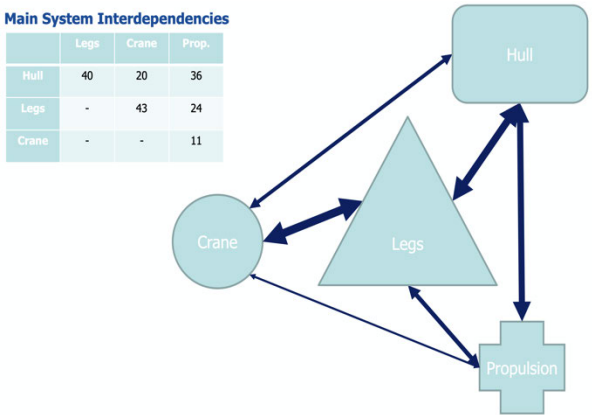


Figure 6 – Main system interdependencies

4.2 LEGS & JACKING SYSTEM

The two main design decisions for the legs system is the number of legs and type of leg. This is highly complex subject in itself, so the discussion here will be necessarily simplified.

4.2 (a) Number of Legs

There are a number of factors when considering the number of legs for a WTIV. These include:

- Effect on deck space
- Effect on hull shape
- Effect on hull strength
- Effect on leg load balance
- Effect on crane accessibility
- Stability of the jacked vessel
- Stability in case of leg punch-through
- Cost

Since the legs system can be nearly half the cost of the WTIV, there is a strong incentive to minimise the number of legs. The lowest practical number of legs for a WTIV is three legs. Although most vessels have four legs and some also have six legs.



Figure 7 – Examples of various number of legs

Six legs provides for the best hull in terms of shape and strength and also is most stable and safe from punch-throughs. On the downside, having more legs places compromises on the deck space and crane accessibility and costs more.

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It should be noted that while cost increases with the number of legs, it is not linear with fewer legs needing to be stronger. The pros and cons can be seen in the following table. Four legs are justifiably the most common.

	Deck space	Ship shape	Hull struct.	Load balance	Crane access	Jacked stability	Punch-through	Cost	TOTAL
Weight	M	L	L	L	M	H	H	M	
3 Legs	+	-	+	+	+	-/+	-	+	32
4 Legs	+	-/+	-/+	-/+	+	+	-/+	-/+	37
6 Legs	-	+	+	+	-	+	+	-	33

Table 3 – Number of legs & weighted score

4.2 (b) Type of Legs

There are two main type of legs used for jack-up vessels. Plate legs are normally built up from rolled or fabricated steel plates into cylindrical or square section legs. Plate legs use hand-over-hand jacking systems. Truss legs are built up from rolled tubular steel sections into a triangular truss structure. Truss legs use rack-and-pinion jacking systems.



Figure 8 – Plate legs (L), Truss legs (R)

For early WTIVs, plate legs where primarily used due to their lower cost. However, as demand for jacking in waters deeper than 40-50 meters has increased, truss legs have been favoured due to their lighter more efficient structure and faster jacking speed, albeit at a higher cost.

Compared to jack-up drilling rigs, that are designed to jack a few dozen times in its life, the legs of a WTIV must be designed for at least 2,500 cycles, with future vessels designed for over 5,000 cycles. This is generally achieved by increasing the number jacking motors to spread the load on the leg racks.

Rack-and-pinion jacking systems are also faster than hand-over-hand. This is especially important as WTIVs will spend much of their time jacking up and down.

4.2 (c) Spudcans

The spudcans at the foot of the legs must support the WTIV when jacked-up. They must be designed to cope with a variety of seabed conditions from silt and clay to sand and rock. The main design factors of the spudcan are their foot area and bottom shape.



Figure 9 – Spudcan & leg being lowered into leg well (Samsung HI)

The spudcan area will determine the ground pressure and seabed penetration. Typically, a WTIV will have a standing ground pressure of 40-60 tons per square meter. Larger spudcans are more costly and complicate the construction of the vessel if they cannot pass through the leg wells.

Harder clay type seabeds can be problematic if the legs do not penetrate deep enough. The spudcans could slide and cause the legs to bend. The spudcans bottom will often have a skirt or centre cone to prevent sliding on such seabeds. The seabed conditions and geology of each OWT installation site is already well understood from detailed surveying and studies when determining the suitability and foundation design. It may be necessary to modify the spudcans to suit the specific seabed condition.

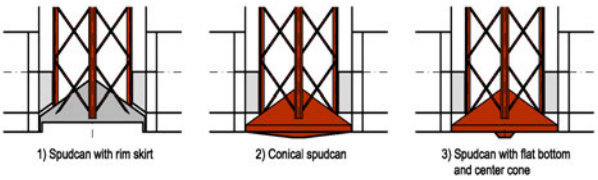


Figure 10 – Spudcan types [4]

In some vessels, the spudcans have buoyancy tanks to counter-act the weight of the leg and reduce the power required for leg retraction. Each leg can weigh many hundreds of tons. The spudcans can also have water or air jetting services to help them break the suction effect when extracting the legs out of the seabed.

4.3 HULL & DECK STRUCTURE

As can be seen in Section 4.1, the hull and leg systems have a high level of design interdependencies. The number and arrangement of legs have a direct effect on the cargo deck layout and the shape of the hull.

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4.3 (a) Hull Lines

The hulls lines of a WTIV are challenging, since the most efficient shape for cargo layout and crane accessibility is where the length and beam are equal. Some WTIVs are designed with a barge type foreship with little or no attempt to streamline the hull. Other vessels, especially those with six legs, are decidedly more ship like.



Figure 11 – Hull types, barge-like (L), ship-like (R)

WTIVs with barge shaped hulls are limited in speed to 8-10 knots, while those with more ship-like hulls are able to achieve 12-14 knots. While the difference may seem quite small, if the construction site is 100 nautical miles away, over the construction period for 100 wind turbines the time saved by the faster vessel could amount to a few months. As windfarms move further offshore, the vessel speed becomes even more significant.

Complicating the hull lines is the necessity to integrate thrusters into the bow and stern area to provide good manoeuvrability. This is covered further in Section 5 – Propulsion.

4.3 (b) Global Loads

The global structure of the hull must be designed for the required hogging and sagging wave forces while navigating but also the leg loads when jacked up. The dead loads can be highly variable depending on the how the OWT components are arranged on deck. Furthermore, the live loads must also be considered during crane operations.

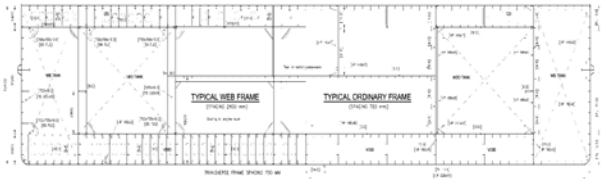


Figure 12 – Typical WTIV midship section [4]

4.3 (c) Local Loads

The cargo deck must be designed for heavy local loads and have the flexibility for different load outs including piles, jackets, towers and nacelles. To enable this a grid of deck hardpoints is arranged at regular spacing both longitudinally and transversely. Typically, such a grid would have a spacing of 1.5 meters and able to take a deck load of 10-20 tons per square meter. Additionally, due to the large acceleration loads that will be experienced, for example by 100 meter high towers in a rolling seaway, the deck must be designed to take both positive and negative vertical loads.

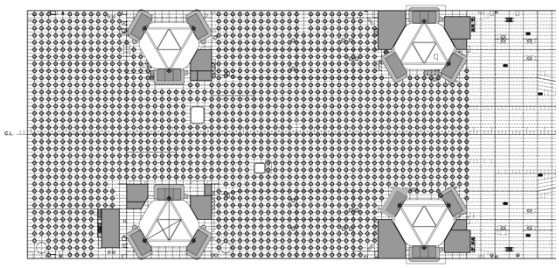


Figure 13 – Typical WTIV deck hardpoints [4]

The deck also needs to have a grinding allowance to for a lifetime of sea fastenings. A three millimetre allowance over an area of 5,000 square meters is over 100 tonnes of steel.

4.4 PROPULSION SYSTEM

The demands placed on the propulsion and manoeuvring system of a WTIV are significantly greater than for other vessels. These include:

- Dynamic positioning
- Thruster installation
- Machinery cooling
- Fuel systems

4.4 (a) Dynamic Positioning (DP)

With the need to manoeuvre precisely, WTIVs usually have a DP2 propulsion system to provide redundancy and safety in case of equipment failure, such as a generator engine or thruster. Higher specification vessels will employ at least four generators, three bow thrusters and three stern thrusters to achieve a reasonable DP2 performance.

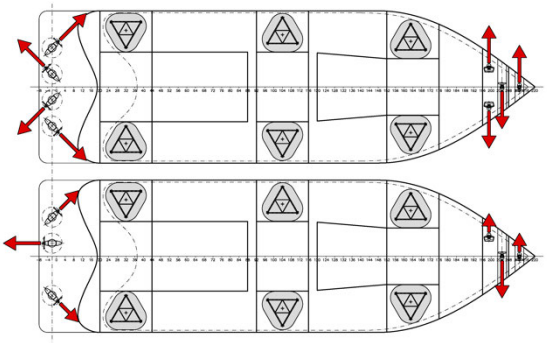


Figure 14 – Intact DP (T), Thruster failure (B) [4]

Dynamic Positioning modelling and control systems must be programmed for a vessel with a highly variable geometry. The forces from wind, waves and currents can change significantly when the legs

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are extended and retracted. The largest WTIVs have about 4,000 square meters of leg area exposed to wind and ocean currents. The required thruster force to counter a 40 knot wind load or one knot current on the legs alone is about 100 tons bollard pull.

During jacking operations, when the legs touch-down onto seabed the DP must be put into a low-gain control mode to prevent the thrusters fighting against the legs. The same applies to the transition between from being pinned by the legs to floating free when the legs are being retracted.

4.4 (b) Stern Thruster Installation

The barge like hull of the WTIV provides a number of challenges for installation of thrusters. At the stern, the wide beam and relatively shallow draft of the vessel can cause thruster ventilation when rolling in a seaway. An azimuth thruster can have a thrust loss of about 75% with just 5% propeller emergence. Thruster ventilation will result in impact loading on the transmission with potential damage and failure of gear teeth.

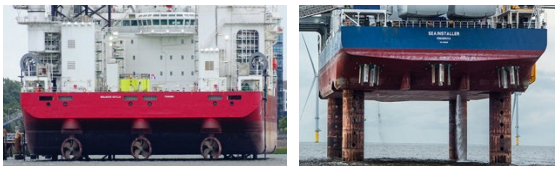


Figure 15 – Azimuth thrusters (L), Cyclic propellers (R)

By placing the thrusters closer to the centreline to reduce the occurrences of propeller emergence will reduce their effectiveness due to increased thruster shadowing. Many WTIVs are using podded thrusters with integral motors and no geared transmission, or cyclic propellers that are not adversely affected by thruster ventilation.

4.4 (c) Bow Thruster Installation

Installation of tunnel type bow thrusters on WTIVs is complicated by the wide beam and short foreship. Thrusters in long tunnels cannot produce full thrust due to frictional loses. Using azimuthing thrusters at the bow is difficult unless the thrusters are below the hull which would increase the vessel draught significantly from about 6 meters to 9 meters, which would limit operations in shallow coastal waters.

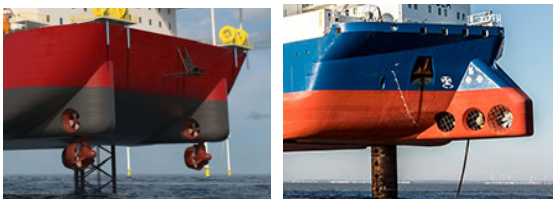


Figure 16 – Azimuth thrusters (L), Tunnel thrusters (R)

Many recent WTIV's are using a combination retractable azimuth thrusters and tunnel thrusters. Retractable thrusters are more complex and expensive but are necessary to provide adequate thrust at the bow without compromising shallow water operations. Directional stability of the short and wide WTIVs hulls is poor, especially in following seas and bow mounted azimuthing thrusters can be used to provide more effective course keeping.

An additional complication for thrusters on WTIVs is the shaft seals will undergo constant pressure cycling as they subjected to water pressures of up to 10 meters and then to atmospheric pressure when jacked-up. The thruster's lubrication systems must be designed for this operational cycling.

4.4 (d) Machinery Cooling

Ships use vast quantities of seawater to cool their machinery systems. Typically, for every megawatt hour of propulsion or electrical energy produced, a megawatt hour of heat is created and absorbed by the sea. When a WTIV is jacked-up, there is no direct access to seawater for cooling.

A number of solutions for machinery cooling have been used on WTIVs. Some early vessels used air-cooled radiators, although as the vessels became larger, this became impractical due to the size of the radiators needed. Some vessels use a closed-circuit seawater recirculation system in double-bottom tanks, with the hull bottom acting as a large radiator surface. The volume of seawater needed is considerable, hundreds of tons, and limits the deadweight available for the cargo. Cooling effectiveness also decreases as the ambient sea and air temperature increases to the point of being ineffective at about 20 degrees Celsius.

The method used by most WTIVs today is to use submerged pumps that are connected to the leg structure, or that can be lowered separately into the sea with flexible hoses and a reel management system. These pumps need to lift the seawater about 20-30m and are often driven by hydraulic motors and power packs adding to the complexity of the set-up.

4.4 (e) Fuel System

The load-out port is normally as close to the new wind farm as possible, so the time the WTIV spends in transit is minimised. Therefore, fuel consumption has not been a high priority for operators and designers. However, with increasing international commitments to mitigate climate change, operators are looking at ways to improve the green profile of their WTIV's.

Some of these initiatives include looking at greener fuels such as LNG and methanol. Although these fuels require a larger volume for the bunker tank

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because of gas fuel requirements and lower calorific value (methanol), finding adequate space within the vast WTIV hulls has not posed a problem.

The WTIV spends much of this time with generators running but only lightly loaded. This wasteful 'spinning-reserve' is needed for immediate power availability and not waiting for generators to be started. This normally happens when manoeuvring with thrusters or during crane operations.

Spinning-reserve can be usefully employed to charge batteries. Power from the batteries can then used when demand is high instead of needing another generator to be brought on-line. This concept is known as peak-load-shaving. Furthermore, rack-and-pinion leg jacking systems are able to recover about 60% of the jacking-up energy to batteries when the vessel is jacking down. A single jack takes about 10 megajoules of energy.

4.5 CRANE SYSTEM

The crane is the main tool of the WTIV and is well known in the market that crane capacity is one of the main limitations preventing current vessels from being hired. The main factors considered for the crane specification and installation on a WTIV are:

- Load radius
- Load height
- Crane installation

4.5 (a) Load Radius

Most current WTIVs cranes are able to lift about 1,200 tons but only at a load radius of about 10 meters. Since the crane will need to access OWT components over the entire deck, the useful load radius is about 300 tons at 40 meters. This is about the weight of current 5-8 MW wind turbines.

The load radius of future OWT in the 12-15 MW class will be requirement 500 tons at 40 meters. This corresponds to a crane with a maximum load of at least 2,000 tons. However, many vessels that are being built today have cranes specified to about 3,000 tons, to future proof and give more flexibility for lifting heavy foundations.

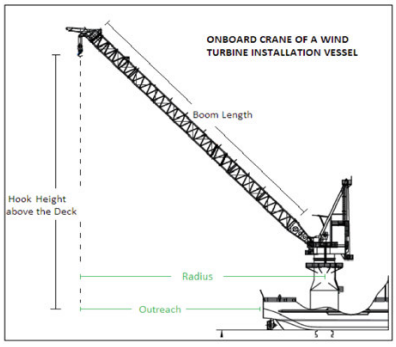


Figure 17 – Crane load radius nomenclature [5]

4.5 (b) Load Height

The other critical crane dimension is the load height. This is normally determined by the crane boom length, in the case of lifting from the deck. However, for a WTIV when lifting to sea level there are other factors such as leg length, water depth and the jacking height. The boom length has grown from 100 meters to over 150 meters for the next generation of WTIVs.

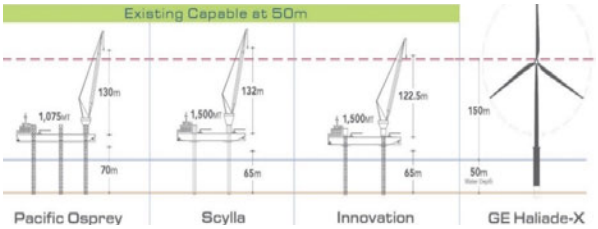


Figure 18 – Crane load height in 50m water [6]

For example, a WTIV crane may only be able to lift a tower piece 80 meters high off the deck, but it will be able to lift a nacelle onto the installed tower even though the tower is 95 meters above sea level. As OWT constructions methods have matured, installation of towers in a single lift is now the norm since it reduces deck space and installation time.

4.5 (c) Crane Installation

Where to locate the crane on the deck is another key design aspect. The crane must have good access to all the whole deck and be able to work within space restrictions created by the legs. It must also be possible to secure the long crane boom on a boom rest when the vessel is afloat.



Figure 19 – Leg work-around crane lifting 350t nacelle

Some common crane locations have been between the aft legs, in the vessel centre and directly next to a leg. As cranes have grown from a few hundred tons capacity to over 1,000 tons, the physical size of the cranes have grown to a point that the crane itself occupies a significant amount of the deck space. Therefore, it has now become the norm to have a work-around crane located around the aft starboard leg. It may seem that this location would place more load on the host leg, however a typical heavy load adds only about 2-3% over the static leg load. Also

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ballast water transfer can also be used to help balance leg loads during very heavy lift operations.

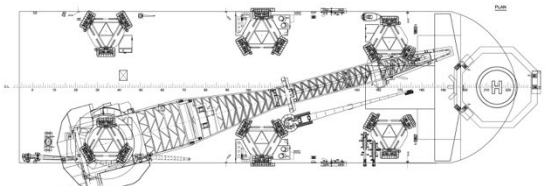


Figure 20 – Leg work-around crane deck layout [4]

The extreme crane boom lengths have created challenges in how to arrange the boom rest. One design is to have a complex tapered boom arrangement so that the boom will fit between the forward legs. Another solution is a parallel twin boom that will sit over the front leg. Although this simplifies the crane design and cost, the vessel must always jack-up before the boom can be luffed in or out of the boom rest.

5 FUTURE DEVELOPMENTS

5.1 TURBINE INSTALLATION VESSELS

It is clear that the development of the WTIVs is closely tied to the growth of OWTs. In addition to maturing construction methods, larger OWTs have been key in driving down the cost of offshore wind energy. With floating OWT still in its infancy, larger WTIVs are recognised as the only options for installing fixed bottom OWTs.

KNUD E. HANSEN has been active in developing these next generation of WTIVs for a number of leading European offshore construction companies. The following table compares some of the vessel principal particulars. These vessels have a newbuild cost of about 450 MUSD.

Operator	Jan De Nul	Van Oord	KEH
Name	Voltaire	-	Atlas C
Year in service	2022	2024	Concept
Length (LOA)	170 m	175 m	170 m
Moulded beam	60 m	-	60 m
Hull depth	14.6m	-	13.2m
Design draught	7.5m	-	6.5m
Cargo area	7,000 m^2	-	6,800 m^2
Jack deadweight	16,000 tons	-	18,000 tons
Crane max. load	3,000+ t	3,000+ t	3,000 t
Crane load height	163 m	-	160 m
Max. water depth	80 m	70+ m	80 m
Speed	11.5 kn	-	12.0 kn

Table 4 – Principal particulars of recent WTIV by KEH

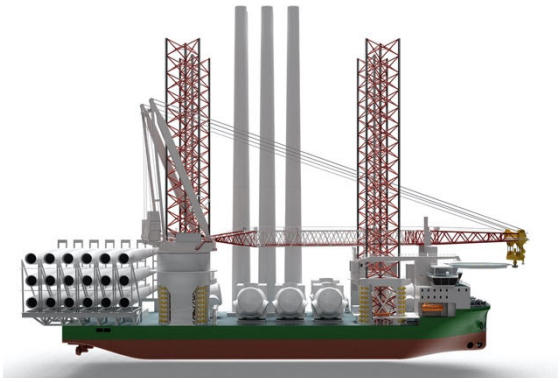


Figure 21 – Atlas C (KEH concept design)

5.2 OTHER CONSTRUCTION VESSELS

While self-sufficiency has continued to be fundamental to the WTIV concept, specialisation is increasing as offshore windfarms move into deeper water and construction methods mature. WTIV are highly complex and expensive vessels, whose hire time must be optimised to reduced construction costs.

As windfarms move into deeper water, the foundation type has changed to the gravity and jacket type that do not require the high level of handling precision for installation compared to the mono-pile type. Furthermore, the weight and size of these foundations are considerably more massive than the wind turbines they are supporting. Therefore, installation of foundations is changing to vessels with even larger cranes and greater deck space than WTIVs. However, despite being even larger than WTIVs, these vessels do not need expensive legs to jack-up.



Figure 22 – Heavy lift vessel for foundation installation (Jan De Nul)

In further specialisation, the WTIV only undertakes the physical erection tasks of the OWT on-site. Once construction is complete, the WTIV will move onto the next wind turbine installation. The final set-to-work and testing of each wind turbine is carried out by smaller and less expensive Commissioning Service Operation Vessels (CSOV) which may take a few days to complete.

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5.3 DESIGN USING VIRTUAL REALITY

The concept 3D model of the vessel is being used by the client for various internal and external communication and promotion purposes where a realistic visual impression of the future vessel is needed. The model is also brought into ShipSpace™, a virtual reality design review and collaboration tool. This is particularly useful with the complex geometric relationship between the crane, legs and cargo on a WTIV.

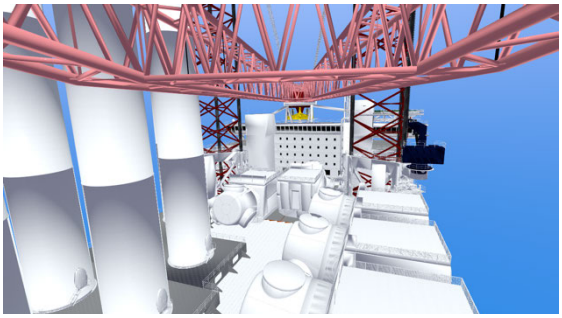


Figure 23 – VR review of WTIV crane operations (ShipSpace™)

The detailed model enables also the owner, crew and other stakeholders to review and comment on the vessel arrangement from a human factor engineering perspective. The ShipSpace™ system enables users to explore and investigate the entire vessel in virtual reality, which has proven to enable more accurate, thorough and much richer feedback from stakeholders and subject matter experts when compared to looking at drawings or pictures of the vessel. Users often comment that the convincing experience provided by the ShipSpace™ system is akin to being on board a real vessel.

As the basic design is finalised and detailed drawings and 3D models are received from the shipyard, ShipSpace™ is being used to verify that the final design elements will meet with the initial capabilities specified and also any operational concerns, such as accessibility to equipment for maintenance.

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7 LIST OF TABLES & FIGURES

TABLE 1 – PRINCIPAL PARTICULARS OF SOME WTIV BY KEH 2
TABLE 2 – WTIV DESIGN DEPENDENCIES 4
TABLE 3 – NUMBER OF LEGS & WEIGHTED SCORE 5
TABLE 4 – PRINCIPAL PARTICULARS OF RECENT WTIV BY KEH 9

FIGURE 1 – OFFSHORE WINDFARM PRINCIPAL PARTICULARS [2] 1
FIGURE 2 – OFFSHORE WIND TURBINE MAIN COMPONENTS & FOUNDATION TYPES [3] 2
FIGURE 3 – WORLDS FIRST WTIV, MPI RESOLUTION 2
FIGURE 4 – INSTALLATION METHOD & REQUIRED LIFTS [3] 3
FIGURE 5 – NACELLE BEING LIFTED ONTO A TOWER 3
FIGURE 6 – MAIN SYSTEM INTERDEPENDENCIES 4
FIGURE 7 – EXAMPLES OF VARIOUS NUMBER OF LEGS 4
FIGURE 8 – PLATE LEGS (L), TRUSS LEGS (R) 5
FIGURE 9 – SPUDCAN & LEG BEING LOWERED INTO LEG WELL (SAMSUNG HI) 5
FIGURE 10 – SPUDCAN TYPES [4] 5
FIGURE 11 – HULL TYPES, BARGE-LIKE (L), SHIP-LIKE (R) 6
FIGURE 12 – TYPICAL WTIV MIDSHIP SECTION [4] 6
FIGURE 13 – TYPICAL WTIV DECK HARDPOINTS [4] 6
FIGURE 14 – INTACT DP (T), THRUSTER FAILURE (B) [4] 6
FIGURE 15 – AZIMUTH THRUSTERS (L), CYCLIC PROPELLERS (R) 7
FIGURE 16 – AZIMUTH THRUSTERS (L), TUNNEL THRUSTERS (R) 7
FIGURE 17 – CRANE LOAD RADIUS NOMENCLATURE [5] 8
FIGURE 18 – CRANE LOAD HEIGHT IN 50M WATER [6] 8
FIGURE 19 – LEG WORK-AROUND CRANE LIFTING 350T NACELLE 8
FIGURE 20 – LEG WORK-AROUND CRANE DECK LAYOUT [4] 9
FIGURE 21 – ATLAS C (KEH CONCEPT DESIGN) 9
FIGURE 22 – HEAVY LIFT VESSEL FOR FOUNDATION INSTALLATION (JAN DE NUL) 9
FIGURE 23 – VR REVIEW OF WTIV CRANE OPERATIONS (SHIPSPACE™) 10

8 AUTHORS BIOGRAPHY

Ken Goh holds the position of General Manager, at Knud E. Hansen Australia and specialises in mechanical engineering and advanced concepts in ship design. His project experience includes ferries, cargo, offshore, research, icebreakers and naval vessels. He is also active in the development of autonomous and wind powered vessels.

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Development of Nauti-Craft's 3rd Generation Deck Pitch and Roll Control System

Liam MacFarlane - Nauti-Craft - liam@nauti-craft.com

Laurie Walker - Nauti-Craft - laurie@nauti-craft.com

ABSTRACT

In 2015, Nauti-Craft developed its original Deck Angle Control System (DACS) as an additional capability for its unique multihull vessel suspension system. This system enabled the pitch and roll of the deck of the prototype vessel to be reduced by 75% while the vessel was loitering. The objective of the system was to provide a stabilised deck to facilitate improved occupational health and safety for commercial and military marine applications.

The developed system incurred significant weight penalties on the vessel and required a substantial power input to provide the active deck control capability.

After five years of development, two subsequent generations of DACS were identified and simulated, with the purpose of improving responsiveness, reducing system weight, and decreasing power consumption.

Both the 2nd and 3rd generations of DACS were developed using MSC Adams multibody physics simulations combined with control algorithms created and validated using Matlab Simulink. While the 2nd generation offered substantially increased responsiveness and a 10% reduction in both weight and power through simulation, this was insufficient to justify completion of development through to system build.

The 3rd generation system comprised an entirely new hydraulic control philosophy, improved responsiveness, a weight saving of almost 30% and a power reduction of 70% over the original system.

This paper describes the evolution through the 2nd generation system and onto the development of the 3rd generation system. It then describes how the use of Adams simulation modelling has been used in the DACS development, and the results of the 3rd generation developmental testing programme.

INTRODUCTION

Background

In the commercial, defence and search and rescue sectors, where operators must transit in adverse conditions, shock load levels cause substantial OHS risks. The original purpose behind the invention of the nauti-craft^{TM} suspension system was to reduce the shock load, or what is termed Whole of Body Vibration (WBV), experienced by the operators and passengers of high-speed marine craft. This goal was realised by effectively separating the main deck from the hulls of a catamaran and installing a passive hydraulic suspension system on each corner, with internal hydraulic interconnections to enhance ride quality (see Figure 1).



Figure 1: Demonstration of the shock mitigation ride control benefits of the nauti-craft suspension system during high-speed transit using the 8m prototype vessel.

After years of development, an additional system dubbed the Deck Angle Control System (DACS) was installed, to actively control the angle of the deck relative to the hulls. DACS is used for several features on the nauti-craft suspension system, including “roll-in”, where the deck is banked-in during corners at high-speed, and “loitering stabilisation”, where the pitch and roll angles experienced on the deck while loitering in rough sea conditions are reduced. This paper focuses on the “loitering stabilisation” feature (see Figure 2).



Figure 2: Demonstration of the loitering stabilisation feature in rough seas using the 8m nauti-craft prototype vessel.

Objectives

The objective of this study was to design a Deck Angle Control System (DACS) which interfaces with the nauti-craft passive suspension system. This DAC system must reduce deck pitch and roll angles by at least 50% while the vessel is loitering. The weight and power-demand of the DACS must be significantly reduced, in comparison to the 1st Gen DACS, to feasibly install the system on a nauti-craft suspension-equipped High-Speed Light Craft (HSLC). The performance and power-demand of the system are to be assessed and verified using MSC Adams multi-body dynamics software.

NAUTI-CRAFT DACS EVOLUTION

1st Gen DACS

The 1st Gen DACS was designed to be integrated into the original "Dual H2" suspension system installed on the 8m prototype (see Figure 3). The Dual H2 system consisted of two superimposed hydraulic circuits with one supporting the vessel in pitch and the other supporting the vessel in roll. Each circuit featured a cylinder in each corner, resulting in a total of 8 cylinders on the vessel.

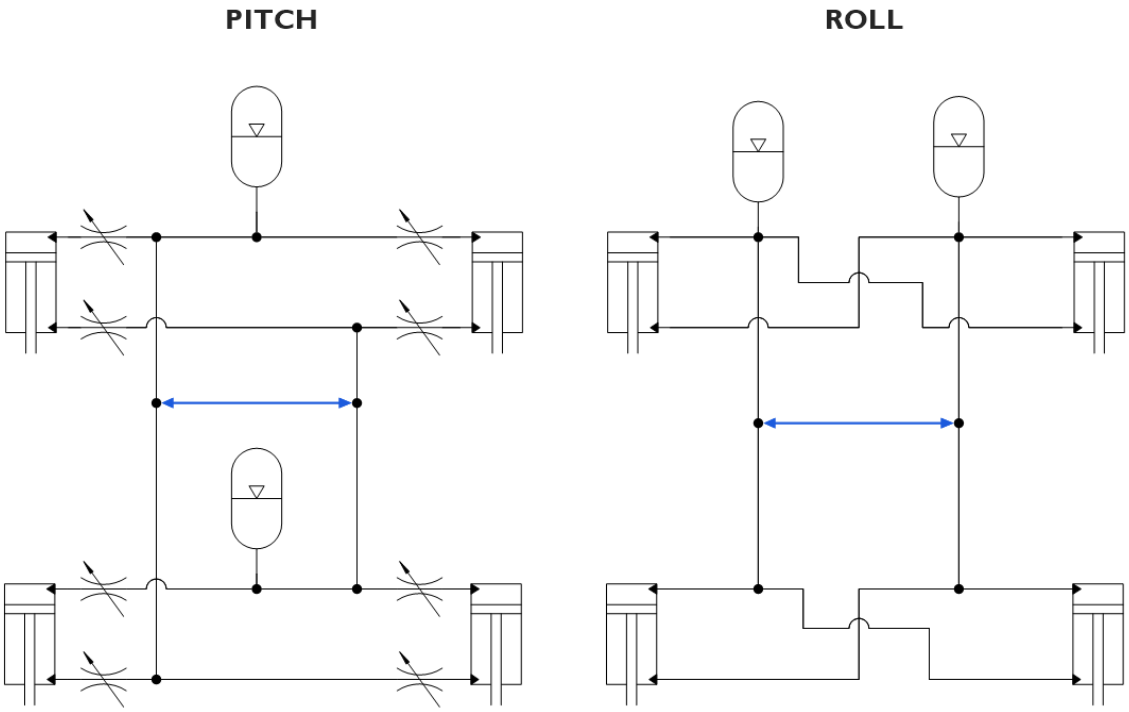


Figure 3: Hydraulic schematic diagram of the original dual H2 configuration used on the 8m prototype vessel. Blue arrows between the system circuits demonstrate the fluid transfer paths for active pitch and roll control.

1st Gen DACS controlled the pitch and roll of the vessel by transferring fluid between cylinders within each of the "pitch" and "roll" support circuits, as depicted by the blue arrows in Figure 3. The responsiveness and controllability of the system was found to be greatly enhanced by removing the accumulators (gas springs) from the hydraulic pitch and roll support circuits

using isolator valves. This configuration was found to offer a 75% reduction in peak loitering pitch and roll deck angles, but this came with significant weight and power penalties.

1st Gen DACS relied upon transferring fluid between cylinders using a "flow intensifier" (see Figure 4). The flow intensifier converts high differential pressure (dp) / low fluid flows to low dp / high fluid flows. This system was developed to enable large volumes of fluid to be rapidly transferred between cylinders to provide the requisite roll and pitch response to achieve satisfactory DACS operation. The flow intensifier was a heavy double-piston, single-rod cylinder with a flow multiplication factor of 3. This meant that while fluid was simultaneously supplied to, and drained from, the corresponding control (inner) chambers of the intensifier at high inter-chamber dp, the system chambers output fluid at three times the input volume at one third of the dp. The intensifier was sized to transfer enough fluid to reach the pitch and roll extremes of the suspension system (e.g. ID=100mm, stroke=320mm for the 8m prototype's pitch circuit) – this made the DACS heavy.

Secondly, the high-pressure supply flow into the flow intensifier was driven by a constant pressure-setpoint Hydraulic Power Unit (HPU) through a proportional directional flow control valve. The supply pressure was set to accommodate the maximum pressure required, with control valve fully open, in the worst case loitering stabilisation operation. Often when an intensifier movement was required to correct the deck pitch or roll, the forces imparted by the support circuit dps did not resist, but in fact assisted the movement. Although in these instances, no pressure was required to move the intensifier, the HPU pressure was being used to drive the motion, resulting in excessive heat generation over the control valve. This occurred for any movement required by the controller, making DACS highly inefficient. Strict weight- and power-budgets in the HSLC industry necessitated the development of a far more efficient DACS configuration.

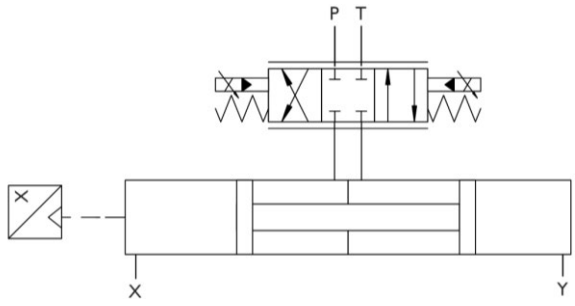


Figure 4: Hydraulic schematic of flow intensifier control circuit.

2nd Gen DACS

During the development of 2nd Gen DACS, weight reduction was sought after by various means. In parallel with the ongoing DACS studies, work was also being undertaken into the development of a simplified 4-cylinder hydraulic arrangement which provided heave, pitch, and roll support. This configuration, dubbed the 2-Half-H system, had been identified as the future of the nauti-craft system for the first range of nauti-craft equipped smaller recreational vessels. This arrangement was preferred for low weight, hydraulic simplicity, and reduced cost, but did not initially feature the DACS function, as it was deemed too costly and complex for the recreational market.

As confidence grew in the 4-cylinder approach and its applicability to larger commercial vessels, the team decided to investigate means of achieving DACS within the 2-Half-H configuration. The solution was found in a system dubbed “DACS X” (see Figure 5). It was determined that by using this configuration, the deck angle could be actively controlled in pitch and roll by pumping fluid between diagonally opposite cylinders.

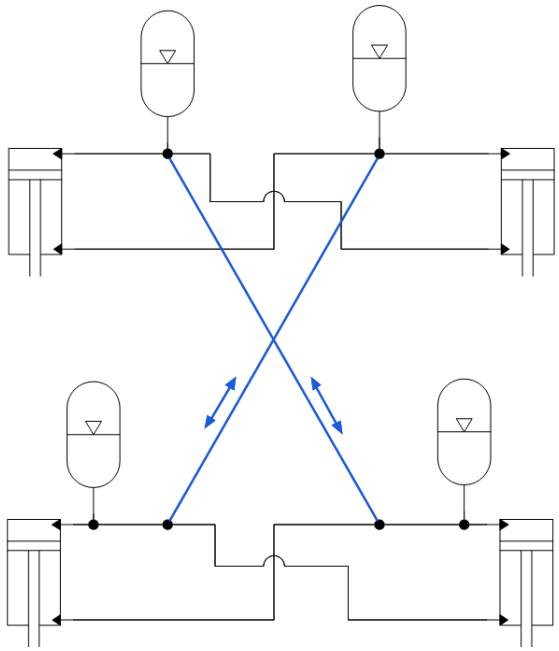


Figure 5: Hydraulic schematic of the 2-Half-H support configuration. Blue arrows between the system circuits demonstrate the fluid transfer paths for active pitch and roll control.

In the DACS X system, pitch of the system could be achieved by pumping fluid in both connections in the same longitudinal direction (e.g. front to rear), while roll was achieved by pumping fluid in both connections in the same transverse direction (e.g. port to starboard). As an example, the shift of fluid from rear to front creates a pitch-up situation, while shifting fluid from port rear to starboard front, and port front to starboard rear creates a roll to port.

Initially the 2nd Gen DACS retained the flow intensifiers to move the fluid, however it was determined that these could be replaced with a proportional directional control valve installed into each corner circuit (see Figure 6). These valves were connected to the constant pressure-setpoint HPU and tank, which could be used to drive each corner up and down. The concept being that one diagonal corner could be driven up while the opposing corner could be lowered in a controlled fashion via the proportional valving.

A further refinement arising from MSC Adams simulations was the observation that often the deck could be controlled to remain level by allowing fluid to flow freely between diagonal cylinders. For example, if the suspended mass had a naturally heavier end and fluid was allowed to flow between diagonal cylinders, then the vessel would “fall” down on that end. If the flow of this fluid was controlled through proportional interconnection valving, the angle of the deck could be maintained at, or close to, level whenever the heavy end is lifted by an incoming wave. This concept was termed “passive DACS” as it did not require input power, only the control of passive fluid flow to prevent the deck from “falling over”.

Further iteration of this system through Adams simulations enabled us to determine that in balanced load cases, very large percentages of a deck angle control operation could be achieved through passive DACS, due to the inertial and dynamic effects of the mechanical system. These simulations also showed that there were large variations in power consumption across different headings and sea states. In some instances when wave periods coincided with the appropriate vessel Response Amplitude Operators (RAOs), the suspension system was excited by the sea state, generating large quantities of heat power due to the damping required in passive DACS. In other situations, substantial input power was required to actively drive the suspension to achieve satisfactory deck levelling performance.

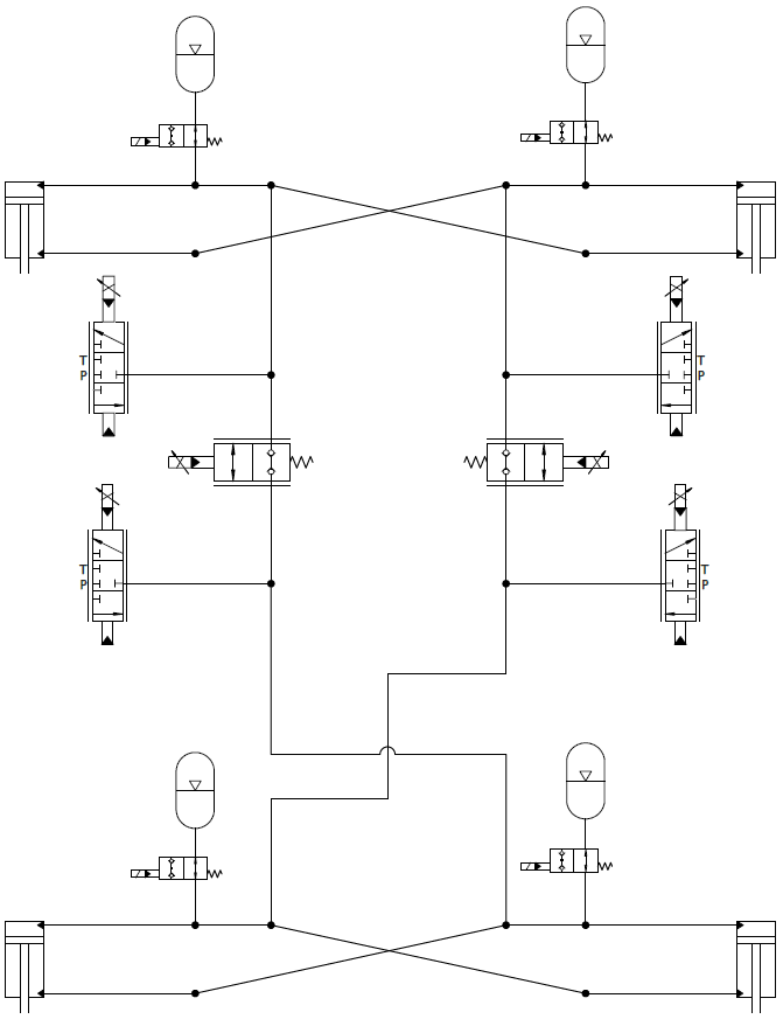


Figure 6: Hydraulic schematic of the 2-Half-H support circuit including 2nd Gen DACS valving.

Although the weight and power improvements made by the 2nd Gen DACS were promising, the HPU still required a high pressure setting, as it had to be set relative to the gauge pressure of the support circuit rather than the delta between the circuits. Also, while in some instances power consumption was minimal, in other instances power consumption was up to 90% of that of Generation 1. This resulted in less of a power reduction than required to meet the project target. As a result, further development of the DACS was warranted.

3rd Gen DACS

As outlined above, the new 4-cylinder approach dubbed the 2-Half-H arrangement contained both springing and damping functions within a single hydraulic cylinder on each corner of the vessel. This system was a step change improvement in cost, weight and complexity when compared to the previous system for smaller recreational vessels.

A challenge arose, however, as the team investigated vessel designs greater than 20-30t. As these vessel weights increased, cylinder sizes in the 4-cylinder arrangement became disproportionately large and heavy. Adams analyses of these vessels indicated that the hydraulic system flows arising from the superposition of damping and springing deployed through the same cylinder created highly inefficient system configurations. The simple solution to this issue was to separate the system back into an 8-cylinder arrangement with 4 support cylinders and 4 damping cylinders. An example of this can be seen in Figure 7 where the support and damper cylinders can be seen on the swingarm with the bump-stop cylinder separating them.

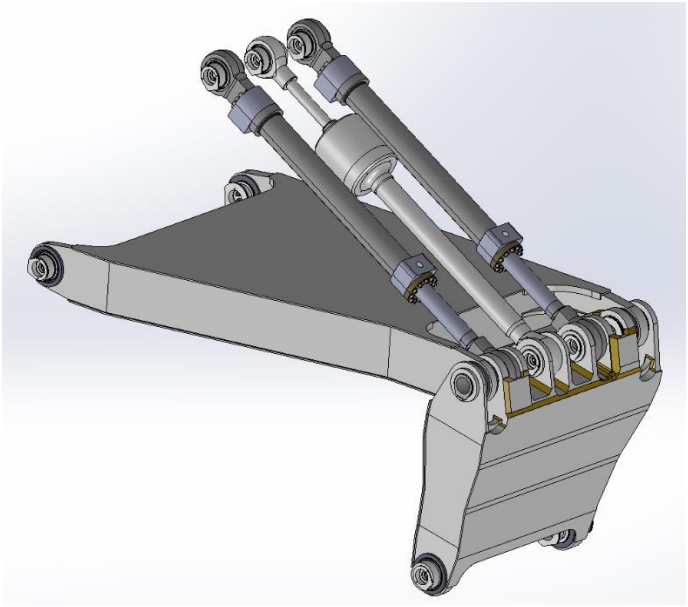


Figure 7- Front Swingarm- Support cylinder left, bumpstop centre and damper cylinder right.

While the DACS X system identified previously would have been feasible under the new 4 support/4 damping cylinder configuration. The team conducted a high-level review of the new 4 support + 4 damping cylinder configuration to identify any potential methods for achieving Deck Angle Control while further reducing weight and power consumption.

The solution to this came from adding the DACS actuation capability to the damper cylinders to create “DACS units”. The new DACS units (one per corner) could be used to not only damp the suspension motion during transit operation, but could also actively drive the roll and pitch of the suspension during loitering stabilisation. To achieve this, the support circuit first needs to be interconnected in the “X” formation as in Figure 5, such that it provides the heave support, but no roll or pitch support. Once the support circuit is interconnected and free in pitch and roll, the deck can be pitched and/or rolled through the position control of a pair of DACS units at either the front or rear of the vessel. As the support cylinders are hydraulically

connected diagonally and mechanically connected to the DACS cylinders, an actuation at the port front DACS cylinder produces an equivalent displacement in the port front and starboard rear support cylinders, one compressing and the other extending. In this way, only two of the four damper cylinders are required to act as DACS units to provide the DACS capability. In addition to this, with the deck fully supported in heave by the support cylinders, the hydraulic power required to impose pitch and roll motions can be reduced substantially when compared to the power required to pump fluid into and out of the support circuits as in the 2nd Gen solution.

To convert the damper units to DACS units, proportional directional flow control valves ("Active valves") connected to pump and tank lines, are added in parallel to the valving in the damper units. An orifice isolation valve is also added to enhance controllability (see **Error! Reference source not found.**). This combination of valves provides a highly efficient means of providing the DACS control, this will be explained further below.

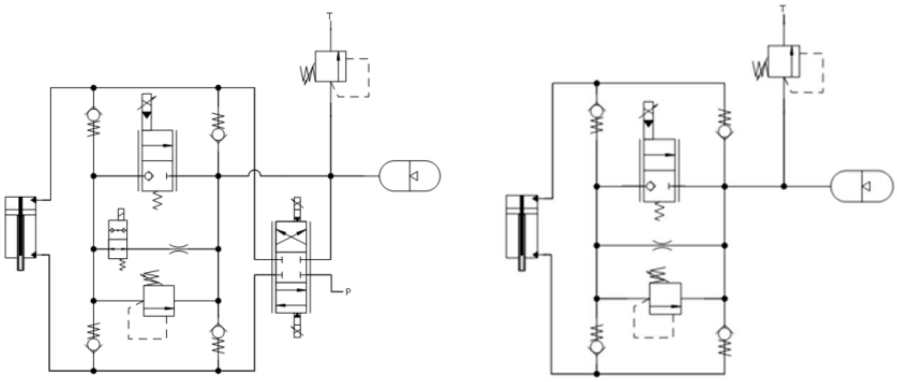


Figure 8: A schematic of a DACS unit (left) and damper unit (right).

3rd Gen DACS also exhibits the passive DACS feature identified in 2nd Gen, with some differences. In 3rd Gen, passive DACS can be achieved by transferring fluid between the top and bottom chambers of the DACS cylinder to control deck angle as required. When this is available, the valve historically used to damp the suspension during transit ("Damper valve") is used to restrict the inter-chamber flow to control the pitch and roll of the deck. If this valve was fully open or omitted from the circuit, the deck would tilt uncontrolled. The elegant reuse of the damper valve in the DACS feature offers a reduction in cost and complexity.

When DACS cannot be achieved via passive means, active control of the DACS cylinders is provided by the active valves. These valves meter high pressure fluid into the upper or lower chamber of a DACS cylinder, while simultaneously draining fluid from the opposite chamber to tank, thus achieving the flow and cylinder velocity required for deck angle correction. One of the key benefits of separating the DACS control from the support circuit is the substantial reduction in required actuation force. This enables smaller cylinders to be installed for a given HPU pressure setting, reducing the flows necessary to achieve the required responsiveness and therefore provides a substantial power saving.

Additional valving is also used in the system configuration; however, its role is outside the scope of this paper.

MODELLING

Overview

To assess the feasibility and performance characteristics of the 3rd Gen DACS, the implementation of the system on an 18m Crew Transfer Vessel (CTV) was modelled in the multi-body dynamics software package, MSC Adams. The model included the hydraulic system characteristics, dynamic/inertial effects of the structural components, mechanical travel limitation forces, and hull-water interaction forces.

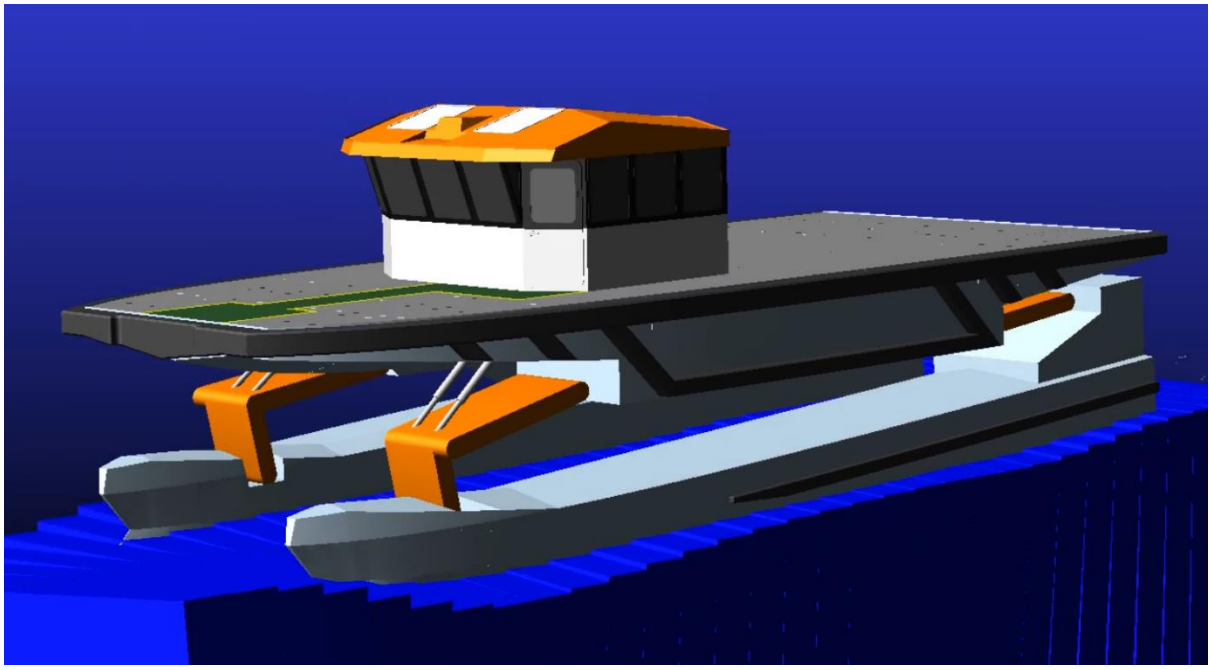


Figure 9: Loitering stability simulation of an 18m CTV in bow-quartering seas created using MSC Adams.

Hydraulic Modelling

The behaviour of the hydraulic support system is simulated using Nauti-Craft's custom discretised hydraulic model (see Figure 10). The fluid in the hydraulic system is modelled as discrete bodies with motions coupled to resemble that of the hydraulic interconnections. Fluid inertial effects are modelled by setting the mass of each body to that of the fluid it represents, while fluid friction is modelled by applying damper forces to each body of fluid according to the oil characteristics and pipework selected. Fluid and line compliance is also modelled using spring-like elements in the circuit with linear pressure-volume stiffness.

For the DACS simulations, the block diagram in Figure 11 was implemented. The pitch and roll rates were measured at the deck and fed through pitch and roll PID controllers, converting the measured angular velocity to a command flow required. The pitch and roll command flows are then summed appropriately to obtain the command flow at the valves connected to the front-left and front-right DACS cylinders, as seen in Figure 7**Error! Reference source not found.**. The command flow is then converted to a command cylinder velocity, which passes through a lag filter representing the valve characteristic to give the actual velocity imposed on the cylinder in the model. For each test case the deck angles, cylinder actuation forces and velocities were exported from Adams to be used in the post-processing.

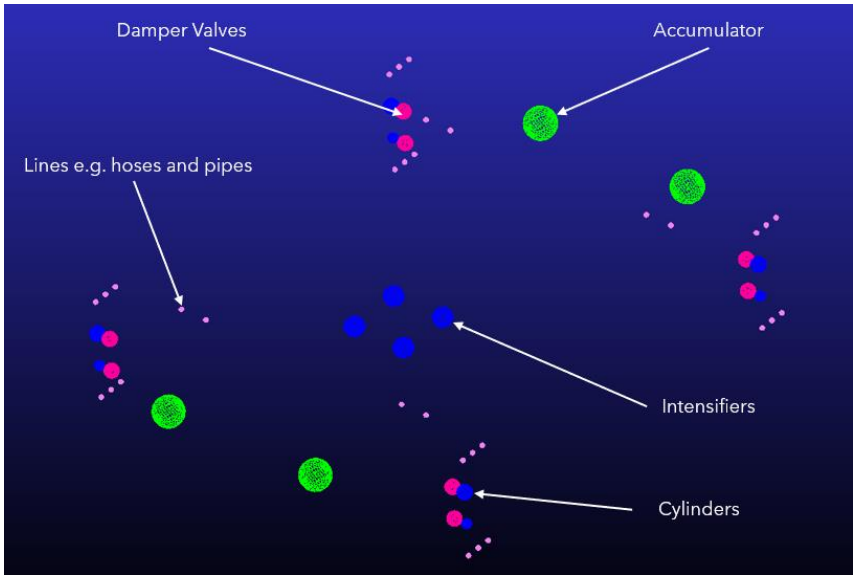


Figure 10: Nauti-Craft's custom discretised hydraulic model created in MSC Adams.

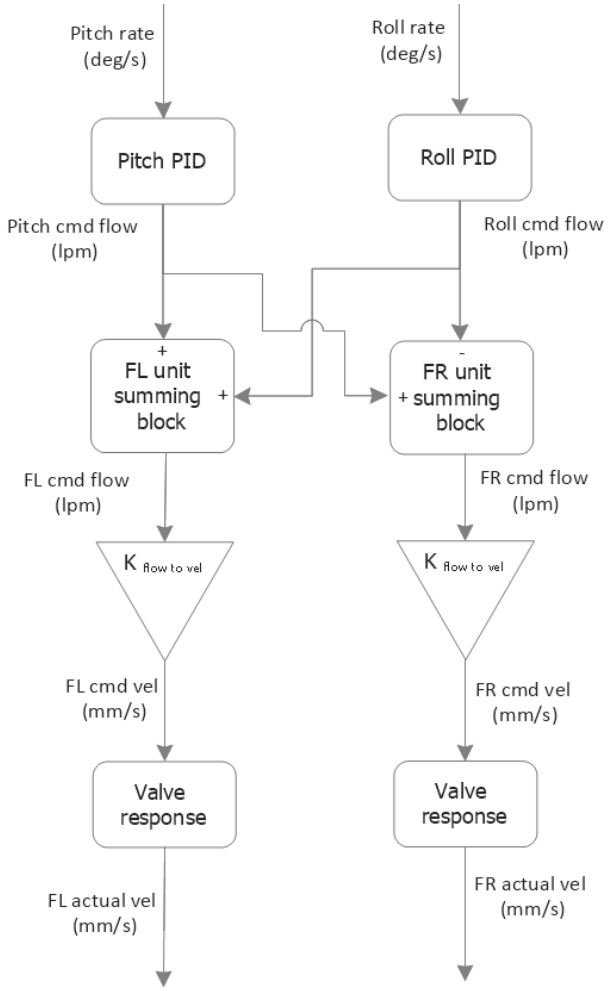


Figure 11: Block diagram of the Deck Angle Control System implemented in the Adams simulations.

Further insight into the frequency response of the system is available via MSC Adams, allowing for the pitch and roll controllers to be fine-tuned to give greater results. A frequency

sweep of the input signal and measurement of the resultant deck angle behaviour was simulated on flat water and used to create open loop bode plots. This allowed for the controllers to be analysed in the frequency domain within the MATLAB Simulink environment.

Hull-Water Interface Modelling

The behaviour of the hull-water interface is simulated using Nauti-Craft's custom discretised water model. As seen in Figure 9, the water surface is discretised into 25 water columns along the length of each hull, which heave and roll according to a predetermined sequence to emulate a given sea state. A JONSWAP spectrum is used to determine the frequency and amplitude of 20 sinusoidal position vs. time waveforms, which are superimposed to define the water height history at a distant wave source. Deep-water wave speed formulae are then used to determine the propagation of each sinusoid component, thus determining the water surface height at each water column position at any given time.

The model uses relative measures between each segment of the hull form and its relevant water column to determine the resultant force exerted on the hull segment by the water. The force calculation includes the hydrostatic buoyancy forces, hydrodynamic wave propagation (damping) forces and added mass characteristic forces.

Post-processing

The data from the Adams simulations were then exported for post-processing to determine the overall performance and HPU requirements.

By comparing the deck angles for a locked vessel and DACS-enabled vessel simulated in the same sea-state, the performance of a given DACS controller could be assessed.

Using the DACS cylinder actuation force and velocity data, it was possible to obtain the pressure and flow requirements at the DACS cylinders for the simulated controllers and sea states. Firstly, the required flow and dp across the DACS cylinder chambers were analysed at each time step to determine whether the cylinder would need to be driven, or whether the required flow could be achieved through the passive DACS e.g. if the cylinder is compressing and the pressure in the over-piston chamber is significantly greater than that of the under-piston chamber. If the cylinder actuation was available via the damper valve, the corner circuit could operate as a closed circuit, requiring no fluid input. However, if the cylinder required to be actively driven, the fluid would need to be sourced from the HPU, which needed to be modelled to estimate efficiency and weight of the system.

A secondary numerical model was created in the post-processor to determine the required sizing of the components in the HPU to supply fluid according to the Adams data. The HPU configuration modelled (see Figure 12) contains a fixed-speed pump-motor unit supplying fluid to maintain a hydraulic accumulator at pressure according to a window set by a pressure switch. Characteristics of the HPU including accumulator volume, accumulator precharge, pressure switch settings, pump-motor rated flow and pressure could then be set to minimise overall HPU weight and electrical power requirements.

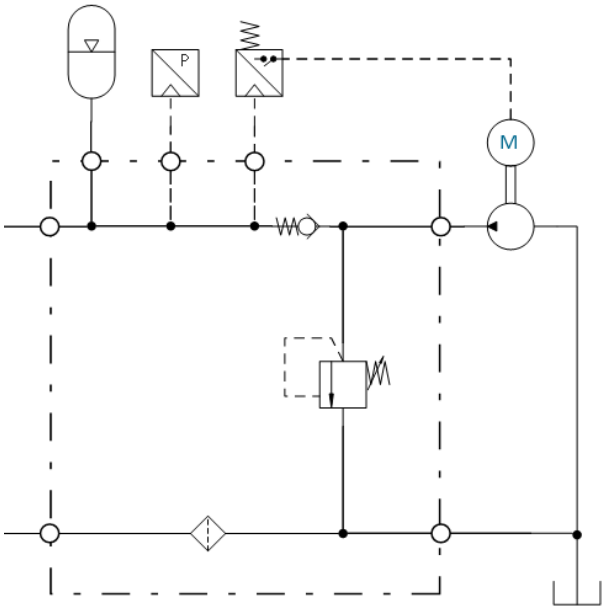


Figure 12: Hydraulic schematic of the HPU.

The deck angle reduction offered by the DACS as well as the estimated weight and power requirements of the DACS could then be assessed against those of the objective to determine if a successful system had been developed.

Limitations

The analytical process undertaken had the following limitations:

- The waves generated by the dynamic contact between the hulls and water were not modelled.
- The slope of the water in the lateral-vertical plane across the beam of the vessel was assumed to be linear at any point along the hull length.
- Horizontal hull-water interaction forces e.g. surge, sway were not modelled.
- The supply accumulator gas was assumed to behave polytropically.
- Although the pitch and roll controllers implemented on nauti-craft suspension systems would need to be discretised, these were modelled as continuous in Adams.
- Thermal effects on the system response were not modelled.
- Cavitation of the hydraulic fluid was not modelled.

RESULTS

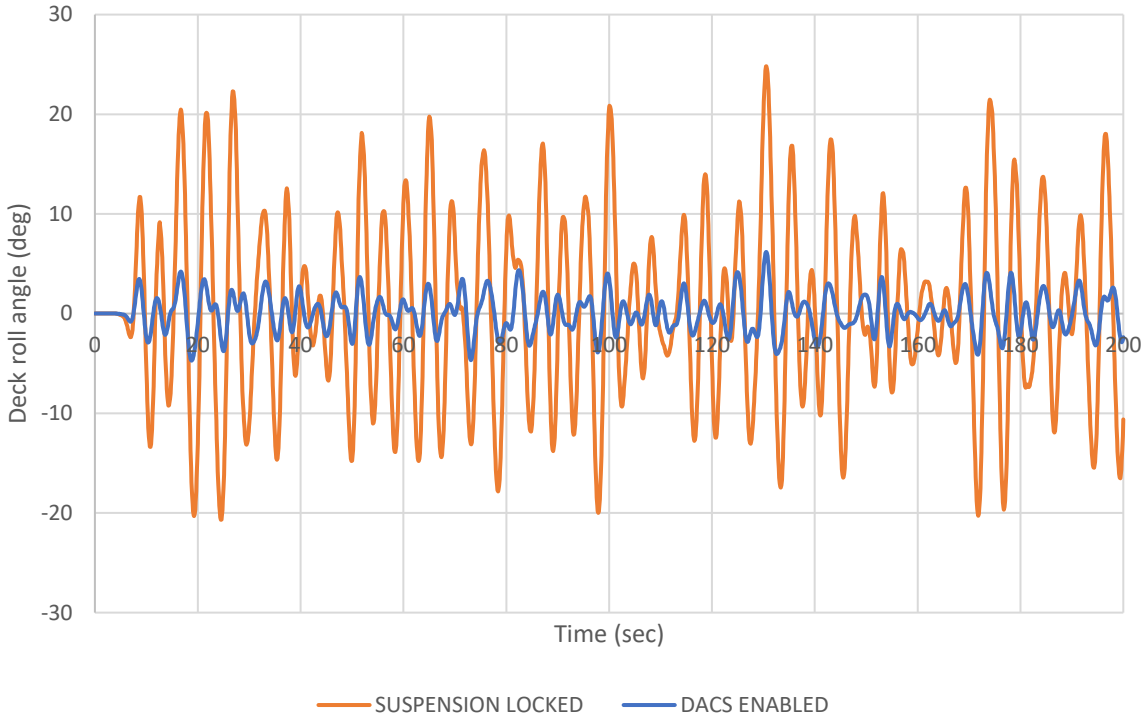


Figure 13: Plot comparing deck roll angles experienced on an 18m CTV while loitering in Hs 1.75m beam seas for locked suspension and DACS enabled cases.

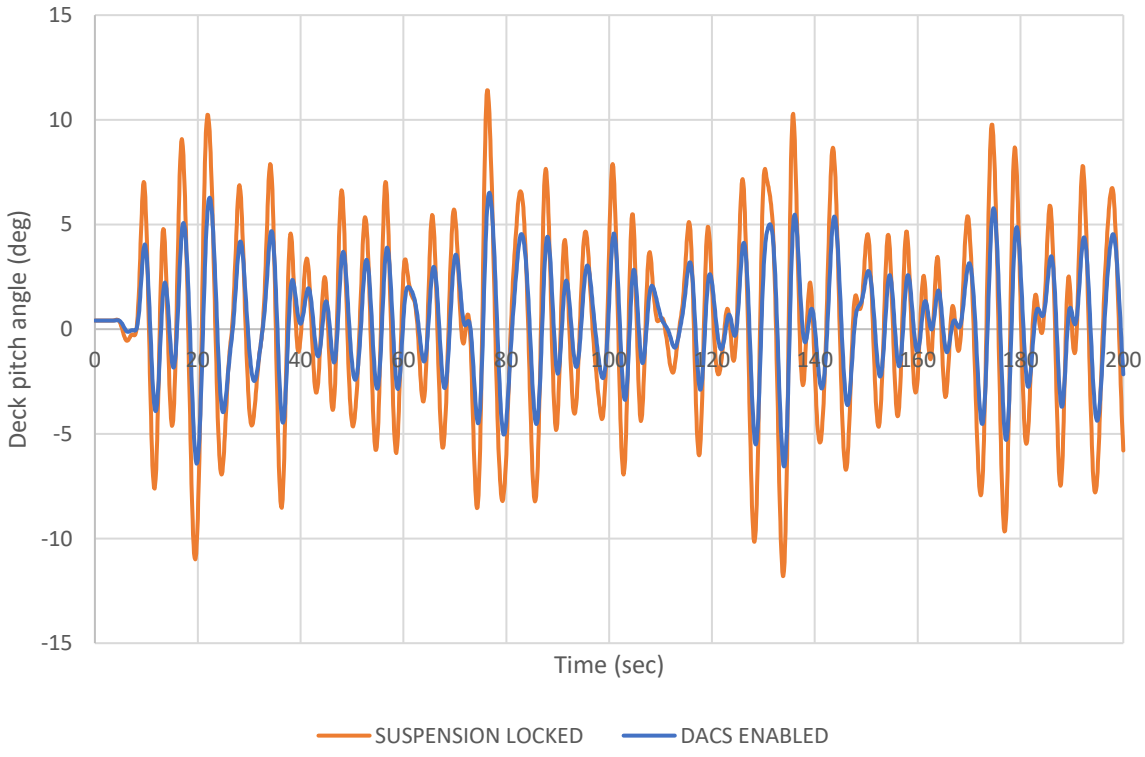


Figure 14: Plot comparing deck pitch angles experienced on an 18m CTV while loitering in Hs 1.75m head seas for locked suspension and DACS enabled cases.

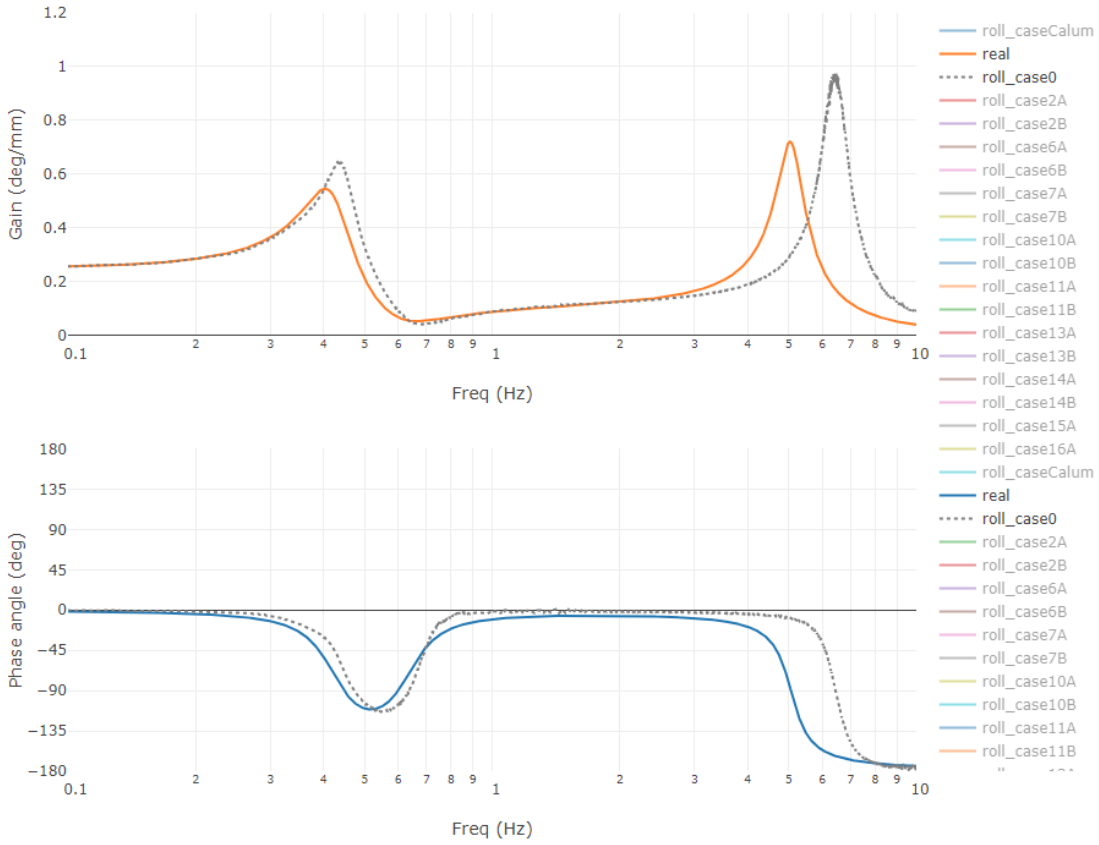


Figure 15: Bode plot comparing the open loop roll response of the system generated in Adams to that of sea trials data for an 8m prototype vessel.

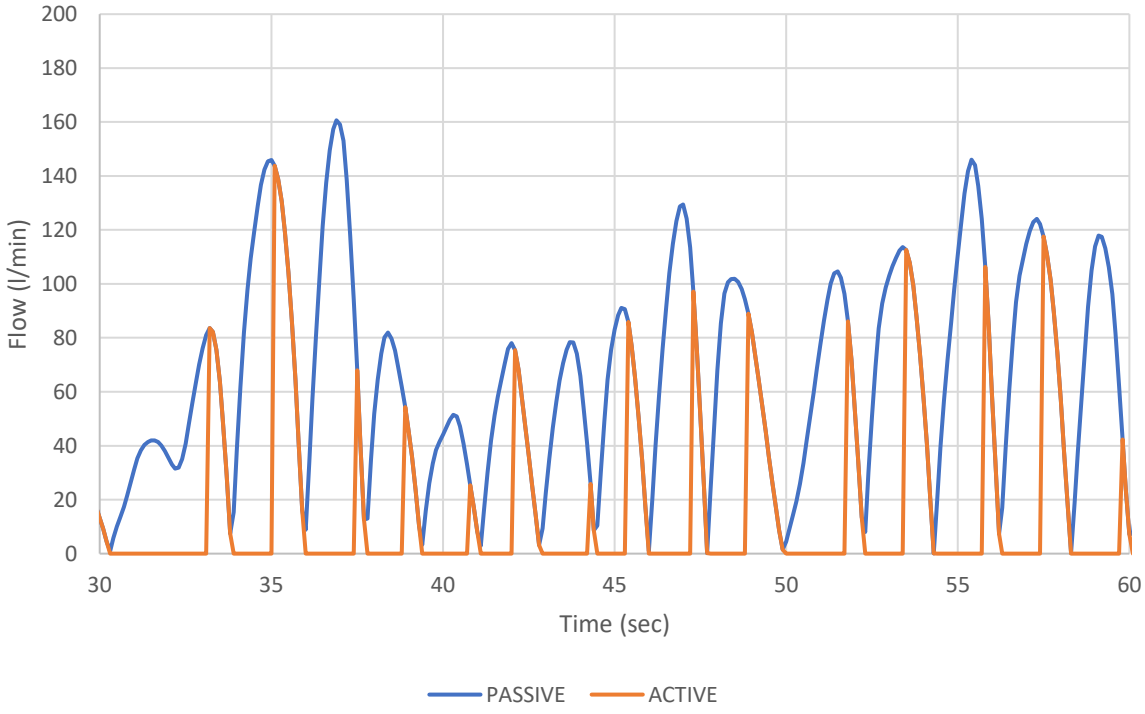


Figure 16: Plot comparing the "PASSIVE" flow through the damper valve to the "ACTIVE" flow through the active valve with DACS enabled in Hs 1.75m head seas.

DISCUSSION

As displayed in Figure 13 and Figure 14, the peak-to-peak deck angle reduction as a result of 3rd Gen. DACS is 75% in beam seas and 50% in head seas. In particular, the 45 degrees of roll travel and the linear roll geometry of the 18m suspension system enable the large amplitude roll behaviour seen in the locked vessel to be attenuated significantly.

Figure 15 shows a typical open loop bode plot comparison between sea trials data and data generated via Adams for the roll response of the entire mechanical system. Plots such as this were used to validate parameters such as fluid compressibility against reality as well as tune the pitch and roll controllers.

Figure 16 illustrates the utilisation of the passive damper flow path with loitering DACS enabled in Hs 1.75m head seas. The majority of the actuation of the DACS cylinders can be achieved by simply "allowing" the cylinder to compress or extend according to the passive pressure differentials which occur in the system. Since 1st Gen DACS required all cylinder actuation flows to be sourced from the HPU (regardless of the passive pressure differential generated), a remarkable 70% reduction in electrical power demand is achieved by the 3rd Gen system.

CONCLUSIONS

The utilisation of MSC Adams as a design tool has proven insightful and beneficial in the development, validation, and high-level design of the 3rd Gen Deck Angle Control System. End-user requirements have been successfully converted into system requirements via highly customisable dynamic modelling and representative indications of the system performance have been reported to significantly de-risk the system before progression to the prototype phase. Through detailed simulation and post-processing, the lightweight 3rd Gen DACS has been conceptually demonstrated to perform loitering stabilisation with unprecedented efficiency.

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Fast generation of highly representative 3D models of large maritime platforms

Ben Mashford (ben.mashford@shoalgroup.com), John Furness, Thomas Watkins (Shoal Group Pty Ltd)

ABSTRACT

Understanding the signature of a platform is critical to its survivability, especially in a world of proliferating advance threat systems that are dependent on sensors for autonomously identifying targets. The signature of a platform is highly dependent on geometry and is influenced by small configuration changes. As such, a fast and inexpensive method of Radar Cross Section (RCS) analysis is necessary to support changes through platform life and during operations. Effective RCS analysis is dependent on a highly representative 3D model of the platform of interest. The integration of commercial technologies including LiDAR, photogrammetry, artificial intelligence & machine learning, and uncrewed aerial vehicles has given rise to a capability for the fast generation of representative 3D models. The capability offers a real and necessary opportunity to improve survivability through greater self-awareness of a platform's signature. This paper outlines Shoal Group's support to the Joint Survivability Tactics Validation Unit (JSTVU) and Defence, Science and Technology Group in realising this capability, and provides a vision for the future of survivability.

INTRODUCTION

Operational Context

Radar guided anti-ship systems are a primary threat for Naval Ships. As a result, the survivability of ships can be improved through careful management of its electromagnetic spectrum. RCS is a measure of how detectable an object is with radar [1]. To manage RCS and increase ship survivability there are a range of techniques including, reducing it or using active decoys to distract adversary systems [2]. However, to manage an RCS, it must first be measured.

The necessity to continue to improve RCS measurement methods comes from the expected technology advancements in radar guided anti-ship weapons. Technologies including machine learning [3] will allow targeting systems to become more discerning in picking out their true target. Therefore, the need is clear to continue to advance the technologies in RCS management and measurement.

A ship RCS model is the prediction of the likely RCS from a range of observable angles. Commonly, there are two methods for developing an RCS model, which are:

1) Measurement - By measuring directly reflected radar signal from the target. However, the resulting RCS model is limited to the measured radar frequencies, measurement angles and effect of environmental conditions.
2) Simulation - Building an RCS model through simulation using high-fidelity models of the radar sensor, the environment, and a 3-Dimensional Digital Representation (3DDR) of the ship, with material properties. The degree to which this 3-dimensional

representation matches the as-built or modified ship can reduce confidence in the RCS model.

There is an opportunity to improve ship RCS management by increasing the accuracy of the 3DDR for RCS model simulation. The experimentation presented in this paper seeks to improve the process for generating a sufficiently accurate 3DDR of a ship.

Purpose

Given the imperative to improve RCS management, there is an opportunity to improve the accuracy of the 3DDR and thus the accuracy of the simulated RCS.

This paper presents an investigation conducted to improve the utility of the 3DDR for enhancing the prediction of ship RCS via simulation.

Capability Concept

To improve the utility of the 3DDR, the proposed concept is required to reduce costs, to offer results expediently and to meet the required accuracy to simulate a valid RCS. Cost is assumed to be reduced by using commercially available hardware. Achieving rapid results requires that the measurement equipment be able to, at short notice, deploy measurement systems and process the measured data quickly. Accuracy will be judged by comparing the resulting RCS model to measured RCS values.

The concept, as presented in Figure 1, involves an Uncrewed Aerospace Vehicle (UAV) and other handheld equipment for capturing sufficient data to render the 3DDRs. The 3DDRs is then processed into an RCS model and outputs made available for decision makers.

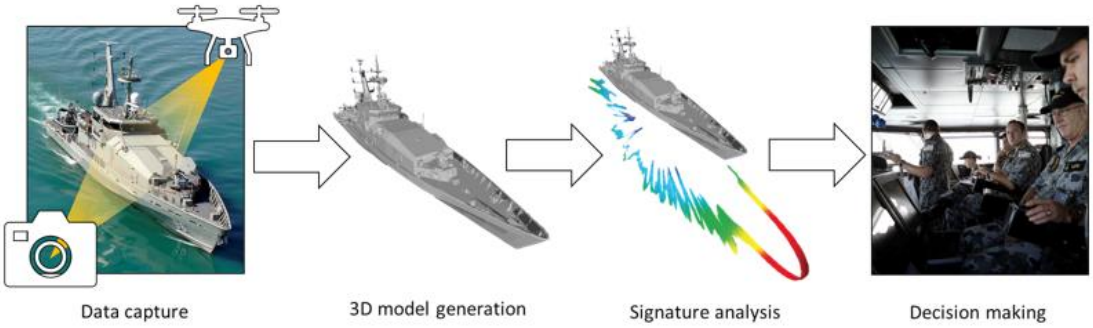


Figure 1. Capability concept

TECHNOLOGY SURVEY STUDY

Study Scope

Prior to a proof-of-concept trial, it was determined that an initial technology survey was required to study and better understand the available sensors for generating ship 3DDR. This study was concluded in 2019 and identified potential technology options and their feasibility in capturing a sufficiently accurate 3DDR.

Objectives of technologies feasibility study were to:

- Explore the application of commercially available UAV capture technologies

- Assess accuracy of 3D model outputs made by various technology platforms

The technology survey consisted of a market survey of commercial service providers and a follow up trial of those providers. Four providers were identified in the market survey which proposed a range of solutions, each using LiDAR or photogrammetry technologies. The specifics of each option are outlined in Table 2.

Photogrammetry [4] is a software workflow that uses a set of overlapping RGB photos as input, that then undergo post-processing into a 3D model via a sequence of data processing steps. A key step in this process is a *feature identification and matching stage*, where corresponding feature points are aligned across photos taken from different camera angles.

LiDAR using a laser-scanning system and combines it with a range of technologies to localise the scanner to observe where an object in space is observed by the scanner. To localise the position of the scanner a combination of inertial management system, Global Positioning System (GPS) [5] or Simultaneous Localisation And Mapping (SLAM) [6].

The MV Besant (see Figure 2) was selected as the subject ship of the trial due to its representative size and shape and was available at the time of the trial.



Figure 2. MV Besant that was the subject of Phase 0 trials

Study Conduct

The trial compared the various methods of UAV-mounted capture systems against known measurements from a LiDAR survey conducted on MV Besant. The known measurements are listed in Table 1.

Table 1 List of truth data dimensions

	Laser Scanning Australia (LSA) (ground-based LiDAR)
B – Ship Beam	16.003 m
C – Width of Bridge	13.079 m
D – Height of Mast	9.496 m

	Laser Scanning Australia (LSA) (ground-based LiDAR)
E – Diameter of Starboard Radome	1.496 m
F – Diagonal of Port Stack Top	3.773 m
G – Length of Forward Deck Winch Box	7.624 m
H – Width of Forward Deck Winch Markings	13.644 m

The trial was conducted both alongside the Warf and in the harbour at naval base HMAS Stirling, WA between 29 Apr 2019 and 3 May 2019. Table 2 summarises the results of the trial with service providers anonymised to provider A, B, C and D. The results presented are the average mean error when compared to the Truth measurement.

Table 2 Summary of trial results

	System description	Location	Flight time	Average measure error	Measure error StDev
A	Airborne SLAM LiDAR	Alongside	10 mins	50 mm	32 mm
	Airborne SLAM LiDAR	Harbour	10 mins	40 mm	39 mm
	Airborne photogrammetry	Harbour	1 h 37 mins	61 mm	37 mm
B	Airborne LiDAR (with ship motion correction)	Harbour	28 mins	156 mm	112 mm
C	Airborne photogrammetry (using control points)	Alongside	39 mins	39 mm	30 mm
D	Airborne photogrammetry (without control points)	Alongside	40 mins	14 mm	11 mm
	Airborne photogrammetry (using control points)	Alongside	40 mins	9 mm	5 mm
	Airborne photogrammetry (without control points)	Harbour	22 mins	19 mm	9 mm

The trend in the results was clear, photogrammetry using RGB cameras showed a clear advantage in capturing the dimensions of reference measures on the MV Besant. The trend is presented again in Figure 3. At the time of the trial, no provider was offering a solution to fuse together LiDAR and photogrammetry point cloud data to see if it could improve results.

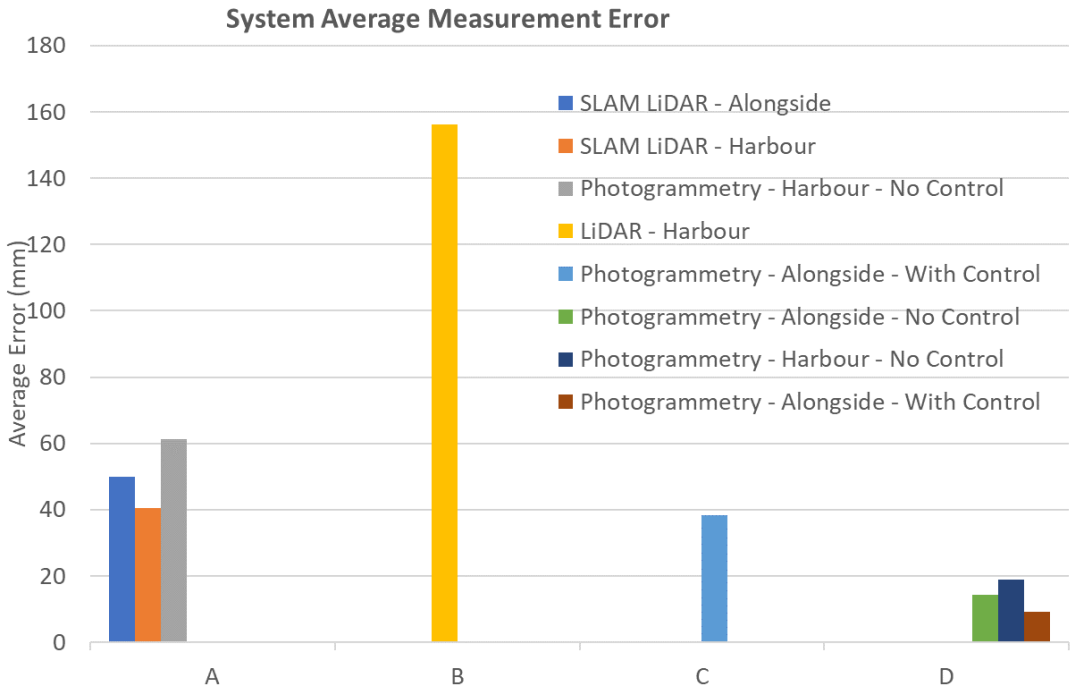


Figure 3. Trial measurement error

Scoping further work

Photogrammetry proved to be the most successful tool for accurate measuring of Ship size and structure. In addition, to surveying the technology options, the trial presented an opportunity to learn about photogrammetry and shape future research. An important learning from of this work is that achieving high accuracy in control point measurements does not necessarily ensure the model is of sufficient quality for RCS simulation applications.

Some examples of common issues in photogrammetry-derived 3D data are shown in Figure 4. There are various regions of the mesh where holes in the 3D model are present. These defects are typically the result of photographs taken of featureless surfaces or arise from photos taken with poor lighting conditions. Low quality capture images will cause problems in the feature matching step that makes up part of the photogrammetry pipeline, resulting in holes and other defects appearing in estimated 3D surfaces. In turn, these holes in the 3D model output will lead to incorrect RCS simulation results due to radar signals being reflected in a way that does not match reality.

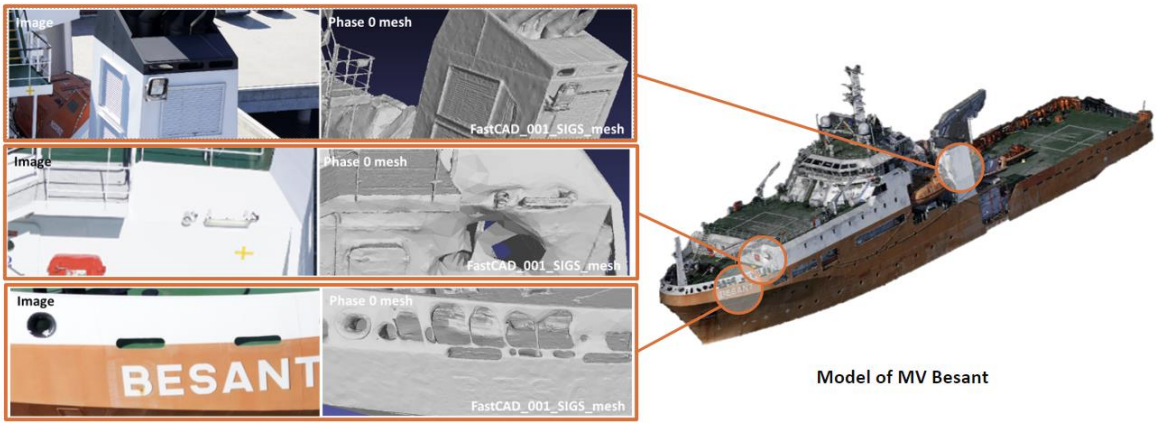


Figure 4. Close-up of details on MV Besant and corresponding resultant 3D mesh

PROOF OF CONCEPT TRIAL

Trial Scope

As a result of the initial trial, the service provider that previously demonstrated the best performance was engaged to conduct a further trial, with the following aims:

1. Design and implement a UAV capture & photogrammetry workflow for generating an accurate 3DDR of a large platform
2. Trial the technology workflow on a Navy ship

Photogrammetry Process Improvement

The Photogrammetry improvement activity builds on the last trial with the aim to improve the data collection, processing and resultant 3DDR for RCS simulation. The outcomes to be explored in this work include new methods of data processing to resolve issues in the 3DDR and explore how the technology might translate over to a Naval vessel. The objectives of studying photogrammetry process improvement was to:

1. Determine how techniques in photogrammetry perform against a Naval ship with grey featureless surfaces
2. Determine if handheld image capture can be used to augment shortcomings in drone-based capture of images
3. Identify the extent to which small configuration changes can be identified from two different UAV captures
4. Understand how data processing techniques such as Machine Learning can be applied in the generation of representative 3D models

Data Capture

The subject of capture for this trial was the HMAS Coonawarra, an Armidale Class Patrol Boat (ACPB). Before being photographed by UAV, preparation activities were undertaken that included laying down markers to allow accurate measurement of known points across the vessel. These control points are used as spatial calibration inputs in the photogrammetry workflow.

To examine the ability of photogrammetry to detect small configuration changes, two captures of the vessel were made with different ship configurations. Configuration changes included:

- Removing the awning
- Removing the RHIB
- Open and closing hatches

Each capture of the vessel required at least three flights at three different altitudes to ensure complete coverage. An example of a typical flight path is shown in Figure 5. Overall, around 70 Gigabytes of photography was collected over two configurations and each took approximately 3 sorties and 2 hours to collect the data.

It was recognised that any airborne capture platform (UAV) will encounter situations where photography is limited by occlusions and other complicating factors. It was hypothesised that complimentary handheld photography would improve the capture accuracy in these areas and the so trial also included photography made by an operator onboard the vessel deck. These photographs were added to the UAV-captured set before undergoing photogrammetry processing.

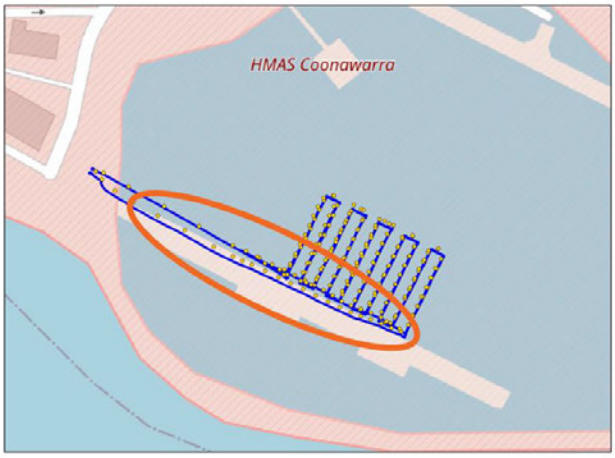


Figure 5. Flight path taken by UAV (blue line).

Data pre-processing

After transfer to a computer workstation, the capture data was pre-processed via application of a number of image manipulation techniques. These algorithms (both classical and machine learning based [7]) were applied to the photographs to enhance contrast,

deblur, denoise, and enhance edges within the photographs. Image pre-processing can lead to higher photograph quality, which assists in the feature-matching process.

Photogrammetry

Photogrammetry comprises a pipeline of processing actions for which Bentley Context Capture [8] was used. Processing steps include:

1. Feature extraction. This step involves extraction of distinctive groups of pixels (features) that can be automatically identified across multiple capture photos.

2. Image matching. This step identifies which photos in the capture set contain significant overlap (i.e., they are looking at the same part of the scene). The algorithm works by analysing the features that were extracted in the previous step.

3. Feature matching. Here, the algorithm aims to match all features between candidate image pairs.

4. Structure from motion. This step is where the 3D geometric structure (point cloud) of the capture subject is inferred.

5. Depth maps estimation. This step produces a depth value of each pixel in every image, as viewed by the identified camera positions. It then combines depth maps to estimate the statistically likely 3D position for every pixel found in overlapping images. The output from this step is a dense point cloud.

6. Meshing. This step converts the dense point cloud to a 3D mesh by connecting the vertices to form polygons.

Similar to the previous trial, large plane surfaces and details where the UAV couldn't see did not resolve well. However, two improvements were investigated. The first was better management of the Context Capture settings, including applying *planar simplification*, which aims to detect planar surfaces in the point cloud and replace these areas of the geometry with a flat plane. This is effective at removing some artifacts but when the threshold is set too high, it will remove features that should appear in the output. This effect is demonstrated in Figure 6. Optimising the use of this technique requires further investigation.

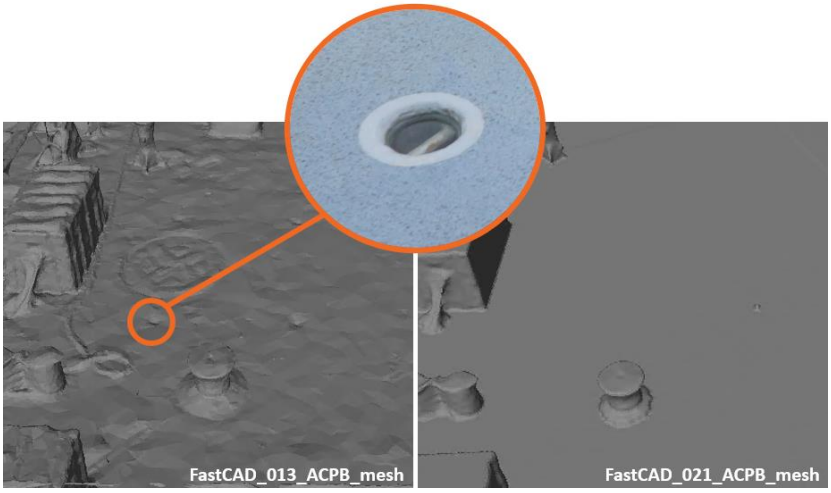


Figure 6. Example of a genuine surface undulations removed through planar simplification (right).

The second improvement is combining handheld and UAV images into the one processing pipeline. In this case the handheld images from a different camera could resolve details in cavities or out of sight of the UAV. These cavities can be corner reflectors, a key artifact for RCS prediction, and so are important to resolve. See Figure 7 for example of the improvement.

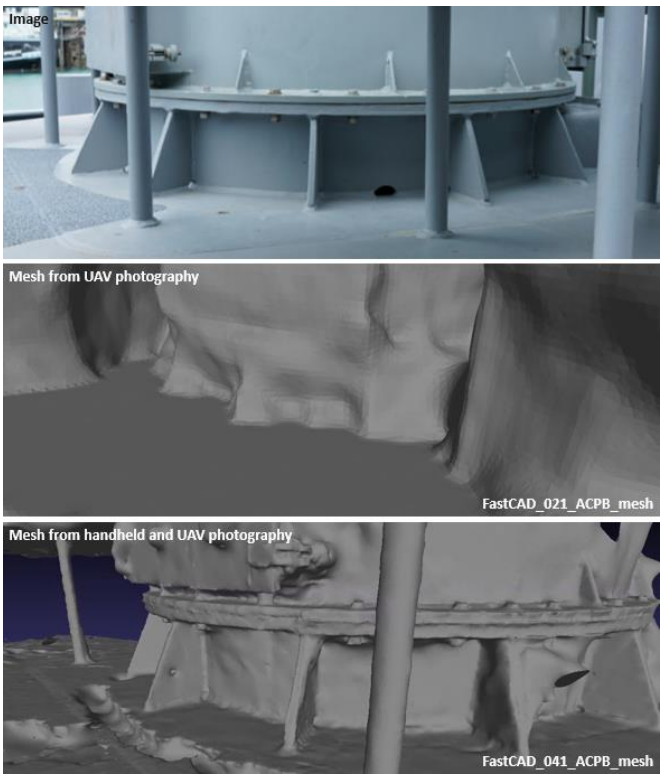


Figure 7. Photograph (top) and 3D models of gussets on an ACPB using UAV photographs (middle), and both UAV and handheld photographs (bottom)

Post-processing

Post-processing of a photogrammetry-derived mesh can have a dramatic effect on both output quality and on polygon count of the resultant 3D model. A variety of post-processing algorithms were applied during this investigation, including:

- Smoothing [9](both classical smoothing algorithms and machine-learning based)
- Hole-filling algorithms
- Point-cloud or mesh simplification (reducing the number of vertices/polygons in the 3D data)
- Outlier removal (removes artifacts and noise in the captured point cloud)
- Poisson surface reconstruction [10] (constructs the mesh from a point cloud)

Deep learning-based methods have been developed and applied to mesh post-processing tasks [11] [12]. These methods use a deep neural network model that has been trained on matching pairs of pristine and noisy point clouds, allowing it to learn a mapping from noisy input samples to the clean output sample. When this trained model is applied to unseen samples, the neural network generates a cleaned version of the input data as its output. An example of these is shown in Figure 8 where a trained deep learning model was applied to section of the captured 3D model.

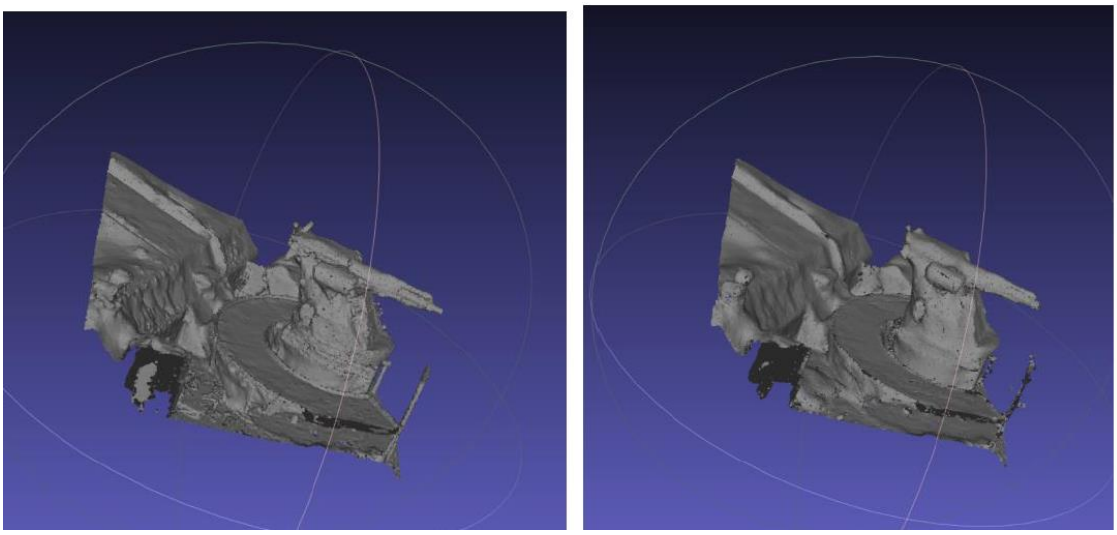


Figure 8. Mesh generated from raw point cloud (left) and from point cloud after deep learning filter model applied (right)

It was found that deep learning models for point cloud cleaning are a promising path to improving output mesh quality but a certain level of capture fidelity is still required to realise the potential of this approach.

Detecting configuration changes

As part of the trial, capture scans were made on two configurations of the vessel in order to understand how configuration changes can be automatically detected.

From each of the two configurations, a separate 3D model was generated, and these were compared via a point cloud-comparison algorithm. Briefly, this algorithm will compare two point clouds (A and B) by considering each point in A and searching for the distance to the nearest neighbour point in B. As shown in Figure 9, large changes between models are identified in red and these regions indicate that significant configuration changes have been made in those areas. Detection of smaller configuration changes is also possible but requires accurate alignment of the two point clouds, as well as high quality capture data.

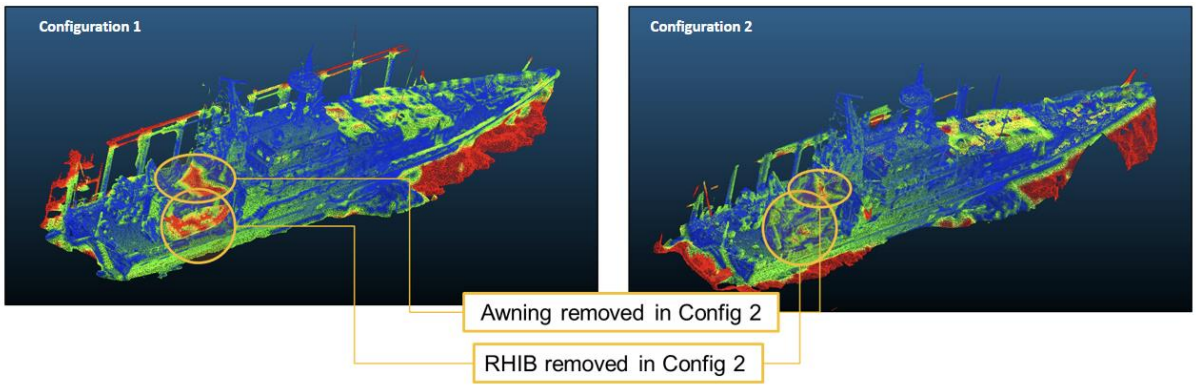


Figure 9. Example of identifying changes on the platform using a point cloud comparison method

DISCUSSION

At the conclusions of the trial some of the weaknesses of photogrammetry and generation of the 3DDR could not be resolved sufficiently for RCS modelling. As depicted in Figure 10, regardless of the different processing methods tried, large grey surfaces still could not be resolved, and defects changed unpredictably with environmental conditions. Figure 10 shows configuration one in direct sunlight and configuration two in overcast conditions with resulting wide variation in surface form.

However, the model generation could be improved in several ways, The first was blending together images taken with different cameras by hand and with overhead UAV. This helped resolve the detail of cavity spaces which can be important for RCS prediction. Secondly, the photogrammetry processing could be optimised to remove noise as shown in Figure 6 and there is an opportunity to optimise this processing differently across the model depending on texture. Finally, it was demonstrated that a neural network could be used to clean up point cloud data, although further work remains to fully benefit from this approach.

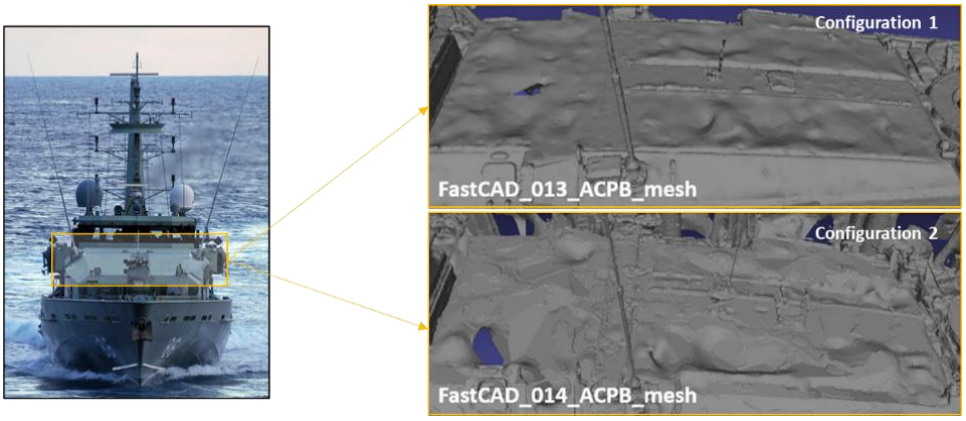


Figure 10. Exemplar of deficiency in photogrammetry

In addition, it was found to be feasible to use the point cloud data to detect configuration changes, and so with continued investigation of 3DDR generation there exist new opportunities for improved workflows in signature management. For example, accurate identification of configuration changes will permit updating a model from a known baseline rather than building it from scratch.

CONCLUSION

Through these most recent trials it was demonstrated that photogrammetry alone is not suitable for RCS analysis and there remain several challenges before an RCS model can be generated from images of a ship. Photogrammetry using UAV-based capture data can quickly generate a model of a large platform, but the resulting model exhibits defects around areas of uniform grey surfaces and occluded surfaces.

Techniques and processes including applying machine learning techniques show promise in cleaning up models but not to a degree that is sufficient for RCS simulation.

To engineering a system that can quickly build an RCS model after a configuration change there are several further steps required:

1. Build the detailed operational concept that covers ship signature management to countering radar-guided anti-ship systems, including detailed measures of RCM model suitability and effectiveness.
2. Address shortfalls in photogrammetry performance by assessing new workflow improvements such as projecting a texture onto smooth, featureless surfaces (assisting in feature matching), and further technological advances such as fusing LiDAR and photogrammetry together.
3. Identify or build a suitable surrogate for Ships as the target to improve the frequency and ease of conducting trials.

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SESSION 7

Naval Ship Technology

Macro trends in propulsion system selection for warships to facilitate maritime carbon emissions reduction from an engine builder's perspective

A cost-effective approach to extending the life of naval surface platforms
Refereed

Digital twin for naval platform operations
Refereed

Real-time digital-twin for naval platform through-life support and life-cycle risk reduction

Maritime carbon emissions reduction in warships: an engine builder's perspective

Gary Wilson (Gary.Wilson5@Rolls-Royce.com) and Richard Partridge (Richard.Partridge@Rolls-Royce.com), Rolls-Royce Defence

Introduction

This paper considers the technical and logistical challenges of reducing emissions of carbon dioxide (CO_2) and other harmful emissions by naval vessels without affecting the vital roles that navies need to perform. When achieved by efficiency improvements, reducing emissions can help navies at the same time as helping the environment by lowering cost and increasing endurance. After a discussion of some key trends, this paper considers the options for achieving these improvements and discusses what is required to help ensure the best choices in design and operation are made.

Key Trends

This section will introduce key trends in technology, the environment and economics that impact all maritime operations and highlight their significance to navies. The response of the maritime community to climate change, the development of sustainable fuels and electrical systems, and the needs of navies will be described to provide background ahead of detailed discussion in the remainder of the paper.

Climate change

Climate change needs little introduction with events such as COP26 [1] receiving considerable media coverage and the tangible effects becoming observable across the planet. The International Maritime Organization (IMO) is helping to reduce the impact of shipping on the climate through initiatives such as the Carbon Intensity Index (CII), which is part of its 2018 Initial IMO Strategy for Reducing GHG Emissions from Ships [2]. The IMO has a mandatory fuel oil data collection system, and this is used to calculate and rank vessels about 5,000 GT by their CO_2 emitted per ton of cargo and nautical mile. The rankings are used to prescribe corrective action plans that will become increasingly stringent. With shipping accounting for approximately 2.5 % of greenhouse gas emissions globally [3] there is an ongoing need for the industry to become more sustainable. It is noted that navies have different priorities to commercial ship operators, but since naval ships often adopt practices from commercial ships, such as through classification society rules, it is useful to understand these sectors.

Reducing the net carbon emissions of engines by changing their fuels can reduce the impact of shipping on climate change. Net emissions consider the full lifecycle from the initial production of the fuel through to its combustion in the engine because there are technologies that can create fuel using CO_2 captured from the air. Crops used as feedstock in biofuels naturally capture CO_2 as they grow, and this is released again when the fuel is burned, so the net emissions are limited to the energy required for production, storage, transportation, etc. Synthetic fuels can be made with CO or CO_2 captured from the atmosphere in a process referred to as direct air capture (DAC) [4], but power is consumed in their production and the source of this power strongly affects their net emissions. If the power comes from sources such as wind turbines then net emissions will be relatively low, but if it came from a source such as a coal power station there are unlikely to be environmental benefits to its adoption, so the full lifecycle needs to be considered.

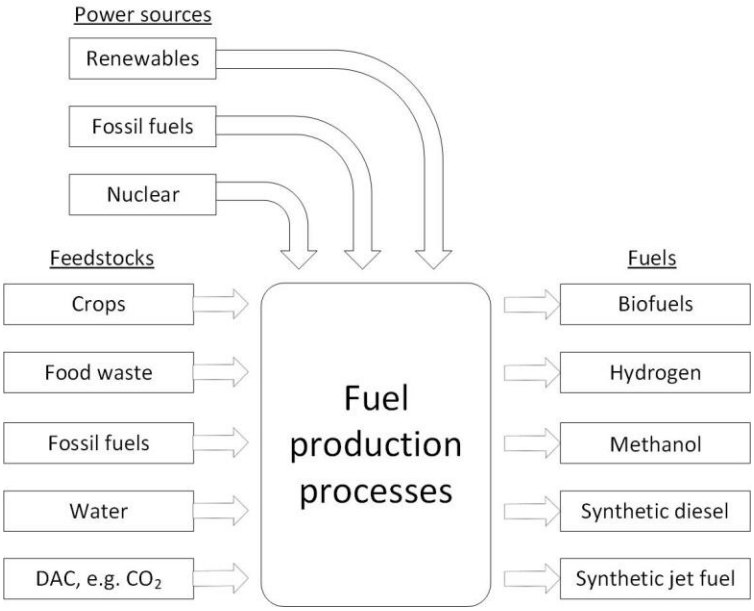


Figure 1: An example of the variety of feedstocks, power sources and fuels available

Figure 1 shows and example of the variety of feedstocks, power sources and fuels that may form part of biofuels and synthetic fuels. It is not an exhaustive list and it does not show the combinations used in each fuel, but it highlights that many combinations are possible and so assumptions cannot be made about the contribution of a particular fuel to net emissions reductions. It is necessary to examine the full lifecycle of the fuel to understand its environmental costs and benefits.

Security of supply, the economics of sustainable fuels and their impact on naval operations also needs to be considered. Navies operate with standardized fuels, such as those produced to North Atlantic Treaty Organization (NATO) standards. These are currently produced from commoditized crude oil and are readily available with known contents and properties. As fuels diversify with the introduction of new technology, and as oil is displaced as the base of fuels, availability could be affected. If navies opt to continue with current fuel standards this could mean higher prices for what may become a more niche market. If they instead begin to use whichever fuels are available at port within an acceptable price range, they will need processes to rapidly assess the fuel that is available to ensure adequate performance can be achieved. Rolls-Royce is conducting such evaluations for both diesel engines and gas turbines for civilian applications in conjunction with fuel suppliers such as Shell [5].

Reducing fuel consumption will reduce CO_2 emissions as well as providing operational advantages. Platform design and the configuration and control of the power and propulsion (P&P) system influences fuel consumption because diesel engines and gas turbines have a specific fuel consumption that varies with their load. The quantity and size of the engines used in each operation are optimized to provide the desired trade-off between performance and fuel consumption. This trade-off can be challenging but Rolls-Royce has been part of the journey towards the electrification of P&P systems that can enhance flexibility and provide navies with more options in how to operate. Hybrid-electric and fully-electric propulsion systems also provide greater flexibility in the vessel layout because the prime movers do not need to be located at

the shaft lines and thus may be located considering factors such as survivability and how to best utilize space inside the vessel for operations.

Using multiple diesel generators or gas turbine generators allows power sharing that keeps each engine operating close to its most efficient point while maintaining adequate margin. In combat situations fuel consumption will be a lower priority than ensuring power is available and so all engines may operate, but for the rest of the time it may be possible to reduce the number of engines operating to optimally load the others and to help with maintenance-related through life costs. This is especially true in vessels that spend long periods operating at slow speed.

In some applications, energy storage systems may contribute to this flexibility by supplying power during peak demand and being recharged at times when other loads are low to help to keep engines at their optimal point. The round-trip efficiency of the energy storage, including any power converters in the path, needs to be considered to establish if the fuel savings will offset these losses. Direct current (DC) distribution systems can also increase flexibility because the prime movers' speed can be varied to help minimize the specific fuel consumption. Energy storage and DC systems can help to supply large, pulsed loads, such as directed energy weapons. Energy storage can do so by being the power source for these loads, or at least by 'peak-lopping' or smoothing the transient the gensets will experience, while DC systems may do so because they can tolerate a greater dip in the engine speed than may be possible with an alternating current (AC) system.

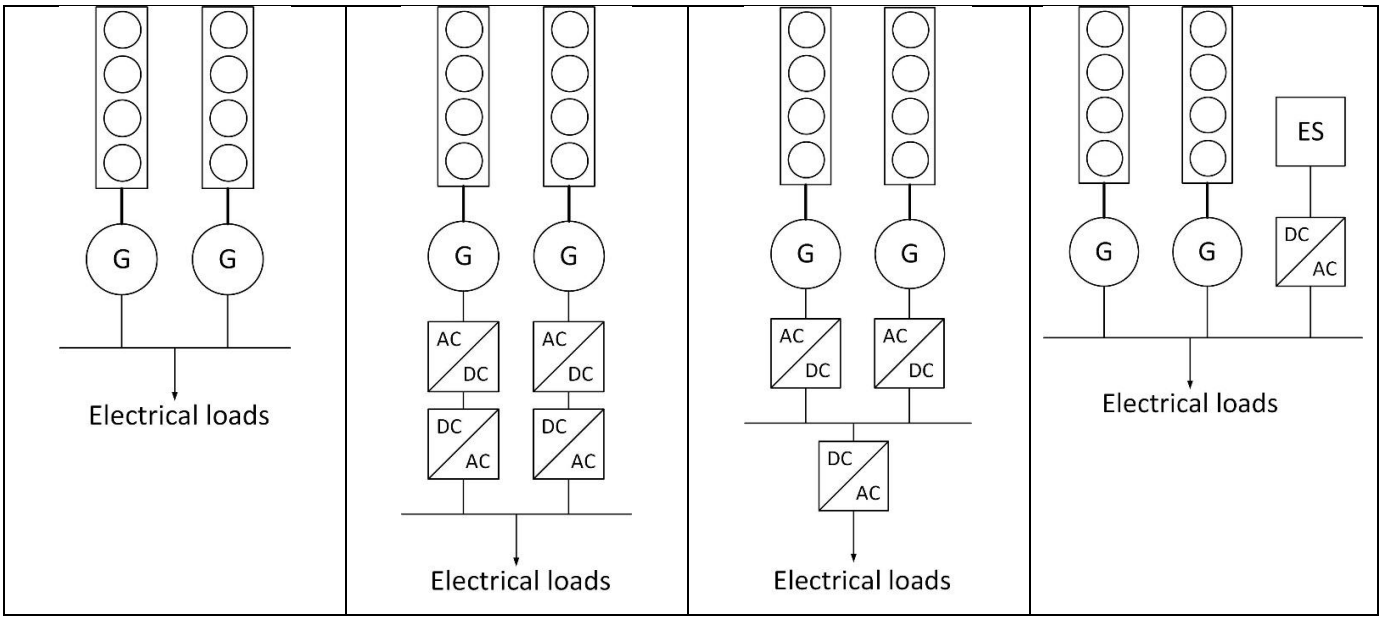


Figure 2: Four examples of generators, power converter and energy storage combinations

Figure 2 illustrates the diversity of options available for designing hybrid or fully electric P&P systems including power converters and batteries. Generators – of equal or of different sizes – supply fixed frequency AC remains the most conventional way of doing so. Alternatives include variable speed and frequency generators supplying AC or DC buses and combining generators with an energy storage system in which the power converter synchronizes with the grid and controls the power flow. This is not an exhaustive list, but it is intended to show the range of options that the designer may consider.

Naval Operational and Military Needs

- Platform design – whilst capital warships fortunately operate mainly in peace time, they are designed for high-threat/combat states and as such must achieve and sustain a relatively high speed. This has a major influence on platform design especially the block coefficient and L/B ratio, severely constraining space above and below decks for the location of equipment and systems. Given that warships are primarily weapons platforms, this places an onerous requirement for power-dense propulsion and power generation systems to maximise space available for mission systems. This is compounded by the need to configure arrangements to meet naval redundancy, vulnerability and survivability requirements – the latter mandating physical separation. Compared to merchant vessels, warships often also have different equipment maintenance philosophies – including Upkeep-by-Exchange (UxE) – which prescribes removal routes consuming additional space.
- Range and endurance – normally expressed at the ability to achieve a specific distance at a certain speed of advance against a predefined sea state and maximum volume or mass of fuel – is a very important measure of warship performance especially for 'Blue water' navies, and those with extraordinarily large operational areas.
- Signatures (stealth) – reducing susceptibility by minimizing above and below water signatures including but not limited to airborne, structure borne and underwater radiated noise, infrared and visible e.g. smoke. To meet stringent naval requirements, equipment and systems will often have to be fitted with abatement technology, which adds to the mass, spatial requirements and cost of ownership. This is true for all warships but is mission-critical for ASW platforms and other vessels that require noise-quiet states to successfully fulfil their military missions.
- Installed electrical power – which has become a strategic resource in terms of meeting programme requirements for platform life given the rate of change of (increasingly power-hungry) mission system technology and the need to sustain the military relevance of the programme for longer via technology insertion through-life. In addition to the progressively growing electrical load demand requiring more adaptability in new programmes, the electrical system must sustain stringent naval quality of power supply (QPS) requirements across the life of the platform e.g. voltage and frequency.
- Fuel security of supply – including the availability of fuel within and autonomous from the task group. Whilst this has always been a logistical challenge, it would likely be compounded by fuel diversity especially if navies diverge from fuel types and grades used with the merchant marine, potentially leading to diminished military capability in certain operational areas/scenarios.
- Underway replenishment implications – an evolution unique to navies – is another important consideration if moving away from standardized fuels and or those which are readily storable, transported and pumped between vessels in a replenishment-at-sea (RAS) evolution. 'RASing' is already a very safety-critical operation, and again this could be compounded by using additional or replacement fuels with different properties.

The technical and operational challenge of moving to alternative and more sustainable fuels is significant. The next section will review some of the opportunities at equipment, system, platform and even infrastructure level to give an insight into some of the possible potential solutions.

Technical Solutions

Incremental design improvements for higher thermal efficiency

Enhancing the efficiency of diesel engines and gas turbines reduces CO_2 emissions because the fuel required for a given power output is reduced. Engine enhancements may also reduce emissions of harmful pollutants such as NOx and particulate matter (PM), so this is the subject of ongoing research. Emissions reductions may be further increased by optimizing the operation of engines with synthetic fuels and biofuels given these fuels can also reduce emissions.

In simple terms, the efficiency of a diesel engine is the ratio of the brake power output to the energy per second entering the engine as fuel. Sources of inefficiency include incomplete combustion, heat transfer through the exhaust gas, engine body, lubricants and cooling jackets, friction losses and power required for auxiliaries, such as pumps. Options for increasing the combustion efficiency can include increasing compression ratio of the cylinders, improving fuel spray atomization, optimizing fuel injection timing, improving the fuel/air mixing and deactivating cylinders at lower loads. These options may require new materials and geometry to handle the higher pressure and to encourage fuel mixing.

New materials may also be used to reduce friction between the pistons and cylinder, or to reduce heat transfer from the fuel/air mixture to the engine body. Improved lubricants may also reduce friction and enhanced pumps, e.g. using electrical motors in place of shaft-driven pumps, can help to reduce the losses of the overall engine system. Waste heat recovery in the form of thermoelectric generation and organic Rankine cycles are options for reducing the losses associated with exhaust gas heat, but their impact on the combustion efficiency and any exhaust after-treatment would have to be carefully considered.

Gas turbines operate by accelerating a mass of compressed air using heating and expansion in the combustor that then drives the turbine. The mass flow is proportional to both the mass and the velocity of the air and so a larger diameter engine allows for the same mass flow at a lower velocity, which can help to reduce friction and turbulence in throughout the engine. This can be further improved by correct design of nozzles and passages to direct air in optimal ways from the inlet, through the compressor, combustor and turbine right through to the exhaust outlet.

The choice of axial or radial compressor, and the number of stages in a compressor influences its efficiency because these can be selected to produce the required compression ratio while minimizing losses. Factors that can enhance efficiency include minimizing the blade tip clearance between the rotating compressor and casing, reducing friction and turbulence and designing means to improve the temperature distribution of the compressor shafts and discs. Correctly matching the compressor to the turbine is essential to maximize efficiency.

As with diesel engines, fuel burning influences gas turbine efficiency and suitable atomization is essential. Annular combustors also contribute to overall efficiency because they require less cooling than alternative designs. To maximize efficiency in the turbine it is desirable to have a high entry temperature and thin, light turbine blades. However, thinner blades could compromise maximum operating temperature without careful choice of blade material and cooling design. Increasing compressor efficiency by leveraging the power and functionality of modern computational design tools, and 'stiffer' engines with reduced or actively managed-tip clearance will help to increase pressure ratio. Higher firing temperatures are also achievable in the latest aerospace engines by adopting advanced materials including ceramics and sophisticated thermal barrier and cooling technology.

Engine re-design for emerging fuels

The degree of redesign required for biofuels and synthetic fuels depends on how much they differ from current fuels. Some fuels have very similar properties to current fuels and can be immediately substituted for them with no modifications being required at all. For other fuels, testing may reveal a need to tune control parameters such as injection timing to optimize efficiency, as would be done with diesel. However, for fuels such as hydrogen that cannot be ignited by compression, it will be necessary to make more substantial modifications to reciprocating engines to provide spark ignition.

Biofuels and hydrogen are being developed as alternatives to fossil fuels to help reduce net carbon emissions. The word "net" highlights that, while carbon dioxide is still released in the combustion of biofuels, in some technologies it is taken from the atmosphere when the biofuel is made. Biofuels can come from waste products from the food industries, including from animal fats, or they can come from feedstock planted specifically for this purpose. However, there are environmental and ethical concerns with biofuels too, such as the potential for food supplies to be displaced so land can be farmed for biofuel feedstock and the use of fertilizers on the feedstock [6]. The biofuel must therefore be examined carefully to ensure it is indeed an environmental improvement on the fossil fuel it displaces, and all net carbon emissions caused by its production and transportation must also be considered.

The green credentials of hydrogen are also variable. Hydrogen is mostly derived from fossil fuels and other chemicals and therefore is associated with carbon emissions. Hydrogen can also be obtained from water through electrolysis, but this currently accounts for only around 2 % of hydrogen production [7]. Furthermore, hydrogen produced by electrolysis is only as low carbon as the power source used in its production. Where wind, solar or tidal power are used then it is indeed a low carbon fuel, but if the power plant supplying the electrolysis operates on fossil fuels then it merely moves the emissions. The world will need a very large increase in hydrogen production from renewable sources for it to truly be considered a green source. Furthermore, access to clean water may become a growing challenge due to climate change and the overall global population growth, so there are ethical considerations in its use to produce fuel.

Biofuels and hydrogen have different properties to fossil fuels and the impact on the power output of engines, their ability to handle step loads and the temperature and composition of their exhaust gases will need to be considered. Furthermore, biofuels are more diverse in their feedstocks and chemical compositions than standard military fuels derived from fossil fuels, so processes and testing equipment

may be needed to confirm the suitability of fuel supplies, which may increase operating costs. Training to perform this quality checking and to operate and maintain engines that use it may add expense too.

Substitution of fossil fuel-derived diesel or jet fuel for synthetic fuel or biofuel with identical properties would of course be the most straightforward way to reduce the environmental impact of naval ships. However, if these properties differ then a study would have to be conducted to evaluate its impact on engine design and certification, emissions, maintenance schedules, operating costs and power output. Processes for testing fuel and inspecting fuel tanks may also need to be updated. If fuels differ such that engine modifications need to be made, such as to install spark ignition, or even such that the engines themselves have to be replaced then much deeper studies would have to be conducted examining the costs and benefits of doing so. The remaining life of the vessel, its ability to perform its intended missions and the differing lifecycle costs of the existing and alternative engines would have to be carefully considered, and it may be that this is judged not to be viable.

System design

While gas turbine generators are used on some naval ships, arrangements such as combined diesel electric or gas (CODLOG) and combined diesel electric and gas (CODLAG) are more common because diesel engines tend to provide greater volumetric and gravitational density at lower power ratings, e.g. less than 4 MW. This section thus considers the design of diesel electric systems with the assumption that a gas turbine is used in boost mode to drive the propellers through the gear box when operating at higher speeds.

The specific fuel consumption in each cylinder varies with the fuel-air mixture during the combustion stroke. When more fuel is burnt in a stroke the combustion happens at a higher temperature and a more complete combustion occurs with less fuel being wasted through the exhaust. It is thus desirable for the combustion temperature to be higher, which corresponds to a greater force being produced during the stroke, although it is noted that higher temperatures may lead to greater heat loss through the engine body and cooling and to higher NOx emissions. The optimal fuel-air mixture therefore typically corresponds to around 70 – 80 % of the rated power output at the nominal engine speed.

Three options exist to help ensure the optimal fuel-air mixture is used in each cylinder when a given engine is driving a load that is outside the optimal 70 – 80 % range. Cylinder deactivation can be used where the cylinders have individually controlled injection arrangements and it minimizes fuel consumption by only using selected cylinders when the load is lower so that those that do operate produce an optimal force in each stroke. However, as the torque on the crankshaft is the sum of the force provided by each cylinder, there may be undesirable oscillations in the torque if this method is used and it is therefore more common for each cylinder to provide an equal contribution to the engine power output.

As power is the product of speed and torque, running an engine at a lower speed for a given load means a greater torque on the crankshaft, which corresponds to a greater force being produced by each cylinder. In other words, at a slower speed there is a higher ratio of fuel to air and so the desirable higher temperature combustion can occur. Where engines are the prime movers in diesel generators this corresponds to a lower output frequency, and this would be a problem if the generator directly connects to a conventional fixed-frequency AC system because the generator needs to produce an output that has

the same frequency and phase as the rest of the network. Power converters can be used to rectify a variable frequency AC output to DC and, if there is a fixed AC system, invert it again to produce the required frequency and phase to match the grid. This therefore allows the fuel consumption to be minimized for a given load.

Energy storage, such as batteries and fuel cells, can be used to optimize the fuel consumption of engines whether they are fixed or variable speed. When the engine load is lower than the optimal 70 – 80 % range then the energy storage can be charged to increase the load. When the load is greater than 70 – 80 % the energy storage can be discharged to supplement the generator output and help the diesel engine to remain at its optimal output. Furthermore, energy storage may increase the power margin, and this can help to handle large power transients without excessive engine speed variation or excessive engine temperatures. Alternatively, energy storage can be used in place of spinning reserve and this improves overall system efficiency because reserve power is available without the losses resulting from prolonged engine running with low- or no-load.

Energy storage systems or standalone power converters can therefore be used to minimize the fuel consumption of the electrical system for a given load but there are trade-offs to consider. While the power electronics semiconductors and controllers are small and light compared with an engine, the harmonic filters, transformers and switchgear that may form part of the full system can significantly add volume and weight, so size weight and power studies need to be conducted to quantify these downsides and enable the advantages and disadvantages to be considered carefully. This is especially true when energy storage in the form of batteries is used because they not only add mass but also can increase the risk of fires [8]. Large battery systems need a dedicated room with cooling, ventilation, fire detection and fire suppression systems, which further adds to the cost and volume of the overall power system.

Changing to variable engine speeds or adding energy storage systems may reduce emissions for the reasons covered in the previous section, and may also contribute to improved power quality since either option would enhance the ability of the power system to respond to large transient loads. However, as noted, these options would require at least power converters to be added, and in the case of energy storage it may require spaces in the ship to be converted to house a large battery system. Aside from the engineering costs, equipment costs and the costs of training the crew, this may also mean spaces previously used for missions needs to be converted to house the new equipment and so a balance has to be struck between meeting environmental requirements and continuing to meet military objectives. The reduced fuel costs and increased vessel endurance are benefits that would also form part of the overall assessment.

Waste Heat Recovery (WHR)

WHR is used extensively in the merchant sector where ships travel at constant speeds for prolonged periods, e.g. days and even weeks, at ‘steady-state’ machinery conditions, and can have a very positive impact on ship economics. Although opportunities may exist for WHR in warships, they must fulfil the military needs of the programme, including operating profiles and concept of employment (CONEMP) of the power and propulsion system. In practice, WHR using high-grade heat recovered from propulsion engines is usually less viable due to the highly variable nature of the lever setting/power output of

propulsion machinery even in peacetime operation, resulting in poor return on investment of the CAPEX of the additional systems and equipment required for WHR.

Fuel Cells

Fuel cells that produce electricity from hydrogen are an alternative to internal combustion engines for providing power to some military loads. These may provide quieter, cleaner power without the thermal signature of internal combustion engines [9], and therefore could provide operational advantages. However, hydrogen has wider flammability limits and requires less energy to ignite that other gases [10], and therefore its storage will need careful consideration. Furthermore, fuel cells may need forced cooling, require regular maintenance cycles and have a voltage that varies with load, which means that power converters are required. Again, new processes and training will add to operating costs if fuel cell-based power supplies are introduced.

The volumetric energy density of hydrogen relative to diesel is an important consideration for the vessel designer. While the gravitational energy density of hydrogen is close to three times that of diesel, its volumetric energy density is only around one quarter [11] at temperatures that would be expected in a marine environment. This means that either large tanks will be needed for its storage, or that it must be compressed to increase its volumetric density. Compression leads to the need for cooling and it bring safety risks and the possibility of loss of fuel through leakage. In addition to overall power-density of fuel cells, there is intolerance to sudden thermal (load) transients associated with small island power generations, e.g. ships with large consumers constantly going on and off.

Warship design

The previous sections have discussed emerging fuels and the engine and power system designs that might be used to help to reduce CO_2 and other emissions that may have a damaging effect on the environment. This section will briefly discuss options for upgrades to existing ships and for the design of new ships to meet or at least lessen these environmental challenges and to address technological developments.

Incremental efficiency improvements in in-service hull and appendage design are possible and have been implemented by various navies. These include one or a combination of bulbous bows, transom flaps, modern anti-fouling paint, propeller hub caps, to name a few. This has also extended to trials and adoption of LED lightbulbs, variable-speed drives for large pumps e.g. HPSW pumps (or at least two-speed motors), and other similar techniques to minimize electrical load demand, with some success.

An opportunity which is often over-looked for new builds is early design optimization of the hydrodynamics of not just the propeller and shaft line, but also its integration into the after section of the hull and the associated appendages – taking a system of systems approach. For a given ship speed, this approach can increase efficiency and minimize installed power requirements, with the associated savings in volume and mass feeding a virtuous circle in the warship design spiral.

Operability

Given these complications, it might be that the most suitable way to reduce the environmental impact of existing vessels is through equipment health monitoring to ensure the engines are at optimal states of maintenance and by using energy management and the implementation of 'smart meters' to facilitate better operator situational awareness to best determine the power each engine should supply during each operating mode. Such modifications would require only limited new instrumentation, if any, and may only need to involve changes to control settings or software. They can also be developed offline and trialed in simulation or derived from data collected while the ship is in operation, perhaps even using artificial intelligence. Such modifications are not without risk and would still require many engineering hours to be spent validating them and ensuring undesirable or dangerous outcomes would not occur, but they are still likely to result in lower-cost enhancements than replacing or modifying the engines.

Emerging equipment technology

For new builds in the coming decades there are many opportunities for introducing new power and propulsion systems. The approaches mentioned above could be more easily adopted in a new design, but the size weight and power trade-offs would still have to be made. Gas turbine generators in the range of 5 – 10 MW running sustainable fuels could form a new basis of integrated fully electric propulsion systems that enhance power density while minimizing emissions. Fuel cells could provide very quiet power for certain equipment and missions if suitable means to store the gas are developed. Small modular reactors are also being developed with the aim of them being available for civilian use by 2030 and this could enable them to be adopted as a highly power dense source of electrical power in the following decades, which would be of great value given that electrical loads on ships continue to grow in both their average and peak power demands.

In addition to EHM, which provides an insight into the condition of on-board assets, another important aspect worthy of consideration are tools to provide feedback on real-time fuel consumption and especially the impact of operator behavior. Although the 'Hire car' mentality is hopefully a thing of the past, deploying 'smart meters' on board would undoubtedly remind the crew of the more economic operating points in terms of matching engines and machinery states to ship speed, for a better outcome.

Holistic operations

Given the cost and technical difficulty of implementing many of the technologies reviewed, there is a compelling need to widen the aperture and include the shore-side infrastructure in addition to the actual sea-going fleet, due to the relative ease of implementing net zero carbon (NZC) technologies in land-based facilities. A recent example is the Rolls-Royce Filton, Bristol factory which achieved NZC in 2021 via the implementation of photovoltaic cells and ground-source heat pumps etc. [12].

Conclusions

This paper has considered naval P&P system design considering the increasing demand for electrical power and the continuing trend across the world of replacing fossil fuels with alternatives that do less to cause

climate change. Emerging fuels can help to lower emissions by using CO_2 captured from the atmosphere by crops or industrial processes, or through their use as a store of energy from renewable power, such as wind turbines. Their introduction may present technical and logistical challenges to navies and the reduction in net emissions depends heavily on how they are produced, so they are not a straightforward way to cut emissions. Furthermore, it must be kept in mind that military needs must come before environmental concerns for navies.

Alternative power sources, such as fuel cells, energy storage and small modular reactors may also play a role in providing power on naval platforms. They are at varying degrees of technology readiness for applications on land and for commercial marine, which can help to inform naval ship designers and operators of their advantages and disadvantages. However, being less mature than diesel engines and gas turbines in the naval domain is a limitation, and for technologies such as fuel cells, batteries, supercapacitors, etc., energy density may present a challenge given platforms are increasingly facing space and weight constraints.

Demand side load management, as commonly used in domestic utilities, may help ship crew to minimize fuel consumption by providing more detail about how their operational decisions are influencing power demand. This is one example of how data analytics can help to improve performance and reduce environmental impact, and the use of equipment health monitoring to optimize the operation of the P&P system is another. Iterative efficiency improvements such as LED lighting and variable speed motor drives for auxiliary loads are also ways to minimize the demand for power.

New fuels, alternative power sources, demand side load management and improved engine designs can all contribute to lower emissions and improved performance, but optimal system design may be the key means to achieve these objectives. This systems approach begins with careful understanding of the operations the platform will undertake and the demands on the P&P system in each operating mode. It also includes decisions around the quantity, type and configuration of the engines, gearboxes, power converters, propulsion motors, etc., and the design of their control systems. Furthermore, careful decisions must be made to ensure that using approaches such as DC distribution or adding energy storage results in the expected overall efficiency improvements. Lessons learned from previous classes are a crucial part of design optimization, and the continuing evolution of modelling and simulation and artificial intelligence provide new tools to the system designer.

This combination of knowledge and experience, data and design tools are essential to minimizing environmental impact while still meeting military needs. Given recent advancements in mission system technology and that its rate of change far exceeds the ship design and build cycle, installed power generation has become a strategic resource in terms of prohibiting or enabling the through-life technology insertion of new weapons and sensors as they become available, and thus sustaining the military relevance of the programme.

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Towards a Cost-Effective Approach to Extending the Life of Naval Surface Ships

B. Cartwright, M. Renilson, and D. McGuckin
Pacific ESI, Sydney, Australia
T. Magoga
Defence Science and Technology Group, Melbourne, Australia
L. Mulcahy and R. Melchers
University of Newcastle, Newcastle, Australia
A. Chhor
University of New South Wales, Sydney, Australia

ABSTRACT
Deterioration of the hull and structure, due to the accumulated effects of corrosion, fatigue, and collision damage, is a key factor in the decision to withdraw a naval ship from service. Similarly, knowledge of the material state of the structure informs any Life of Type Extension (LOTE).

Monitoring and effecting repairs on structural deterioration are significant contributors to both through-life costs, and reduced platform readiness. During planned dockings, the decision to remediate or defer structural defects has historically been based on experience and judgement; a conservative outlook is likely to result in more repairs, and cost, than necessary.

Digital engineering approaches to understanding the current materiel state of a ship, and predicting the future state in possible operational scenarios, are emerging. For shipyards and maintainers, such approaches can be used to provide ship life-cycle models and subsequent sustainment services. One of the advantages of digital engineering approaches is that the unique configuration and maintenance history of each ship in a class can be related to available in-service information or predicted usage (for example, speed and encountered sea state).

This paper demonstrates a digital engineering approach to link the encountered sea state to the structural responses in the ship accounting for the material state of the ship. This capability can be used in evidence-based prioritisation of repairs to assure the required seaworthiness level of the ship, decommissioning planning, and LOTE studies. For demonstration purposes the focus within this paper is an assessment based on global ship stress response, but local stress and watertightness may also be considered in the future with suitable refinement of the technique. The potential impact is reduced maintenance costs and improved understanding of the mission-readiness of the ship to inform individual ship and fleet tasking. The paper concludes with a description of future work.

1. INTRODUCTION

All ships require frequent maintenance to ensure their continued safe operation. Naval ships are no exception, where the recent whole of life costs for capability are quoted as being typically 70% in sustainment and 30% in acquisition [1]. As ships age, their maintenance requirements typically increase, thereby further increasing cost and reducing availability [2, 3].

In general, the maintenance of a naval ship is connected to its Operational and Support Intent (OSI). The OSI describes how the ship will be operated and supported logistically. If there is a requirement to deviate from the planned maintenance schedule, the tasking of the ship may be limited. For emerging deployments, the usage upkeep cycle may be rearranged. As a result, risks due to deferred maintenance can arise, such as those relating to emerging defects.

It may be necessary to extend the life of an in-service ship, often due to delays to the construction of replacement ships. This requires a Life-of-Type Extension (LOTE), which may incur substantial costs in addition to major lack of availability whilst the LOTE is being undertaken. The majority of surface ships in the Royal Australian Navy have undergone a LOTE program [4]. The main activities of LOTE typically focus on hull structure and machinery aspects [5].

Scheduled maintenance for machinery and systems is often dictated by vendors and is warranty related. Maintenance activities are prescriptive (for example, replacement of consumables and components). In comparison, hull and structure maintenance requires surveyors with experience to interpret the condition of the ship against Class Guidelines or empirical rules. This is an acquired skill. Application of the safety factor necessary to account for this can result in considerable conservatism, leading to more repairs and associated costs than necessary. Thus, the development of a data-driven approach to assess which maintenance activities are required and which can be deferred, over the usage upkeep cycle, is key to reducing the cost and improving the availability of naval ship – particularly those requiring LOTE.

For perspective, the current sustainment budget for the Royal Australian Navy Anzac-class frigates is approximately $375m for 2020-2021 [7]. A small percentage in maintenance that can be saved or deferred, through a better understanding of the needed versus planned hull maintenance may result in a saving of millions of dollars. Therefore, to understand and appropriately manage the risks associated with maintenance deferrals, maintenance rescheduling, and aging, there is merit in developing data-driven tools to support decision-making.

The structural life of a ship can be limited by its fatigue life, under long-term exposure to wave-induced loads [6]. There are accepted procedures for determining the loads on the ship in waves, the stress responses, and hence the fatigue life of the ship. From the time of the design of the ship, a plan can be established to provide regular maintenance to ensure the required fatigue life of the ship structure is met. However, the role of the ship may change during its life, due to changes in operational requirements, upgrades and/or structural modifications. These changes may alter the original estimate of the fatigue life of the structure. Therefore, it is important to

understand the influence of these changes to the loads on the ship and in turn the through-life management of the ship.

This paper demonstrates a digital engineering approach to link the encountered sea state to the structural responses in the ship, accounting for the material state of the ship, via a case study. The paper is organised as follows. Section 2 briefly discusses typical hull and structural defects. Section 3 presents the case study ship, method, analysis and results. Section 4 discusses both the results and their potential applications. Section 5 describes the path to increase the robustness of the proposed approach. Finally, the conclusion is given in Section 6.

2. EXAMPLES OF HULL AND STRUCTURE DEFECTS

To gain an appreciation of the types, frequency, and extent of structural defects in naval ships, a review of a selection of recent Royal Australian Navy frigate hull survey and defect reports was conducted. The types and extent of deterioration to the primary structure were catalogued, with the view to incorporate in a numerical model of the loads and ship structure.

Three types of defects were reported that could influence the structural integrity of the ship: corrosion; cracks and fatigue; and damage resulting from a collision or impact event. Of these, corrosion was most widespread. Defects are exemplified in Figures 2.1 and 2.2 respectively, which show a deep corrosion pit and a crack detected in a weld seam of a stiffener.

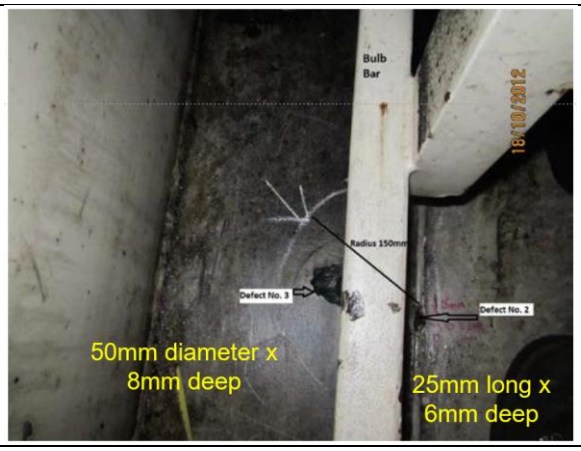


Figure 2.1. Example of deep corrosion pit to shell plate



Figure 2.2. Example of crack detected in weld seam of stiffener to plating

Most instances of corrosion were not considered critical. However, a small number of cases of deep corrosion over a large area, as well as severe pitting corrosion, were reported. Corrosion was most severe at junctions of frames/stringers/bulkheads, on topside decks, in tanks (water ballast, fuel oil, sludge) and in sea chests.

All severe crack and corrosion defects were repaired during the five-year deep maintenance event. Consequently, the majority of defects found in the subsequent survey were likely less than five years old. This was evident in the consecutive hull survey reports for one ship, where existing defects were not present in a later hull survey report of the same ship.

3. CASE STUDY

In the case study, the stresses in a frigate are analysed.

3.1. Method

The method employed is that of numerical simulation within a general-purpose software tool for structural and acoustic applications. The software tool consists of an explicit (time-marching) Finite Element (FE) solver with intimate coupling to a Mesh-free Smoothed Particle Hydrodynamics (SPH) solver within the one software package. The ship is modelled using the FE solver, and the fluid - representing an ocean with waves - is modelled using the SPH solver. Waves are created according to moving floor technique as described in [9].

The global motions predicted using this approach have been partially validated by comparison with those obtained from industry-standard software tools [8].

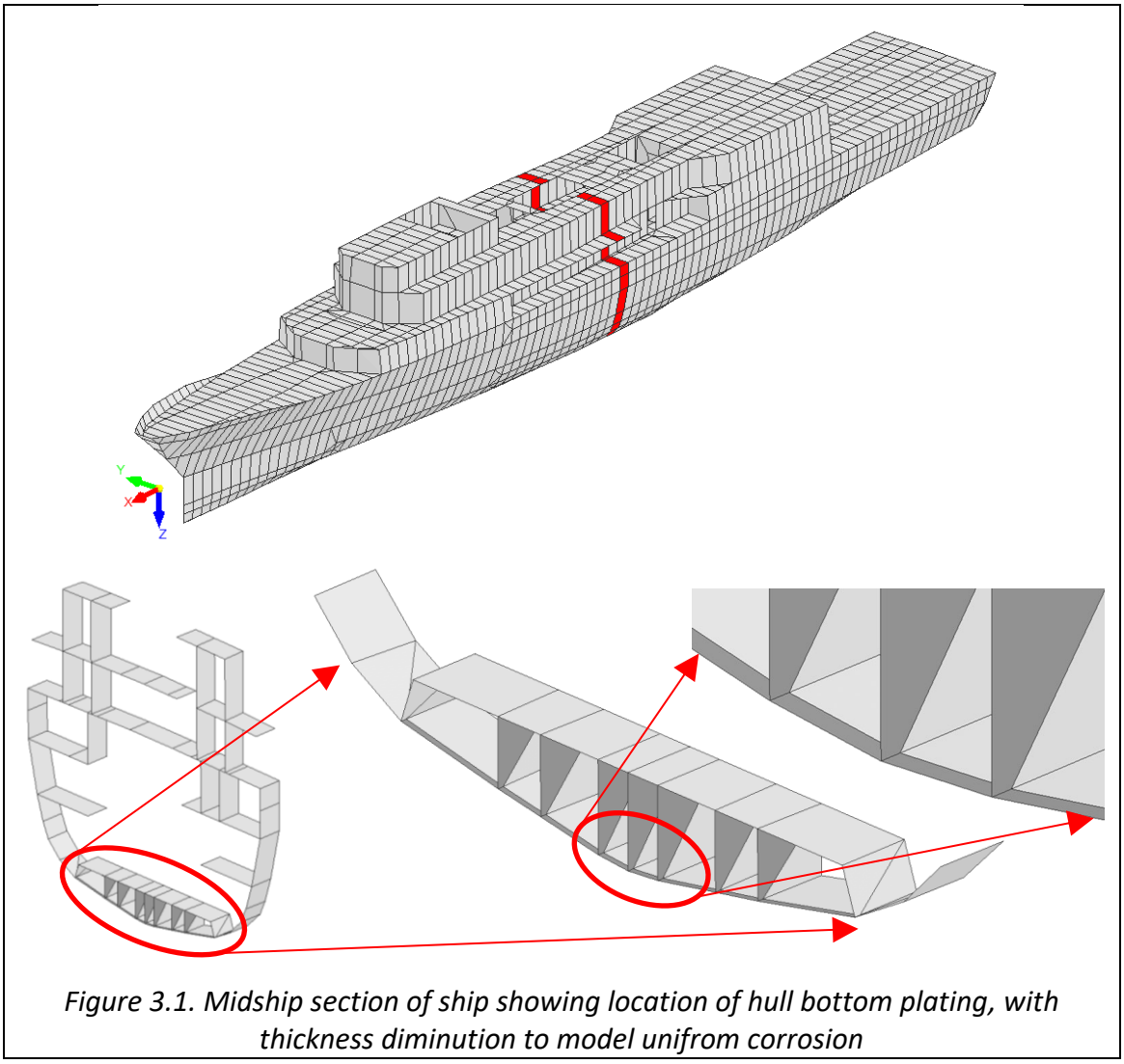


Figure 3.1. Midship section of ship showing location of hull bottom plating, with thickness diminution to model unifrom corrosion

Figure 3.1 shows the FE model of the ship, and some internal structural detail of the model. The assumption of linear elasticity is assumed in the FE model. The model does not contain bilge keels or appendages. The plating, internal walls and bulkheads of the ship are represented by shell elements, and structural elements such as girders, frames, stringers and stiffeners are represented by beams and bars along the edges of the shells.

The motions of the ship, and the applied loads, are derived from the interaction of the FE ship model and the SPH waves [8, 10]. The interaction of the FE model of the ship and the mesh-free representation of the waves occurs simultaneously and continuously in the general purpose explicit solver [11].

The numerical wave tank had a length of uniform depth of 10xL, where L is the length of the ship, an upstream and downstream beach of approximately 1.25xL, a width of 1xL, and a depth of approximately 20% of L. These dimensions were determined to avoid side-wall effects across the range of speeds of interest, and to provide sufficient wave-encounter events to establish a steady response of the ship to the waves.

The numerical simulation allows visualisation of parameters such as stress and strain on the model as it traverses a numerical wave, and evaluation of parameters such as shear forces and moments with time at specific locations in the ship. Making a change in the ship structure, for example due to a fatigue crack or thickness diminution due to corrosion, and running the numerical simulations again provides a prediction of how that structural change will influence the stress or strain in the ship for that given load case.

If the ship survey reveals degradation, this degradation can be incorporated into the model of the ship structure and the stress state of the ship with degradation examined. Similarly, a repair to an existing defect could be incorporated into the model.

3.2. Analysis

A numerical simulation was performed to predict the response of the ship at constant forward speed into head seas. The operating conditions were a Froude number (F_N) of 0.18, ratio of ship length (L) to wavelength (λ) of 1.0, and wave height (H) divided by wavelength of 0.028.

Although a tank depth of only 20% of wavelength in a conventional rigid tank would imply a shallow wave condition, the moving bottom technique mimics deep water wave behaviour in depths less than half a wavelength deep, as described in [9].

For this demonstration, the FE model of the ship has hull plate thickness reduction applied to an athwartship line of narrow shell elements midship on the bottom of the hull. This area of plate thickness reduction is an idealisation of uniform corrosion wastage of the hull plating, as might be expected with surface corrosion. This approach is similar to that conducted by the United States Coast Guard in their structural assessment of aged ships [12].

The elements of reduced thickness are the bottom hull plating and longitudinal girders adjacent to the thinned hull plate, as shown in Figure 3.1. This area of the frigate was chosen because:

- It is an area that is difficult to maintain, and difficult to inspect;
- Hull survey reports indicate significant corrosion in this area; and
- It is highly loaded (vertical bending moment) in both the hogging and sagging conditions.

To illustrate the technique, the thickness of the selected shell elements was reduced from the original thickness to 60%, 40% and 20% of the original thickness to emulate degradation. At each new thickness, a complete time-domain simulation of the ship in head seas was conducted. The simulation results are then examined to reveal the longitudinal stress in the wasted shell elements.

One approach to limit the probability of crack initiation of structural members is to asses during the design stage whether there is sufficient fatigue strength; that is, sufficient strength against crack initiation under dynamic loads during operation. This is described by Germansicher Lloyd (GL) in its Rules for Classification and Construction [13]. A fatigue strength analysis is performed for structures predominantly subjected to cyclic loads, the assessment of which can be based on a permissible peak stress range for standard stress spectra, or on the cumulative fatigue damage ration. If only considering the peak stress range ($\Delta\sigma_{max}$) due to seaway-induced dynamic loads and assuming a linear stress spectrum, fatigue strength analysis is not required if $\Delta\sigma_{max}$ is less than or equal to the fatigue strength reference value ($\Delta\sigma_R$) multiplied by 2.5. For a particular structural detail (for example, a longitudinal butt weld), the fatigue strength reference value is taken from the applicable S-N curve at $2x10^6$ cycles of stress range.

3.3. Results

Figure 3.2 shows four different instances of the stresses induced in the ship as it encounters a wave at forward speed during the time-domain simulation. The colour on the ship relates to the longitudinal stress component of the shell elements – red for tension and blue for compression. The dark-blue line represents the wave surface.

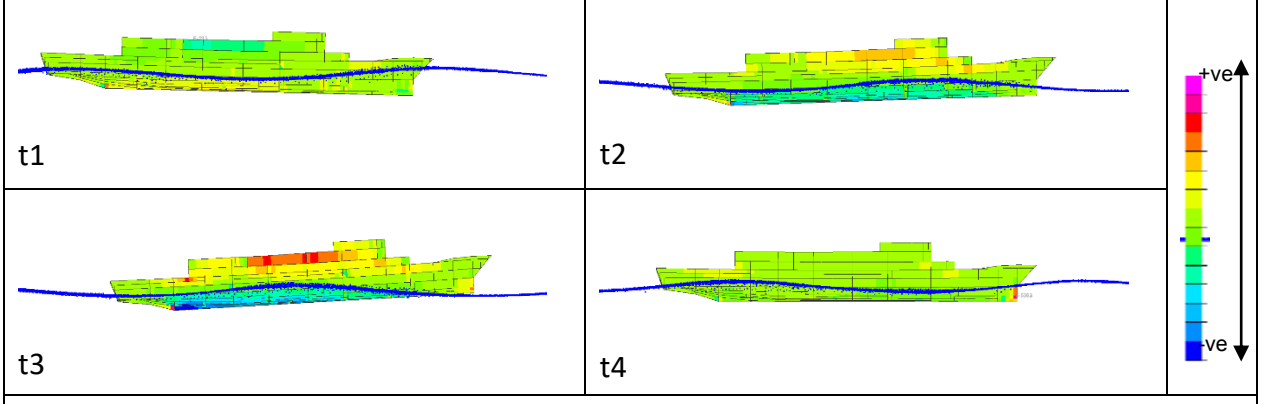


Figure 3.2. Stress distribution in ship at four instances during simulation

In this example the influence of the introduced local plate thickness reduction was found to have negligible effect on the heave and pitch of the ship. This was a check to ensure that reducing the hull plate thickness locally was insufficient to change the flexibility of the ship and therefore change the global response of the ship in waves.

Figure 3.3 shows the normal stress σ_N, in the longitudinal direction, non-dimensionalised by the allowable (design) stress σ_{allow} as a function of time at the reference structural location for each level of remaining thickness. As expected, the peak stress magnitudes are smallest with 100% thickness and are greater for the smaller plate thicknesses.

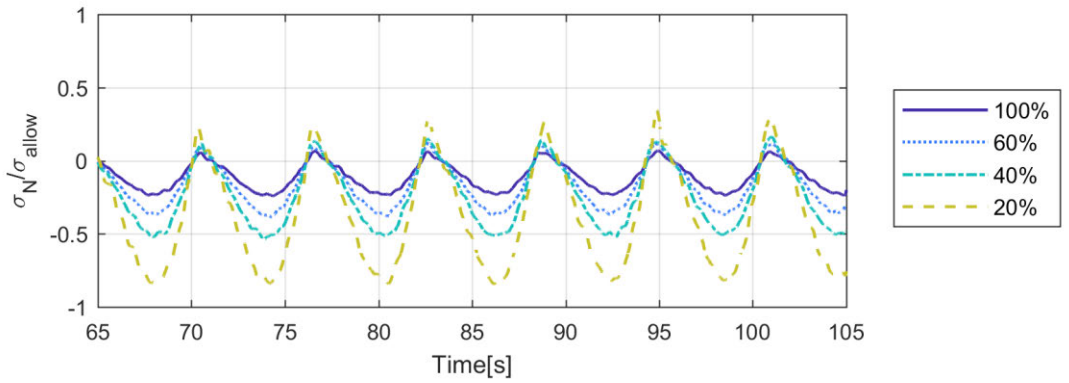


Figure 3.3. Normal stress, in longitudinal direction, at reference structural location, for 100%, 60%, 40% and 20% remaining thickness of plate (for F_N=0.18, L/λ=1.0, and H/L=0.028)

Figure 3.4 illustrates the change in the normal stress range at the reference structural location with change in thickness diminution, for the given load case. Also indicated in the plot are the minimum plate thickness of 80% specified in the class rules, the allowable (design) stress, and the fatigue strength reference value for the given structural detail. For the considered load case, the fatigue strength reference value is exceeded when the remaining plate thickness is less than ~38% of the original thickness.

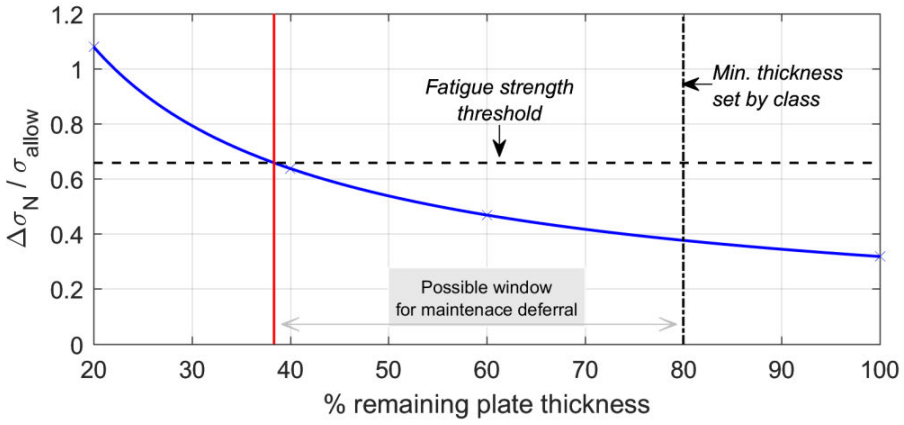


Figure 3.4 Normal stress range against plate thickness at the reference structural location, for F_N=0.18, L/λ=1.0, and H/L=0.028.

4. DISCUSSION

Charts indicating stress magnification as a function of plate thickness, such as those shown in Figure 3.4, can be used by capability managers to understand the relative risks that arise due to deferred maintenance, and how these risks can affect a structural life extension. If, for example, prioritisation of defect remediation is such that a particular area of corroded hull plating could not be renewed during a planned maintenance period, it may be permissible for the ship to be available for tasking as long as the stress range in the affected structural member does not exceed the reference fatigue strength. The risk could further be managed by applying an operational restriction. In addition, if the remaining plate thickness was slightly less than 80% (the minimum thickness set by the classification society), it may be permissible to safely defer the associated defect rectification, resulting in a considerable cost saving and increased ship availability.

Figure 3.4 illustrates how this approach can help determine the criticality of structural defect. Although the result presented here represents the response of the ship at one operating condition, to enable advice on maintenance prioritisation, it is necessary to expand the analysis to a range of environmental conditions, including: sea state; ship speed; and heading relative to the principal wave direction. Thus, an envelope of maximum stress at fatigue-critical or referral structural locations would be developed, to provide data-driven evidence on what maintenance is required, and what levels of deterioration are acceptable in critical/primary structural members and details.

The concept of analysing the local stress of a degraded ship structure is not novel, as shown by [12]. However, the novelty of the approach here is the method of establishing the time-varying response of the ship at predetermined or assumed conditions (for example, based on the OSI). The next stage of the work would be to consider long-term operational conditions, including extreme values. Such conditions might entail breaking waves, green-water on deck, stern and/or bow slamming, or even heaving-to of the ship due to wave-steepness. This level of solution robustness could lead to improved risk management related to operations and maintenance decision-making, by providing a more reliable structural response prediction of the ship at such limit-state conditions. Validation is needed to provide an understanding of the accuracy of the described process. Further, while the numerical technique will still provide results, as the physics increases in complexity greater validation is required.

The concept described in the current paper could underpin a Digital Twin (DT) of the ship structure. In addition to being a real-world system, the core components of a DT include one or more digital models, sensor data plus fusion logic (for example, the expected versus the measured strains in the hull), and a decision or outcome that will change based on the output of the DT [14, 15]. An example of sensor data could be real-time monitoring as acquired and correlated by a structural health monitoring system, such as described in Magoga and Morris [16]. The anticipated outcomes from a DT of a naval ship structure include enhanced resource allocation, logistics planning, and in-situ decision-making [17].

5. FUTURE WORK

There are a number of areas that require further development for this technique to become a robust tool to a fleet operator or maintainer, as follows:

- The example presented in this paper is exercised at one operating condition. To be useful for engineering purposes, the response is required across the range of operating conditions of the ship: ship speed; wavelength; and wave height.
- Simulations in oblique waves will place elements of the ship under greater stress due to torsional loadings, and so operating conditions in oblique seas must be included in the analysis.
- To cover the operating conditions of the ship, it may be necessary to repeat the analysis for selected conditions at different load conditions.
- The numerical simulation technique described here is computationally intensive. For example, Figure 3.3 presents four simulation results, each of which required about 20 hours on 72 cores of Intel(R) Xeon(R) CPU E5-2695 to evaluate.
- To conduct the complete analysis across a range of operating conditions, as discussed above, would therefore require either considerable computational power, or a considerable amount of time. However, it is felt that with the computing power available today this could easily be achieved in a realistic period, running simultaneous simulations on a moderate cluster of 3,000 cores.
- It must also be acknowledged that the software used here is generic FE software. It is not tailored to give solutions or outputs in naval architecture terminology. To facilitate the preparation of simulation runs, the execution of the runs on a cluster, and ultimately the interpretation of the results in a cost-effective manner will likely require some custom coding or front-end Graphical User Interface / Human-Machine Interface. However, this is a common process, and so should be economically possible.
- Validation of the numerical simulation approach is still required. To do this it is necessary to have access to appropriate validation data. The acquisition of such data across – and specifically at the boundaries of – the operation conditions for the ship are likely to only be only possible through model testing. This is a costly process. However, the extents of the available data should be made available for correlation and validation by numerical simulation.
- Although discussion here has been limited to that of Life of Type extensions of naval ships, the concepts proposed could also be used to provide a risk-based decision support tool for operations and maintenance applications.

6. CONCLUDING REMARKS

Deterioration of the hull and structure, due to the accumulated effects of corrosion, fatigue, collision or other operational damage, is a key factor in the decision to withdraw a naval ship from service. Repairing such damage is a significant contributor to the through-life costs, and reduced availability of the ship to the fleet. The decision to remediate or defer structural defects has historically been based on experience and judgement, with risk adverse decisions likely to result in more repairs, and cost, than necessary.

This paper has described a novel fluid-structure numerical simulation technique to determine the structural loads within a ship operating in a seaway. The results presented are encouraging. However, such a new technique requires rigorous validation across benign to severe operating conditions before the technique can be used as a universal tool.

It has been demonstrated how this technique can be used to determine the stresses in an element of the ship structure when subjected to waves, and the consequent influence of local plate "wastage" due to corrosion on these stresses. The resulting data-driven approach to determining what maintenance is necessary, and what can be safely deferred, will result in a considerable cost saving and increased ship availability.

It is suggested that, in addition to normal fleet maintenance, such an approach should be incorporated within the planning and costing capability of any future LOTE program.

7. ACKNOWLEDGEMENTS

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Use of Thematic Analysis to Investigate the Application of Digital Twin for Naval Platform Operations

Teresa Magoga, Anthony Woolley[+], Peter Hield, and John Chisholm
Defence Science and Technology Group, Australia
[+]anthony.woolley@dst.defence.gov.au

ABSTRACT

Day-to-day naval platform management and operations are increasingly reliant on advanced digital engineering concepts. Functional requirements for these concepts are guided by the need for adaptation to rapidly changing operational and threat environments, fiscal constraints, and rapid technology refresh cycles. Identification of the relevance of emerging digital engineering concepts requires an understanding of the user perspective in the application of those concepts. The primary concern of the user is the suitability, accuracy and timeliness of the output from analysis tools and decision-making software. One emerging concept is known as the *Digital Twin*. A Digital Twin consists of a virtual model of a physical system with a data-driven bidirectional communication framework connecting the virtual model to the physical system. In the case of managing naval platform operations, the Digital Twin may represent whole-of-platform or elements of the platform. A platform deployed Digital Twin will provide real-time support for platform and system health monitoring, prognostic analysis and survivability operations. The Digital Twin may also be deployed on shore for capability sustainment and remote support for a deployed platform. To understand the user requirements for a Digital Twin capability supporting naval platform operations, a study was performed in which naval personnel with in-depth experience across multiple job roles (at sea and ashore) were interviewed. Decision-making for each job role was identified, including information requirements supporting the decision-making. Presented is the output from a thematic analysis of interviewee responses, identifying key features the authors consider relevant for the successful integration of a Digital Twin capability to enhance naval platform operations.

1. INTRODUCTION

The Royal Australian Navy (RAN) must be resilient and adapt to rapidly changing operational and threat environments. Thus, to maintain fleet and platform readiness and ensure agility, the RAN should seek to exploit relevant technology advancements. Consequently, to establish fitness-for-purpose, the technology advancements and RAN operating environments must be assessed. One technology domain that is increasingly utilised in day-to-day naval operations is referred to as *digital engineering*. In particular, the concept of *Digital Twin* is an emerging, multifaceted digital engineering technology with capability to support the management and operations of physical assets.

A Digital Twin is a virtual representation of a physical object for the purpose of simulating, understanding and managing the operations of the physical object [1]. The original concept of a Digital Twin was proposed in support of manufacturing [1], and this remains the primary focus. For example, Defence original equipment manufacturers, such as BAE Systems and Navantia, are investigating Digital Twin concepts for the transition to new digital engineering technologies in naval shipbuilding [2, 3]. However, the capabilities afforded by a Digital Twin can also be utilised in naval platform management and operations.

To understand the utilisation of a Digital Twin in support of naval platform management and operations, there is a need to understand the associated management processes and information requirements. To form this understanding, semi-structured interviews were performed with RAN service personnel, Defence Australian Public Servants and Defence contractors across several RAN job roles. The interview data was then analysed using a technique known as *thematic analysis* [4].

The thematic analysis performed in this study identified key features of RAN platform management and operations that could be enhanced by the implementation of a Digital Twin capability. The key features represent required functionality for governance and management systems, and are a valuable input to inform the functional requirements of a Digital Twin for naval platform management and operations.

The remainder of this paper defines the Digital Twin concept (Section 2); describes the study methodology (Section 3); presents output from the thematic analysis (Section 4); and discusses the requirements of a Digital Twin capability supporting naval platform management and operations in relation to the thematic analysis (Section 5).

2. DIGITAL TWIN

The definitions of a Digital Twin are as variable as the application domains to which it is applied [5, 6, 7, 8]. Consequently, there is a diverse and incomplete understanding of the Digital Twin concept [1, 5, 9], such that: there is no generally accepted definition for a Digital Twin; there is no agreement regarding the features a Digital Twin should possess; and there is no agreement regarding the scope a Digital Twin should encompass.

It is commonly accepted, though, that a Digital Twin is a virtual representation of a physical system for the purpose of modelling the lifecycle of the physical system [1, 5, 7, 9]. It is comprised of a multi-scale, probabilistic simulation framework utilising real-time physical system data and physics models to monitor and predict the behaviour and performance of the physical system. The key enabler for the Digital Twin is a data-driven bidirectional communication framework, known as a *Digital Thread* [10, 11, 12], connecting the physical system to the models within the simulation framework. The Digital Thread maintains continuity and cohesiveness of data and information, and links disparate information sources (such as policy manuals, databases, the physical systems, and the virtual environment). Connectivity with the physical object enables the Digital Twin to monitor and control the behaviour of the physical object.

Figure 1 presents a conceptual framework for a Digital Twin in support of naval platform operations (derived from [5, 13]). The framework consists of two primary components. The first component is the physical platform connected to shore-based facilities. Databases on board the platform, and at shore-based facilities, record platform system state using automated sensor systems, and manual data input services installed on the platform and at the shore-based facilities. The second component consists of modelling and simulation (M&S) tools connected in an integrated framework via the *Simulation Architecture*. The example presented in Figure 1 represents a conceptual M&S framework for the analysis of naval platform Integrated Survivability [14, 15]. The modelling components include the simulation of crew behaviour [15, 16, 17] (*Command and Control Model*, *Damage Control Central Model*, *Crew Movement Model*, *Damage Control Teams Model*, *Crew Billet Database*, and *Library of Standard Operating Procedures*); the simulation of the platform and platform

systems (*Ship Systems Model*, *Capability Model*, and *Ship System and General Arrangement Database*); and the simulation of the threat and of damage progression [15] (*Ship Signature Model*, *Susceptibility Model*, *Damage Interaction Model*, *Repair Model*, *Flood Model*, *Structural Integrity Model*, *Fire Model*, *Toxic Hazard Model*, *Ship Movement Model*, and *Sea Model*). Similar M&S frameworks may be developed for platform health and usage monitoring, and sustainment management. The Simulation Architecture facilitates data transfer between the M&S tools, with software logic rules to ensure data compatibility and fidelity. Connectivity between the physical platform and the shore-based facilities provides input to the M&S framework to perform prognostic and predictive analysis. Output from the analysis enables informed human decision-making to enact change on, or in relation to, the platform. Similarly, if so designed, the output may cause automatic system response on board the platform. Not explicit in Figure 1 is that a Digital Twin may be deployed on the platform, or installed at shore-based facilities, or both. On board the platform, the Digital Twin is within a closed environment supporting platform operations using real-time system state information.

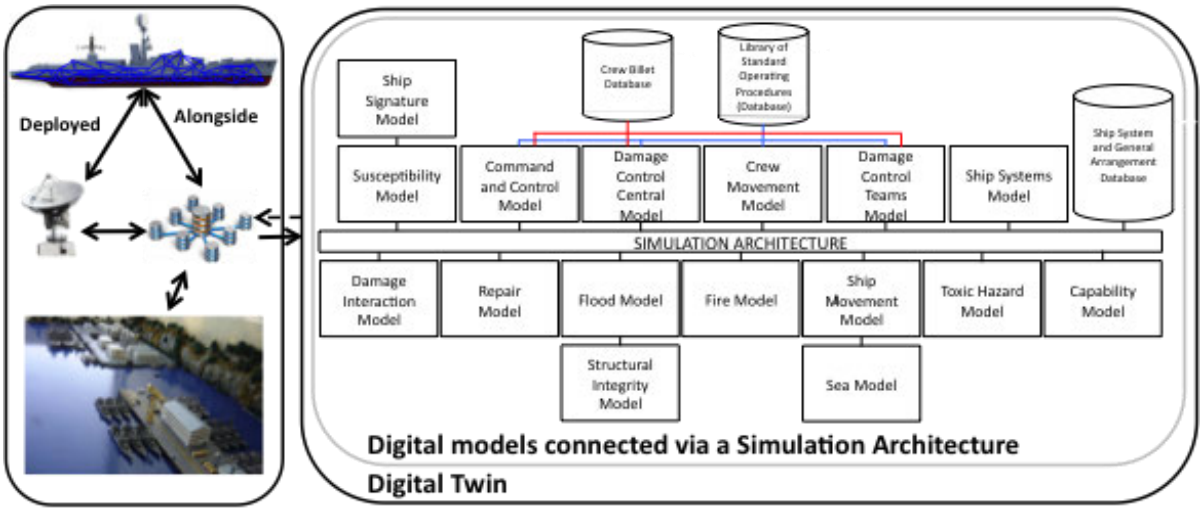


Figure 1: Conceptual model of a Digital Twin in support of naval platform operations

3. STUDY METHOD

The study involved interviewing *suitably qualified and experienced personnel* (SQEP) from the RAN. To focus the interviews, four use case scenarios, encompassing typical naval platform operations, were defined. The interview responses formed the input for the thematic analysis. The methodology is described further in this section.

3.1 The Scenarios

The four scenarios were designed to depict high-level aspects of naval operations. The scenarios were deliberately broad to allow for exploration of processes, decision-making, and information requirements to achieve the aims of the scenario.

Scenario 1: Platform Selection and Readiness - to examine processes relating to the selection and/or readiness of a suitable platform to commit to a six-month task force deployment.

Scenario 2: Through-life Support - to understand managing a fleet of mid-life platforms for the remaining 15 years of capability life. This included the processes to maximise operational availability, to minimise maintenance costs, and for a phased withdrawal from service.

Scenario 3: Underway Management - to understand the provision of operational guidance, including expected versus actual hull, mechanical and electrical system performance.

Scenario 4: Survivability - to understand decision-making during damage control and recoverability of a platform after exposure to a (peace time or combat) damage event.

3.2 Semi-structured Interviews

The authors utilised a semi-structured interview process, which consisted of a series of planned questions with allowance to ask follow-up questions if the need arose. The follow-up questions were to seek clarification of a response, or seek further detail if deemed relevant. There were 21 planned questions for this study, divided into four sections:

1. interviewee demographics: to understand the interviewee's experience;
2. role identification: to understand the duties of the interviewee's current role;
3. decision-making: to understand the decisions to achieve the aims of the scenario; and
4. information requirements: to understand decision-making information requirements.

The set of planned questions were the same for each scenario, as presented in Table 1. Interviews were performed with one interviewer and at least one note-taker.

Table 1: Interview questions

Theme	Question
Demographics	How long have you been in your current role?
	How long have you been with the Australian Defence Organisation (ADO)/Australian Defence Force (ADF)?
	If you are a serving member of the ADF, what were your previous billets?
	If you have served onboard naval platforms: a. what classes of platform have you served on? b. for what duration were you posted on each platform? c. what were your duties on each platform class?
	If you are a civilian, what other job roles have you performed during your career employed by the ADO?
Role Identification	What are your primary duties in a typical day for your current role?
	In your opinion, what makes your job easier?
	What aspects of your job might you consider to be dull, dirty or dangerous?
	What aspects of your job role or policies do you believe are the most difficult to work through?
	What procedures would you change with respect to your job role to make it easier or faster?
	If you were in charge for the day and could change one thing to make your life easier, what would you do?
Decision-making	Thinking of the scenario, what types of decisions are required to achieve the aims of the scenario?
	What time-pressures would you experience to make those decisions?
	Are there any specific policies that would constrain or enable your decision-making?
	What do you consider to be the greatest source of uncertainty that affects your decision-making?
	How could historical job experience be leveraged to better aid you in your decision-making?
Information Requirements	Reflecting on prior experience, what do you think of the reliability or relevancy of the information you have available to you to support your decision-making?
	How do you integrate the information and data into your decision-making?
	Describe a situation you found difficult to process and/or integrate information during your decision-making process?
	What information, not normally available to you, might help you make a decision or arrive at your decision earlier?

Interviewees were identified based on their current job roles within the RAN, and consisted of service personnel and civilian staff. Prior to the interviews, interviewees were provided with a detailed description of the scenario relevant to their job role and the planned questions. This allowed interviewees time to consider their responses.

3.3 Thematic Analysis Method

Thematic analysis is a qualitative data analysis method to identify patterned meaning, or themes, within a dataset [4, 18]. Prior work by Shahzad et al. [19] demonstrated the use of thematic analysis to identify the characteristics and application of Digital Twins for use in building information modeling (BIM); while Jones et al. [9] applied thematic analysis to identify Digital Twin characteristics across application domains as published in the literature.

The identification of themes contributes to providing answers to specific research questions. Themes are identified via a process of data familiarisation, data coding, and theme development and revision. Various techniques exist to perform thematic analysis. For this study, an inductive technique was applied, whereby theme development was guided by the data [18]. Figure 2 presents the inductive process for this study (after [4]).

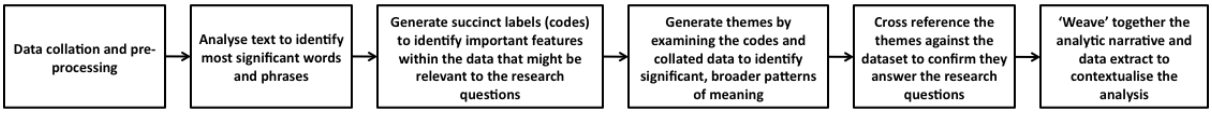


Figure 2: Inductive thematic analysis method

The collection of all the interview records is referred to as a *corpus*. Like any other data, the corpus will require collating and processing (to format the data ready for analysis and remove artefacts that might add *noise* to the analysis). The corpus may also be sub-divided into *data sets*. After collating and processing the interview data, the next step is data familiarisation and identification of significant words and phrases. In this case, 'significance' was determined by a statistical measure known as *term frequency – inverse document frequency* (*tf-idf*) [20]. This measure calculates the frequency of a word appearing in a data set weighted against the number of interview records in the data set containing the word.

Significant words and phrases are collated, and those that are synonymous or related are grouped together. Unique, succinct labels are then given to each grouping of synonymous significant words or phrases. For example, a significant word may have been 'risk'. A related word would be 'assessment', such as 'risk assessment'. Using the significant key words and phrases, the data set is scanned and the unique labels are used as index markers to label sections of the data set that may be of relevance to the research question. For example, the data set could be scanned using the words and word phrases 'risk', 'risk assessment' and 'risk near assess*' (where 'near' identifies words that are within two or three words of each other; and '*' is a wild-card to include words matching, for example, 'assess', 'assessed' and 'assessment'). The associated text would then be indexed using the unique label associated with 'risk', 'risk assessment' and 'risk near assess*'.

When sections of text are identified, the text is examined for themes (with some sections possibly having multiple indexes relating to two or more themes). The identified themes are then related to the research question to contextualise meaning inferred by the themes.

The pre-processing of data and the extraction of significant words and phrases can be performed using appropriate text mining software. For this particular study, *Text Analytics Toolbox* in *MATLAB* [21] was utilised. Similarly, the indexing of relevant text within the data sets associated with significant words and phrases can be performed by software or it can be performed manually. For this study, *QDA Miner Lite* [22] was initially used, augmented with a human-in-the-loop manually scanning the text to ensure relevance of the indexed sections.

4. THEMATIC ANALYSIS OF INTERVIEW RESPONSES

The aim of the study was to identify the suitability of a Digital Twin capability in support of RAN platform management. To focus the thematic analysis, the research question was:

What platform management processes that are required by the RAN might be enabled or enhanced by the implementation of a Digital Twin?

4.1 Demographics

Interviews with SQEP occurred during November-December 2020. Interviews were performed via *Microsoft Teams* and telephone. A total of 13 interviews were performed, with one respondent contributing towards two scenarios. Participants were interviewed individually and were unable to influence responses of other interviewees during the interviews. Interviewees were encouraged to speak freely on the basis of anonymity.

Table 2 presents the number of years of RAN experience for the four scenarios. Since one respondent contributed to two scenarios, they were only counted once in the Total. The range of experience included:

- ranks: Petty Officer (PO); Chief Petty Officer (CPO); Lieutenant Commander (LCDR); Commander (CMDR); and civilian employees;
- career experience:
  - on board ship: Assistant Marine Engineering Officer (AMEO); Deputy Marine Engineering Officer (DMEO); Marine Engineering Officer (MEO); Damage Control Officer (DCO); Repair Base In-charge; and Executive Officer; and
  - shore-based positions: training; System Program Office (SPO); Force Group; overseas posting; and industry;
- platform class postings: Adelaide Class Guided Missile Frigate; ANZAC Class Frigate, Helicopter; Amphibious Assault Ship; Armidale Class Patrol Boat; Auxiliary Oiler Replenishment; Landing Ship, Heavy; Landing Ship, Dock; Landing Platform Amphibious; and Collins Class Submarine.

*Table 2: Number of participants partaking in the interviews (*one participant contributing to two scenarios)*

	Number of Respondents	Total number of years of experience	Average number of years of experience	Median number of years of experience
TOTAL	13*	285	22	23
Scenario 1	2	47	23	23
Scenario 2	5	102	20	25
Scenario 3	3	72	24	24
Scenario 4	4	92	23	19

4.1.1 Statistical Sample Size

A sample size of 13 interviewees is not considered suitable to provide meaningful analysis. In particular, when considering the individual scenarios, there is a lack of diversity. This may result in similar responses due to similar experiences. The similar experiences may be valid but can only be verified with a suitably sized sample set of participants.

Even though the sample size was small, the study can be used to proof the research methodology (such as data collection and analysis techniques). This will enable refinement of the methodology to ensure relevancy of the research output when applied to a suitably sized sample set of participants. The information collected can provide insights and understanding of the processes and decision-making tasks performed in support of naval platform operations. This would assist researchers during future discussions to understand the needs of those performing the tasks and identify application of Digital Twin capabilities.

4.2 Pre-processing of Interview Records

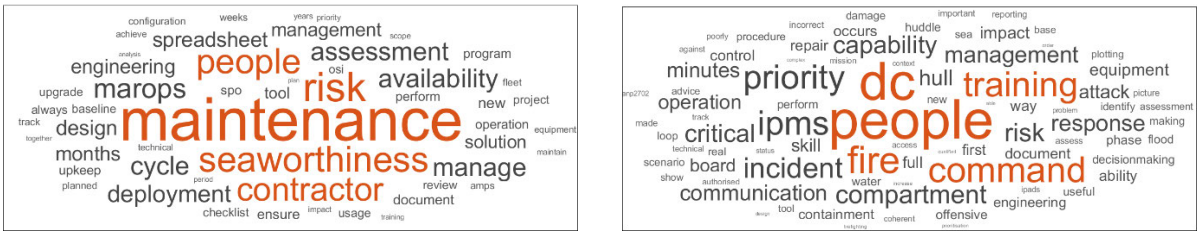
It was necessary to pre-process the corpus to de-identify interviewees. To ensure meaningful words and phrases could be extracted, the corpus was also filtered to remove extraneous content. The resulting vocabulary focussed on the broader sense or sentiment of the corpus. The full method of pre-processing the corpus was:

1. sanitisation of the data:
   a. removal of all demographic information;
   b. simplifying the names of directorates, offices and groups to ‘office’; and
   c. replacing platform names with the word ‘ship’, and replacing platform class names with the word ‘class’;
2. replacing synonymous words (for example, replacing ‘platform’ with ‘ship’);
3. using acronyms rather than full names and phrases, where appropriate;
4. removal of punctuation and words such as ‘a’, ‘and’, and ‘the’;
5. changing upper case text to lower case; and
6. normalising words to their singular form.

The corpus was also delimited by creating two data sets, based on the nature of the scenarios: Scenario 1 and Scenario 2, a shore-based data set; and Scenario 3 and Scenario 4, a sea-based data set. It was believed these groupings would increase the available information for analysis according to shore-based operations and sea-based operations. Except, defining the four scenarios may have biased the analysis by creating themes from the outset and focussing interviewees to provide responses in the context of those themes.

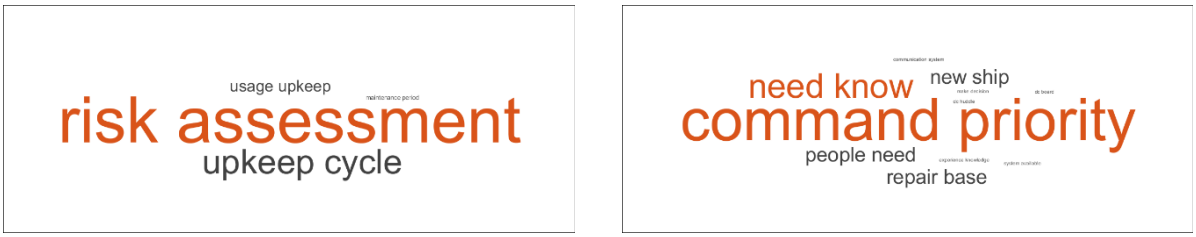
4.3 Identification of Significant Words and Phrases

Tf-idf statistics were generated for words and phrases appearing in each data set and, using those statistics, *word clouds* were created to visually present the significant words and phrases. Figure 3 presents word clouds for the shore-based data set and the sea-based data set. The size of each word indicates the relative significance of a word (the larger the size, the more significant). To be considered a significant word, the word needed to appear at least five times in each data set. In Figure 4, word clouds are presented for key phrases within the shore-based and sea-based data sets. To be considered a significant phrase, the phrase needed to appear at least three times in the respective data set.



(a) (b)

Figure 3: Tf-idf derived word cloud for the (a) shore-based data set and (b) sea-based data set



(a) *(b)*

Figure 4: Tf-idf derived word cloud for key phrases for the (a) shore-based data set and (b) sea-based data set

Examination of Figures 3(a) and 4(a), revealed emergent features: maintenance; risk and risk assessment; seaworthiness; Usage Upkeep Cycle (UUC) (denoted by the related words and phrases: ‘usage’, ‘upkeep’, ‘cycle’, ‘usage upkeep’ and ‘upkeep cycle’); people; and

contractors. These were significant words reflecting primary considerations of the interviewees in support of Scenario 1 and Scenario 2.

Similarly, examination of Figures 3(b) and 4(b), revealed emergent features: Damage Control (DC); command, and command priorities; training; and the Integrated Platform Management System (IPMS). These significant words reflected primary considerations of the interviewees in support of Scenario 3 and Scenario 4.

4.4 Theme Identification

Relevant significant words identified in Figures 3 and 4 were used as codes to index sections of the data sets for further examination and the identification of themes. Some significant words were related but remained as distinct codes during the identification of themes to ensure there was no loss of relevant information. Table 3 presents the identified themes.

Table 3: Key word codes mapped to overarching themes discovered within the data sets

Shore-based (Scenario 1 and Scenario 2)		Sea-based (Scenario 3 and Scenario 4)	
Code	Theme	Code	Theme
Seaworthiness Risk Assessment Risk Deployment Maintenance	Ability to Deploy the Platform	Command Risk Capability Communication	Maintaining Mission Capability
Upkeep Cycle Usage Maintenance Availability Contractor Risk Defect	Provision of Maintenance	DC DC Board DC Huddle Repair Base IPMS Fire Command Priority Communication	Platform Survivability
People	Experience of People	People Training Management Communication	People at Sea

Each theme was worded as a descriptor to convey the intent of the theme, with the wording deliberately chosen to avoid confusion with formal RAN terminology. The themes that may have been biased by the scenarios were: *Ability to Deploy the Platform; Provision of Maintenance*; *Maintaining Mission Capability*; and *Platform Survivability*. The purpose of inductive thematic analysis is for the data to guide the development of the themes. However, each interviewee was responding in the context of the scenario to which they had been assigned. Consequently, the shore-based data set was biased towards Scenario 1 and Scenario 2; and the sea-based data set was biased towards Scenario 3 and Scenario 4. The inductive thematic analysis performed on both data sets then 'discovered' the four scenarios. The themes relating to people were emergent themes. Even though the scenarios may have biased four of the themes, the thematic analysis identified focal points (the significant words) for those themes.

It is not possible to present the raw data used to derive information presented in Table 3. This is due to the sensitive nature of some of the information contained within the data; the availability of space; and to ensure interviewee anonymity. However a narrative may be presented to convey the intent of, and features within, each theme. The following (brief) narrative is an amalgam of feedback provided by the interviewees relating their experiences in support of their respective scenario.

4.4.1 Ability to Deploy the Platform

One significant word that emerged from the analysis was 'seaworthiness'. For the RAN, seaworthiness is the ability of a platform to perform assigned tasking to achieve an operational effect on the proviso that hazards and risks to personnel, the public and the environment are eliminated (or minimised as reasonably as practicable) [23]. As such, mention of 'seaworthiness' in the corpus was discussed in terms of an outcome. Related key words such as 'risk', 'risk assessment' and 'maintenance' appeared in the corpus as contributing factors for the achievement of seaworthiness. Consequently, this theme is the examination of decision-making and information requirements to provide assurance a platform can be deployed and achieve the *Operational and Support Intent* (OSI) [24].

4.4.2 Provision of Maintenance

Maintenance was discussed with respect to scheduling; understanding the provision of maintenance; tracking planned maintenance; the consequences of unplanned maintenance; and performing risk assessments if a platform is deployed with incomplete maintenance or with known defects. There is a strong relationship between maintenance, seaworthiness and maintaining seaworthiness prior to deployment. Managing a maintenance period involves co-ordinating and prioritising stakeholders, including contractors who may have overlapping maintenance periods from one platform to the next. There is a need to understand system and hull history to maintain the maintenance baseline and plan withdrawal dates.

4.4.3 Experience of People

The experience of people was an underlying theme supporting the decision-making and information requirements for decision-making. People may put a different emphasis on different elements of that information during the decision-making process. People need to understand technical details to utilise information correctly and identify errors or anomalies in the information, particularly for risk assessments. More experienced people are able to provide judgement when investigating apparent information errors or anomalies. People who understand their role can lead to forming a 'great culture with a sense of pride' resulting in the achievement of 'positive outcomes to deliver seaworthy capability'.

4.4.4 Maintaining Mission Capability

Assessing the functional output of systems and the impact on capability is difficult. The loss of system functionality may constrain the platform from achieving the OSI. However, systems may have many failure modes and the ability to understand the consequences of functionality loss on platform capabilities requires experience. System monitoring is continuous, with relevant information reported through the chain-of-command to the Officer of the Watch (OOW). The context of the current operation and tactical scenario will dictate the platform readiness level and the required level of redundancy. Evaluation of the patrol cycle, duration at sea, fuel, victualling, and crew fatigue are requirements. These contribute to mission capability status, and system configuration to maintain platform readiness. This requires a clear decision process supported by understanding materiel and system behaviour when exposed to the operating environment.

4.4.5 Platform Survivability

Any deployment is inherently dangerous. Non-combat threat environments include the possibility of collision, fire and grounding. Unavailability of systems can increase associated risks and a lack of understanding those risks can result in damage events. Therefore, the

crew must maintain currency of the fitted systems to understand system performance, operation, and the use of redundancy. Familiarity with boundaries (for example, water tight boundaries) and compartment locations enable the crew to perform DC activities. DC is supported by timely, accurate information regarding actions and system state. Management of resources balanced against priorities is imperative for crew and platform safety.

4.4.6 People at Sea

The ability of the crew to perform their duties is important for deployed platform capability management. The crew needs to be aware of their individual roles, and be aware of the roles of others. This facilitates interconnectedness and enables crew to provide relevant, necessary information when required. Consequently, there is need for significant trust in the DMEO and CPOs to ensure the accomplishment of day-to-day platform operations. Time constraints and increased requirements imposed on crew, without assigning more crew or not having a fully crewed department, present challenges to maintaining operations. The breadth of crew experience is critical in decision-making and the crew must trust in their own abilities, the abilities of the team and their training. Crew might also leverage from the experience of another platform crew to understand issues that arise. Historic experience is also leveraged for problem solving on new platform classes. In some instances, risk related decision-making might require shore-based support and uncertainty can arise due to the availability of SQEP. The theme *People at Sea* contributes to the theme *Maintaining Mission Capability*. A crew with understanding of, and ability to perform, their job role facilitates deployed platform management in achievement of the OSI.

4.5 Theme Analysis

Using the significant words, important sections of the corpus were identified and examined for enablers and impediments to achieving the aims of the theme. Table 4 presents some of these enablers as *key features* supporting a theme.

One common (subtle) detail identified within the corpus, across all the themes, was that of connectivity and continuity. Connectivity and continuity facilitates audit tracking and informed, explainable decision-making. In some cases, this may constitute connecting disparate policy documents to ensure robustness of process and a clearly defined Capability Impact Statement. In other cases, data amalgamation was important for planning and assessment. This encompasses ensuring data validity, and a single source of truth. On board the platform, data contributes to situation awareness (such as required during DC). For shore-based platform management, platform data represents the state of the platform and systems. This will be used for maintenance planning, the supply of spare parts, and monitoring of the remaining useful life of an asset (systems and hull).

The two themes related to people are important considerations. Within the corpus there was recognition for ‘soft leadership’ and interpersonal communication skills. However, these are traits that cannot be enabled by a Digital Twin and, consequently, are not represented in the themes. A Digital Twin can support the management of people, in particular the tracking of technical skills when filling personnel deficiency on board platforms. People are an important factor in naval platform management and operations. They gain experience in achievement of their job roles. Experience enables people to develop *rules-of-thumb*, which they can adapt to new situations or use to ease the transition into new job roles. The quantification of their personal experience as actionable information for use in a Digital Twin is difficult. Instead of thematic analysis, other knowledge elucidation techniques to quantify

rules-of-thumb for the development of actionable information are available [16, 17, 24]. The actionable information would be coded in the form of Artificial Intelligence (AI) that can then be used within the Digital Twin to support decision-making and platform management.

Table 4: Key features inspired by the corpus supporting the themes

Theme	Key features in support of the theme

Ability to Deploy the Platform	- quantitative seaworthiness assessment:
	  o engineering analysis;
	  o data validation and completeness checking; and
	  o risk assessment against the OSI, deployment with a known defect, and deployment with incomplete maintenance;
	- policy manuals (tracking and connectivity);
	- operational endurance analysis and balancing maintenance risks; and
	- crewing.

Provision of Maintenance	- predicting and planning maintenance requirements against the state of the platform; - accessing detailed technical data for equipment; - balance between platform maintenance and platform upgrades; - metrics to estimate duration of maintenance activities and de-conflict work packages within maintenance periods; - engineering change management; - co-ordination between stakeholders to assemble work packages, to manage the workforce, and for transparency and audit tracking; - Reliability, Availability, Maintainability (RAM) and trend analysis; - maintenance management system data remediation; and - identifying and maintaining the maintenance baseline.
Experience of People	- SQEP identification; - tracking and provision of training; and - workforce management.
Maintaining Mission Capability	- Capability Impact Statements; - platform automation; - system monitoring, requirements and reconfiguration; - defect tracking, risk identification and acquittal; - maintenance planning, performing and close out; - explainable decision-making and preventative/predictive maintenance; - endurance monitoring and management; - provision of relevant, up-to-date information regarding operating environment and resource availability during port visits; - data validity and trend monitoring; and - currency of Failure Model and Criticality Analysis (FMECA).
Platform Survivability	- situation awareness and assessment; - identification and restoration of capability baseline; - explainable decision-making; - response planning and prioritisation; - resource prioritisation, tracking and management; - data validation and integration; and - setting Command Aims and Command Priorities.
People at Sea	- tracking of training, skills, experience requirements; - resilience and location monitoring (during a damage event); - personnel deficiency reports and filling of vacancies; and - SQEP identification.

5. DISCUSSION

The study purpose was to identify processes that may be enabled or enhanced by Digital Twin capabilities. Key features in Table 4 are processes considered important (as conveyed during the interviews) to support the four naval platform management scenarios. Consequently, key features can be considered as functional requirements for a Digital Twin capability. Noting, some processes may already be performed well (and tools available to support those processes), while others may have deficiencies.

5.1 Key Features to Functional Requirements

The key features, as they are currently worded, may not seem like functional requirements. However, consider, for example, 'data validation and trend monitoring' (*Maintaining Mission Capability*). This key feature consists of two functional requirements: (1) a

requirement to perform data validation; and (2) a requirement to monitor data trends. Examination of the key features also reveals overlaps in the functional requirements. For example, 'data validation and completeness checking' (*Ability to Deploy the Platform*), 'data validation and trend monitoring' (*Maintaining Mission Capability)* and 'data validation and integration' (*Platform Survivability*) have 'data validation' as a common element. In many instances, these themes will require the same data relayed via sensors connected to platform systems. In some cases, data may be entered manually. Each theme might utilise the data in different ways, according to the needs of the theme, but there will always be a requirement to ensure the sensor and manually entered data are correct and complete.

The key features require analysis to ensure understanding of the functional requirement(s) they convey. For example, 'predicting and planning maintenance requirements against the state of the platform' (*Provision of Maintenance*) contains the explicit requirements: 'the ability to predict maintenance requirements'; and 'the ability to plan maintenance'. It also contains the implicit requirement 'the ability to assess the state of the platform' to enable assessment of maintenance requirements against the platform state. To assess the state of the platform, there is need to monitor platform systems (including the hull) and perform trend analysis. This latter requirement also supports 'trend monitoring/analysis' (*Provision of Maintenance* and *Maintaining Mission Capability)* and platform 'situation awareness and assessment' (*Platform Survivability*). Furthermore, 'situation awareness and assessment' (*Platform Survivability*) also encompasses the situation external to the platform and the progression of fire, smoke and flooding internal to the platform. To perform trend monitoring/analysis and situation awareness and assessment, there will also be that need for data validation, completeness checking and remediation. This will likely be followed by a need for data aggregation suiting the respective functional requirement.

5.2 Implementation of Functional Requirements for a Digital Twin

Implementation of the functional requirements will require analysis of suitable off-the-shelf technologies and/or research for the development of bespoke software and hardware tools. For example, the *Predictive Materiel Availability and Sustainability Tool* (*PMAST*) was bespoke software for maintenance predication and sparing analysis developed for a naval platform sustainment management digital engineering environment [26]. *PMAST* utilised system configuration models, in the form of Reliability Block Diagrams (RBDs), and the sparing analysis to enable prediction of platform operational availability for the duration of a mission. More contemporary techniques are now available for system modelling that should suit a range of applications supporting naval platform management [27].

Other techniques for failure prediction might be used, such as Deep Learning (a machine learning technique based on artificial neural networks). For example, Namuduri et al. [28] reviewed sensors and Deep Learning techniques for use in predictive maintenance. Related techniques might also be suitable for the implementation of the functional requirement 'predicting and planning maintenance requirements against the state of the platform' (*Provision of Maintenance)*. The same techniques may also suit the functional requirements supporting *Maintaining Mission Capability* (while the platform is at sea) to monitor platform systems to ensure system operations and predict failures. Consequently, some functional requirements will have overlapping implementation methods; while the implementation of other functional requirements may be unique. The required functionality may be implemented as specific modules, like those presented in the M&S architecture of Figure 1.

As discussed in Brett et al. [29], modularisation enables updating of specific elements of the digital environment without disrupting other elements.

Data is a key enabler for the implementation of almost all the functional requirements derived from the key features. Processing and validation of data will, therefore, be an important consideration of any digital environment. Implementation of the capabilities suiting the functional requirement of data validation and correctness vary. In some instance, *edge computing* [30] may be utilised, whereby data processing occurs at the source of the data collection (or very close to the source). In the case of legacy naval platforms, though, retrofitting edge computing may be cost prohibitive. In that case, data processing would need to occur closer to the M&S architecture.

As highlighted in Section 2, there is no specific implementation for a Digital Twin framework. Network infrastructure to enable the Digital Twin is specific to the needs of the domain to which the Digital Twin will be applied [31]. Consideration will need to be given to data collection frequency, fidelity and security [9, 32] and will be dependent on the needs of the models within the M&S architecture. Analysis of legacy systems will also be required to ensure connectivity within the Digital Twin environment. Finally, analysis of computing infrastructure will enable the suitable specification of the Digital Twin implementation requirements facilitating connectivity internal to the platform to enable decision-making at sea; between the platform and shore-based facilities to enable shore-based support and platform management; and between shore-based facilities to effectively utilise data from disparate information sources.

6. CONCLUSION

A thematic analysis of interviews with relevant RAN SQEP identified six themes in support of RAN platform management and operations. The key features associated with each can be used to derive Digital Twin functional requirements supporting naval platform management and operations. However, existing technologies and frameworks within the RAN may already provide some of the identified functionality. Consequently, when implementing the Digital Twin, consideration will need to be given to connectivity with legacy infrastructure.

Implementing a Digital Twin environment is not standardised. It is bespoke to the needs of the application domain. Further work is required to identify suitable computing infrastructure (such as, communications, databases, and hardware requirements) to ensure connectivity and security. Identification of, or development of, suitable modelling software will be required to fill gaps not currently supported by legacy systems.

The themes and functional requirements were derived from interviews with 13 RAN service personnel, Defence Australian Public Servants and Defence contractors. RAN experience was broad, ranging from PO through to CMDR across nine platform classes. Experience included RAN training roles, SPOs and Force Groups. However, the statistically small sample size of interview respondents would not likely give suitably diverse insights into the issues encountered by personnel supporting RAN platforms. Consequently, a broader study will provide greater understanding of functional requirements for a Digital Twin supporting naval platform operations and ensure achievement of the OSI.

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Real-time Digital-Twin for Naval Platform Through-life Support and Life-Cycle Risk Reduction

Wang Y. Kong, Jake D. Stringfellow, Daniel Birt and Hugh D. Torresan
Defence Science and Technology Group, Department of Defence, Australia
wang.kong@dst.defence.gov.au, jake.stringfellow@dst.defence.gov.au, daniel.birt@dst.defence.gov.au, hugh.torresan@dst.defence.gov.au

ABSTRACT

Naval platforms are highly complex, with stringent reliability requirements and highly interdependent systems. Substantial maintenance and upgrade activities are required through-life to ensure reliability, to maintain a capability edge and to satisfy evolving requirements. Digital engineering techniques utilising modern computational power provide many solutions to technical challenges presented by the platform. A digital-twin based on real-time simulation can offer a welcomed alternative to existing methods, leading to reduction in cost, effort and schedule.

Real-time simulations execute in synchronism with time in the physical world, and enable a high level of interactivity with users during runtime. This technique generates a representative digital-twin / analogue of the target system, offering a safe space for testing of operating procedures, troubleshooting, and research activities. This digital twin can ease availability pressures of the platform, while providing a realistic environment for tasks such as training of personnel without a full complement of hardware.

This paper presents a case study of a digital twin of the power and energy system of a hypothetical hybrid electrical naval platform, and explores the application of real-time simulation as a key digital engineering tool for supporting through-life technical activities of a platform.

INTRODUCTION

Naval Platforms are highly complex, with millions of components, and interdependent systems necessary to achieve their desired functionality. Substantial maintenance and upgrade activities are required through-life to ensure reliability and to maintain a capability edge. Digital engineering is increasingly being used to overcome technical challenges posed by rapidly changing operational requirements and resulting complexity of modern platform design.

Digital engineering techniques take advantage of the immense computational power of modern computer systems. This has created tools for designers to examine various operating scenarios and design options in detail, in a reasonable time. The ability of digital engineering to effectively manage vast amounts of data from disparate sources creates opportunities for collaboration between designers working across various different aspects of a platform during its full life cycle. This enables for more global optimisation of the product, compared to traditionally siloed design processes.

Throughout the life cycle of a platform, various digital engineering activities are required to overcome a range of technical challenges. These activities can be grouped according to the functions and time-scale they occupy. Micro time-scale activities focus on detailed characterisation of individual subsystem or components, while medium time-scale activities focus on whole of system behaviour, and finally, long time-scale activities typically focus on optimising operation and improving maintenance processes. It is important to choose a

suitable time-scale for digital models, too small and simulation times become unfeasible, while too long means loss of important detail. Some examples of technical challenges and digital engineering solutions for each time scale are shown in *Table 1*. There is a high degree of interdependence between these activities with results of one feeding into another.

With an ability to explore whole of system behaviour, activities in the medium time-scale play a key role during system integration, testing and operation phases of a platform. These activities provide designers and operators vital insights into the system's overall behaviour. In this time-scale, real-time simulation becomes a viable option.

Time Scale	Technical Challenges	Technical Disciplines/Tools
Micro (ns-ms)	Noise and vibration	Mechanical and structural analysis FEA, multiphysics simulations
	Detailed characteristics of subsystems	Circuit and electromagnetic theories FEA, multiphysics simulations
Medium (ms-hours)	System integration, whole of system stability analysis	High level model of subsystems Real-time and multiphysics simulations
	Hardware testing	HIL, real-time simulation
Long (hours+)	Operation planning	Operational research
	Training and operating procedures development	Real-time simulation, virtual/augmented reality
	Condition monitoring and degradation models	Material sciences

Table 1. Examples of digital engineering solutions aiding technical challenges in a maritime platform

REAL TIME SIMULATION AND DIGITAL TWIN

Real-time simulation is a specialised technique where a computer model is executed in synchronism with time in the physical world, i.e. 1 second of simulation time is executed in 1 second of real-world time. A distinct advantage of real-time simulation is the high level of interactivity, since it generates useable and accessible results as it progresses. This allows users to observe, record and interact with a running simulation similar to how a user would interact with a physical system.

While real-time simulation offers users a digital analogue of the real system, hard constraints on the computation time often limit individual components to simplified average mathematical models. Real-time simulation models are useful for examining whole of system behaviour (at milliseconds and above), with a greater focus on macro behaviour of key characteristics rather than detailed physical models often used in other simulators.

Digital Twin refers to a concept where a dynamic model is constantly updated with data obtained from sensors and other data sources, such that it gives an accurate and up-to-date

digital representation of the underlying physical system or its' "digital twin". As an up-to-date and accurate representation of the physical system, the digital twin provides an avenue to explore the system's behaviour offline for technical activities which support a platform through-life.

A verified real-time digital twin is invaluable through the life of a platform, by providing a full real-time "digital clone" of the platform where technical activities can be conducted in a high fidelity, risk free environment. The increased interactivity of the real-time simulation can be exploited for technical activities such as the design of operating procedures, operator training, and troubleshooting. These characteristics are especially valuable for circumstances where the real platform is unavailable, or for safety considerations where dangerous scenarios are desired to be explored and trained for. It is also relatively easy to adapt the simulation to new conditions with considerably less effort and cost compared to a physical system. The verified digital twin would act as a basis to rapidly make modifications through the life of the platform with confidence, and provide a digital platform for training of operators on upgrades prior to the upgrade of the physical platform.

A further level of integration may be achieved with automated collection of physical system data and the integration of this data as an input into a digital twin that is run in parallel to the platform. The digital twin uses sensor outputs as well as system control commands to attempt to match the physical system states as it operates. The digital twin would then be able to generate and store a more comprehensive snapshot of unobserved system states that may be invaluable as a starting point for fault-finding and investigation. During operation a digital twin may be used as a branching point to test operating scenarios, before performing them with the platform. The effects can be safely observed in the digital twin, before being performed where consequences could be significant.

The case study in this paper will illustrate how a real-time simulation can be used to explore the whole of system behaviour of a platform.

REAL-TIME MODEL OVERVIEW

The power and energy system of a hypothetical hybrid diesel-electric powered ship has been developed to demonstrate the real-time simulation of a maritime platform's power and energy system. This system is roughly the size of an offshore patrol boat [1].

A block diagram of the simulated power and energy system is shown in Fig. 1. . The power system is split into two identical, independent buses representing the port and starboard sides. Each bus contains the following components:

- A 6 MW rated diesel generator, consisting of a diesel engine and a synchronous generator connected to the dc bus via an active rectifier.
- A 20 kAh, 800V rated battery connected directly to the dc bus.
- A fixed hotel load.
- A 4 MW rated, multi-phase brushless direct current (BLDC) propulsion motor.
- A fixed pitch propeller - with a model designed to approximate its operating performance while partially submerged due to rough sea states.
- Hotel and propulsion loads can be powered from either dc buses.

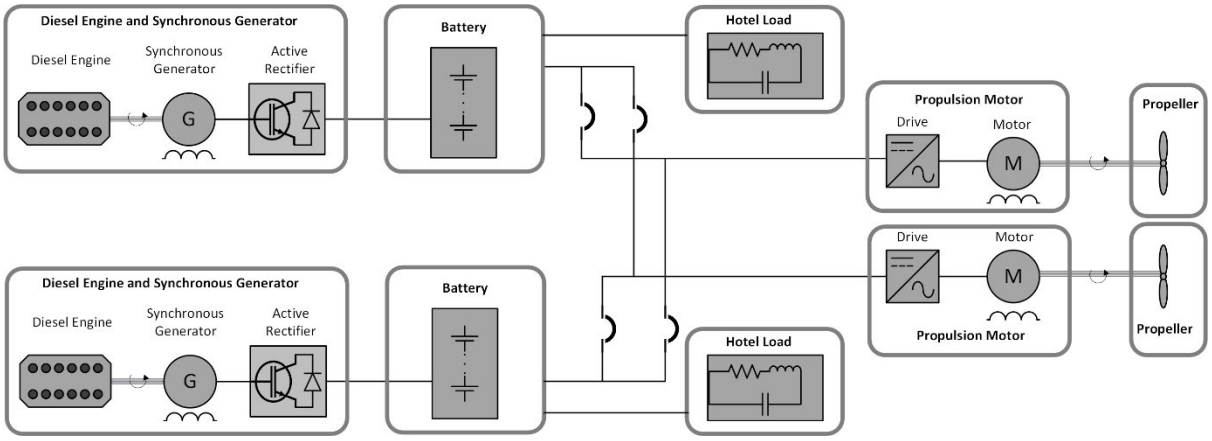


Fig. 1. Block diagram of simulated power and energy system with dual bus arrangement

The directly connected storage batteries sink and source any power imbalance in the power system due to short term excess or deficiencies in the diesel generators. This enables the generators to be operated at maximum efficiency without the need to follow the load profile. The loads can also be supplied solely by the battery should generation be unavailable.

The power system has been implemented in the RTDS simulator [2]. The runtime interface for this model is shown in Fig. 2 that depicts a top-level single line view of the model. Live updates during runtime display key system parameters as the simulation progresses. This interface enables interactivity between the user and the model while the model is running through a variety of input components. A user can interact with the simulation much like the real system to gain insights in its behaviour under a wide range of operating conditions and user inputs. Parameters that can be dynamically altered are as follows:

- Key system parameters including propulsion motor speed references, propulsion load, and output set points of the generators.
- Hotel and propulsion/motor loads can be re-routed to either supply bus.
- Each generator subsystem can be independently controlled and adjusted.
- Each propulsion motor can be independently controlled and individual phase windings can be disconnected to emulate winding faults.

Diesel Generators

A 6 MW rated diesel generator (DG) set is connected to each of the two isolated dc buses. Each DG set consists of three components: a diesel engine, a synchronous three phase ac generator and a three phase H-bridge active rectifier. The diesel engine model is based on a mean value model [3], as modelling the detailed combustion processes is difficult due to computation constraints. The engine is regulated to a constant speed by a proportional integral (PI) speed governor. This generator control system can operate at a constant output power or bus voltage regulation to a commanded reference as required to supply the loads and charge the batteries and is adjustable by the user during runtime.

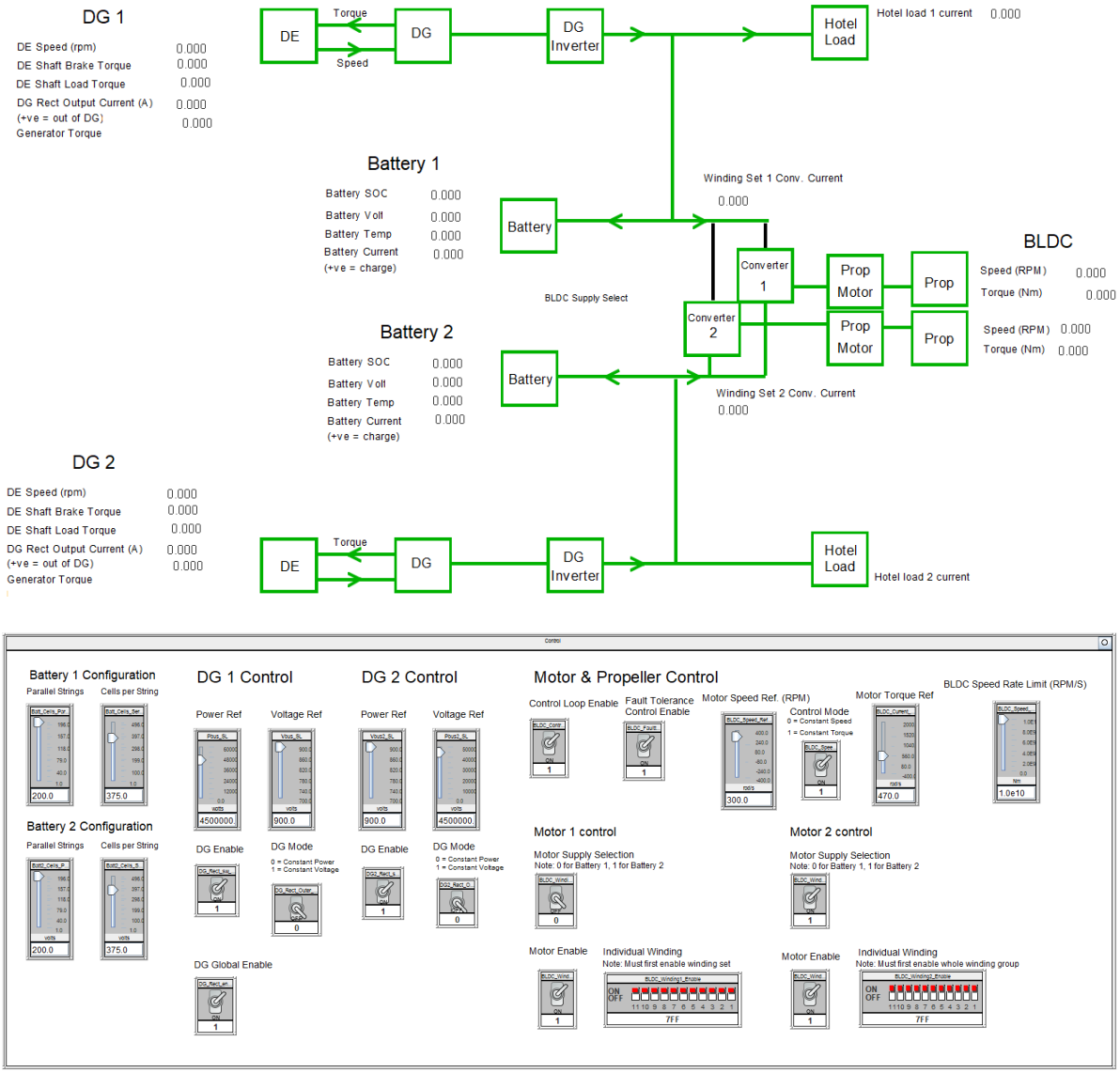


Fig. 1. RTDS Runtime Screen, Top: Power system single line diagram with metering components, Bottom: User control interface to provide inputs into the real time simulator.

Propulsion Motors

Multiple phase machines are often used in high performance maritime platforms as a mean to provide high torque and power density. However, a multiple phase machine is challenging to model [4] in real-time simulation as each phase must be driven by a converter. It becomes infeasible to simulate behaviour of each switch in real-time due to the large number of switching devices. Hence, for this work an average model has been developed instead. The impact of this simplification on the remainder of the power system is expected to be minimal due to the filtering effects of the motor drive dc link capacitance and the high mechanical inertia of the shaft and rotor. Detailed losses are not modelled.

The control of the motor is implemented with nested PI speed/torque and current controllers. A high level controller regulates the motor speed or output torque and coordinates the converter bridges by specifying their commanded current reference. This is a standard control structure for a large drive system. The drive system is configured to forbid regeneration into

the bus. This minimises the risk of over voltage in the dc bus during rapid deceleration of the motor. A brake chopper is installed in the motor drive to sink the energy regenerated during braking. The regeneration and deceleration capabilities of the motor are limited by the rated capacity of the chopper.

A simple fault tolerant control scheme is implemented to compensate for loss of phase windings in the motor. This scheme adds a compensating current component to each healthy phase reference current during a fault. This current is chosen such that the ideal post-fault torque waveform is equal to the pre-fault torque, with the aim to maximise performance with all available resources. However limits in current control bandwidth prevent these ideal waveforms being achieved practically.

Storage Battery

This model includes two batteries rated at 20kAh and 800V. These batteries are modelled using an electrical equivalent circuit approach [5] as shown in Fig. 2, and are based on experimental data from a 100Ah commercial off-the-shelf battery system.

The storage batteries are arranged as 200 parallel strings of 375 series cells to satisfy the voltage and power requirements. The large number of cells means it is not feasible to simulate the response of each individual cell. Instead, the response of a single cell is scaled to represent a battery of the desired configuration.

Key parameters in this model can easily be modified to reflect cells of different state of charge (SOC), health, age or make.

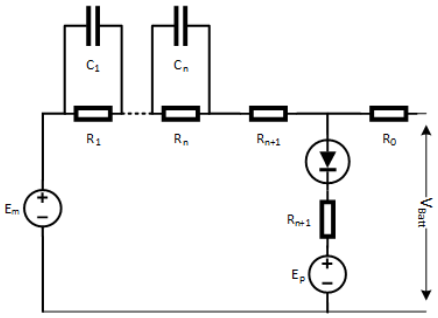


Fig. 2. Equivalent cirucit diagam of a single battery cell

Hotel and Propulsion Load Model

For simplicity a fixed 2.5Ω resistive load (256 kW at 800 V) is connected to each bus to model the hotel loads. However, it is possible to include a more sophisticated load profile if required.

The propulsion load is modelled as two fixed pitch propellers that are directly coupled to each motor via a shaft. The propeller model uses a map to calculate the thrust and hydrodynamic torque from the ship advance angle.

A case of interest is a propeller operating near the surface or partially lifting out of the water during operation in high sea states. The effects of a propeller operating near the surface can cause a large loss of propeller thrust and torque. As propulsion component dominate a platform's power demand at high speed, any fluctuation in the propeller's behaviour can have dramatic effects on the power and energy system. In practice significant experimental data would be required to create an accurate model of these near surface effects, however a

representative model [6] is used including a static approximation of key factors such as aeration effects and the Wagner effect as a function of submergence depth, as well as a dynamic calculation of submerged blade area based on blade angle.

RESULTS OF SIMULATION CASE STUDIES

The runtime interface of the real-time power and energy system model allows the user to interact with a running simulation, and aims to provide accurate feedback in real-time. Three scenarios are selected to demonstrate the capability of the model. For simplicity the two system buses are identical throughout each scenario and waveforms are all presented for only Bus 1. Bus 2 can be assumed to be identical in these scenarios.

Partially Submerged Propeller

This scenario explores the implications on the power system of the platform when operating at a high sea state where the propellers regularly pierce the water surface. Fig. 4. shows the results of applying a sinusoidal submergence depth to emulate operation of the platform in conditions of roughly translating to sea state 5 (wave height 2.5 – 4 metres). When the propeller pierces the water surface, a significant loss in load torque is observed. The effects on the power system are examined under two propulsion motor control regimes; constant speed control or constant torque control.

In Fig. 4., between 0 and 7.5s the motor is operated in a constant speed mode. To maintain constant speed, the electromagnetic torque produced by the motor follows the load torque variation. This variation in motor torque is also seen by the power system as large variations in currents drawn from the dc bus by the motor. As discussed, to optimise efficiency the diesel generators are operated in a constant power mode, hence the spike in motor load power must be provided by the battery. This variation in battery load produces a corresponding variation in the dc bus voltage.

Between 7.5 and 15s, the motor is operated in a constant torque controlled mode. The propeller load torque continues to vary with propeller submergence, however the motor provides simply the average torque of this varying waveform. Dynamically this difference in load and supplied torque leads to a variation in the propeller's speed as the submergence depth changes. The variations in speed also interact with the constant torque to provide a non-constant power drawn by the motor, however the variations are less significant when compared to the motor being operated in the constant speed mode.

It can be observed that the effects of this scenario have the potential to be significant to stability and sizing of the power system. While not examined in this simplified model, additional domain tools would be likely to be required to further analyse the effects of noise and vibration due to surface piercing behaviour of the propeller. The real time simulation allows for rapid testing and trialling of control methods and conditions.

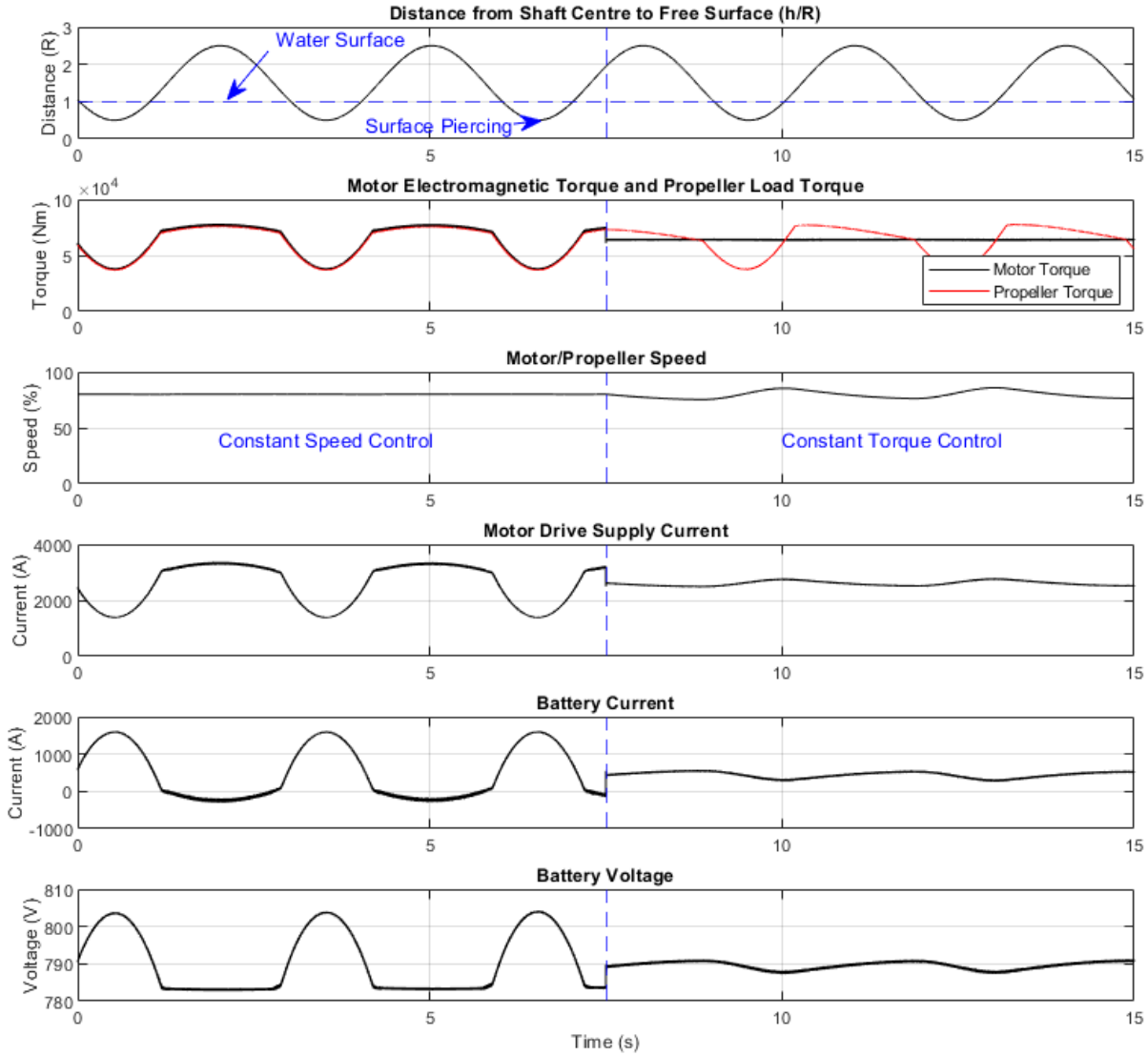


Fig. 4. Operation of propellers near surface and surface piercing and the effects on the power system. Motor torque, speed and current, Battery current and voltage waveforms.

Crashback

In this scenario the platform is initially traveling forward with both motors running at full speed. The ship then attempts to reverse direction as quickly as possible with a step change in the commanded propulsion motor speed from 100% to -100% of the rated speed. The initial states of the storage batteries are identical. The diesel generators are initially operating at a constant power at 80% capacity. Due to the identical nature of the components and simulated loads on the two dc buses, only one set is shown in the results below.

The resulting propulsion motor response is shown in Fig. 5.. The motor is first slowed by the propeller's drag and negative torque production in the motor (re-generation mode). Ideally as much negative torque as possible should be applied to motor to increase the rate of deceleration. The magnitude of the applied torque is restricted by the mechanical limits in the motor and associated systems (e.g. shafts, couplings, etc.), and the rating of the brake chopper. As the motor slows, the motor torque can be seen to follow a curved shape determined by the braking chopper's rating and the motor speed at that instant. As the motor speed approaches 0 rpm, the motor torque limit is reached and becomes the limiting factor in deceleration. When the speed transitions from positive to negative, the motors start to operate in the reverse

direction, the brake chopper is removed, and the maximum negative torque is applied such that the motor can accelerate as quickly as possible. The centre plot shows the supply current drawn by the motor drive. When the motor decelerates, the current drawn from the supply reduces towards zero and remains near zero until the motor direction changes. At this point the current then returns towards the initial motoring level.

The bottom two plots in Fig. 5 show the response from the diesel generator. When the motor load on the power system is reduced to zero almost instantaneously, the storage battery acts as a slack bus and takes the full power from the generation (minus a small hotel load). To prevent the storage battery from being overcharged, the generator output is quickly reduced to limit the battery current to its rated level of 2000A. During this time, as the generators can no longer output the commanded constant power without overcharging the batteries, the generators are temporarily operating in a current limited mode. The step change in generator power has a corresponding deviation in speed from its desired reference before the engine speed governor provides control adjustments to return the speed to its desired value.

Fig. 6 shows the storage battery current and voltage. During braking the propulsion load reduces to zero, but some time is required to adjust the output of the diesel generators. Hence for a brief period the excess power from the generators flows directly into the battery and the charge current significantly increased beyond its current rating until the generator reduced its power output sufficiently to limit the battery charge current to 2000A. If the storage battery had a larger power rating, it would be possible to use the battery as a buffer for a more controlled ramp down of the generation, or to simply ignore the load variation until the load is returned. The dc bus voltage also has a step increase due to the sudden increase in charge current causing a large voltage drop across the internal resistance of the battery. After the initial step just in battery voltage, the rise in battery voltage rate increased then slowed as the chemical reaction of the battery adjusts to the high charge current and the internal resistance normalises (reduces). When the propulsion motor returns to motoring during the later stage of the reverse operation, the load current increases and the dc bus voltage starts to return towards its initial level.

This scenario shows some of the complexity caused by interactions between different parts of the control system. The real-time simulation allows for rapid trialling of control parameters and evaluation of the response of the power and energy system as a whole.

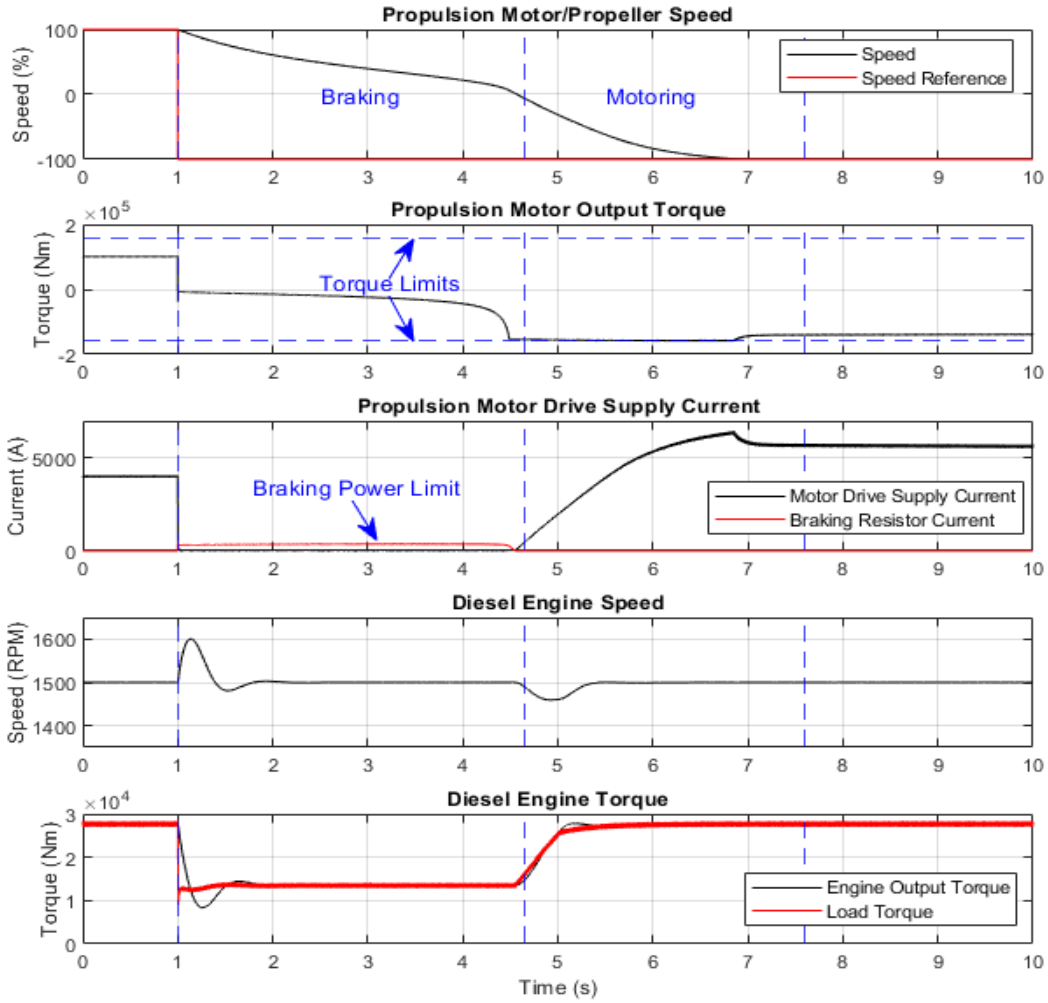


Fig. 5. Crash back operation: engine torque and speed, motor torque, speed and current waveforms. Speed is positive when the motor is spinning the propeller in the forward direction. Torque is positive when applied in the direction of positive speed

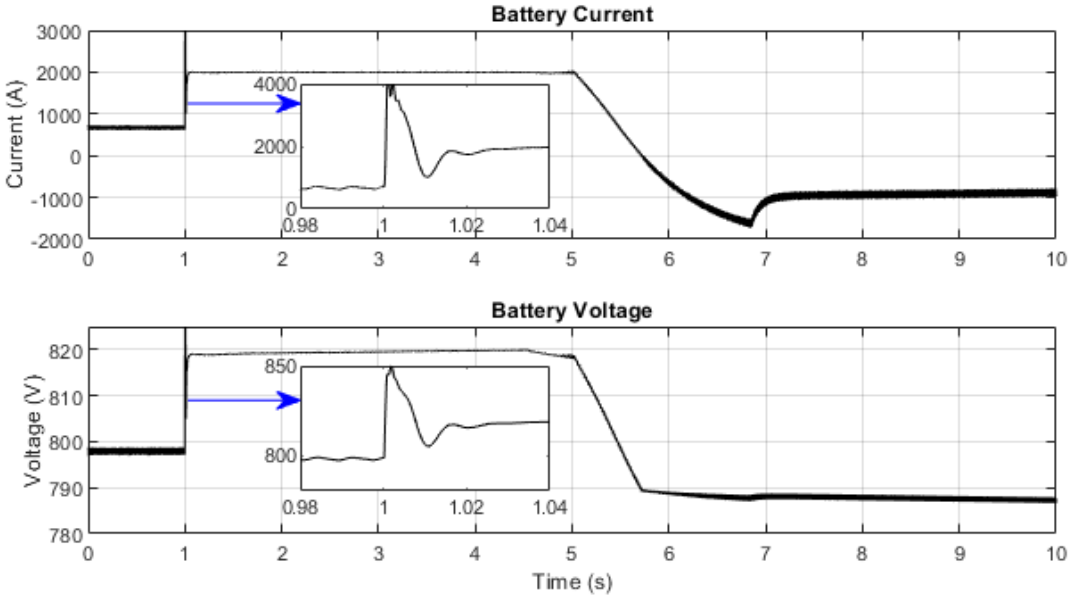


Fig. 6. Crash back operation: storage battery current and voltage waveforms, negative for current flow out of the storage battery (discharge)

Motor Winding Fault

The final scenario explores the performance of the power and energy system when a propulsion motor suffers a fault in one of its winding. If a fault occurs in one of the motor windings, it is often desirable to continue to run the motor at a reduced capacity with the faulted phase open circuited. It is therefore important to understand the performance of the motor in such faulted state. Fig. 7 shows the performance of the motor during normal operation, then after a single winding is open circuited (phase 'a' of each motor) at 2 seconds. At 3 seconds a fault tolerant control algorithm started and attempt to optimise the performance of the motor.

Pre-fault (0 – 2 seconds) there is minimal torque ripple shown in the results. The use of an average switching model ignores the effects on torque due to switching harmonics which leaves a near ideal torque pre-fault. Post fault but before the fault tolerant control algorithm kick in (2 - 3 seconds), a significant increase in torque ripple can be observed. This magnitude of torque ripple corresponds to the torque that was previously generated by the faulted phase, as the control scheme is initially assuming that all phases are working correctly. The fault also introduced a substantial ripple component in the dc current drawn by the motor drive which originally supplied the faulted winding, and this supply current ripple will then effect the remainder of the power system.

At 3 seconds, the fault tolerant control strategy is started which modifies the current waveforms in the healthy phases to compensate for the faulted phase. It can be observed that this strategy significantly reduces the ripple component in the motor output torque and current drawn by the motor drive.

The real time interface allows for an easy method of testing the motor and power system response under varying fault scenarios and observing the system response. This could be a valuable tool for visualising performance of the system at non-standard operating conditions during design phase and for training of operators after the system is delivered.

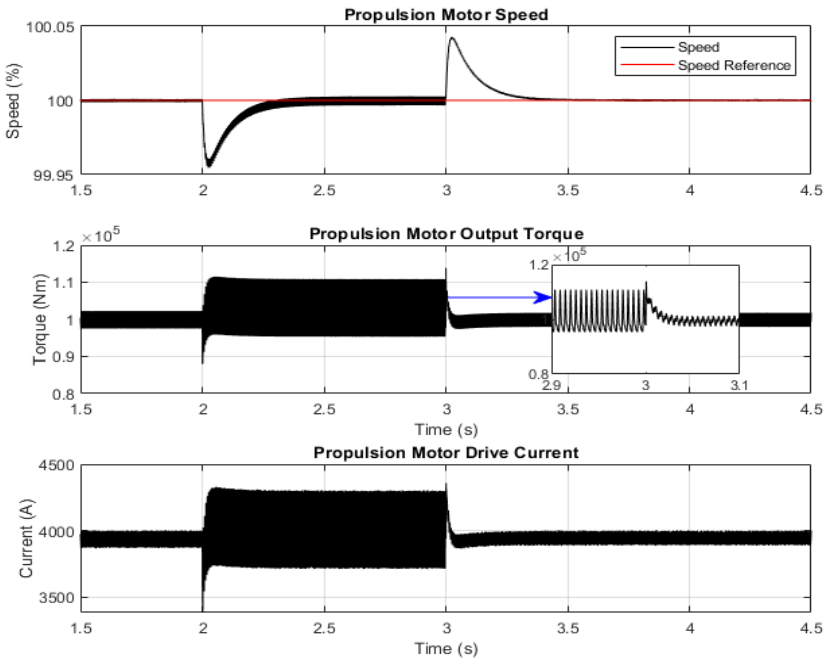


Fig. 7. Motor performance with a single 'open circuit' winding fault started at 2s and fault tolerant control scheme started at 3s

CONCLUSION

This paper presented the use of digital engineering tools as a method of dealing with the increased complexity and requirements of modern naval platforms. Many platform challenges and tools were identified across a range of process time scales. Real-time simulation of a platform power and energy system to create a 'digital twin' was identified as a key area to solve technical challenges such as system integration, stability analysis, hardware testing and operator training.

A real time simulation model of a hybrid electric ship power system was presented as a case study of a real-time platform model to overcome technical challenges in such systems. Real-time simulation enables applications that were previously not possible with traditional simulations. A user gains a large amount of interactivity with the simulation as it runs. This allows for improved operator training as realistic power systems interactions can be captured and interacted with in real-time.

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SESSION 8

Autonomous Vessels

An Australian code of practice for autonomous and remotely operated vessels
Refereed

An enabling framework to support COLREGS compliance for autonomous and remotely operated vessels

Technological readiness of XLUUV autonomy for effective anti-submarine warfare operations

Mission and situation awareness autonomy delivered through Artificial Intelligence and Machine Learning

Autonomous vessel regulation in Australia: Why an Australian Code of Practice is required.

Authors: Rachel Horne*, Maaike Vanderkooi**, Damien Guihen***
**Trusted Autonomous Systems and PhD program QUT Faculty of Law, info@tasdcrc.com.au*
***Vanderkooi Consulting Services*
****AMC Search, University of Tasmania*

ABSTRACT
The operation of autonomous or remotely operated vessels ("autonomous vessels") in Australia requires compliance with the Australian maritime regulatory framework. This national framework is built on a series of assumptions based on traditional vessels; for example: humans on board must be protected; operational risk increases as the vessel travels further from shore, and humans will be making navigational decisions from onboard. For autonomous vessels, the assumptions underpinning the regulatory framework do not always apply. The relatively recent uptake of autonomous vessels in Australia has highlighted the difficulties in applying the existing regulatory framework to them, particularly due to the lack of tailored standards and the uncertainty and delay it causes.

This paper argues that an Australian Code of Practice for autonomous vessels is required, because the existing available standards are not suitable. This argument is in three steps; Part 1 sets out briefly the challenges for operating autonomous vessels within Australia's domestic maritime regulatory framework; Part 2 outlines the draft Australian Code of Practice released for public consultation by Trusted Autonomous Systems in 2021 and how it benefits operators in navigating the regulatory framework; and Part 3 demonstrates the efficacy and advantage of the draft Code by outlining how it could assist operators of a small autonomous vessel being used in Australia, the REMUS 100.[1]

INTRODUCTION
The general term 'autonomous vessel' describes vessels capable of a broad range of autonomous and remote operations.[1] More specific terms are used to describe whether the vessel operates on the water surface or sub-surface and whether it is remotely operated or autonomous. For example, Autonomous Surface Vessel (ASV); Autonomous Underwater Vessel (AUV); Unmanned Surface Vessel (USV); and Unmanned Underwater Vessel (UUV).[2]

Autonomous and remotely operated vessels ("autonomous vessels") are used by many nations for a growing range of commercial and defence activities.[1] In Australia, the first regulatory approval for an autonomous vessel was issued in 2017, to the C-WORKER 5 Autonomous Surface Vessel (ASV). It is estimated that the Australian Maritime Safety Authority (AMSA) has allowed approximately 10 – 20 commercial autonomous vessels to operate in Australian waters under a Specific Exemption or other tailored regulatory

[1] The authors would like to thank the peer reviewers and coordinator for their efforts, together with Prof. Kieran Tranter for his ongoing support.

treatment,[2] including for hydrographic surveying, pipeline monitoring, reef monitoring, and defence-related activities.[3]

Internationally, many nations are still establishing their regulatory approaches for autonomous vessels.[4] A number of Codes and Standards for autonomous vessels have been developed internationally in the last five years, including the *UK Code of Practice for Maritime Autonomous Surface Ships 2020*, the *LR Code for Unmanned Marine Systems 2017*, and DNV GL's *Autonomous and Remotely-operated Ships Class Guideline 2018.*[5] These Codes and Standards can be used as a reference for Australian autonomous vessels, but the significantly different Australian operational context and domestic vessel technical standards limit ease of use.[5] There are also several uncertainties remaining that need to be answered to further inform Codes and Standards, such as whether autonomous vessels are considered "ships" for the purpose of international and domestic law.[4] The Regulatory Scoping Exercise recently completed by the International Maritime Organization Maritime Safety Committee is an important first step in progressing the international regulation of autonomous vessels.[6]

This paper argues that an Australian Code of Practice for autonomous vessels is required, because the existing available standards are not suitable. This argument is in three steps; Part 1 sets out briefly the challenges for operating autonomous vessels within Australia's domestic maritime regulatory framework; Part 2 outlines the draft Australian Code of Practice released for public consultation by Trusted Autonomous Systems in 2021 and how it benefits operators in navigating the regulatory framework [7]; and Part 3 demonstrates the efficacy and advantage of the draft Code by outlining how it could assist operators of a small autonomous vessel being used in Australia, the REMUS 100. Future case studies are needed to consider the diverse range of autonomous vessels in operation in Australia, ranging in autonomy levels [8-9], size, speed, and capability.[10]

PART 1: CHALLENGES FOR OPERATING AUTONOMOUS VESSELS IN AUSTRALIA

This part identified three primary challenges for the operating of autonomous vessels in Australia. These are lack of tailored standards, lack of a common benchmark for good practice, and lack of resources to support the regulatory process.

Autonomous vessels are primarily regulated by AMSA, under the same framework as 'traditional' vessels, as domestic commercial vessels (DCVs) under the *Marine Safety (domestic commercial vessel) National Law Act 2012* (National Law).[2] The regulatory requirements that apply to domestic commercial vessels [11-13] arise from the National Law, the National Law Regulation, Marine Orders 501 – 507 and the National Standard for Commercial Vessels (NSCV) [14-15]. Domestic commercial vessels are required to hold a unique vessel identifier [16], certification related to survey [16] and operations [17], and be crewed by persons holding the required certificate of competency.[19] The National Law also requires compliance with General Safety Duties by the vessel owner and master, together with anyone else responsible for designing, manufacturing, constructing the vessel or its

[2] AMSA also regulates regulated Australian vessels under the Navigation Act 2012. However, this paper will only deal with domestic commercial vessels, as there is a lack of clarity regarding requirements for autonomous regulated Australian vessels, and no available regulatory decisions by AMSA to provide guidance.

equipment, or interacting with the vessel (including crew and passengers). Failure to comply with requirements set out in the National Law can result in fines and imprisonment.[3] [20-22] The National Law contains a range of flexibility mechanisms that are intended to enable operation without meeting the full scope of requirements. These mechanisms are Specific Exemptions, General Exemptions, and Equivalent Means of Compliance. Specific Exemptions require application directly to AMSA and enable operation without meeting specified National Law requirements.[4] General Exemptions apply to the operators and vessels that fit the specified criteria, and either apply as of right (i.e., without needing to apply) or have an application process. To grant an exemption, AMSA must be satisfied that the exemption concerned, together with the conditions to which it is subject, will not jeopardise the safety of a vessel or a person onboard a vessel.[23] The National Regulator may impose conditions on exemptions, for example, continuous monitoring while an autonomous vessel is operating, or imposing a speed limit.[24] Equivalent Means of Compliance (EMOC) [25] relate specifically to the NSCV, and enable an operator to comply with a Required Outcome stated in the NSCV by means other than a listed Deemed to Satisfy Solution (DSS). EMOCs are generally not used where the applicant's intent is to avoid compliance with a Required Outcome, rather than seeking an alternative way to comply with it.[5]

In 2021 AMSA issued a Guidance Notice for small, unmanned vessels, which outlines AMSA's approach to specific exemption applications related to a certificate of survey. It applies to vessels less than 12m in length, non-passenger vessels or fishing vessels, operating in operational areas C, D or E.[6] The Guidance Notice identifies the specific issues to be addressed in an exemption application and increases clarity for applicants by indicating AMSA's expectations. The Guidance Notice is an example of AMSA seeking to support operators within the existing regulatory framework.

The challenges raised by the existing regulatory framework

The existing regulatory framework was not intended to apply to vessels without humans on board, and which rely on a spectrum of remote operation, autonomy, and artificial intelligence to operate. The challenges raised by the lack of tailored standards include reliance on exemptions and resulting uncertainty and delay, and lack of a common benchmark for good practice. There is also a lack of resources available to support stakeholders to understand and negotiate the complex regulatory process.

[3] For example, an intentional act or omission that contravenes National Law s12(1) Duty of owners of domestic commercial vessels to ensure safety of vessels, marine safety equipment and operations, carries a penalty under s13(1) National Law of imprisonment for 2 years, or 1,800 penalty units, or both.

[4] An example of a General Exemption that is commonly used by autonomous vessel operators is Marine Safety (Temporary Operations) Exemption 2020 (Cth),[24] which is referred to as EX07. EX07 enables Temporary Operations Permits to be issued which allows a vessel to operate for up to 90 days without certification. Temporary Operations Permits are often used by autonomous vessel operators to test and trial their vessels and gather data to support an application for certification (for example, a Certificate of Operation).

[5] Marine Orders provide the detail of requirements, processes etc. for the obligations identified in the National Law, [25-31].

[6] The vessels also must not carry persons while underway, carry dangerous goods, engage in vessel towage operations or be set up for that purpose, have an inboard engine operating on fuel with a flashpoint of less than 60 degrees Celsius or operate at greater than 10 knots. The vessels are also expected to be supported by a rescue vessel capable of providing support within 6 hours.

Lack of tailored standards

There are no standards incorporated into the Australian maritime regulatory framework which are tailored for autonomous vessels. This means if operators cannot comply with the existing standards, or choose not to because compliance is overly onerous, they must rely on exemptions to operate.[7] Reliance on exemptions raises uncertainty regarding timeframe and outcome, and places a resources burden on both the applicant and AMSA. For example, applying for and granting exemptions can require a prolonged period of communication between both parties to create a common understanding of the vessel and proposed operation, and the conditions which are appropriate to be imposed. This burden is exacerbated by the two challenges mentioned below; lack of a common benchmark for good practice, and lack of resources to support stakeholders through the regulatory process.

Lack of a common benchmark for good practice

There is a lack of a common benchmark for good practice for the design, construction, survey and operation of autonomous vessels in Australia. While there are several international Codes and Standards available, the analysis conducted by Vanderkooi Consulting on behalf of TAS in 2021 identified that their ease of use was significantly limited by the different Australian operational context, the smaller vessels common in Australia, and the need for alignment with the NSCV.[5] This lack of a common benchmark means operators and AMSA do not have a common starting point for their expectations of how autonomous vessels are designed, constructed, surveyed and operated, leading to uncertainty from all parties and delay. For example, it means applications must be assessed on first principles every time, rather than against a standardised set of requirements acknowledged to be best practice.

Lack of resources to support stakeholders to understand and negotiate regulatory process

There is a lack of resources available to support stakeholders to understand and negotiate the Australian regulatory process, resulting in further uncertainty and delay. Operators currently need to either navigate the AMSA website and review several web pages relating to general domestic commercial vessel requirements or contact AMSAConnect via email or phone to lodge a query. There is no published summary of the specific regulatory requirements and processes for autonomous vessels, and no way to quickly access this information. The involvement of new types of designers and operators, including engineers without a maritime background, and who may not know about AMSA or understand the maritime operating context, makes the need for publication of accessible information more pressing. A lack of stakeholder resources also adds to the resource burden faced by AMSA as more operators need to seek individualised advice, rather than relying on published guidance materials.

The lack of suitable stakeholder resources is likely for several reasons, including because of the lack of tailored standards or common benchmarks of good practice to refer to, the resulting individualised nature of assessing applications, and the nuance and complexity of the regulatory framework. It is also likely reflective of the limited resources available within AMSA as a safety regulator to produce guidance materials that draw together regulatory and policy, operational, and survey-related advice of the nature needed by autonomous vessel operators. If there were tailored standards and a common best practice benchmark to

[7] For example, a Specific Exemption from the requirement to comply with the requirement to hold a Certificate of Survey under the National Law.

reference, it would likely be easier to put in place the sort of resources that stakeholders need to understand and negotiate the regulatory process.

PART 2 THE AUSTRALIAN CODE OF PRACTICE AND HOW IT BENEFITS OPERATORS IN NAVIGATING THE REGULATORY FRAMEWORK

This part discusses the voluntary Australian Code of Practice for the Design, Construction, Survey and Operation of Autonomous & Remotely Operated Vessels ('Australian Code of Practice'). The development of the Australian Code of Practice was led by Trusted Autonomous Systems (TAS), with a Consultation Draft released in November 2021, and intended publication in March 2022. The Code was developed with support and ongoing engagement from AMSA and a wide range of commercial, Defence and Government stakeholders and industry members. The purpose of developing the Australian Code of Practice was to provide a tailored voluntary standard suitable for autonomous vessels operating in Australia, and therefore improve efficiency and reduce uncertainty for these vessels within the maritime regulatory framework. The intent is for operators to comply with the Australian Code of Practice as a common benchmark of good practice, and to provide evidence to AMSA of their compliance, to receive a specific exemption enabling operation. The Guidance Materials which will be published alongside the Australian Code of Practice are intended to provide clear information on regulatory requirements and process, how to use the Code, and how to demonstrate compliance.[8] These Guidance Materials are intended to address the third challenge identified in this paper, being the lack of resources to support stakeholders in understanding and negotiating the regulatory process.

Prior to development of the Australian Code of Practice a Report was prepared analysing existing, publicly available, standards and codes for autonomous vessels, and providing recommendations.[5] Informed by the Report and consultation workshops, the following key principles were identified:

- the Code should align with the Australian regulatory framework for conventional DCVs as far as possible and appropriate;
- a risk analysis approach, which focuses on the impact of potential failures, should apply to the development and testing of novel systems on the vessel; and
- requirements should be commensurate with risk posed.

Draft content for the Australian Code of Practice was then considered by 11 workshops with government and industry stakeholders, including AMSA, vessel operators, accredited marine surveyors, seafarers, creators of autonomous technology, ship and equipment builders, Australian Defence and Defence industry stakeholders. The outcomes of these workshops informed the development of the draft Australian Code of Practice.

Under the Australian Code of Practice, modified conventional vessel standards and additional performance requirements apply to the vessel's navigation and situational awareness system; control system; communications system; and operations. These, and other novel systems on the vessel, must be developed through risk-based analysis. In addition, there are requirements for contingency planning, software integrity, cyber security, testing, vessel surveys, and third-party review of risk assessments. To ensure that the requirements of the Australian Code of Practice are tailored to the risks of the vessel, it includes three vessel categories: autonomous

[8] Note the Guidance Materials and Australian Code of Practice are expected to be published in February 2022.

and remotely operated marine equipment; survey-exempt vessels; and vessels in survey, as set out in Figure 1.

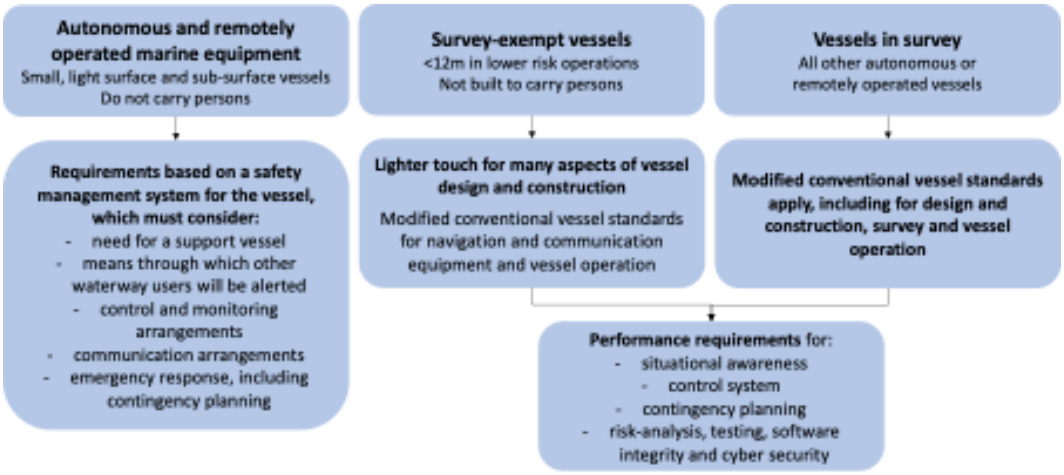


Figure 1. Vessel categories in the Australian Code of Practice

Autonomous and remotely operated marine equipment requirements

This category includes small, light and slow vessels, including vessels likely to be less than 5 metres in length and operating at speeds slower than 5 knots. [32] The Australian Code of Practice requires that "…vessel and operational risks are managed through a safety management system, which identifies risks and includes procedures to eliminate or minimise those risks so far as reasonably practicable. The safety management system must address the need for a support vessel; the means through which other waterway users will be alerted as to the presence of the vessel; the control and monitoring arrangements for the vessel; communication arrangements; and emergency response arrangements, including contingency planning."[32] These vessels are also required to "…be collected within a reasonable period if it stops operating, not contain hazardous materials that may pose a risk to the environment or third parties if the vessel stops operating, and comply with some aspects of COLREGS, such as the lights requirements."[32]

This category will be particularly assistive for operators of smaller autonomous vessels such as the REMUS 100 or Coral AUV, in providing them with a tailored regulatory approach that matches the risk profile of the vessel and its proposed operation. It provides certainty in the applicable requirements and should enable a faster regulatory process for the operator, and a lesser resource burden on AMSA in assessing it. The resources available in the Guidance Materials will assist operators in completing their safety management system and appropriate crewing assessment, and in understanding what to apply to for AMSA for, and how.

Survey-exempt vessel requirements

This category includes "…low complexity vessels less than 12 metres in length which are not built to carry persons and do not carry dangerous goods, tow other vessels or have an inboard petrol engine." [32] The Australian Code of Practice, consistent with the existing requirements for lower risk conventional vessels, contains requirements related to "…the construction, flotation/stability, machinery, steering, watertight weathertight integrity and fire safety aspects of the vessel...modified conventional vessel standards and additional performance requirements apply to the vessel's: navigation and situational awareness system; control

system; communications system; and operations. These, and other novel systems on the vessel, must be developed through risk-based analysis. In addition, the draft Code requires survey-exempt vessels to meet requirements for contingency planning, software integrity, cyber security, testing and third-party review of risk assessments." [32]

This category will be particularly assistive for operators of medium autonomous vessels such as the Ocius Bluebottle, ixblue DriX, or Saildrone in providing them a tailored regulatory approach that matches the risk profile of the vessel and its proposed operation. Similar for the previous category, the Survey-exempt category provides certainty in the requirements that apply, and how to demonstrate compliance with those requirements. It should enable a faster regulatory process for the operator, and a lesser resource burden on AMSA in assessing it. The resources available in the Guidance Materials will assist operators in completing their documentation, including the Concept of Operations, Design Record, and Safety Management System.

Vessels in survey requirements
This category includes all vessels that do not fit the categories of 'autonomous and remotely operated marine equipment' or 'survey-exempt'. For these vessels, "…modified conventional vessel standards and additional performance requirements apply to all aspects of the vessel, including its: navigation and situational awareness system; control system; communications system; watertight and weathertight integrity, construction, engineering, stability and auxiliary and anchor systems; fire safety system; and operations. All novel systems on the vessel must be developed through risk-based analysis." Vessels in survey are also required "…to meet requirements for contingency planning, software integrity, cyber security, testing, vessel surveys, and third-party review of risk assessments."[32]

This category will be particularly assistive for operators of larger, faster, and higher-risk autonomous vessels in providing them a tailored regulatory approach that matches the risk profile of the vessel and its proposed operation. Similar for the previous category, the Survey vessel category provides a higher degree of certainty in the requirements that apply, and how to demonstrate compliance with those requirements. It is closely cross-referenced with the NSCV, but with amendments or additions to ensure it is appropriate for autonomous vessels, enabling a faster regulatory process and a lesser resource burden on AMSA in assessing it. The resources available in the Guidance Materials will assist operators in completing their documentation, including the Concept of Operations, Design Record, and Safety Management System.

The development of the voluntary Australian Code of Practice was necessary to address the lack of tailored standards for autonomous vessels operating in Australia, the lack of a common benchmark for good practice, and the lack of available stakeholder resources. Elements of the project, such as the initial analysis undertaken of existing standards and codes, the extensive consultation undertaken with AMSA and other stakeholders, and additional reviews of the Code content by AMSA, points towards its capability in addressing those challenges. Once the Australian Code of Practice is publicly released, and operators start using it as part of their regulatory process, it will be possible to gather evidence to determine whether the Code has truly addressed these challenges and to what degree.

PART 3 IDENTIFYING THE IMPACT OF THE AUSTRALIAN CODE OF PRACTICE THROUGH A CASE STUDY: SMALL AUV - REMUS 100

This part uses a case study to highlight the challenges faced by operators of autonomous vessels in Australia, and to identify the impact of the Australian Code of Practice in addressing those challenges. The REMUS 100 was chosen as the subject of the case study because it is a popular off-the-shelf small autonomous vessel, the required data was available to the author, and the author had operational experience with it and the corresponding regulatory process. Further case studies should be developed to represent the breadth of autonomous vessel types in operation in Australia.

This case study starts by setting out the vessel particulars and common operational practices for the REMUS 100, and then identifies the regulatory requirements that apply under the existing maritime regulatory framework, together with the requirements that will apply under the Australian Code of Practice. The case study will conclude with consideration of the impact of the Australian Code of Practice.

The REMUS 100 (Figure 2) is a compact AUV and part of the REMUS (Remote Environmental Monitoring UnitS) series of vehicles, which is amongst the most commonly used AUVs in the world. The REMUS 100 is designed to operate to a depth of 100 m, with a speed of approximately 4 knots, depending on current conditions. The system is propelled by a single propellor and powered by a bank of lithium-ion batteries. The REMUS 100 is typically about 1.8 m in length, 0.19 m in diameter and weighs between 35 and 55 kg in air. Endurance of the REMUS 100 varies by generation, configuration, and operational conditions, but ranges between 4 and 20 hours.



Figure 2. REMUS 100 beginning a dive to map seabed on the west cost of Tasmania. (Guihen)

The small size of the vehicle makes it suitable for rapid environmental assessment, where a large area can be surveyed from a small boat. This is particularly beneficial in regions that are difficult or dangerous to access, or where a certain range to the seafloor is desired. The AUV is deployed from a support boat using a cradle or by hand. Two people are typically required to lift the vehicle into and out of the water, making for low logistical overhead and with operation from small support boats quite common.[9]

[9] Further operational information for the REMUS 100: At the start of deployment, the AUV acquires a GPS signal to establish a location. Most commercial AUVs contain an inertial navigation system (INS), which aligns with the GPS while the AUV is at the surface. Once this alignment is of sufficient quality, the AUV is ready to dive. After checking for errors, the operator triggers the start of a mission and the REMUS follows a set plan that has been provided to it. In general, they have limited freedom to deviate from this plan, except where obstacle avoidance sonars are fitted, in which case the AUV may enact a basic avoidance behaviour, such as early termination of the mission or change of depth. Though the AUV attempts to follow the plan, it is not always capable; strong currents, degraded navigation, or system faults may complicate the trajectory of the mission. AUV missions are typically monitored by humans at the surface, who keep a watch for other water users, as well as for the position and status of the submerged asset. There are currently no commercially available systems to support either the avoidance of boats by the AUV when surfacing or the updating of position to other users. These functions must therefore be performed by human operators. Communication between the operators and the underwater vehicle is limited to acoustic modem messages that are significantly bandwidth constrained and have update frequencies of 30 to 120 seconds. The operation of platforms like this challenge the traditional notion of watch-keeping, crew competencies and the legal definitions under which the platform operates.

Domestic commercial vessels are required to have a unique vessel identifier, a certificate of survey, be listed on a certificate of operation, and be crewed by persons holding the required qualification, unless a specific exemption or general exemption applies. General safety duties also apply to the owner, operator, crew, and other persons interacting with the vessel. A Safety Management System (SMS) must also be developed for the vessel and proposed operations. It is necessary to consider the specific regulatory requirements that apply to a vessel based on its specifications, intended operation, and risk factors, noting these factors also impact the flexibility mechanisms that are available. The below information has been presented in a consciously detailed way, to highlight the complexity and nuance involved in the regulatory process, and the difficulty this causes operators and AMSA.

Unique vessel identifier (required)

The REMUS 100 must have and display a unique vessel identifier,[35] unless an exemption applies. It is unlikely that the general exemption *Marine safety (Vessel identifiers) Exemption 2020 (EX01)* would apply because the REMUS 100 does not fit the exemption parameters.

Certificate of Survey (likely exempt)

There must be a Certificate of Survey in force for the REMUS 100,[36] unless an exemption applies or the Guidance Notice previously mentioned applies.

If an exemption or the Guidance Notice applies

There are several options that would need to be explored by the operator, as follows:

- *Marine Safety (Certificates of survey) Exemption 2021* (EX02): If the REMUS 100 was intended to operate in sheltered (D or E) waters, it could be exempt from the requirement to hold a Certificate of Survey under EX02, noting that an application for approval is required, and conditions include, unless the National Regulator determines otherwise, compliance with specified design and construction standards.
- *Marine Safety (Class C restricted operations) Exemption 2021 (EX40):* If the REMUS 100 was intended to operate in E, D, or the designated part of C waters, it could be exempt from the requirement to hold a Certificate of Survey under EX40, noting that an application for approval and an initial survey is required, and there are a range of conditions that need to be complied with.
- *Guidance Notice – Small unmanned autonomous vessels:* If the REMUS 100 was intended to operate in E, D or C waters, it fit the scope and requirements identified for the Guidance Notice, and an application for a specific exemption were made and approved, it could be exempt from the requirement to hold a Certificate of Survey.

If a Certificate of Survey is required

If a Certificate of Survey was required, for example, if the REMUS 100 was to be operated in B or B extended waters, an application must be made to the National Regulator, and the National Regulator must be satisfied that the vessel meets the standards mentioned in Marine Order 503 (Certificates of survey - national law) 2018 for the vessel. For the REMUS 100, if it is surveyed by an accredited marine surveyor and not a recognised organisation, and if it is classified as a 'new vessel',[10] the applicable standards are set out at Marine Order 503

[10] The standards which apply to a vessel under Marine Order 503 depend on whether it is classified as an existing vessel, transitional vessel, or new vessel. These terms are defined at Marine Order 503 s22. A vessel is a new vessel if it does not fit the definition of an existing vessel, generally being a vessel constructed before 1 July 2013, or a transitional vessel, which is

s7(3),[37] including in relation to arrangement, accommodation and personal safety, watertight and weathertight integrity, construction, fire safety, engineering, stability and equipment. If an election was made for the REMUS 100 to be surveyed by a recognised organisation, also known as a classification society, the applicable standards set out in s8(2) are a combination of the class rules and the NSCV. The owner of the REMUS 100 would need to contact an accredited marine surveyor or recognised organisation for assistance in identifying the requirements that apply to the vessel, and to conduct the required surveys, in accordance with the *National Law – Marine Surveyors Accreditation Guidance Manual 2014.*

Certificate of Operation (required, plus a specific exemption)

The REMUS 100 must be listed on a Certificate of Operation, [38] unless an exemption applies. It is understood AMSA's current policy is that an autonomous vessel cannot meet minimum crewing requirements if there are no crew on board, meaning a specific exemption is also required, together with the Certificate of Operation.

If an exemption applies

If the REMUS 100 was intended to operate in sheltered (D or E) waters, the relevant exemption to consider is *Marine Safety (Certificates of operation) Exemption 2020 (EX03).* This exemption does not require approval, and the applicable conditions are that the vessel must (a) have and comply with a safety management system that addresses the operation requirements in Schedule 1 and 2 of Marine Order 504 that apply to the vessel; or (b) comply with Part A of the ISM Code (noting that for complying with Part A of the ISM Code, the relevant national requirement for crewing is clause 6 of Schedule 1 to Marine Order 504). It is noted that Schedule 1 of Marine Order 504 contains minimum crewing requirements, and therefore will be difficult for an autonomous vessel to comply with. Under s4(4) and (5) EX03 the owner of a vessel can apply for approval to operate in a way that does not comply with a condition, but the approval is limited to no more than 90 days.

If a Certificate of Operation is required

If a Certificate of Operation is required, an application, together with a declaration that there is a safety management system in place for the vessel, must be submitted to the National Regulator, and to approve the application the National Regulator must be satisfied that the vessel meets the criteria set out in s5 MO 504. The criteria include that the vessel has a unique vessel identifier, and the operation of the vessel complies with Schedule 1 of MO 504 or Part A of the ISM Code.[39] S7 Marine Order 504 lists the conditions that the certificate of operation is subject to, which includes that there continues to be a safety management system in place for the vessel.[40]

Crewing

The REMUS 100 must be crewed by persons holding the required certificate of competency,[41] unless an exemption applies. Marine Order 504, Schedule 1 – Operation requirements, requires an appropriate crewing assessment, noting that the number and certification of the determined appropriate crewing must be at least equal to that of minimum crewing.[42] As per the table in Schedule 1, for a vessel less than 12m in length, the minimum crewing is 1, and the certificated crew and master is stated as 1.[42] This means that, subject to the appropriate crewing assessment, the minimum crewing for the REMUS 100 could be 1

generally a vessel which was a new vessel but then a change mentioned in Schedule 1 Marine Order 503 occurred, or the vessel's certificate of survey ceased to be in force for more than two years. It is likely most autonomous vessels will be 'new vessels', i.e. vessels built after 1 July 2013.

person. NSCV Part D Crew competencies, Schedule 2 Duties holder may perform, sets out the duties able to be performed for each certificate. It is likely that the operator of the REMUS 100 would need to hold a Coxswain Grade 2 NC or a Coxswain Grade 1 NC, subject to the exact duties being performed and further advice from AMSA.[43]

Specific exemption from minimum crewing

If it is determined that a specific exemption is required from the minimum crewing requirement, or from a crew competency requirement, the operator will need to apply for a specific exemption.[44] Reviewing the Guidance Notice – small unmanned autonomous vessels will assist operators in understanding the type of information AMSA will require.

It is evident from the regulatory analysis that identifying the exact regulatory requirements and flexibility mechanisms that apply to the REMUS 100 is a complex, nuanced process, requiring an understanding of the National Law, Marine Orders and the NSCV, and the exact operations intended to be undertaken. There are also options in some cases that an operator would need to choose between, requiring an understanding of the benefits and limitations of each approach. This complexity leads to uncertainty and delay for operators and AMSA.

Regulatory analysis – requirements under the voluntary Australian Code of Practice

The Australian Code of Practice is divided in to 3 clear categories, with specific requirements applying to each category, as illustrated in Figure 3.

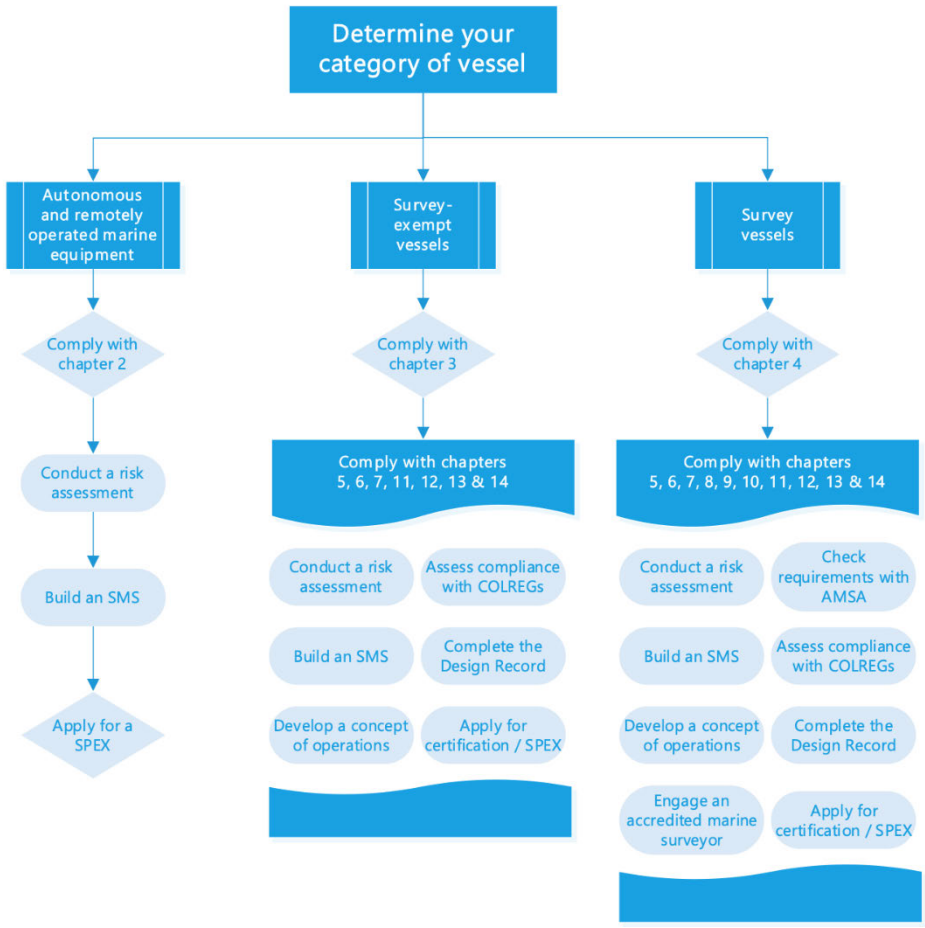


Figure 3, Diagram identifying requirements for each category, Guidance Materials for Australian Code of Practice, March 22

An operator seeking to comply with the voluntary Australian Code of Practice must identify which category and corresponding requirements apply, prepare the necessary documentation, and then apply for a specific exemption from AMSA, for example from the requirement to hold a certificate of survey and certificate of operation. The operator would be expected to provide evidence of compliance with the Code to AMSA as part of their application. The Guidance Materials that accompany the Australian Code of Practice provides diagrams, lists, concise information and examples to assist with all steps in the regulatory process.

It is likely that the REMUS 100 would be classified as autonomous and remotely operated marine equipment under the Australian Code of Practice, because of its small size and low operating speed.[45] The requirements that apply are compliance with Chapter 2 of the Code and preparation of a Safety Management System, with evidence of compliance then being provided to AMSA with an application for a specific exemption.

Safety management system

Assuming that the REMUS 100 is classified as autonomous and remotely operated marine equipment, the Australian Code of Practice requires a Safety Management System to be prepared and implemented for the vessel which: identifies the risks to the safety of the vessel, the environment and persons on or near the vessel; includes procedures to eliminate or minimise the identified risks so far as is reasonably practicable; is documented and readily accessible for a person who uses the system; and is kept in the control station for the vessel. There are specific requirements for what the safety management system addresses, such as the need for a support vessel, means to alert other waterway users, control and monitoring arrangements, communication, emergency response planning, and visibility of the vessel for other waterway users.

Other requirements

The Australian Code of Practice also requires the vessel to: be operated in accordance with an appropriate crewing assessment undertaken by the owner or operator in accordance with Marine Order 504; not have the potential to leak fuel and other matter that may pose a risk to the environment should the vessel be lost or become irretrievable; not contain hazardous materials that may pose a risk to the environment or third parties should the vessel be lost or become irretrievable; be collected within a reasonable period if it stops operating; not pose a significant danger to persons in the water; and comply with the applicable light requirements of COLREGS when on the surface.

COLREGs (collision avoidance requirements)

Small autonomous marine equipment will be likely to be classified as an 'inconspicuous vessel' under COLREGs and as such are required to display a white all-round light that is visible for 3 miles. There are also light requirements in COLREGs for vessels restricted in their ability to manoeuvre. Unless the vessel has the capabilities to comply with the requirements of COLREGs that apply to these scenarios, the vessel must: avoid narrow channels and fairways; avoid using or approaching traffic separation schemes; avoid inshore traffic zones; not cross a traffic separation scheme; and if a sailing vessel, avoid other sailing vessels. The Australian Code of Practice contains guidance on how these requirements are met. In addition, many chapters (which apply to survey-exempt vessels and vessels in survey) will be informative for the design and operation of the REMUS 100, including Chapters 5-14.

It is evident from the regulatory analysis that identifying the exact regulatory requirements that apply to the REMUS 100 under the Australian Code of Practice is quite straightforward,

although the operator must still apply for a specific exemption from AMSA to enable operation. Where previously the operator needed to consider multiple flexibility mechanism options, which were all drafted for traditional crewed vessel, they are now presented with a clear path and supporting information. Operators can also access information on how to prepare the documentation required, including examples, in the Guidance Materials, which aids understanding and certainty, and lowers the resource burden on operators and AMSA.

In assessing the impact that the draft voluntary Australian Code of Practice could have, the main factors that stand out are certainty in the applicable requirements, certainty of available flexibility mechanisms, lack of decision points for operators, and availability of resources to aid understanding. These factors point towards a conclusion that the draft Australian Code of Practice could address the challenges raised by autonomous vessels operating in Australia, including lack of tailored standards, lack of a benchmark for best practice, and lack of resources available to support stakeholders. Once the Australian Code of Practice is publicly released and has been used by operators, it will be possible to identify the practical differences made by the introduction of the Code, and the degree to which it has resolved the challenges identified in this paper.

CONCLUSION

The Australian maritime regulatory framework was created for vessels with crew on board, not for autonomous vessels and remotely operated vessels. The differences in design, construction, survey and operation between traditional vessels and autonomous vessels means it can be hard for an autonomous vessel operator to identify the applicable requirements, standards and processes in the current regulatory framework, and to understand how to use existing flexibility mechanisms to achieve more suitable regulatory treatment. These difficulties can lead to additional expenses and delay and can act to discourage the development and use of autonomous vessels in Australia. These challenges necessitated the development of the draft voluntary Australian Code of Practice, which is intended to represent best practice in Australia. While the case study provided in Part 3 reflects positively on the capability of the draft Australian Code of Practice and accompanying Guidance Materials to alleviate the challenges identified, no firm conclusions can be drawn until the Code is published and used. Further assessment should be made after the first 12 months of use, to determine the degree to which it has addressed the challenges identified in this paper, and where it could be further improved. At the very least, the draft Australian Code of Practice Code will be useful for operators and AMSA in benchmarking current best practice consistent with the approaches taken internationally, and in identifying consistent documentation requirements to support applications for certification.

Further regulatory change by AMSA is needed to ensure operators can use the Australian Code of Practice more seamlessly, with a view in the future to incorporating it as a formal part of the Australian maritime regulatory framework. Ultimately, a new category in the NSCV for autonomous vessels, an operational area designator for sub-surface operations, and tailored qualifications requirements, will also help operators and AMSA to better tailor regulatory requirements and to simplify the process required to achieve certification. Many operators will be watching with interest to see what regulatory initiatives are in store in Australia for 2022 and beyond.

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FIGURES

Figure 1. Vessel categories in the Australian Code of Practice

Figure 2. REMUS 100 beginning a dive to map seabed on the west cost of Tasmania

Figure 3. Diagram identifying requirements for each category, Guidance Materials for Australian Code of Practice, March 22

For more information on the Australian Code of Practice, including how to provide feedback, please contact the authors.

An enabling framework to support COLREGs compliance for Autonomous and remotely operated vessels

Robert Dickie
Frazer-Nash Consultancy
r.dickie@fncaustralia.com.au

Marceline Overduin
Frazer-Nash Consultancy
m.overduin@fncaustralia.com.au

Edward Gray
Frazer-Nash Consultancy
e.gray@fncaustralia.com.au

Andrejs Jaudzems
Frazer-Nash Consultancy
a.jaudzems@fncaustralia.com.au

Rachel Horne
Trusted Autonomous Systems
Rachel.Horne@tasdcrc.com.au

ABSTRACT

Autonomous systems of various sizes, forms and speeds are already at sea, on the surface and beneath it. The Convention on the International Regulations for Preventing Collisions at Sea 1972 (COLREGs) published by the International Maritime Organization (IMO) govern the 'rules of the road' at sea. The autonomous maritime industry has been wrestling for years with the challenge of 'compliance' with regulations phrased from the underlying assumption that a human being is operating the vessel. The IMO may update the COLREGs in the future to accommodate autonomous vessels, but the intervening gap needs bridging. In addition, the lack of a universal approach causes difficulty in achieving a consistent application of regulatory authority. There are efficiencies to be gained for designers, operators, and regulators of autonomous and remotely operated vessels in the development of a repeatable compliance framework designed to reduce these burdens.

This project took on the COLREGs challenge by developing an enabling framework which supports a practical and appropriate level of compliance for autonomous vessels. It considered the specific issues posed by COLREGs and aligned them with the concepts of Sense, Perceive, Decide and Act. The work considered whether the combination of capabilities required by each COLREGs Rule were essential in all cases or whether mission planning could be used to reduce or eliminate the potential for challenging scenarios, thereby mitigating the risks. The output of this project is a consistent, scalable, and justified compliance methodology to support the autonomous maritime industry in complying with the 'spirit' of COLREGs.

1. INTRODUCTION

The Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) were adopted by the International Maritime Organization (IMO) in 1972, entered into force in 1977 and were last updated in 1996. COLREGs governs the 'rules of the road' at sea. It has a native structure principally based on parts and Rules, where each Rule consists of individual rules. They describe the features that vessels must have to facilitate being seen and identified, define means of communication between vessels for the purposes of signalling intent, and most importantly they describe the navigational behaviours expected of vessels in proximity to one another, for the purposes of avoiding collision. It's clear from the terms and phrases used in COLREGs that the notion of navigational or operational decisions being made remotely

or by computers was not considered. Consequently, whilst autonomous surface vessels (ASVs) of various sizes, forms and speeds are already operating at the sea, the methods by which these vessels can demonstrate that they "comply" with COLREGs are unclear.

The autonomous maritime industry has been wrestling with the challenge of 'compliance' with COLREGs for years, in terms of both understanding how it applies, and how to demonstrate compliance. The challenge for the designer or operator of an autonomous vessel is that the regulations are phrased from the underlying assumption that a human is operating the vessel. This results in the Rules being subjective and relying on the assumption of human sensing and intuition. Where an autonomous control system is performing some or all of the functions a human previously would have been performing it can be difficult to work out, in a practical sense, what constitutes 'compliance' in a way that a regulator would accept. This difficulty stems from autonomous technology not replicating human behaviour directly, rather it is emulating a subset of the human skillset using a combination of sensors, decision making processes, and actuators.

Regulating bespoke ASVs without the use of a framework is an onerous task both for the regulator and for the designer or operator. With the uptake of autonomous systems predicted to continue increasing, the bespoke approach places an undue strain on regulators to have available the resources required to maintain consistency and timeliness when assessing each compliance case. It can also lead to the development and testing of the ASV incurring additional costs, delays, and operations being restricted by more limitations than may be reasonable based on the actual risks presented. There are therefore significant efficiencies to be gained for designers, operators, and regulators of autonomous vessels in the development of a repeatable compliance framework that is designed to reduce these burdens.

The work presented in this paper was aimed at identifying the stated and unstated capabilities required for COLREGs compliance. It does not currently provide a regulator accepted means or process for assessing the compliance of an ASV. Instead, the purpose of this work is to provide a common means of understanding which capabilities are relevant to each rule of COLREGs and identify a suggested method of demonstrating that capability. This project was undertaken by Frazer-Nash Consultancy on behalf of Trusted Autonomous Systems (TAS) and this paper describes the development of the enabling COLREGs compliance framework.

2. PROJECT OVERVIEW

This project addressed the COLREGs challenge by developing a "COLREGs Operator Guidance Framework", which assists operators to understand the COLREGs Rules that apply to their vessel and operation, and how to demonstrate compliance to a practical and appropriate level. The framework translates COLREGs into language that is more suitable for autonomous vessels, identifies the specific capabilities compliance requires across the categories of sense, perceive, plan and decide, and act, and identifies the type of evidence recommended to be provided. The framework enables consideration of the specific risks posed by the full spectrum

of autonomous vessels, thus allowing flexibility in the operator's approach to compliance. The framework forms part of the new voluntary Australian Code of Practice.

The guiding principles for the COLREGs project, were:

1. The compliance methodology will be repeatable and scalable across a broad range of autonomous vessels – The framework developed is agnostic of ASV type and size. It has introduced novel ways for ASVs to demonstrate the necessary capabilities for COLREGs compliance, which should increase the number of ASVs which can comply.
2. The underpinning philosophy of the compliance methodology will be logical, reasoned and justified by argument – The framework is supported by a precursor excel workbook which provides the detailed justification behind how the framework was developed. This paper explains the thinking and logic behind the framework.
3. The compliance methodology will be enabling rather than constraining whilst upholding the purpose and spirit of COLREGs – The framework, in conjunction with the new Australian Code of Practice for the Design, Construction, Survey, and Operation of Autonomous and Remotely Operated Vessels (Australian Code of Practice), provides ASV designers and operators with new avenues by which COLREGs compliance can be achieved. The concepts proposed from this work will provide a starting point for the ASV industry to collaborate on the few real challenges posed by COLREGs compliance.
4. The use of the compliance methodology will be simple to follow and supported by guidance – The published framework is simple to understand. Its rollout will be supported by industry engagement. The framework is also supported by a guidance note on its use. Further options to encourage engagement are being considered.
5. The project aims to develop a methodology that can be agreed to by the regulator – The framework is centred on identifying the capabilities and potential evidence types to demonstrate to a regulator that the ASV is capable of understanding and actioning COLREGs as needed during operation.

With these guiding principles in place, attention could turn to the introduction of concepts to reduce the burden of compliance for ASVs. Applicability of COLREGs is dependent on the physical features, type of operation, and constraints of the vessel. Key to the project was identifying that the burden of demonstrating COLREGs compliance for an ASV can be reduced using the following process:

1. Identify Rules that are not applicable to an autonomous vessel based upon its physical features.
2. Identify Rules that are not applicable to an autonomous vessel based upon the operations that are intended to be performed.
3. Where Rules are applicable for the vessel and context, identify the capabilities needed to demonstrate the following options scale:

- Compliance – confirming that it is feasible for an autonomous vessel to comply and therefore that compliance should be achieved.
- Equivalence – where it is not feasible for the autonomous vessel to comply with the wording of the regulation as is, but where it is feasible to achieve the spirit of the regulation, developing a defendable definition of equivalency.
- Mitigation – where it is not feasible for the autonomous system to comply with the requirement directly or through equivalence, drafting a replacement requirement which mitigates in-full or partially the risk presented by non-compliance.
- Limitation – where any of the above options are not feasible, assisting the operator in deriving operational limitations which will mitigate the risk presented by non-compliance

The above process is built into the framework, and enables a more nuanced, flexible approach to determining which Rules apply to the vessel and proposed operation, and whether a vessel is compliant with COLREGs or not. This approach suits the complexity of autonomous vessels. It recognises that required capabilities could be housed in the vessel itself, a control centre, or a combination. Additionally, recognising that if a capability is not available, avoiding the situation which gives rise to the applicability of the relevant Rule still results in COLREGs compliance (i.e. imposing a limitation).

3. PROJECT STAGES

The challenge presented by COLREGs for ASVs is that the regulations are phrased from the underlying assumption that a human being is operating the vessel. It relies on the human to understand the meaning of both the stated and unstated capabilities needed to action the applicable Rules consistently and adequately. Assisting designers and operators of ASVs to comply with COLREGs requires the capture of the elements of the existing subjective set of regulations and translating them to be objective and discrete. This approach is primarily applicable to the Rules contained within Part B, which defines the expected behaviour of vessels operating within sight of each other or in restricted visibility. Therefore, the principal focus of this project became the decomposition of COLREGs, classification of the capabilities required to comply with each Rule, and then translation of the Rules to be implementable for ASVs. The initial methodology for translating COLREGs for ASVs began as is shown below in Figure 1, and its delivery is described in sequence.

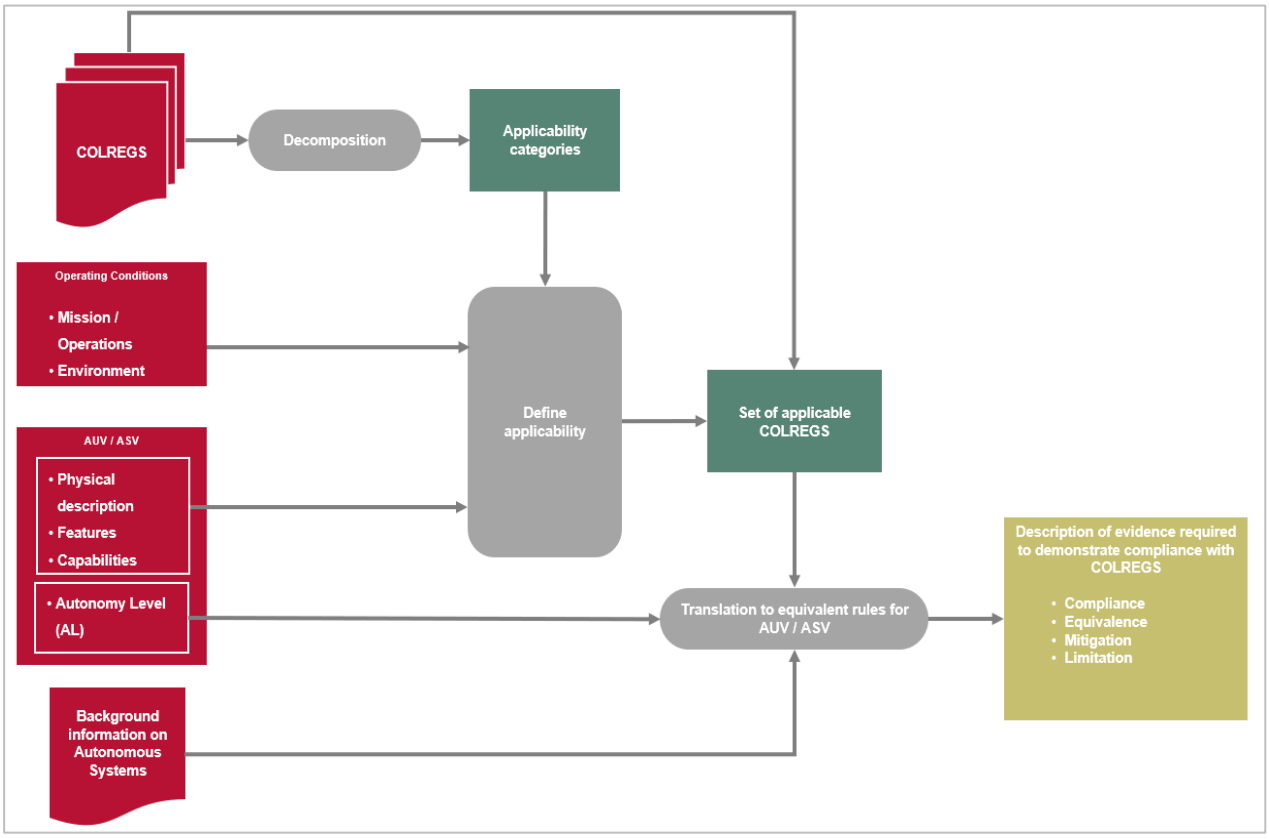


Figure 1: Methodology for COLREGs compliance

3.1 Decomposition of COLREGs by vessel features

COLREGs consists of a broad set of Rules that was authored to cater for all surface vessels operating in a wide range of scenarios. As such, there are references to very specific vessel features, physical characteristics, and navigational circumstances. However, this established and familiar structure does not allow for intuitive identification and down-selection of Rules and their constituents to relevant vessels. The initial decomposition of COLREGs formed the foundation for a filter tool to down-select the vessel-specific subset of applicable Rules.

The decomposition of COLREGs was intended to assist ASV manufactures and operators to concentrate their efforts on the applicable subset of COLREGs specific to their vessel. Applicability of the entirety or a subset of items of each Rule within COLREGs is based on expected operating conditions, as well as the features and characteristics of the ASV under consideration. Four filter criteria based on the ASV under consideration were identified. Each of these categories, and the values possible within that category, are presented below.

1. Length (L):
    - $L < 7m$
    - $L < 12m$
    - $L < 20m$
    - $12m \leq L \leq 50m$
    - $L > 100m$
2. Vessel type:
    - Power-driven
    - Sailing
    - Seaplane
    - Wing-In-Ground effect
3. Vessel features:
    - Speed of less than 7 knots
    - Equipped with an anchor
    - Equipped with operational radar
    - Restricted by draft
    - Restricted in ability to manoeuvre
4. Operating visibility conditions
    - Restricted visibility
    - Inconspicuous/partly submerged

3.2 Classification of required capabilities

Following the decomposition of vessel features referred to in COLREGs, the stated and unstated capabilities for each Rule can be classified. For COLREGs to be interpretable and applicable to autonomous systems, there needs to be translation of the human operator-focussed Rules to capabilities aligned with those of autonomous systems. A review of COLREGs in its decomposed form identified that Rules generally include references to:

- Entities and conditions that must be ascertained; and,
- Decisions that must be made; and,
- Actions that must be taken.

This breakdown shares similarities with the four high-level processes employed by autonomous systems to execute their intended functions, as in AI: a modern approach (Russel & Norvig, 2010). This is illustrated in **Error! Reference source not found.**, prepared for this

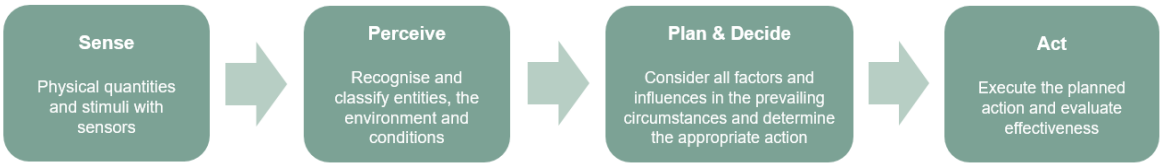


Figure 2: High level functional flow diagram for ASV decision making

project.

The functional groups of Sense, Perceive, Plan & Decide, and Act form the foundation of informed decision making and behaviour, and provide a logical categorisation of autonomous system requirements and capabilities. This grouping can be applied to COLREGs, establishing a capability-aligned structure for demonstrating compliance against each Rule.

Some phrases and terms used in COLREGs are not directly applicable to the capabilities of an ASV. A further exercise was then undertaken to "translate" these challenging terms into language which is more recognisable as a function, and therefore easier to apply when considering an ASV. Translation of terms is presented in Table 1.

Table 1: Translation of COLREGs terminology

COLREGs Terminology	Framework Terminology
Prevailing circumstances	Presence and characteristics of other vessels Light/sound signals produced by other vessels Course and course change of spotted vessels over time
Visibility state and range	Time of day Weather conditions Visual obstructions

COLREGs Terminology	Framework Terminology
Ocean conditions	Wave height Wind speed Water depth
Environment boundaries	Traffic separation scheme/narrow channel locations Location of separation lines and zones Start and end location of traffic separation schemes
Reliability of radar information	Deconflict sensor information

Once the functional flow and translation of terminology used within the Rules was complete, the Rules were interrogated further to identify specific capabilities which were required to deliver COLREGs compliant behaviour in all conditions. As part of this project, the capabilities have been grouped into categories, these groupings are presented in Figure 3.

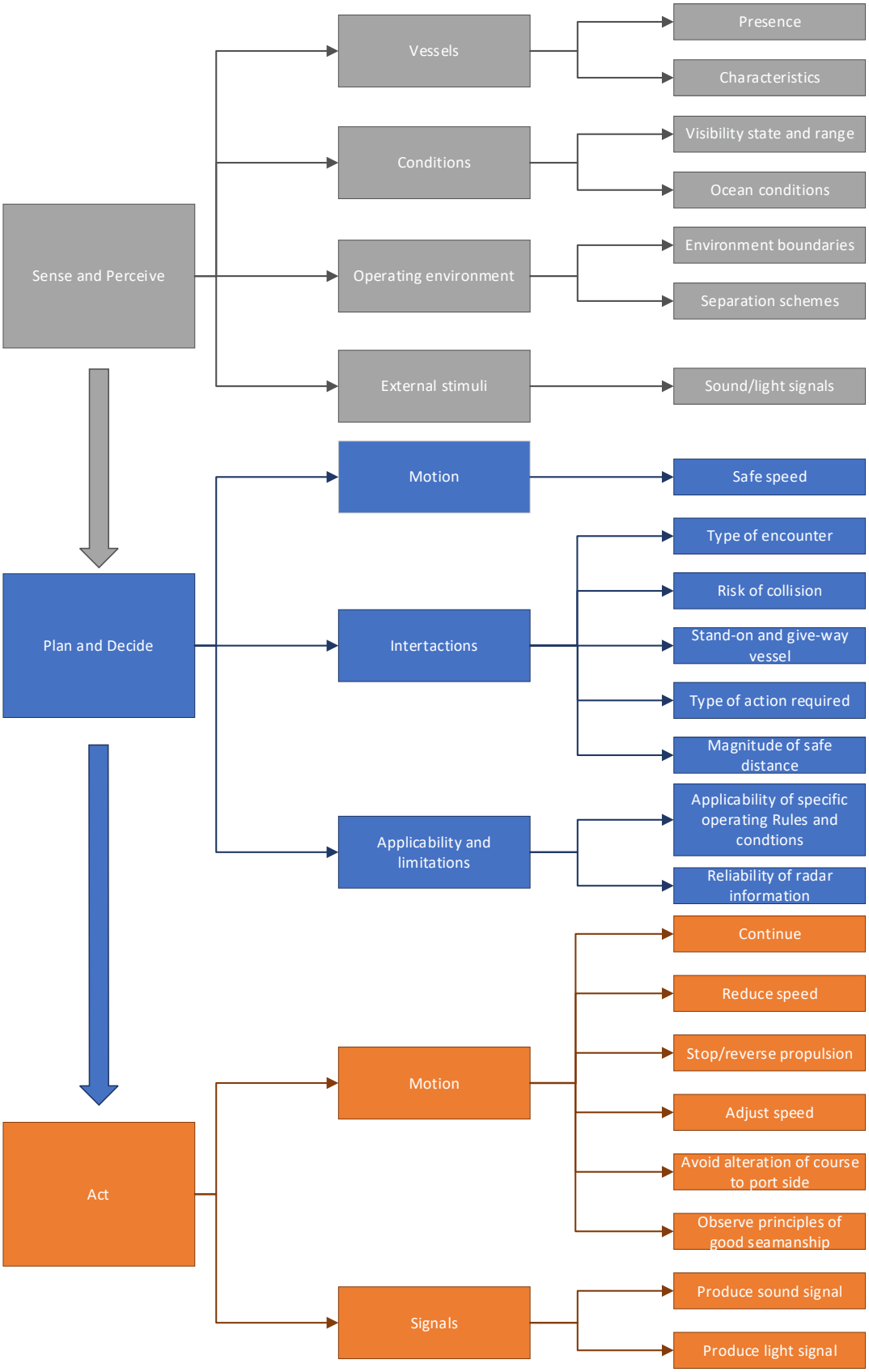


Figure 3: Functional categorisation of capabilities

The full set of capabilities would be needed by an ASV to demonstrate it can comply with every rule contained within COLREGs. However, whether the full set of capabilities is needed for the ASV is dependent on scope of intended operating conditions. ASVs tend not to be general purpose vessels for all conditions and environments, but rather are designed to fulfil a specific function such as surveyance or data collection.

4 EVIDENCE FOR COMPLIANCE

Verifying that an ASV has the necessary functionality to comply with the Rules outlined in COLREGs, particularly from a regulator's perspective, will require evidence. Evidence types should be system-independent so as to not inhibit or constrain the ASV technology innovation process. A suitable regulatory body will need to review a body of evidence submitted by an ASV designer/operator in order to consider granting permission to operate (Certification). This project precedes significant engagement with regulators, therefore the proposal for the evidence required to support ASV compliance against the new framework is preliminary. Three types of evidence are proposed, for the verification of the

i) Physical features and sensors,

ii) Software capabilities, and

iii) Operational performance.

They are broadly similar to those which would be expected to be provided for crewed ships.

4.1 Physical features and sensors – the role of a design record

A design record is proposed for two purposes. The first is to verify that the physical characteristics of the ASV are compliant with the lights, shapes, and sounds specifications defined within Parts C, D and the relevant Annexes of COLREGs. Where this is not possible, the ASV can consider any exemptions permitted by Codes of Practice or seek an exemption from the regulator.

The second function of the design record is to identify the type, quality, and quantity of sensors used for situational awareness and to determine how sensor information is then processed effectively to provide accurate situational awareness and inform planning. This record is intended to provide an estimate of the functionality of the ASV based solely on the quantity and quality of the data it can collect, process, and action. This aspect of the record will be key to:

- Demonstrating that the ASV is equipped with all required capabilities required (based on COLREGs Rule Applicability and Context)
- Describing whether each capability is provided on-board (autonomous capability) or is provided through human oversight from a neighbouring vessel and/or from remote control centre;
- Explaining when human oversight will need to be provided, i.e. continuous or only for specific occasions; and

- Detailing any mission constraints which will be required due to a lack of capability.

It will be important for ASVs to comply with existing or introduced standards/specifications as they emerge. A design record, which facilitates comparison with the framework and can then act as evidence, would be both effective and efficient for this purpose.

4.2 The software capabilities – how the ASV makes decisions

Verification of the vessel or onshore operator's capability to make decisions in accordance with the applicable Rules and regulations is discussed within this section. Two types of verification are proposed, with the type applied dependent on whether the vessel uses automated/autonomous or human operator decision-making. A combination of these two types is possible, where the vessel operates using automated decision making until such a time that human operator decision making is required. In which case both the verification methods should be undertaken.

4.2.1 Automated/autonomous decision making - Simulation

Simulations are a rapid, affordable, and scalable method of observing how a system behaves within a virtual environment. For this reason, simulation is proposed as the primary evidence format to observe and evaluate the situational awareness and subsequent logical decision making used to control the ASV.

4.2.2 Human operator decision making – Testing

Human decisions made offboard the vessel require the operator to have the necessary understanding of Rules and regulations. Testing of the remote operator could be conducted using existing methods or methods developed specifically for remote operators. Work has already been undertaken to develop training and qualifications for remote operators by the Australian Maritime College (AMC). Means of testing of remote operators must be established to a standard that provides sufficient evidence that the operator has the underlying knowledge and understanding for safe and effective decision making.

4.3 Sea trials

Confidence that the ASV can consistently action the decisions made by the software in a timely manner, or receive the decisions made by the onshore operator, is gained via sea trials. Trials are the most time and resource intensive form of evidence. For this reason, only a subset of action-based Rule items were selected. Seventeen items spanning multiple Rules within Part B are recommended for sea trials. The items and the Rule within which it is contained is listed below:

- Rule 6 – Safe speed, item a in the absence of operational radar, item (a) and (b) if the ASV is equipped with operational radar.
- Rule 8 – Action to avoid collision, items b, d, and e
- Rule 9 – Narrow channels, items d and e
- Rule 10 – Traffic separation scheme, items c and h
- Rule 13 – Overtaking, item a

- Rule 14 – Head-on situation, item a
- Rule 15 – Crossing situation
- Rule 16 – Action by give-way vessel
- Rule 17 – Action by stand-on vessel, item b
- Rule 18 – Responsibilities between vessels, item a
- Rule 19 – Conduct of vessels in restricted visibility, item e

Each item above was selected on the basis that it corresponds with the highest complexity requirement of that Rule. The consistent, accurate, correct, and predictable actioning of the appropriate Rule items by the ASV would constitute a successful sea trial. Successful demonstration of these items should provide confidence to ASV operators and the broader maritime industry that the ASV is COLREGs compliant. This will contribute to establishing the trust needed to enable the ongoing development and deployment of ASVs.

Planning and development of a suitable sea trials program was beyond the scope of this project. Such planning and development of trials will require engagement between ASV industry stakeholders and the relevant regulator.

5. CONCEPT FOR FURTHER COLREGS COMPLIANCE

In completing this work, it became apparent that there were a small number of concepts deployed by COLREGs which are so "human centric" that they are not amendable to translation to ASVs. This is because COLREGs often lists considerations which must inform a decision without providing specifics on how those issues should inform decisions, or the priority which should be given to each consideration. Acknowledging this, the project identified six concepts which ASVs should address in order to demonstrate COLREGs compliance, but which are challenging and require further consideration by broader industry to benchmark and progress. These concepts are:

- Vessel classification: Classifying the type, activity, and constraints of an approaching vessel is required when determining which Rules in COLREGs are applicable and which vessel must give way.
- Encounter classification: Applicability of Rules in Section B of COLREGs is dependent on the type of encounter between two vessels. The type of encounters e.g. crossing, overtaking are not defined further so ASVs need a common approach to allocating an encounter type.
- Action to avoid collision: The type of action needed to avoid collision is dependent on the encounter type, vessel type of both the approaching vessel and the own vessel, and each vessel's ability to manoeuvre. Both a hierarchy for right of way and for the incremental escalation of actions to avoid collision is needed.
- Definition of safe passing distance: safe distance is subjective and dependent on a multitude of factors. These can be summarised as: range of visibility, presence and characteristics of other vessels, wind speed and direction, water depth, proximity to

navigational hazards, and vessels own characteristics (length, speed, manoeuvrability).

- Definition of safe speed: The consideration of this concept is very similar to that of safe distance.
- Definition of good seamanship: Good seamanship is an inherently human centred construct, referring to the skill and acumen of the seaman. It is proposed to be broken into its constituent parts: good judgement, predictability of actions, timeliness and magnitude of actions, navigational capability, and consideration of other vessels.

The full report for the project proposed ways forward for each of the above concepts. This will be used to initiate consultation with ASV industry stakeholders. There are also several useful published papers describing methods which could be used as solutions to these challenges.

Undertaking this project has delivered an enabling framework which will provide a foundation from which the ASV industry can move forwards. It has also identified and defined a set of tougher challenges which will require further collaboration to overcome. We propose that industry stakeholders now collaborate on developing harmonised solutions to these challenges.

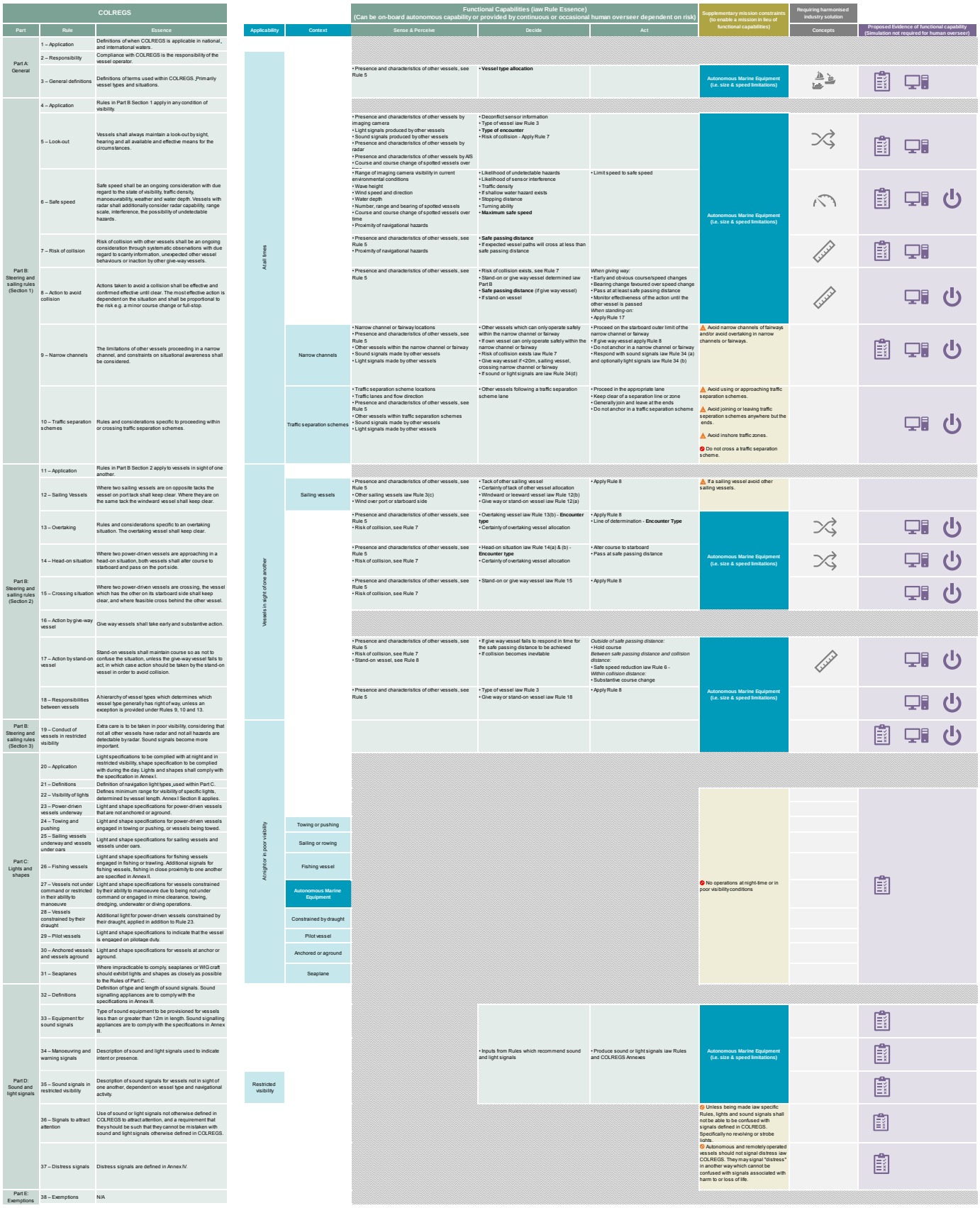


Figure 4: Enabling framework for COLREGs compliance for ASVs.

6. CONCLUSION

Autonomous vessels operating on or below the surface of the ocean will gradually increase as the technology matures. Safe operating conditions for both crewed and uncrewed vessels is facilitated by the application of COLREGs. The Rules listed within COLREGs form a consistent and common understanding of the actions and considerations needed between vessels to avoid collision. Whilst COLREGs was written with the underlying assumption that a vessel would always be crewed, the essence and 'spirit' of the regulations can be distilled and defined for uncrewed vessels. Using the five defined project principles, a system agnostic, scalable, enabling, consistent framework was derived.

Decomposing COLREGs highlighted the need to define six concepts to support system agnostic consistent application of Rules. These concepts are intended to standardise the process of vessel recognition, type of encounter, determination of right of way, and the magnitude of action needed to adhere to the unwritten principles of good seamanship. Long term benefit can be realised by fostering agreement and implementation of these concepts before mass adoption of autonomous marine vessels occurs.

Findings and recommended concepts presented in this paper will need industry input and agreement before they can be finalised and implemented. Input will be sought via the review and refinement of findings and by running workshops with industry and Defence stakeholders.

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Technological Readiness of XLUUV Autonomy for Effective Anti-Submarine Warfare Operations

Commander Simon McCowan, Royal Australian Navy, simon.mccowan@gmail.com

INTRODUCTION

There has been considerable developmental efforts into Uncrewed Underwater Vehicles (UUVs), including Extra-Large UUVs (XLUUVs), over the last two decades. Alongside this developmental effort, there has been a renewed focus on Anti-Submarine Warfare (ASW) with the increase of submarine fleet sizes throughout the world [1]. Traditionally, ASW operations have been resource (personnel, platforms and expendables) intensive operations [1, 2]. Significant benefits could be realised (cost saving of up to 70%) through employing autonomous systems, [1, 3].

The use of XLUUVs for ASW operations is a complex problem constrained by current technology for autonomy, energy storage density, reliability, sensor, and communication technology [2, 4, 5]. Of these constraints, it is the development of a reliable energy system which was a significant risk in the USNs 2004 UUV Master Plan [6] and remains a significant consideration for future development [5, 7, 8]. The key challenge in XLUUV design is then the balance of energy storage with autonomous processing requirements. Consequently, this paper looks at identifying the aspects of XLUUV autonomy to conduct ASW operations. In doing so a methodology has been developed to identify the autonomous function, information, and decision requirements in order to determine system technology readiness.

AUTONOMOUS VEHICLES – XLUUVS AND SUBMARINES

The XLUUV, by its design and nature, is and will be an autonomous vehicle. Through the definition of Autonomy, a crewed submarine can also be seen as an autonomous system of autonomous systems. When viewing the XLUUV and submarine through the lens of the RAND autonomous vehicle taxonomy [8], there are very few significant differences. This view is based upon submarine literature [9-14] and XLUUV literature [1, 5, 15, 16]. Noting the expectation that XLUUVs will conduct comparable missions, this is not unexpected. Consequently, the submarine operational functions can be used as the starting point for developing the autonomous functions and decisions required of an XLUUV.

Further, this crucial point provides an avenue for the development and testing of the autonomous elements required for an XLUUV. That is, current crewed submarines (and/or their land-based test sites) could be used as surrogates for development and testing.

ANTI-SUBMARINE WARFARE

Anti-submarine warfare (ASW) is the military process of detecting, tracking and engaging an adversaries submarine(s) [1, 2]. ASW operations are conducted as either [1, 2, 6]:

- Hold at Risk: by patrolling a chokepoint or harbour/port entrance/
- Maritime Shield: through clearance of an operating area for maritime task force.
- Protected Passage: maritime shield operations for a moving taskforce.

Due to the typically slower speeds (less than 10kts) of XLUUVs compared to submarines, XLUUVs are better suited to the Hold at Risk operations [1, 2].

ASW Patrol

The operational expectation, due to their size, is that XLUUVs will be launched from a home, or friendly, port [5, 6, 19]. They would then need to transit to, and from, the operating area comparable to a submarine [2, 5, 8]. Binns et al, [5], describe the mission stages for an XLUUV as normal operating modes, from mission planning to return modes (Figure 1)Figure 2. Of the six stages of an ASW Mission, it is the ASW Patrol which will be the most demanding on any autonomous system. Consequently, this paper will focus on the functions, information and decisions required for an XLUUV to complete the ASW Patrol mission stage.

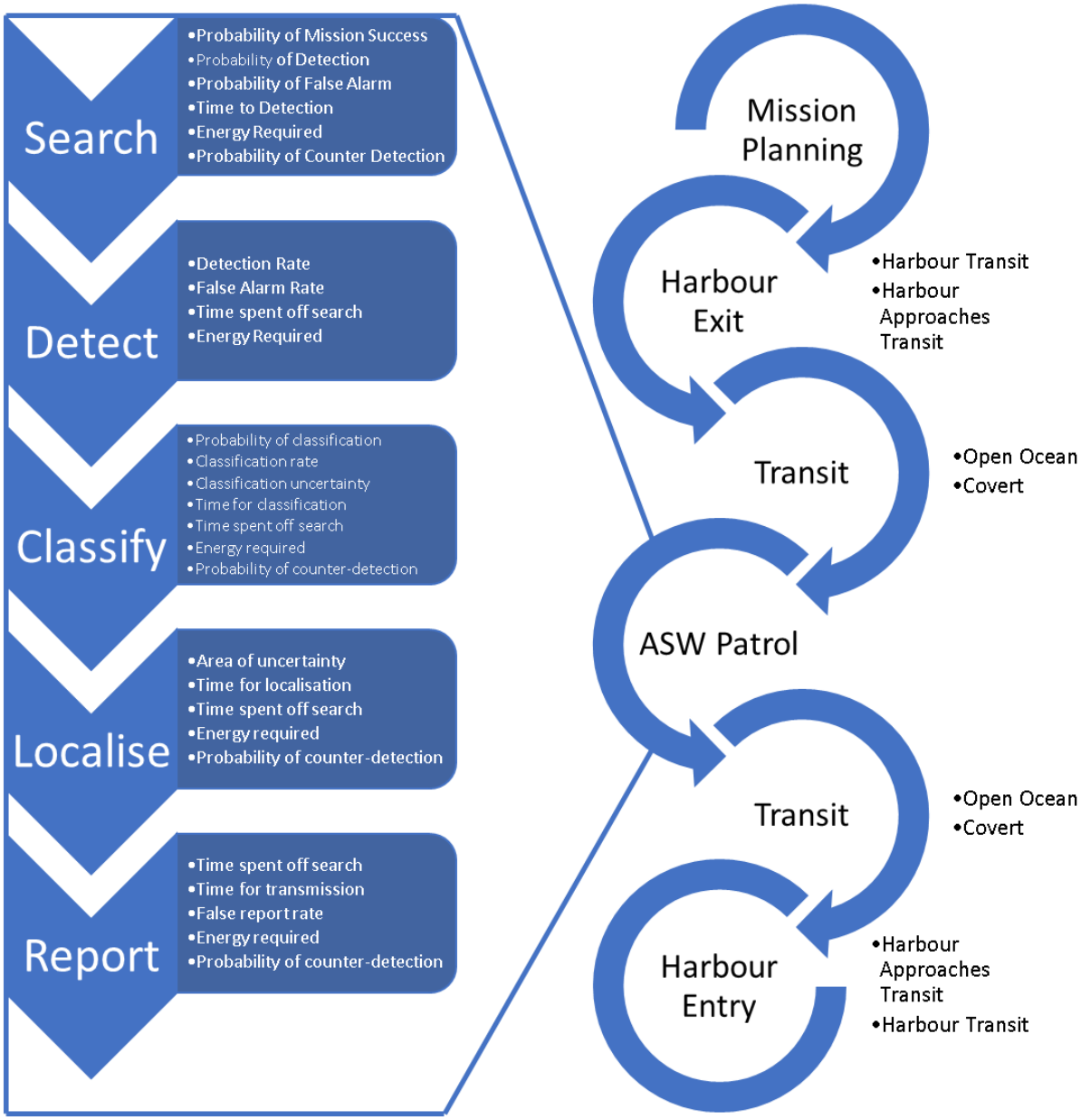


Figure 1 - ASW Mission Overview

ASW Patrol Functions

The following functions, as shown in Figure 1 with their associated measures of effectiveness, were defined for the XLUUV's ASW Patrol:

- *Search*: Determining the optimal sensor placement (search area and path), sensor processing and platform posture for maximising probability of detection [18]. This is based on acoustic conditions [11, 17], platform conditions and tactical picture against provided intelligence [14]. This process is ongoing/continually reviewed [18].
- *Detect*: Determining the optimal sensor processing to drive the mission's success, resolving potential contacts from sensor background clutter [18].
- *Classify*: Determining and employing the optimal classification method (passive / active) and process for classifying the contact[18]. This will have an associated energy cost [12].
- *Localise*: Determining and then employing the optimal localisation method (passive/active) and process (target motion analysis) for localising the contact of interest. [12, 13].
- *Report*: Once a contact of interest has been detected, classified and localised, the XLUUV needs to transmit this information [1, 8]. To do this, the XLUUV needs to determine where, when and how it is to communicate [2, 8].

XLUUV Information Requirements

To determine the information requirements of the XLUUV to act autonomously, a series of questions was posed across the XLUUV's mission profile.

- What information is needed?
- What information can the XLUUV access?
- What information is the XLUUV after?
- What information does the XLUUV need to decide / act upon?
- What information does the XLUUV need to send back?

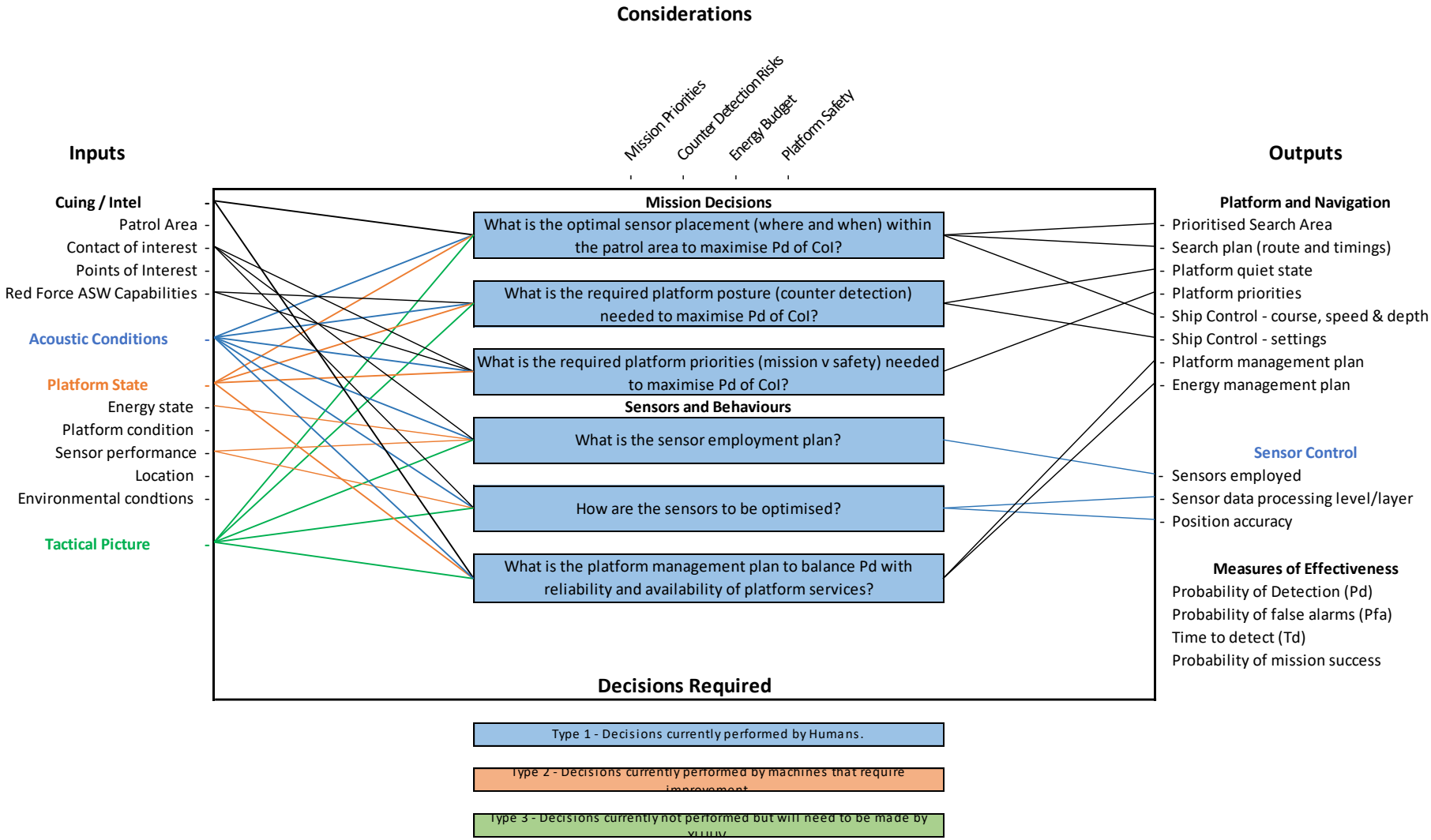
The resultant information requirements were then mapped across the required decisions of the XLUUV. A high-level grouping of these information requirements is at Figure 2 for the Search function of the ASW Patrol.

ASW Search Decision Process

To assist in assessing the aspects of AI required for ASW operations, the decisions across the mission profile, were categorised as:

- Type 1: those made by a submarine human command team during ASW operations.
- Type 2: those currently made by machines that the XLUUV will need to improve upon.
- Type 3: those decisions that the XLUUV will need to make that are not currently made within human based systems

These decisions were further classified as either Mission level decisions, optimisation of the platforms mode or posture, or Sensor/Platform system decisions, optimisation of sensor/platform performance within the selected mode/posture.



From Molina 2016 - using current environmental data and sensor capabilities to create asset path geometry to achieve the highest level of cumulative detection probability

Figure 2 - Search Function: Information, Decisions and Outputs

From the five ASW Patrol functions, the Search function was selected as a guiding example of the methodology developed. This is as the Search function is a continuous process seeking to optimise and adapt the XLUUV's mode and operation for mission success. It is an autonomous system of autonomous systems approach, prioritising the probability of mission success across all sub elements and decisions. As shown in Figure 2 the Search function decisions are Type 1 – decisions currently performed by humans.

In some ways, the other functions, which to an extent are discrete processes, can be viewed as sub-ordinate to the Search function. For these other functions, the mission level decisions will have a level of similarity with the Search function decisions. The sensor optimisation decisions will have a level of similarity to submarine (and other platform) functions, where there is a push for increased use of Artificial Intelligence (AI) to support or make decision [12, 13, 20]. Consequently, the Search function can be seen as the design driver or constraining factor of the system.

XLUUV AUTONOMY

AI for ASW Search Decisions

For the XLUUV to conduct the Search function, it requires the intelligence to make the decisions at Figure 2. To make such decisions the supporting AI needs to be capable of sensing its environment, making decisions based on this perception and executing these decisions through actions [21, 22]. Importantly, the AI needs to continuously adapt through recognising and responding to sensed changes [23]. The mapping of this process, sense, decide and act is at **Error! Reference source not found.**. Further, the elements of sense, decide and act align to the information flow for ASW decisions, input information, decisions, and outputs. This approach will require a system of AI systems [24].

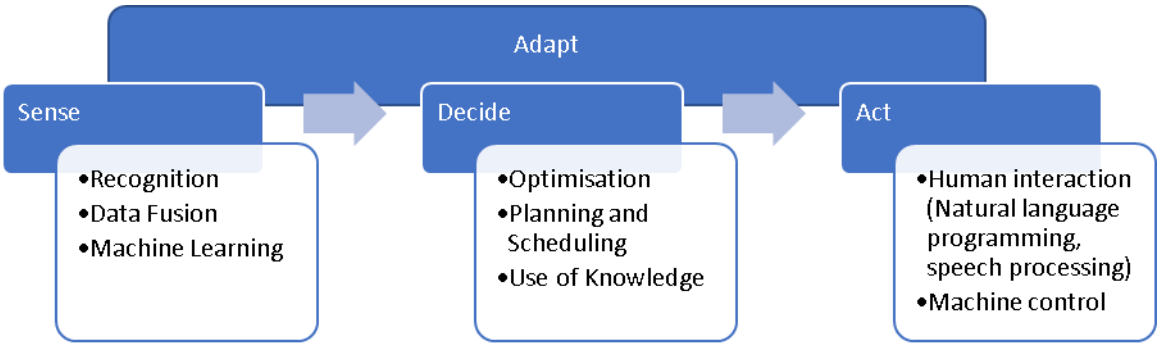


Figure 3 – AI System of Systems

For the XLUUV to perceive its environment and its own state, it must be capable of making sense of the data received. In the case of the ASW Search function, this data will come from a range of sources[1] and in various formats (raw sensor data, feature data, voice communication, text...etc). To make sense of this data a system of AI learning algorithms will be required to create a model(s) from which decisions can then be made. AI algorithms

[1] 3rd party data, external/internal database, platform management sensors, navigational sensors, communication systems, sonars, electro optical sensors and electronic warfare sensors.

suitable for developing this model(s) are those based upon machine learning, feature recognition and data fusion [22]. Machine learning has been used for sonar target classification [20, 25] as well as threat assessment [26]. Data fusion has been used for risk analysis [27], it has also be used and developed for networked UUVs for ASW [3].

Based on its perceived environment and its internal model(s), the XLUUV needs to make decisions at the mission and sensor/behaviour levels. These decisions have a range of objectives, constraints (considerations) and uncertainties. As such, the suite of AI algorithms used to make these decisions will need to include algorithms based on optimisation, planning and scheduling, and use of knowledge [22]. Optimisation algorithms have been developed to assist with campaign planning [28], whilst planning and scheduling algorithms have been used for engagement and mission planning [24, 29]. Finally, AI knowledge based algorithms have been used for both campaign [28] and mission planning [24]. Importantly, for XLUUVs these must be onboard processes if the XLUUV is to be capable of adapting [30].

The output of the XLUUV's decisions will need to interact with other systems and elements (non-autonomous and autonomous). An underpinning requirement for Trusted Autonomy is the ability to explain decisions and the processes for those decisions [31]. Further it will need to convey its intent to other autonomous systems (human or machine based). As such the XLUUV will need to be capable of communicating using natural language processing, speech, data representation …etc. The AI element of the XLUUV will also need to communicate with other systems within the XLUUV to operate control surfaces, propulsion system, communication system…etc [5]. Natural language processing and speech are well covered AI areas within the civilian domain [22]. AI processes and algorithms for conveying information to humans has been developed as decision support tools [3].

Finally, the XLUUV will need to possess a level of adaptability [30, 32]. That is, an ability to tailor the complexity, resource allocation, information requests, responsibilities and over-rides for the autonomous functions supporting sense, decide and act [33]. Such abilities of adaptation can be achieved through a "mission manager" [32] or overarching supervisory AI.

XLUUV Autonomy Readiness

To assess the Autonomy readiness of XLUUV technology the smart autonomous system (SAS) Readiness Level, proposed by Yaxley et al [31], will be used. This method combines the scalar Technology Readiness Level (TRL) (1-9) with a cognitive competence levels (A-F) (Table 1) in a matrix approach [31]. In the SAS readiness level, an SAS may possess only one TRL but multiple cognitive competency levels [31]. Yaxley et al, use Google's *AlphaGo* as a guiding example. Using the SAS readiness levels, *AlphaGo* was assessed as 7.Abc [31]. The number *7* denotes the TRL of *AlphaGo* (system prototype demonstrated in an operational environment) [31]. The capital *A* denotes that *AlphaGo* has the competence of Remembering (recall gameplay and recite an instruction). The lowercase *b* and *c* denote that *AlphaGo* has the potential, with improvements, for Understanding (explain process using words and explain movements) and Applying (Create move and create a procedure for others to follow). As a further example, Yaxley et al propose a minimum SAS readiness level of 4.A.B.C.d.e.f for an autonomous system to meaningful and transparently interact with humans (or other autonomous systems).

Table 1 - SAS Cognitive Competence Levels [31]

Level	Definition
A. Remembering	Recall gameplay, recite an instruction
B. Understanding	Explain process using own words, explain movements
C. Applying	Create new moves, create a procedure for others to follow
D. Analysing	Troubleshoot, identify tasks for training, conduct a test
E. Evaluating	Select the most suitable player, justify a process
F. Creating	Integrate information from multiple sources to create a solution, network with others

This assessment focuses on the autonomy readiness at the system level, not the individual functions. However, this assessment method includes the cognitive competence levels, which can be mapped across to the AI elements identified (sense, decide, act and adapt). That is, cognitive competence levels of A *Remembering*, B *Understanding* and *C Applying* loosely relate to learning (recite instructions, explain movements), and planning and scheduling (create new moves and create procedures for others to follow) AI algorithms. The cognitive competence levels of D *Analysing* and *E* evaluating loosely align to optimisation AI whilst the final level of F *Creating* could be aligned to adaptation AI. Such mapping then supports the ability to assess current autonomy system readiness levels through exploring developments in AI.

For the XLUUV to effectively conduct ASW operations it requires an autonomous system readiness level of *6A.B.C.D.E.F.* That is, a TRL of 6, where the autonomy element has been demonstrated as a prototype in a simulated environment. The required cognitive competence of the XLUUV for it to effectively perceive its environment would be remember (A) and understand (B). For the XLUUV to effectively make ASW Search function decisions, it requires the cognitive competence of applying (C), analysing (D) and evaluating (E). Finally, for the XLUUV to possess adaptability, it requires the cognitive competence of creating (F). Employing the mapped cognitive requirements, it is possible to assess the current state of required elements for XLUUV autonomy (Table 2**Error! Reference source not found.**).

Whilst not in the maritime domain the RAND report *Air Dominance through Machine Learning* highlights both the immaturity and potential of AI for mission planning [34]. Their pre-liminary exploration into AI for mission planning was limited to the first levels of cognitive competence, remembering, and understanding through machine learning. Seeking to develop a comprehensive database (from extensive training) to attempt to solve the optimisation and adaption problems through brute force. They identified significant challenges in doing so, including the need for considerable human input to provide effective training of the AI and that the computational power and time requirements were unable to be determined [34].

Table 2 - Current SAS Readiness Level

Autonomy Function	**AI Algorithms**	**Cognitive Area**	**TRL**	**Cognitive Competence[2]**	**Remarks**
Sense Act	Learning	Remembering Understanding	5 5	A. B.	Mature AI processes in machine learning and knowledge processes, in the maritime domain.
Decide	Planning and Scheduling	Applying Analysing	3 3	C. d.	Whilst planning and scheduling AI exist, they are limited in complexity and maturity for use in the maritime domain/
Decide	Optimisation	Evaluation	2	e.	There has been limited development of optimisation AI in the maritime domain, particularly for resourced constrained applications.
Adapt Act	Adaptation	Creating	1	f.	There has been limited application of adaptation AI, particularly for UUV operations

CONCLUSION

The methodology sought to identify the applicability of XLUUV autonomy for ASW operations. This was through identifying and then analysing the key functions, information and decisions required to support autonomous ASW operations. This paper focussed on the ASW Patrol Search function as it is the most demanding function – presently all decisions within this function are currently made by humans. It was determined that an XLUUV would require an autonomy readiness level of *6A.B.C.D.E.F.* to successfully complete this function.

Current XLUUV autonomy is immature and was assessed as *1A.B.C.d.e.f*. This is as the areas based on machine learning (cognitive competence of remembering, understanding and to a limited extent applying) are reasonably mature. The planning and scheduling AI (cognitive competence of analysing) is less mature as it is has had limited development in the maritime domain and complex environments. Finally, the AI algorithms for optimisation and adaptation (cognitive competence of evaluation and creating) have low maturity (TRLs of 2 and 1 respectively). Based on the analysis, the real challenge (or problem) for developing XLUUV autonomy is around optimisation and adaptation. Importantly it is the development of these AI functions within the XLUUV constraints of energy.

[2] Note: Capitals indicate full competence, lowercase letters indicate partial competence which requires further development

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GLOSSARY OF TERMS

AI	Artificial Intelligence
ASW	Anti-Submarine Warfare
SAS	Smart Autonomous Systems
TRL	Technology Readiness Level
USN	United States Navy
UUV	Un-Crewed Underwater Vehicle
XLUUV	Extra-Large Un-crewed Underwater Vehicle

February 11, 2022

L3Harris White Paper

Mission and Situational Awareness Autonomy Delivered Through Artificial Intelligence and Machine Learning

Prepared by:

Autonomous and Advanced Naval Platforms, L3Harris Technologies

L3 Technologies, Inc., is a wholly owned Subsidiary of L3Harris Technologies, Inc.

Presenter Point of Contact:

Rick Williams
Richard.L.Williams@l3harris.com
+1 8566764741

INTRODUCTION

The long-term strategic competition posed by Russia and China force a reevaluation of current Naval plans and strategies. No longer can we solely rely on exquisite technology isolated to billion-dollar warships to create an asymmetrical advantage. Rather, we must develop offset strategies that deliberately change the calculus of military competition, to one more advantageous. Foundational to this is utilizing manned-unmanned teaming on platforms enabled by autonomous mission and situational awareness payloads.

Platform and payload autonomy plays a vital role in the future of naval operations that support Distributed Maritime Operations (DMO). Significant benefit to the warfighter stems from mission packages carried, and autonomous coordination between the various payloads, distributed platforms, and traditionally manned assets. The addition of hull, mechanical, and electrical (HM&E) autonomy, which allows control and maintenance of systems, such that they can support extended operations at sea, adds yet more benefit.

The importance of unmanned autonomous targeting for greater lethality and survivability of manned platforms is going to be crucial in the distribution of forces as compared to previous concepts when the forces were aggregated with a Strike Group.

The true offset, however, comes through the implementation of Artificial Intelligence and Machine Learning (AI/ML) to deliver mission and situational awareness that maximizes the functionality, safe operating ability, and effectiveness of autonomous platforms. Autonomy is only as capable as the AI and machine learning that is created. Those vessels that employ AI/ML will evolve, to learn the right behaviors in real time, to better suit the mission – whether that be transiting more safely, providing more effective kinetic delivery, or providing better intelligence, surveillance and reconnaissance (ISR).

HOW WE EMPLOY AUTONOMOUS FAMILY OF SYSTEMS

Autonomy takes many forms, and can span from simple decision aid support, to incredibly complex AI/ML algorithms that modify autonomous behavior in real time. In the near term, autonomy's value can fill today's operational gaps in performing the dull, dirty, and dangerous activities that humans no longer want, need, or can do. When assigned to an unmanned, or optionally manned platforms, these activities can often be performed at higher efficiencies, with significantly lower costs and risk to human life than a traditionally manned platform.

AI/ML analytics will process the higher volumes of data needed to make better decisions as the computing power detects the anomalies that human operators cannot observe in real time. Analytically recognizing trends and anomalies will help determine patterns of life that provide better decision making through combat identification or adversarial intentions and warnings. Autonomous surface and subsurface vessels provide an affordable alternative for combating some of the common threat behaviors and tactics we see employed by bad actors around the world. Additionally, the advanced computing power will enable high speed reconnaissance and

remote surveillance, which supports unmanned platforms freeing up the higher-end assets for other mission sets.

Numerous platforms of different size, speed and capability are available to suit customer needs. For example, companies like L3Harris have a wide variety of unmanned systems ranging from 6 to 180+ feet and capable of executing numerous mission sets. In total, L3Harris alone has 440 autonomous unmanned undersea & surface vehicles fielded. These systems are deployed all over the world and service the defense, oil & gas, environmental survey, and scientific sectors. Our Unmanned Surface Vehicles have performed over 2,100 hours at sea without human intervention. Along with these fielded capabilities, L3Harris is building the US Navy's MUSV program and the UK/France Navy's MMCM platforms.



Figure 1. L3Harris MAST-13 Unmanned Surface Vessel

At the core of all our unmanned surface vehicles (USVs) and unmanned conversions is our ASView control software. Autonomous path planning begins with perception data from camera feeds, radar, AIS, lidar, sonars, depth sounders, navigational chart overlays, and other sensors. ASView fuses all inbound perception data together, while taking the accuracy of each device into consideration, to develop a complete and accurate view of the vessel's surroundings. This fused data is then used to identify and classify contacts according to their characteristics. The data determines the current location of these contacts and can predict where these contacts will be over various time horizons based on the continuous collection of historical data. This situation awareness software can be used for a variety of levels of autonomy from fully autonomous operations or simply as a decision aid to an operator.

In addition to our situational awareness and perception autonomy, L3Harris also provides hull, mechanical, and electrical (HM&E) autonomy, which allows us to control and maintain our systems, such that they can support extended operations at sea. This autonomy is responsible for such activity as actuating valves, flushing tanks, and turning systems on and off, to ensure we are capable for operating without an operator. This autonomy also provides the capability to log system performance such that it can be used for condition-based or predictive maintenance.



Figure 2. Medium Unmanned Surface Vehicle

ASVs provide the essential link connecting seabed to space and are natural sensors of the environment around them. Depending on the payloads, that sensing capability can take many forms, from situation awareness to more tactical applications. As noted before, we have a robust unmanned underwater vehicle (UUV) capability, in our Iver family of UUVs, so we have looked for opportunities to combine those systems by autonomously launching and recovering UUVs from our USVs. As we combine those unmanned platforms, it opens new mission sets and new undersea applications, where the USV can transport the UUV over long distances, then send the UUV to do a focused mission. This eliminates or mitigates some of the challenges with UUVs as they can use all their energy on long transits, such that they don't have sufficient mission capability. By teaming USVs with UUVs, we can get the tremendous benefits of both platforms.



Figure 3. AUV Systems IVER 4-900 Unmanned Undersea Vehicle

HOW DOES AI/ML IMPROVE SURFACE AND SUBSURFACE VESSEL AUTONOMY

In the simplest terms, Artificial Intelligence and Machine Learning is when a system processes data to modify its core behavior to adapt to its environment. AI/ML based intelligence can develop deeper insights, discover hidden patterns, and act on high-value opportunities at scale. Advanced capabilities such as AI/ML are critical drivers that empower users in fixing data problems, transforming data during analysis, and automating tedious and error-prone workflows and decisions.

L3Harris's ASView software utilizes AI/ML to enable the deliberative planning. This provides state-of-the-art autonomy, while also ensuring we can learn from all our existing data to train our algorithms going forward. The systems are as good as their perception sensors, so enhancements in those sensors leads to better data to the vehicle. Along the same lines, additional mission capability in the form of sensors and payloads that can function autonomously will enhance the capability of the vehicles to perform relevant missions. For instance, if you have a sensor that can detect that your communication is being jammed, you can autonomously reposition the USV to an area that is not being jammed. These types of capabilities expand the operational value of these systems. We are also leveraging the distributed, and cooperative teaming of these payloads to improve the targeting capability. The addition of passive SIGINT payloads on several distributed unmanned platforms increases the probability of threat detection and identification as well as the accuracy and precision of the target data that's acquired and shared. That's why collaborative autonomy between payloads, and not just platforms is essential and something we are investing into.

Another example of how AI/ML is being leveraged to improve the capabilities of unmanned platforms is in contact classification. The Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) contains multiple rules in which the appropriate response in a given situation varies depending on the vessel type being encountered. Machine Learning algorithms are currently being utilized to ingest vast amounts of imagery data in order to train the autonomy to not only be able to identify contacts, but also classify them based on vessel type. This allows the autonomy to maintain full COLREGs compliance and improve the safety of navigation by reacting to a given situation as a civilian captain would expect. This capability can be further expanded in enabling the autonomy to identify hostile contacts and respond in accordance with the desired mission set.

L3Harris is actively demonstrating "smart" electro-optical and infrared (EO/IR) sensor and signals intelligence (SIGINT) payloads doing passive threat detection and providing target quality threat data into a networked combat system. The tactical edge AI/ML provides a huge advantage on these payloads. As an example, we are developing AI/ML algorithms that can ingest and review massive amounts of Electromagnetic spectrum data to achieve two key things:

- First, these AI/ML agents take the place of data analysts and are able to rapidly classify the spectral data to determine which emitters have key behaviors or signatures that represent potential threats. They can do this much faster than a human operator.

Once identified, these threats are then quickly elevated to manned operators for assessment and appropriate action. L3Harris is leveraging the years of SIGINT experience, and threat data, we have from our Airborne sensors to rapidly demonstrate and bring this capability to the Navy

- And second, these AI/ML algorithms are constantly evaluating the battlespace to determine an aggregate tactical threat level for their manned counterpart platforms. The distributed team of unmanned platforms are able to direct themselves to optimize their signal collection, and if they find that too many ears are listening, then autonomous action, in the form of spectrum signature management, can be taken to go "silent" again. The ability to trigger and monitor these EMCON changes in an instant provides an advantage and give delivers precious time during conflict.

AI/ML can also improve the readiness and logistics of assets. By analyzing data from onboard sensors (e.g. pressure in a generator, flow rate of a compressor, revolutions per minute of fans), a machine learning model can be trained to accurately identify early warning signs in real-time that could lead to machine failures. This means you can detect equipment abnormalities with speed and precision, quickly diagnose issues, take action to reduce high impact downtime, and reduce false maintained alerts.

L3Harris's partnership with Amazon Web Services (AWS) will provide rapid advancement of these AI/ML capabilities through integration of AWS Snowball payloads onboard multiple unmanned platforms. The AWS Snowball provides advanced onboard data collection, analytics, and AI/ML processing of the real-time data being collected by the various onboard perception sensors. Based on the operator's assigned configuration, each Snowball will periodically sync its data set with the AWS cloud server were all the data from each asset can be quickly compiled and fed into the AI engine for further training of the autonomy. These enhanced algorithms and behaviors are then redeployed to each of the unmanned assets so that it can be utilized by the onboard autonomy in decision making, regardless of communications link availability. This cloud processing not only provides enhanced decision making and situational awareness to unmanned assets, but can also be leveraged by manned assets to provide a more informed operational picture.

All of these examples are areas that AI/ML can benefit both unmanned and manned assets in theater. By having common functionality between the manned and unmanned platforms, we are able to effectively use these assets as a team functioning together to execute missions and solve problems collaboratively. Proving out autonomous technology will build trust with our customers, and fully show the advantage of autonomous offerings from relatively low-cost solutions for various missions. L3Harris solutions will combine to relieve the burdens for more expensive manned platforms, while reducing risk to mission and lowering risk to the lives of our military forces, all while expanding operational readiness.

CONCLUSION

Mission and situation awareness autonomy improved through artificial intelligence and machine learning is paving the way for future military and commercial sea-based activities. These systems genuinely save lives by performing a range of dangerous tasks: mine hunting, piracy surveillance, deep-sea survey, the list is endless. As important, they could be the military offset we need to counter growing Chinese and Russian influence and aggression.

SESSION 10

Environment

The role of alternative fuels, electrification, and energy storage in achieving net zero
No paper provided

A zero-carbon framework for shipping

The pathway leading to carbon free shipping
Refereed
Paper only - No presentation

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INTERNATIONAL MARITIME CONFERENCE
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SYDNEY, AUSTRALIA

The Role Of Alternative Fuels, Electrification, And Energy Storage In Achieving Net Zero

Francois Deysel, SeaTech Solutions

An overview of electrification and alternative fuels across the commercial maritime sector. Enabling technologies and maturity for electrification, battery technology, Hybrid systems, fuel cell and alternative fuels such as Hydrogen Methanol and Ammonia. The role of ICE. A look into vessel operational profiles and which power system technology is most suited to which sectors or adaptation to achieve decarbonisation. Operational challenges and benefits of using alternative fuels and electrification.

First movers in shipping's decarbonisation.

A framework for getting started.

A case study for containership feeders in Asia



The Lloyd's Register Maritime Decarbonisation Hub

IMC2022 International Maritime Conference

Executive Summary

The landscape

Previous studies showed that ships using zero-carbon fuels will need to enter the fleet in 2030 and that the most significant hurdle to overcome would be the zero-carbon fuel costs. More recently, the industry debate has been enhanced by different perspectives, policy makers have set up goals and the industry itself is creating its own targets. The debate is now moving on to global transition strategies and identification of first movers. The urgency is now being addressed by plans to launch Green Corridors where first movers can establish demonstrations that will push shipping beyond a tipping point and onto a path consistent with a net-zero 2050 future.

The challenge

The biggest hurdle to launch first movers now is to convert the ambition into action, given the reality of business cases still being too weak to justify the full uptake of costly zero carbon fuels.

Across the supply chain, zero-carbon fuel solutions are not yet seen as a prospective commercial opportunity, often because they do not yet have a robust business case. Often, there is a need to increase the investment readiness level across the entire supply chain, from their production up to their use onboard ships. Detailed analysis to build real business plans can help stakeholders to better understand the risks both inside and outside of their sphere of control.

Our work

This report sets out a framework to help in converting ambition into actions. The framework allows a detailed comparison of different transition strategies across the entire supply chain (from fuel production to its use onboard vessels). The framework can be applied to specific fleet and this analysis has used a case study of hypothetical first movers. The example chosen is a fleet of containership feeders operating in Asia.

Building on the fuel agnostic framework demonstrated in this analysis, the Lloyd's Register Maritime Decarbonisation Hub aims to steer cross-industry alliances that can unearth and accelerate the most resilient energy transitions and enable pilot projects this decade.



Five factors have influenced our approach

In the quest for a sustainable transition in shipping, we look at five important factors

Fleet-specific analysis

To develop a small-case commercial trial, we need to drill down into the specifics and better understand the techno-economic dynamics for each fleet. Building on the high-level analysis of the global fleet as well as the single ship analysis, it is possible to design and analyse fleet-specific fuel transition strategies. In particular, work should focus on fleets of potential first movers and assess several transitions that might be suitable for that fleet.

Decarbonisation transition of a fleet and its fuel supply

A single transition may require a combination of fuels and different production methods to achieve the decarbonisation goals over time. Comparing one fuel against another fuel limits the debate to the characteristics of individual fuels. In this analysis, we shift the focus from a debate about what is the fuel of choice for the shipping industry to a debate about what is the fuel transition of choice for a specific fleet and its fuel supply.

A long-term assessment

There is a contrast between the short-term business case and the end goal of a new regime where shipping relies on sustainable zero-carbon fuels.

This analysis shows that comparing the potential short- and long-term implications of different transition strategies helps to identify the trade-offs that are inevitably embedded in each case.

A collective understanding of how these transitions could play out in the long term will generate the needed confidence for all stakeholders involved to commit to an actionable plan today.

Evaluate fleet and fuel supply at the same time

Examining the fuel transition for shipping across the entire supply chain means identifying benefits and managing any unknowns. Investments have the best chance of success if based on a system solution. The system in this case is the entire supply chain from fuel suppliers to end-users. This can be done by assessing how the fuel supply may evolve in conjunction with the fleet evolution.

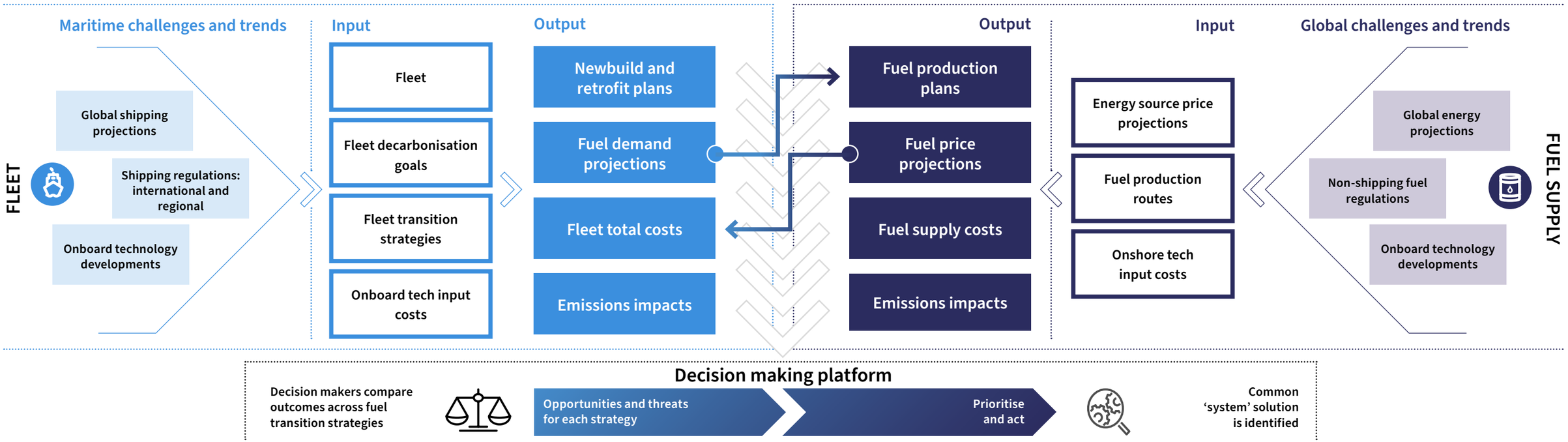
A focus on collaboration to reduce investment risk

The creation of alliances across the supply chain allows for the identification of a system solution with a high chance of success and scalability for a large market, avoiding preconceived solutions that do not work for the entire group of stakeholders.

There is a need for different stakeholders to work together within a framework in which decision making is structured. These alliances should not be limited to technology partners, private shipping and energy supply companies, but should also include financiers and governments within an alliance of stakeholders. The value of a fuel transition can be highlighted, risks can be managed and mitigated, and responsibilities and benefits can be shared across the alliances and beyond members.

The LR Maritime Decarbonisation Hub is engaging with stakeholders to address the actions in this paper to ensure a sustainable transition.

The framework



To overcome the challenges of the first movers and taking into account the factors that influenced our approach, we have set out a framework. The framework allows us to compare different transitions strategies that are selected as inputs based on the collective understanding of a group of stakeholders. It does not look exclusively at the most cost-effective solution, and it does not provide prediction either; it rather allows us to explore the different implications for each strategy. By doing so, it offers new insights, e.g how do transition strategies differ from each other and why. The aim of the framework is to force us to systematically articulate our assumptions, scrutinise and test our conclusions and help to structure decision making.

The framework enables simultaneous assessment of the fleet and fuel supply in order to meet a decarbonisation goal. The major maritime challenges and trends feed into the fleet side of the model (Left hand side) and the major global challenges and trends feed into the fuel supply part of the model (right hand side). These macro drivers are translated into input assumptions on both sides. The macro-elements are used to scope the fleet-specific evaluation by identifying the target fleet and operating route, the most plausible fuel transition strategies, and the potential fuel production routes.

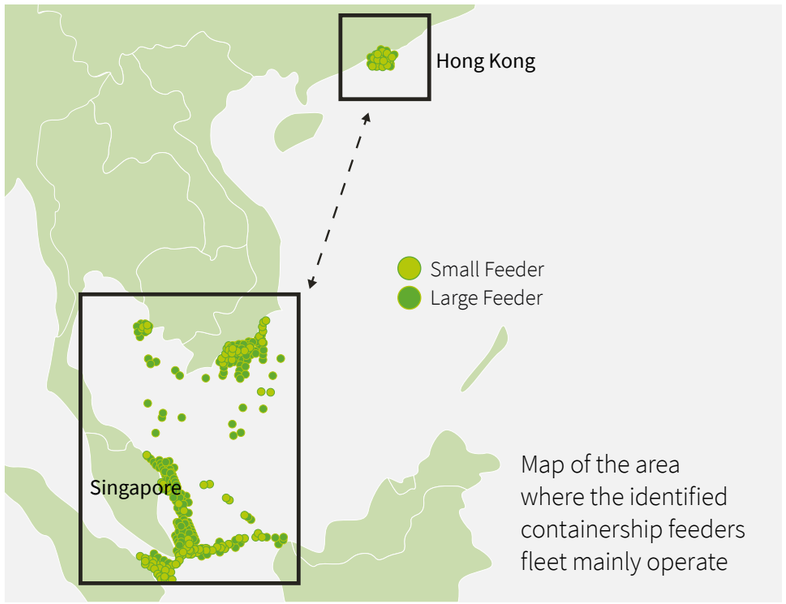
The model generates outputs directly from the input assumptions, as listed in the diagram. The module that generates these outputs works in tandem so that the outputs of the fleet evaluation are used as input for the fuel supply evaluation and vice versa. The outputs are then used to provide answers to a series of specific questions, described in this report. In turn, those answers are used to compare opportunities and risks for each of the transition strategies with the aim of identifying a common 'system solution' that works for all stakeholders involved.

This first version of the framework will be further developed as it evolves over time. This report introduces the new framework and apply it to the case study of containership feeders operating in Asia.

3.1 Which fleet can represent the case of a scalable commercial trial?

A fleet of containership feeders operating in Asia

There are many potential candidate vessel fleets suitable for a scalable commercial trial. In this analysis, we have undertaken a literature review of existing studies to identify a representative fleet that meets certain criteria. By using AIS data, we identified a fleet composed of feeders (totalling ~360 kTEU capacity) operating regionally between Singapore, Hong Kong and other Asian countries nearby. According to our AIS data analysis, 222 feeder vessels are trading mainly in this area with current fuel consumption estimated at 1.4 million tons of fuel oil equivalent corresponding to 4.7 million tons of CO_2 emitted per year (0.4% of global shipping CO_2 emissions in 2018).



Map of the area where the identified containership feeders fleet mainly operate

222 vessels

1.4mt fuel oil

4.7mt CO_2

Today's fleet profile

1,619 Average TEU

359,346 Total TEU capacity

12 years Average age

15,793 nm Average annual distance travelled per vessel

22.4 kdwt Average dwt

3,506,120 nm Total annual distance travelled

Fleet Selection

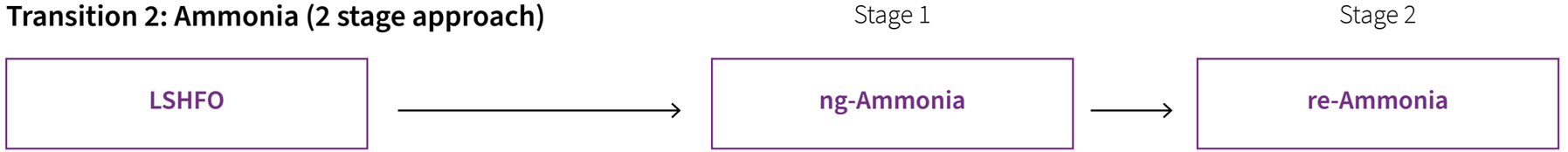
Criteria	Candidate Fleet: Singapore-Hong Kong containership feeders
The type of vessels in the fleet should be in the **'first movers'** category.	This candidate fleet and selected shipping route inspires first-mover projects because: • Containerships are used to transport manufactured goods, often sold directly to end consumers that may be willing to absorb the passthrough costs. Consumer pressure to address climate change is more heavily felt in this vessel type segment, unlike bulkers and tankers, which are further down the chain and less subject to consumer pressure. • Shipowners in this fleet also own more vessels outside of this fleet, and therefore are incentivised to prepare for the eventuality of turning over their wider fleets. Gaining an early technical and practical advantage leaves these owners less exposed to sudden decarbonisation policy changes in future. • These feeders can benefit from regional financial support offered by local port authorities.
The fleet mainly operates in a specific geographical area with a fairly high concentration of cargo traffic regularly calling at specific major hubs/ports so that **stable and reliable energy demand** can be inferred or derived.	• By their nature, feeders remain largely region bound, unlike larger containerships on longer-haul voyages, so these feeders mostly call at regional ports, with the majority of activity falling within the South China Sea. As a result, demand is localised, meaning reliable and relatively stable energy demand estimates can be inferred for this particular fleet.
While the transition of this fleet should deliver a **significant potential emissions reduction,** the fleet transition should also act as a **catalyst for other ships** that call at the identified ports, or ships operating nearby, so that it is likely to have a wider impact, spreading beyond this fleet into a larger market.	• The transition of this feeders fleet offers a significant potential impact by targeting approximately 4.7 million tons in current carbon emissions. When placed alongside the 10 shortlisted corridors identified in the study commissioned by GMF [11], this fleet would represent the 5th highest ranking by potential impact (the GMF study's corridor with the 4th highest impact, Brazil-Asia iron ore corridor, is estimated to currently emit 10.4 million tons of carbon, while the 5th highest impact corridor in the GMF ranking is the Transatlantic containerships corridor with an estimated 3.2 million tons of carbon – therefore the fleet in our study would rank between these). • The fleet operates in Singapore, which is a leading container trans-shipment hub and busy trade region, so has potential to act as a catalyst for all the other ships calling in Singapore or Hong Kong. According to the IAP report [12], the use of new fuels could tap into Singapore's position with extensive regional feedering activities and bunkering capabilities and lead to collaboration between Singapore and industry stakeholders, enabling co-sharing of risks of new investments and sharing of knowledge on common issues.

3.2 Which fleet fuel transition strategies are the most plausible?

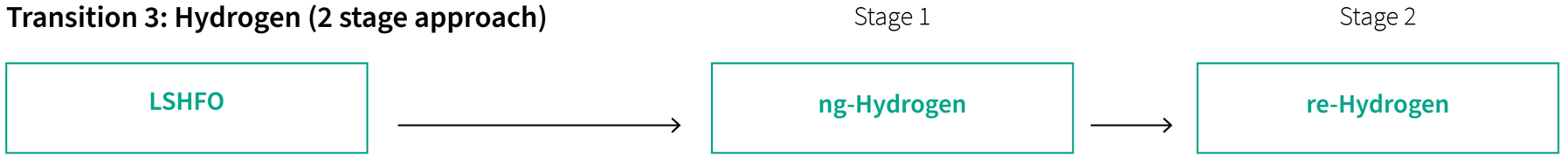
Transition 1: Methanol (3 stage approach)



Transition 2: Ammonia (2 stage approach)



Transition 3: Hydrogen (2 stage approach)



Fleet fuel transitions considered in this study

The transition based on methanol assumes the use of sustainable bio-Methanol as an interim fuel, followed by a switch to ng-Methanol first and re-Methanol in the long term (a three-stage approach). In contrast, the transition based on ammonia assumes initial use of ng-Ammonia from 2025 followed by a switch to re-Ammonia from 2030 (a two-stage approach). The hydrogen transition also employs a two-stage approach, first to ng-Hydrogen from 2025 and later to re-Hydrogen from 2030.

Selection of fleet fuel transition strategies

Through a literature review of the existing information and data available to LR, we have identified three fleet fuel transition strategies[13]: a transition based on methanol (referred to from here as the “methanol transition”), another based on ammonia (“ammonia transition”), and a final transition based on liquid hydrogen (“hydrogen transition”).

While any of these fleet fuel transition strategies sets an overall direction for the energy transition, actual execution can proceed through a series of steps (changing from one fuel to another) that could involve several fuels. Based on LR’s previous work as well as more recent studies, hydrogen, ammonia and methanol that are derived from renewable electricity (referred to from here as re-Hydrogen, re-Ammonia and re-Methanol respectively) are promising long-term solutions, whereas several sustainable biofuels or fuels derived from natural gas in conjunction with carbon capture and storage (referred to as ng-Hydrogen, ng-Ammonia and ng-Methanol) are promising short- to medium-term solutions.

The use of natural gas fuels with carbon capture and storage

Ultimately, the steps of any transition will depend on the cost, availability and sustainability of the intermediate fuels and feedstocks used to produce the fuels. The inclusion of natural gas-derived fuels, although not entirely net-zero carbon due to the carbon capture rates of current technology, may not necessarily be required as a step in all three of the transitions explored in this analysis. They are nonetheless included as a step in these transitions in the interest of exploring transitions which can scale up to meet demand around the world. Several national governments have indicated pursuit of a dual-track hydrogen economy, where both natural gas and renewable electricity production routes will be required to decarbonise national infrastructure. Consequently, shipping, as a consumer of fuels, would no doubt be coupled to the fuels available globally, particularly in the nearer term where natural gas routes, with more advanced infrastructure, are already being used on land to alleviate the pressure on producing the most sustainable renewable electricity derived fuels.

The development of carbon capture and storage will be necessary for the use of natural gas-derived fuels. For this analysis, the IEA’s carbon capture, utilisation and storage (CCUS) study of Southeast Asia[14], which highlights regional potential for large-scale storage opportunities given the deep saline formations and depleted oil and gas reserves, is particularly relevant. Despite Singapore’s limited storage resources, there is potential for regional storage hubs with neighbouring countries, including Indonesia, which is gaining early experience with CCUS solutions and already developing a legal and regulatory framework for CCUS activities.

Further work

Several other fleet fuel transition strategies can be identified and can be explored as further work. For example, a transition could begin using liquefied natural gas (LNG) and then switch to bio-LNG or re-Methane or ammonia. Other transitions could bypass intermediate steps and rely on fuels derived from renewable electricity from the start, or use compressed hydrogen or use a biogenic source of carbon rather than DAC rather than liquid hydrogen. Another plausible methanol fuel strategy could include the earlier use of ng-Methanol, bypassing bio-Methanol. This study is not an exhaustive examination of all potential transition strategies but rather the first step towards a new approach to evaluating decarbonisation strategies. Nevertheless, the selected transition strategies are considered representative of major trends that the industry is likely to adopt.

3.3 How is the decarbonisation goal achieved through fleet turnover?

Newbuild vs. Retrofit

Investment in newbuilds alone is not sufficient to meet decarbonisation goals; retrofitting is crucial to the decarbonisation strategy in the first 15 years of the transition.

The analysis finds that the split between newbuild and retrofit varies slightly depending on the transition. Around 26% of investments over the period to 2050 are retrofits (80-83 vessels). The remaining ~74% of investments (229 vessels) are newbuilds.

Simulating fleet turnover

The progressive switch from one fuel to another over time is driven by the emissions goal set in any specific year. To meet the goal, the fleet turnover combines zero-carbon-powered newbuild ships with retrofitting the existing fleet for zero-carbon fuels. The simulation also factors in the natural tonnage growth, with additional cargo demand growth set at ~3% over the 30-year transition period.

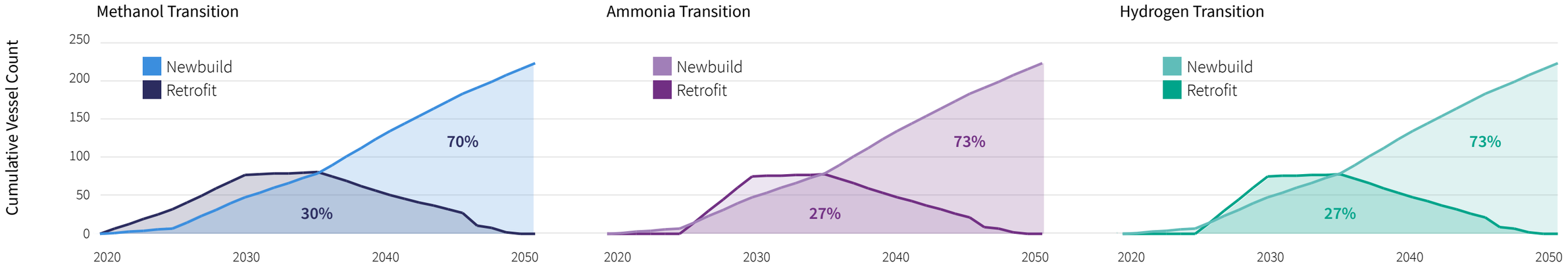
Emissions goals

The decarbonisation goal for the fleet is based on life-cycle (also referred to as 'net' or 'well-to-wake') CO_2 emissions, which includes both upstream emissions from the production of the fuel and operational emissions from use of fuel on board a vessel. Further work shall include other GHG emissions as well as any other air pollutants.

This analysis assumes the decarbonisation goal is broadly in line with a 1.5C trajectory: by 2030, the net CO_2 emissions goal is set at almost 50% of today's baseline CO_2 levels for this fleet.

By 2040, net CO_2 emissions are targeted to reach 28% of today's levels, before falling close to full abatement by 2050. The emissions decarbonisation goal for this fleet is in line with the 1.5C trajectory; however, one can argue that first movers could achieve full decarbonisation earlier than 2050. Further work will include transitions with more stringent decarbonisation goals over time.

Newbuild vs. Retrofit Vessel Count (by fuel transition)



Newbuilds

Low sulphur heavy fuel oil (LSHFO) newbuilds

The newbuilds for the methanol transition are all powered by zero-carbon fuels from vessel delivery, whereas the newbuilds for the ammonia and hydrogen transitions are still powered by conventional fuels up until 2025 due to the combination of potential limited fuel availability and growing cargo demand. However, we only see 7 LSHFO-based ships, delivered before 2025 in each case, which will eventually have to be retrofitted with zero-carbon fuels over 2035-2040. Some retrofits take place as early as 6 years in, highlighting the importance of design flexibility.

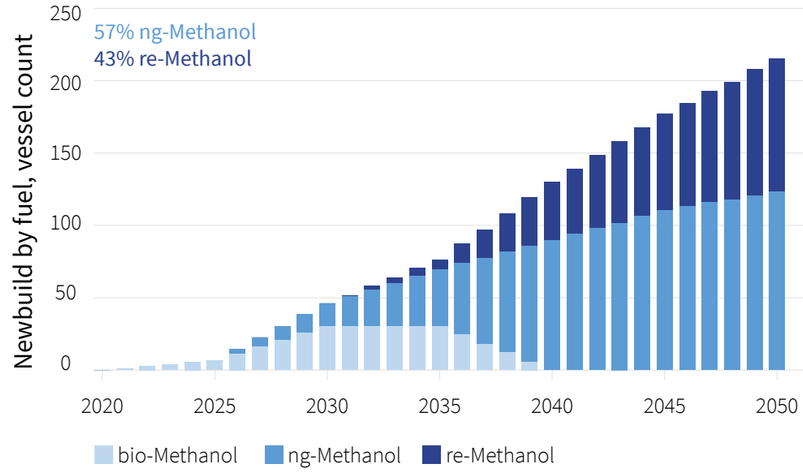
Early adoption of bio-Methanol

In the methanol transition, the use of bio-Methanol allows the transition to begin early in this decade. The construction of methanol vessels in the near term would help to create a demand for methanol in the medium to long term. However, this creates a risk of locking in to a fuel that might not be as competitive as other options in the long term.

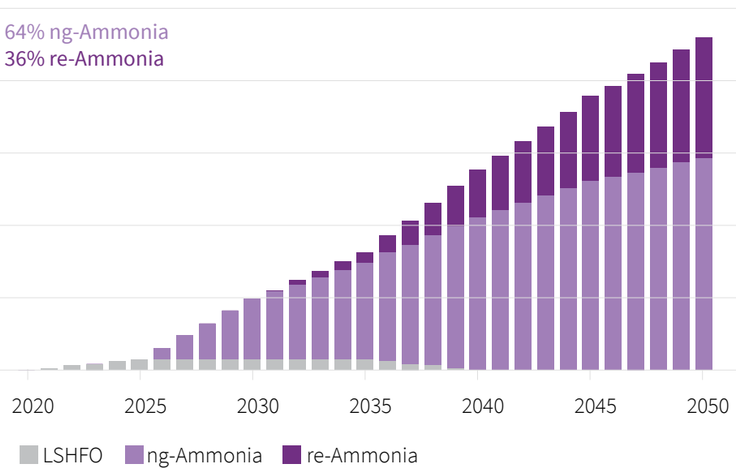
Age profile

The age distribution of the fleet is key to shaping requirements for newbuild vessels to replenish the aging fleet, and this applies to all fuel transitions. In particular, over the 2035-40 period, the natural scrappage rate peaks, driving a greater push for newbuilds over this period.

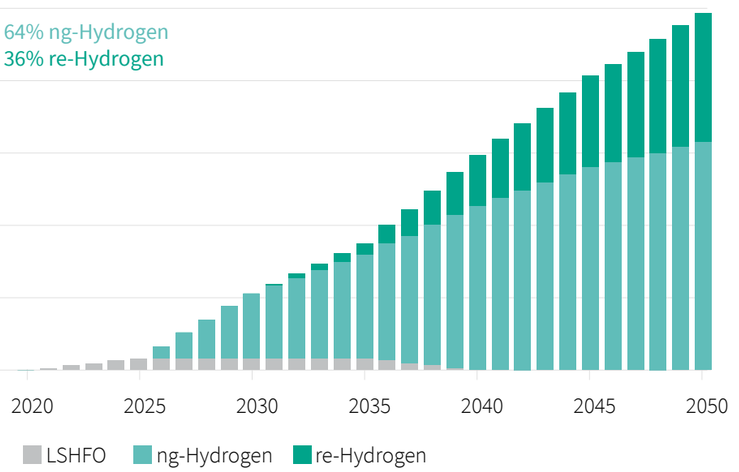
Methanol transition



Ammonia transition



Hydrogen transition



All newbuilds in the fleet simulation are assumed to take the average size of a large feeder container (1,704 TEU), as large feeders make up the majority (92%) of this sample fleet, while only 19 of ships in this sample fleet are small feeders.

Retrofitting

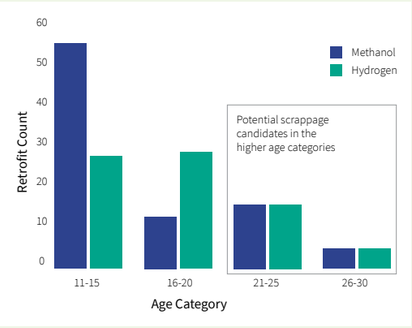
The pace of retrofitting among transitions

The pace and timing of retrofits differs between fuel transitions. For the methanol transition, retrofitting commences almost immediately, due to the early availability of bio-Methanol. Hydrogen and ammonia retrofits ramp up later once ng-derived fuels come online by 2025. The number of ng-retrofitted ships in each of these transitions reaches similar levels to the methanol transition but occurring over a shorter five-year period between 2025-30. The rapid push to retrofit the existing fleet is necessary in the ammonia and hydrogen cases to meet the decarbonisation targets by 2030. However, success will depend on having mature retrofit designs, as well as capacity in the shipyards and equipment manufacturers to deliver successive retrofit projects that could take up to three months each.

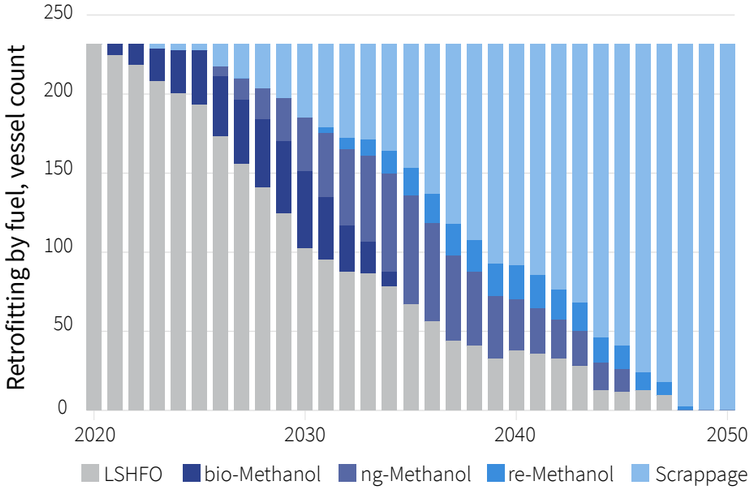
Risk of early scrappage

The analysis of retrofitting can help identify ships at risk of early scrappage.

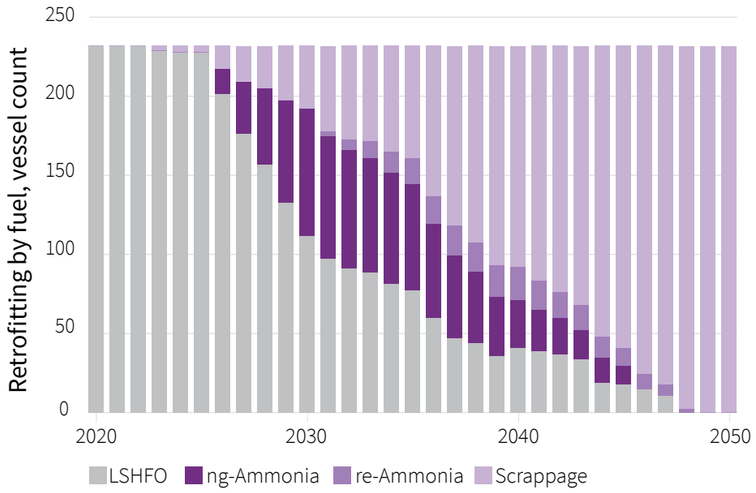
Shipowners may consider early scrappage as retrofitting at a late stage in the vessel's life cycle becomes less economic. Overall, our analysis shows there are 21 retrofitted ships that are over 20 years old (9.4% of the entire fleet), of which five ships are over 25 years old, making these even higher risk for scrappage. This does not vary between transitions – the total number of retrofits needed to meet the decarbonisation goals is similar across all three transitions.



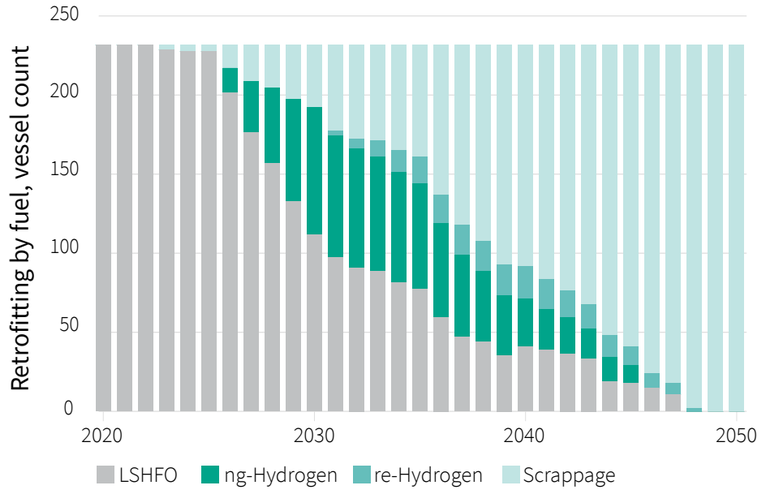
Methanol transition



Ammonia transition



Hydrogen transition



Assumed retrofit cost for a LSHFO-powered ship

Fuel retrofitted	Main engine type	Engine retrofit cost ($/kW)	Storage tank cost ($/kg of fuel stored)
Methanol	Liquid gas/low flash injection	590	Negligible
Ammonia	Gas injection	590	1.3
Hydrogen	Gas injection	590	56

3.4 What is the composition of fleet fuel mix demands?

Methanol Fleet Fuel Transition

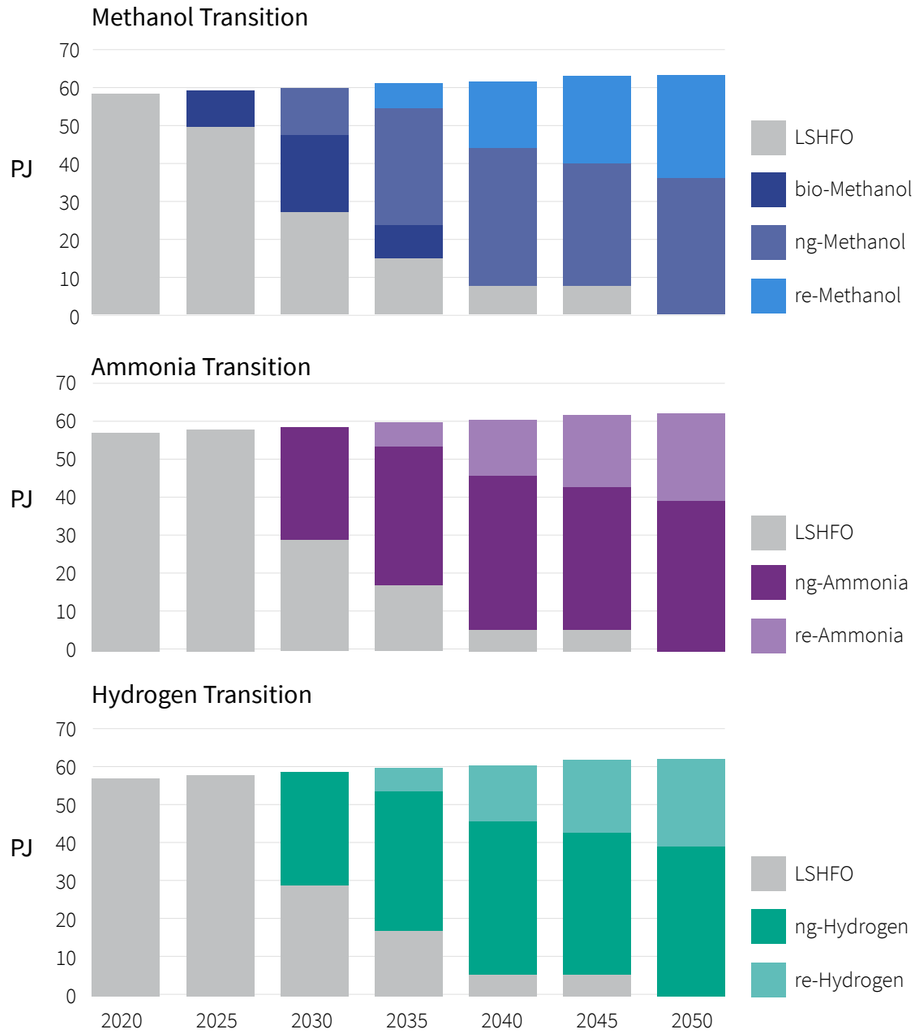
Use of bio-Methanol begins early in the transition, displacing some of the existing LSHFO demand. While bio-Methanol is an option for newbuilds, it is treated as an 'interim fuel' in this analysis as it may suffer from supply constraints and high demand from other sectors, so it is expected to become less economically viable for the shipping sector by 2040, and no longer forms part of the fuel mix from 2040 onwards. Use of ng-Methanol emerges from 2025-2030, and this is followed by re-Methanol growing from 2030-2035. Upon reaching 2050, the majority share (57%) is ng-Methanol, with the remainder (43%) re-Methanol.

Ammonia Fleet Fuel Transition

Between 2025-2030, ng-Ammonia starts to form part of the fuel mix and re-Ammonia is introduced over 2030-2035. Prior to 2025, the fuel mix is composed solely of LSHFO, and newbuilds are also LSHFO ships. These newbuilds are then gradually retrofitted for ng-Ammonia when this alternative fuel becomes available. Reaching 2050, ng-Ammonia accounts for the majority of consumption (64%), with the remainder re-Ammonia (36%).

Hydrogen Fleet Fuel Transition

The hydrogen transition follows a similar path to ammonia, with ng-Hydrogen entering during 2025-2030, followed by re-Hydrogen in 2030-2035. Any LSHFO newbuilds are retrofitted for ng-Hydrogen by 2040. By 2050, ng-Hydrogen accounts for the bulk of consumption (64%), with the remainder re-Hydrogen (36%).



Fuel mix demand

Factoring in tonnage demand growth and decarbonisation goals, the fuel mix of the existing and newbuild fleet evolves over time for each fleet fuel transition, which ultimately has different implications for the 2050 fuel mix. Irrespective of fuel mix differences, for all three fuel transitions, energy demand starts at 57 PJ in 2020 (by comparison, this is roughly ~70% of the total energy demand of the UK domestic fleet estimated in Frontier et al 2018 [15]), and reaches 62 PJ by 2050, satisfied by a mix of ng- and re-derived net-zero carbon fuels. By 2050, LSHFO is fully phased out.

3.5 What are the implications in terms of emissions trajectories?

Potential emissions savings

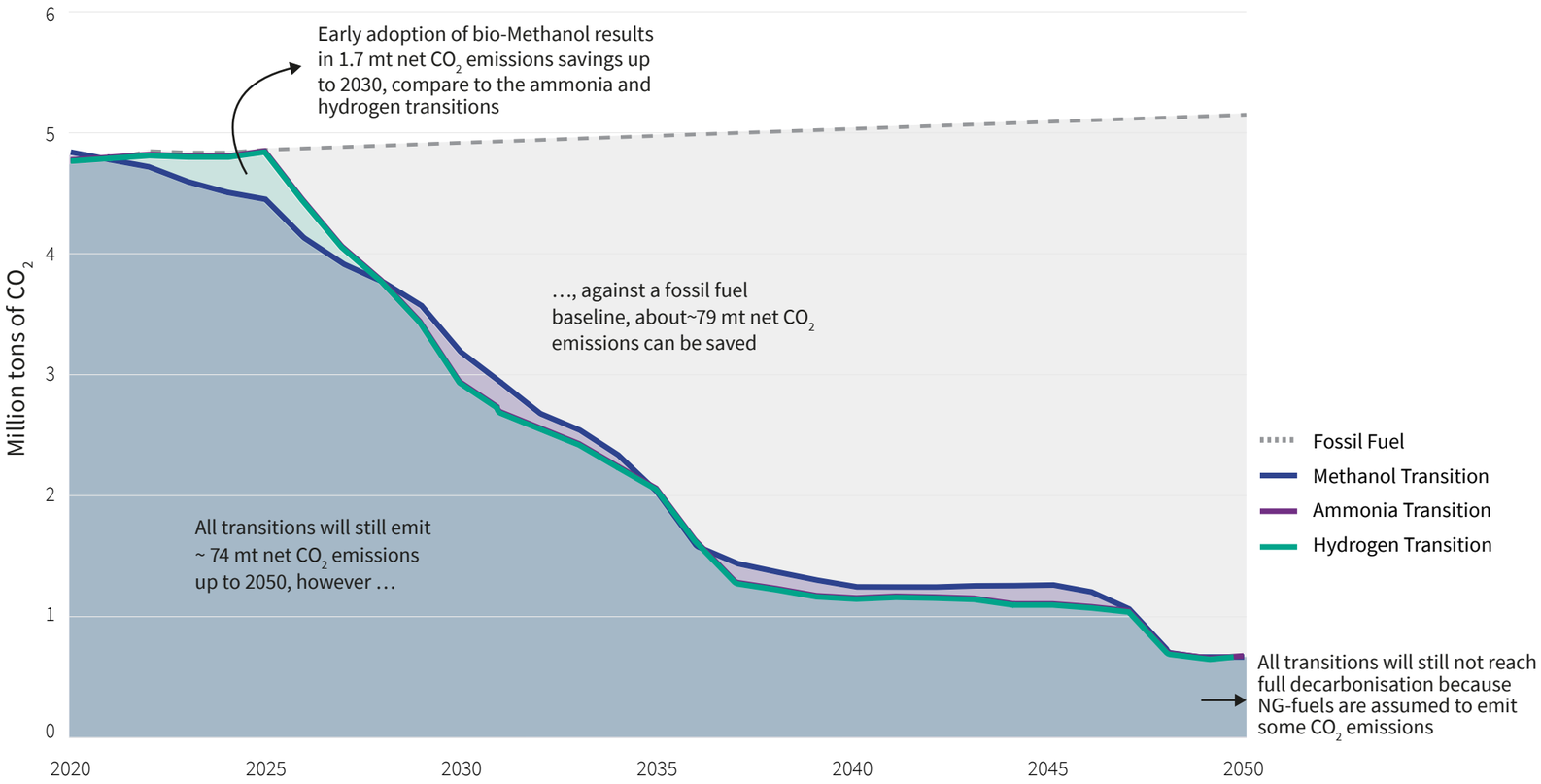
During the transition period, CO_2 emissions will continue, albeit at a decreasing rate, regardLess of the chosen fuel production route. CO_2 emissions are broadly the same for all transitions – about 74 million tons of cumulative net CO_2 emissions given all three are working to the same decarbonisation goals. When compared to a fossil fuel baseline (a scenario where the fleet continues to use LSHFO up to 2050), all three transitions have the potential to save about 79 million tons of net CO_2 emissions. For comparison, this approximates to the combined emissions of Hong Kong and Singapore for one year (80 million tons in 2019).

The impact of early adoption of bio-Methanol

The bio-Methanol transition enables accelerated adoption of alternative fuels relative to the ammonia and hydrogen transitions as bio-Methanol is already available. This would result in about 1.7 million tons of net CO_2 emissions savings up to 2030 compared to the ammonia and hydrogen transitions. For comparison, this is equivalent to saving the emissions of 23 fully-loaded passenger flights between Singapore and Hong Kong every day from today until 2030. However, this early saving is gradually eroded beyond 2030 given that bio-Methanol is assumed to have higher emissions per MJ of energy compared to the ammonia and hydrogen alternatives. It takes 25 years to fully offset the early adoption advantage of bio-Methanol.

Full decarbonisation not achieved

All transitions will still not reach full decarbonisation because ng-fuels are assumed to emit some CO_2 due to the emissions associated with upstream natural gas production and capture rates of carbon capture and storage (CCS). Other GHG emissions are also likely at 2050 as the analysis has not taken into account methane leakage.



(a) Emission factor in net CO_2 ton emissions per ton of fuel: low sulfur heavy fuel oil (LSHFO) = 3.358; bio-Methanol = 0.68; ng-Methanol = 0.34; ng-Ammonia = 0.3; and ng-Hydrogen = 2.
(b) re-Methanol, re-Ammonia and re-Hydrogen have zero carbon emissions.

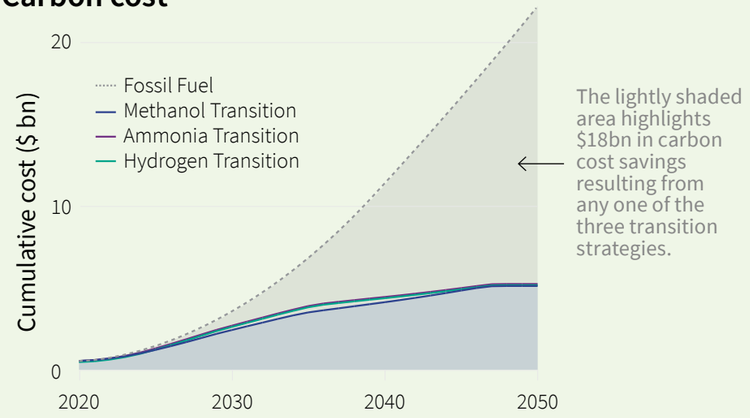
3.6 What are the key cost drivers and how do they differ among transition strategies?

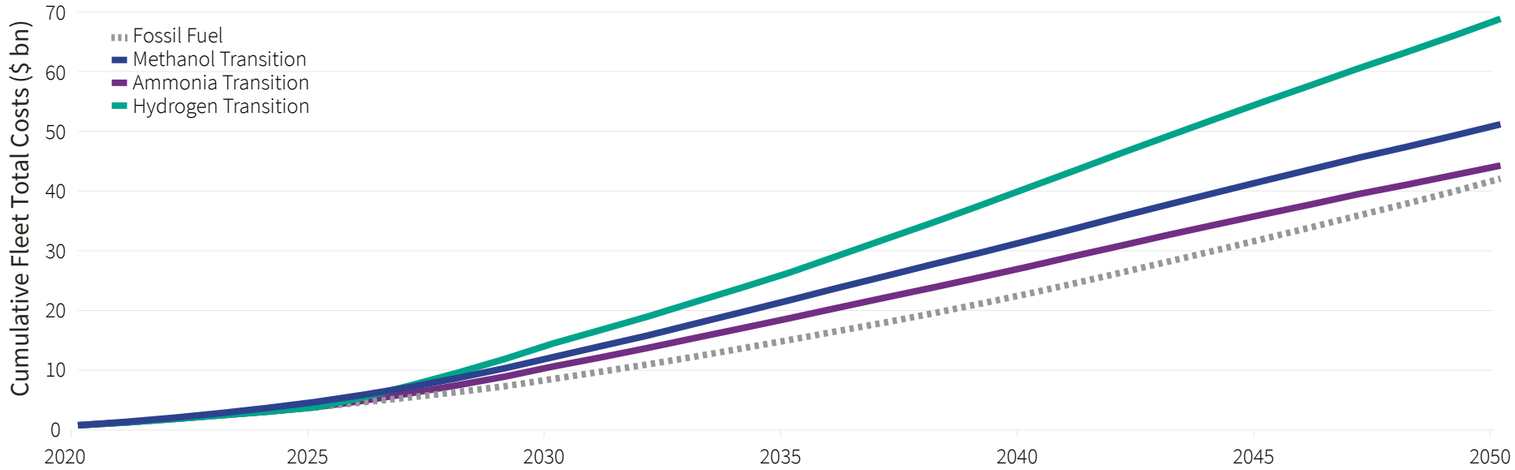
Cumulative fleet total cost

Although the three transitions have the potential to save a similar amount of cumulative net CO_2 emissions up to 2050 (~79 million tons of CO_2), they achieve this at different costs. The ammonia-based transition results in the lowest cumulative fleet total cost (FTC) at $44.5 bn, followed by methanol ($51.5 bn) and then hydrogen ($69.4 bn). *See Appendix A for fleet total cost methodology.*

All three transitions still cost more than the fossil fuel baseline ($42.3 bn) in which all vessels continue to run on LSHFO but pay a carbon price. This means that the assumed carbon price is not sufficient to close the gap with the decarbonisation transitions, but the ammonia transition is the closest, only overshooting the fossil fuel baseline by ~$2bn.

Carbon cost[16]





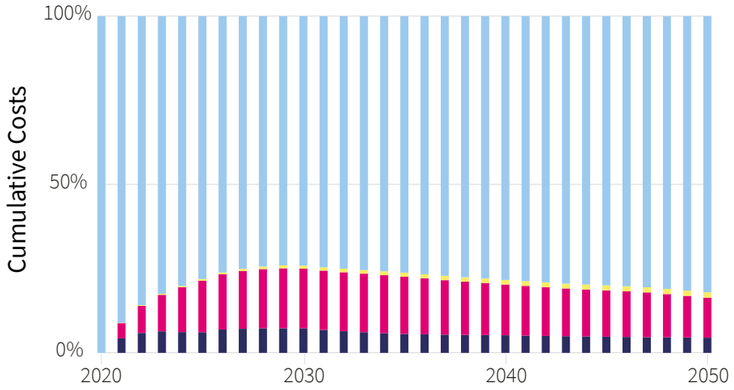
Fleet Total Cost (FTC)

The FTC is the sum of the costs of every vessel in the fleet over a period of one year and is split into several cost categories (voyage costs + CAPEX engine + CAPEX storage + storage impact + carbon costs). It includes the costs of any ships in the fleet that continue to run on LSHFO during the transition.

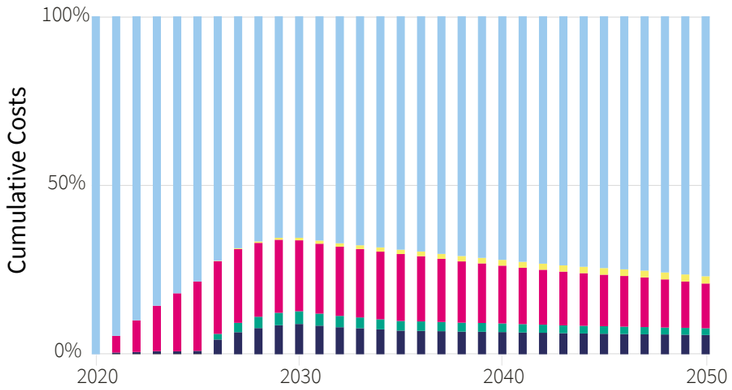
The appetite from end consumers to pay for “green” products should help shipowners pass some of the additional energy transition cost burdens through to the end consumer.

By applying this framework to a fleet-specific case, we can also estimate cargo premiums using the additional fleet costs of each transition relative to a fossil fuel case. These premiums can also change over time as the cost to decarbonise also varies, whereby setting a carbon price that gradually increases also results in cargo premiums declining. In the past, several attempts to quantify these end consumer premiums have been made but this remains an area of uncertainty where further work is required.

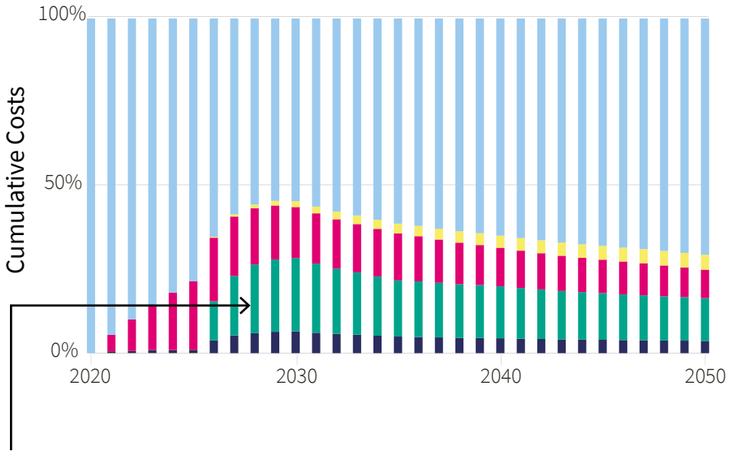
Methanol transition



Ammonia transition



Hydrogen transition

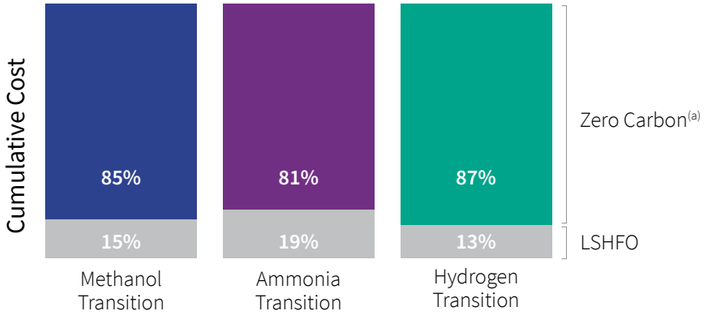


CAPEX Engine | CAPEX Storage | Carbon cost | Rev Loss | Safety costs | Voyage cost

Total voyage cost is the largest cost burden

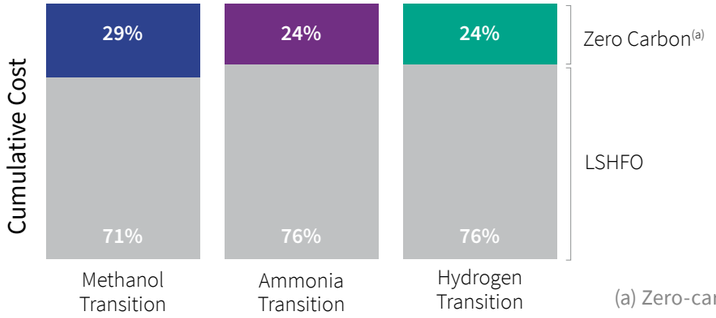
Total voyage cost poses the largest cost burden for all three fuel transitions, representing 82% of methanol fleet transition costs, and 76% and 71% of the ammonia and hydrogen fleet transition costs respectively.

As the zero-carbon fuels are expected to be more expensive, the total voyage costs are predominantly driven by vessels running on zero-carbon fuels, as opposed to LSHFO vessels.



Carbon cost driven by the existing fleet

The carbon cost for each fuel transition is largely driven by the existing fleet that has yet to be retrofitted or scrapped; this accounts for more than 70% of the total carbon cost. The remaining 30% includes other carbon costs associated with the net CO_2 emissions from bio-Methanol and ng-based fuels, subject to 'fugitive' emissions during the CCS process.



The impact of storage costs for hydrogen

The hydrogen transition faces the highest CAPEX costs for storage (e.g. additional insulation and refrigeration costs), reaching $8.9 million over the entire transition period, as well as larger cargo revenue losses (up to $3.1 million) due to the extra storage requirements of liquid hydrogen. These storage-related cost components make up 17% of the cumulative FTC.

Key assumptions: liquid hydrogen storage costs are $56/kg; energy density of hydrogen is 120.97 MJ/kg; and its volumetric density is 60 kg/m^3.

(a) Zero-carbon fuels include all transition fuels except LSHFO

Safety considerations for ammonia- and hydrogen-powered vessels

Several costs fall outside the remit of this study; however, they are considered less material than those included here. One exception could be the potential safety costs – the additional equipment and manpower required to safely operate vessels using more hazardous fuels. Although these have not yet been quantified, they will need to be considered, especially for ammonia- or hydrogen-powered vessels.

Work is currently being undertaken by LR and other partners to guide the use of ammonia as a fuel for shipping. This includes developing a mature and detailed understanding of risk and safety concerns, which will be assessed through a quantitative risk assessment (QRA) methodology. Once a full QRA is concluded, further work should include the acceptability of such risks and the quantification of the associated safety costs. Safety concerns and potential risk mitigation measures identified thus far are summarised below.

Ammonia

In gaseous form, ammonia is a colourless and toxic substance which has a distinct, pungent odour. The release of large quantities of ammonia can lead to the formation of a large ammonia gas cloud that is toxic when inhaled, even at considerable distances from the source of release. Exposure to high concentrations of gaseous ammonia can result in lung damage and death. Adequate safety measures must therefore be implemented to limit the exposure of toxic vapours to those on board an ammonia-powered vessel.

When exposed to liquid ammonia or concentrated vapours, tissue damage can occur rapidly. Suitable protective equipment that covers all exposed skin would be required for crew members in locations with ammonia-containing equipment. In the event of an evacuation, respiratory and eye protection equipment should also be available to everyone on board. A system that can detect leakages of gases and liquid would be necessary to warn crew members against entering contaminated spaces and of discharges from ventilation.

To protect ammonia tanks against overpressure, a pressure safety release system must be installed. This would typically be designed with pressure relief valves (PRV) and a vent mast; however, a traditional vent mast may not provide an adequate level of safety due to the toxicity of ammonia. New solutions such as scrubbers may therefore be necessary to reduce the release to air as much as possible. Ammonia is also very toxic to aquatic life with potential long-lasting effects. Although the release of ammonia to the sea is preferable to keeping the ammonia on board in the event of a leak, a release to water can have catastrophic consequences and should not be underestimated.

Hydrogen

Hydrogen can be stored on a ship cryogenically (-253°C) as a liquified gas or as a compressed gas at very high pressures. Hydrogen has key safety-related properties in its gaseous and liquid form which differ from natural gas and LNG. Hydrogen gas has a low-density, low-ignition energy, wide flammability range and ignites easily. In the selection of materials, it is critical to consider these properties to ensure compatibility with hydrogen and minimise the risk of hydrogen embrittlement and frequency of leaks.

Explosion and fire risks can be reduced through safe layout and process design at an early stage. Storage of high-pressure storage tanks above deck can help to disperse leaks in the open air, reduce cloud size and reduce the severity of explosions. As leaks in contained areas are susceptible to fire hazards, proper ventilation and hydrogen gas detection is required. Selection of suitable hydrogen fire detection technology is also necessary due to low thermal radiation levels from small hydrogen fires and the invisibility of hydrogen flames in daylight.

Hydrogen has an extremely low boiling point, which makes storage in liquid form more challenging and energy-consuming compared to natural gas. Liquid hydrogen stored at cryogenic temperatures is particularly susceptible to pressure build-up from boil-off gas, meaning significantly thicker insulation layers are required for cryogenic tanks. Fast evaporation of liquid hydrogen leaking into a confined space may also lead to a sudden pressure increase if venting is ineffective.

4.1 How must fuel production scale to meet demand?

Two-stage or three-stage transitions

The number of fuels in the fuel mix dictates the type of fuel supply infrastructure development (i.e. two-stage or three-stage transitions). The ammonia transition (a two-stage approach) leads to the construction of ng-Ammonia supply infrastructure first, followed by adding re-Ammonia supply infrastructure at a later stage. The same two-stage approach applies to the hydrogen transition. We assume that every five years, the different fuel type production plants scale up to meet growing demand.

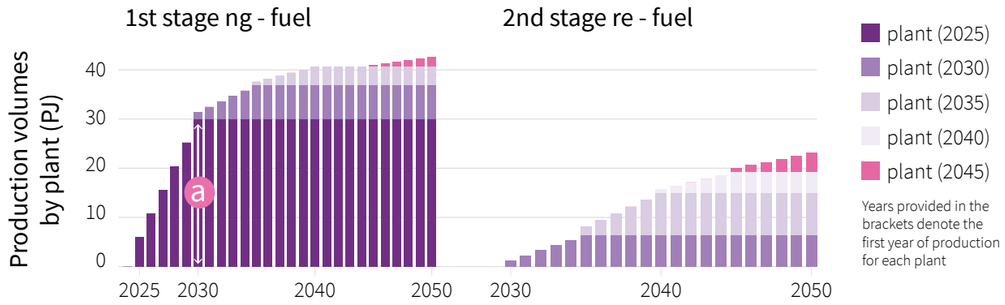
In contrast, the methanol transition has three stages. The transition begins earlier with supply infrastructure necessary to produce the interim fuel bio-Methanol, followed by ng-Methanol and then re-Methanol.

The use of bio-Methanol in this fleet is assumed to decrease from 2025 onwards and so the production plants begin to produce surplus bio-Methanol, beyond the requirements of the fleet, from 2025 onwards. The surplus bio-Methanol is assumed to be diverted to and used in other non-shipping sectors. However, uncertainty around exactly which non-shipping sectors will consume this excess bio-Methanol may impact shipowner confidence when signing offtake agreements with fuel suppliers. This situation is not present in either the ammonia or hydrogen transitions, which are instead more straightforward as demand for each of the zero-carbon fuels in these two transitions only increases over time.

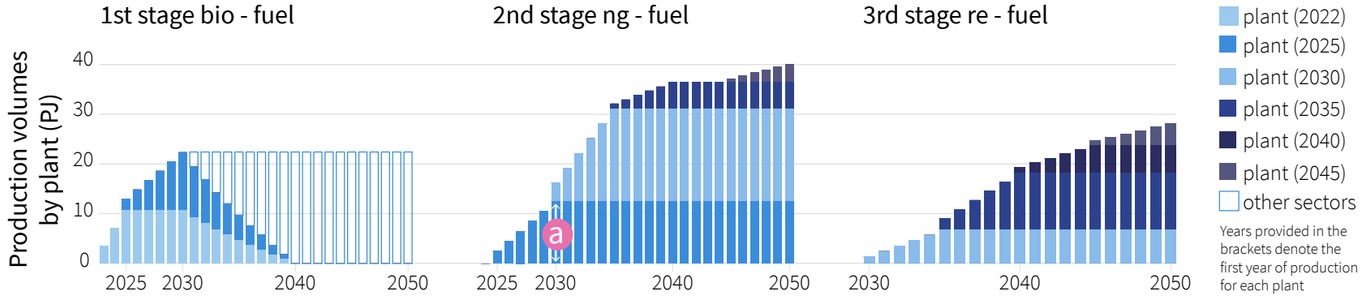


How does the production of the fuel need to scale to meet the required demand?

Two stages –ammonia transition



Three stages –methanol transition



a The first ng-Ammonia plant has a production volume ~2.5 times higher than the first ng-Methanol plant.

Deployment and scaling of the fuel supply infrastructure

The overall fleet fuel transition strategy is closely intertwined with the development of the fuel supply infrastructure. As zero-carbon vessels are built or retrofitted, the fuel demand mix changes. The fuel supply chain responds to this changing demand by building production and distribution infrastructure, beginning in key locations and then scaling that infrastructure as fuel demand grows over time. These charts illustrate the incremental growth in capacity as new plants are introduced and scaled up year by year.

The pace of deployment and pressure to scale

In the three-stage methanol transition, the construction of bio-Methanol supply infrastructure puts less pressure on the development of ng-Methanol infrastructure after 2030. In contrast, the ammonia and hydrogen transitions (two-stage approaches) begin building supply infrastructure five years after the methanol transition in the absence of an 'interim fuel' stage, but to a larger scale. Therefore, the success of the two-stage ammonia and hydrogen approaches depends on the ability to construct a much larger plant at the first attempt in order to keep pace with decarbonisation goals. This adds pressure to scale the infrastructure quickly, and to secure more investment, materials and construction capability in a shorter timeframe.

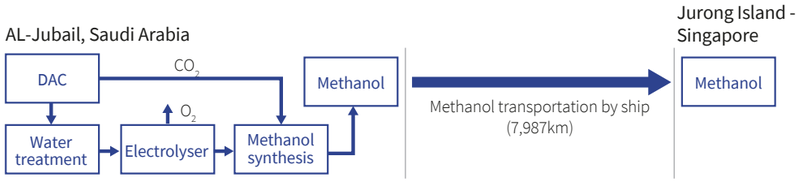
4.2 What are the potential fuel production routes?

Fuel production route and fuel price

This analysis assesses several fuel production routes [17], taking into account the type of fuel supply infrastructure, the sizing of the plants, and the pace of the development required to meet fuel demand. A production route includes the locations for the new plants and where and how feedstock, byproducts and fuels are transported.

The analysis of the fuel production costs is one way to estimate how fuel prices may change in the future. Fuel price is a key factor in driving fleet costs, and therefore also in the selection of the decarbonisation strategy.

Through a literature review of the existing information and data available to LR, this analysis considers 56 plausible fuel production routes for each fuel in each transition.



* see Appendix B for full details

Centralised and decentralised production

Each production route is a fuel production journey. There are multiple production route configurations, varying by both production process and geography. Key factors to consider include where the end product will be produced, the transportation method and route, and whether the feedstock energy source is transported prior to use in production.

For example, one production route may assume that hydrogen is produced and stored in a neighbour country and then transported to and within Singapore; we call this centralised production (C). Another production route may assume that instead of transporting hydrogen, natural gas is transported from a low-cost country before it is stored and transformed into hydrogen in Singapore; we call this decentralised production with import (DI). Finally, another production route may assume that the production is completely decentralised (D), with all production and storage facilities located at the point of use, e.g. re-Hydrogen in Singapore.

To ensure that upstream emissions are kept at a very low level, the use of CCS is assumed in production routes where facilities emit CO_2, e.g. SMR and natural gas liquefaction. The captured carbon is then assumed to be transported and stored permanently in nearby carbon storage basins.

The selected production routes are deemed to be representative examples of those likely to be used in practice, although other possibilities exist.

56 Total production routes

22 Methanol production routes

17 Ammonia production routes

17 Hydrogen production routes

8 Number of countries

19 Supply hubs

8 Carbon storage basins

4.3 What are the most likely production routes?

The levelised cost of marine fuel

We have assumed that the emergence and development of production routes will be driven largely by the anticipated total costs of potential routes, taking into account resources, production, storage transportation and carbon costs. To establish the most likely least cost production route, this analysis uses the levelised cost (LC).

The LC of a marine fuel is the fuel price at which an investor would break even after paying the required rates of return on capital, given the costs incurred over the lifetime of the fuel production route (assumed to be 30 years).

The LC is a straightforward metric for comparison of different production routes, although it does not account for all costs at a system level, e.g. the impact of a plant on the electricity system as a whole.

The LC was estimated for each production route according to the required deployment timing and sizing described previously.

The cost inputs in the LC calculation are broken down by expenditure type, such as costs of direct air capture, renewable electricity costs, transportation, etc. With this breakdown of LCs, we can reveal the key cost drivers for each production route.

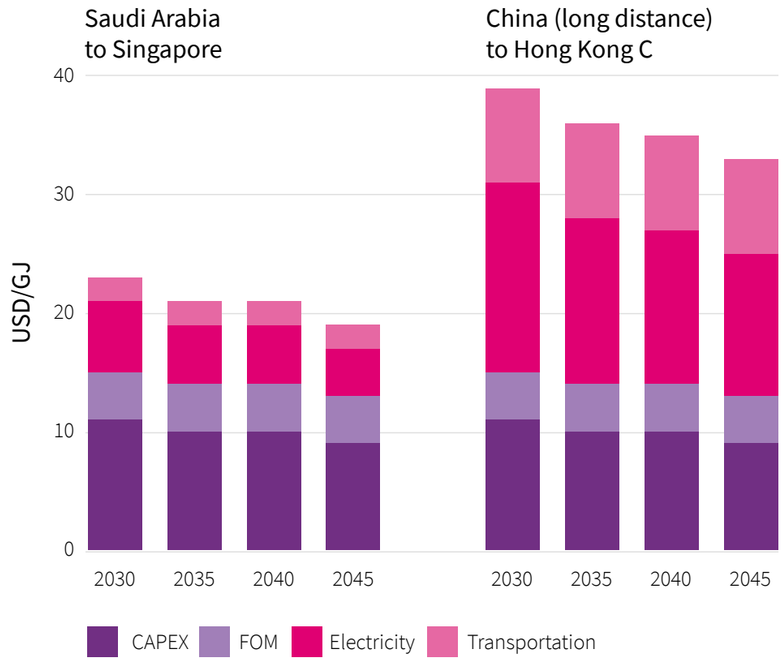
Example of LC breakdown

Facilities built at different times will have different LCs and therefore a different LC value. For example, each fuel production route for re-Ammonia has four different LCs, one for each time the production level scales up.

The breakdown of the LCs by cost category can bring additional insight, such as the potential impact of transportation costs, which depends on the distance travelled and the transportation modes used (ships, trucks, pipelines).

Carbon cost due to CO_2 emissions (such as natural gas) is not accounted for in the fuel supply analysis because a carbon price is applied to the net emissions on the fleet analysis. This avoids the potential double-counting of emissions.

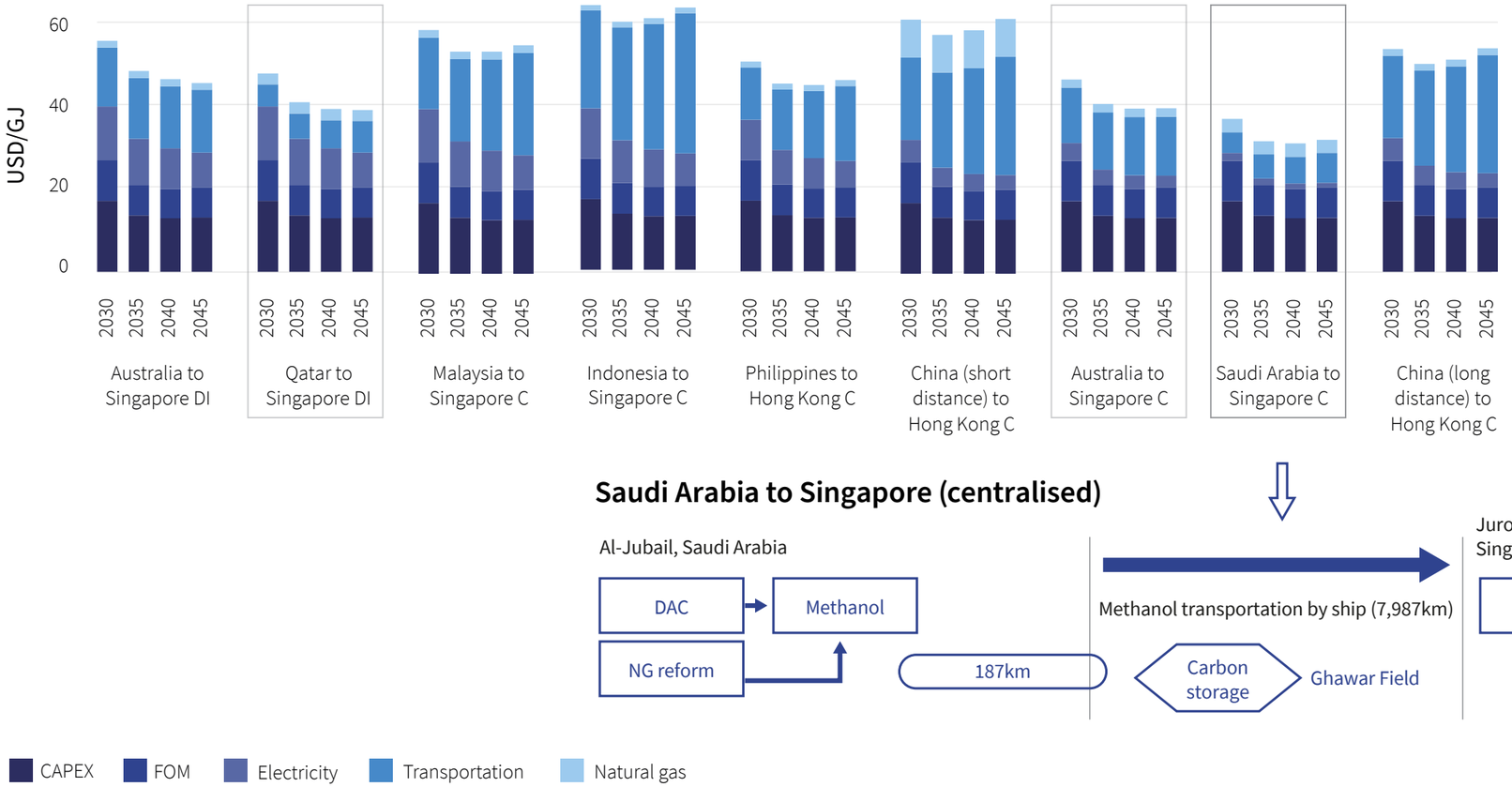
LC of re-Ammonia



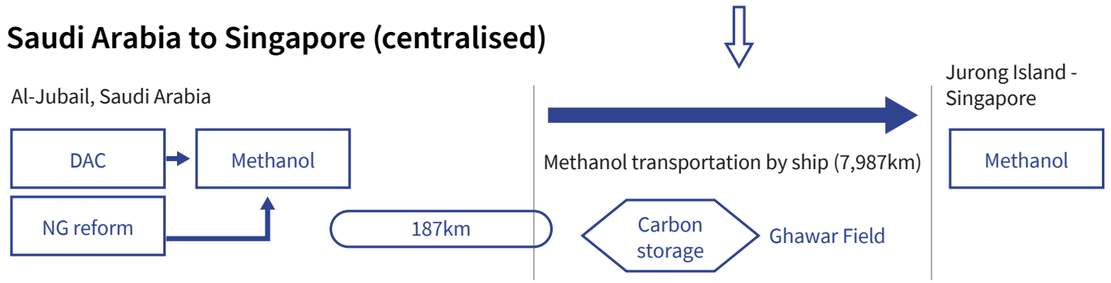
(a) FOM = fixed operating and maintenance costs
(b) See Appendix B for underlying fuel supply cost assumptions

The most likely production routes for ng-Methanol

Levelised cost breakdown for ng-Methanol[18]



Saudi Arabia to Singapore (centralised)



Cost of ng-Methanol production routes

For ng-Methanol, the production route with the lowest LC uses centralised production in Saudi Arabia and methanol transported to Singapore.

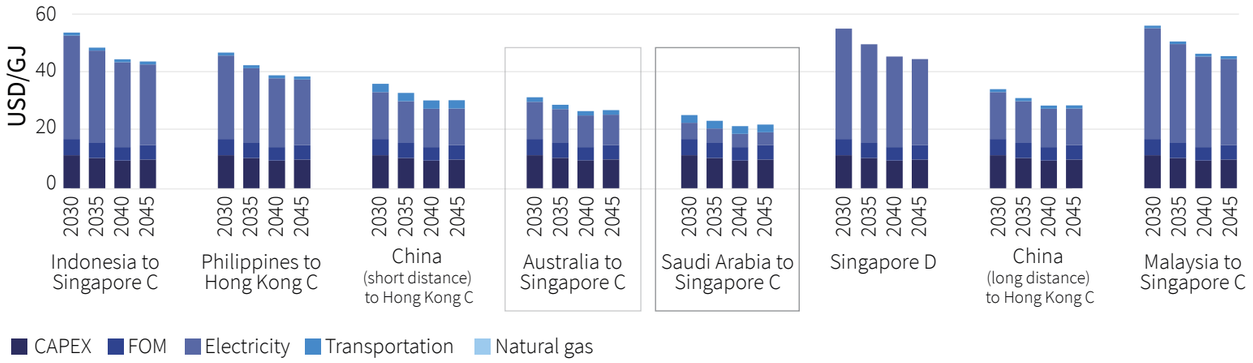
Due to the projected low cost of natural gas in Saudi Arabia, CAPEX on production facilities becomes the major contributor to the LC. The LC of the other production routes is mainly driven by the cost of natural gas.

Other likely competitive production routes include:

- decentralised production in Singapore using natural gas imported from Qatar that is used to make ng-Methanol in Singapore; and
- centralised production in Australia with ng-Methanol transported to Singapore.

The most likely production routes for re-Methanol and bio-Methanol

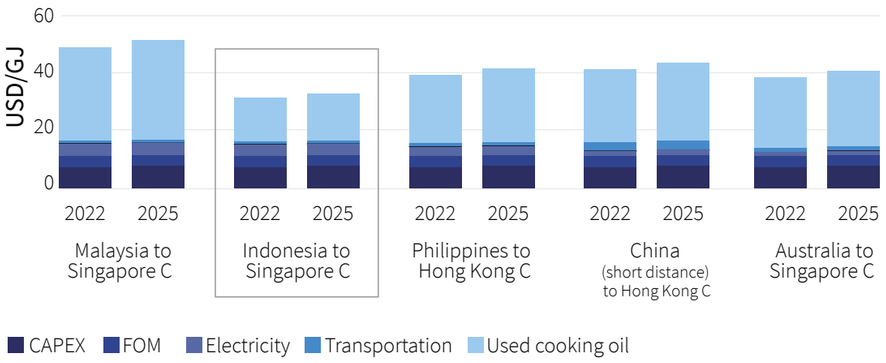
Cost of re-Methanol production routes



The lowest LC for re-Methanol is also the production route using centralised production in Saudi Arabia given the low projected cost of renewable electricity (from 22.8 USD/MWh to 8.5 USD/MWh).

Another likely production route is centralised production in Australia with re-Methanol transported to Singapore.

Cost of bio-Methanol production routes



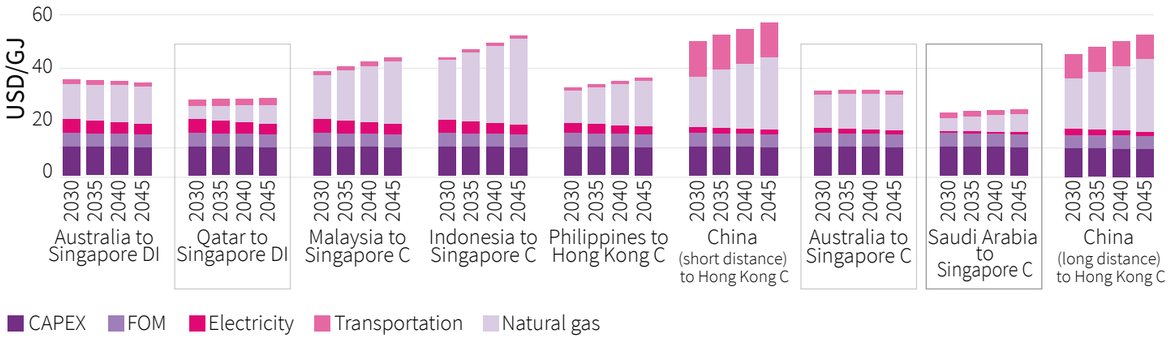
The LC of bio-Methanol production routes is mainly driven by the feedstock cost, in this case used cooking oil (UCO).

The production route from Indonesia to Singapore has the lowest LC, driven by the relatively low feedstock cost of UCO in Indonesia.

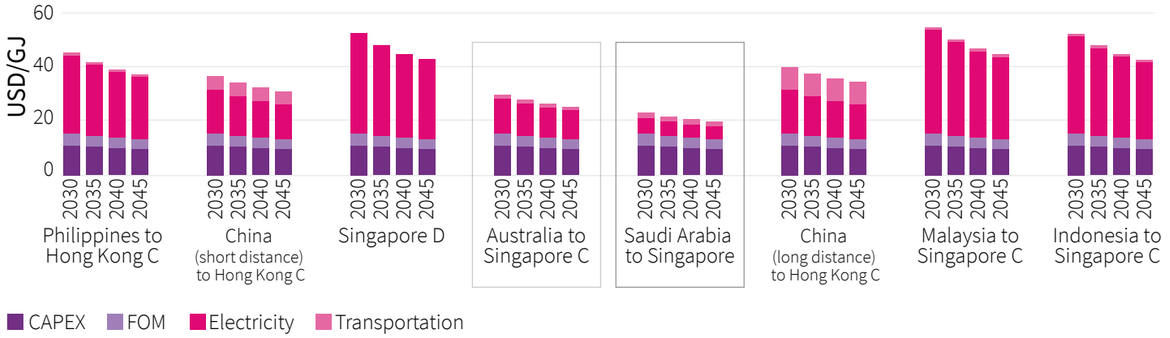
Bio waste cost expected to increase from 11.8 USD/GJ to 28.9 USD/GJ in 2050

The most likely production routes for ammonia

Cost of ng-Ammonia production routes



Cost of re-Ammonia production routes



The ng-Ammonia production routes have a similar pattern to those of ng-Methanol.

The lowest LC production route for ng-Ammonia is centralised production in Saudi Arabia with the final fuel transported to Singapore.

Other likely competitive production routes include:

- decentralised production in Singapore using natural gas imported from Qatar; and
- centralised production in Australia with the resulting ng-Ammonia transported to Singapore.

As for re-Methanol, the lowest LC for re-Ammonia is centralised production in Saudi Arabia, given the low projected cost of renewable electricity. Another likely production route is centralised production in Australia with fuel transported to Singapore.

Co-location opportunity for ng-fuels and re-fuels

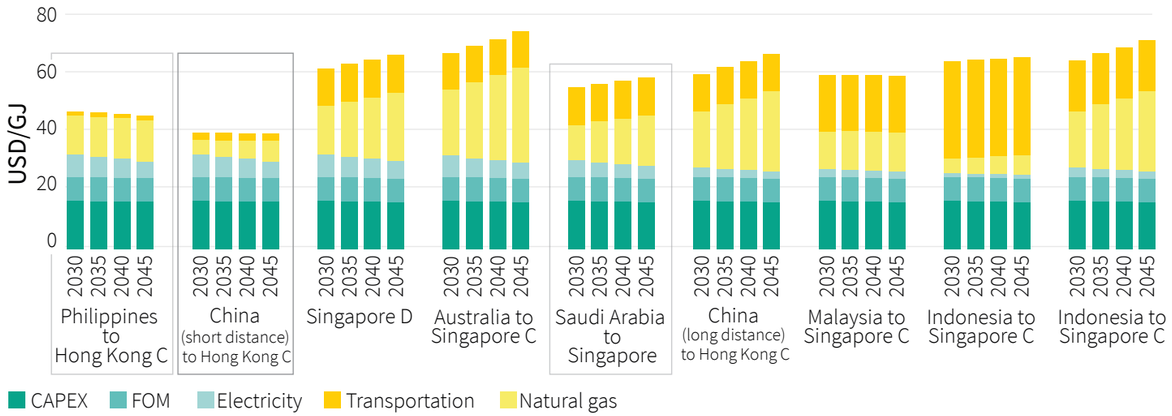
The least cost production routes for ng-Methanol, ng-Ammonia, re-Methanol and re-Ammonia all share the same production location, Saudi Arabia. This could create an opportunity to co-locate production, potentially leading to further synergies and cost reductions.

The most likely production routes for hydrogen

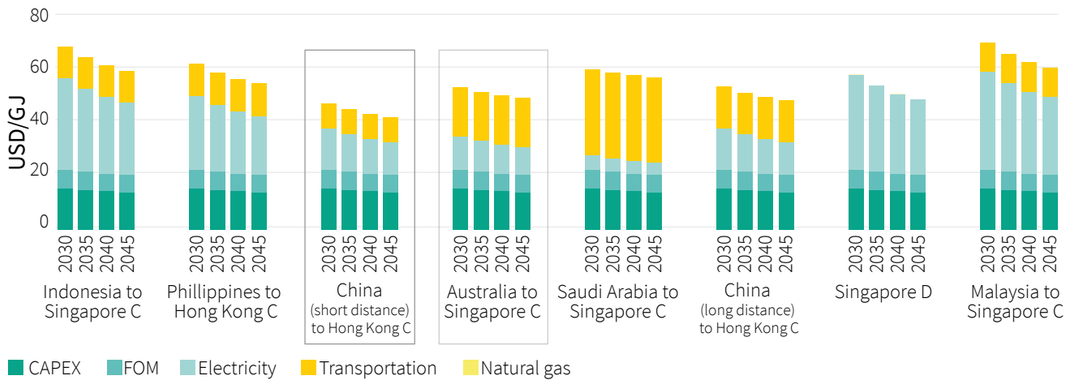
The impact of transportation cost

The ranking of the hydrogen production routes is different to ammonia and methanol due to transportation costs having a higher contribution to the LC.

Cost of ng-Hydrogen production routes



Cost of re-Hydrogen production routes



For ng-Hydrogen, decentralised production in Singapore using imported natural gas from Qatar is the lowest LC option. This implies that the reforming of natural gas to hydrogen (with CCS) would need to be located in Singapore. As a result of potential space limitations in Singapore, this production route may have scalability limits.

The least cost production routes with centralised production are from the Philippines to Hong Kong and Australia to Singapore.

For a low LC of re-Hydrogen, both low electricity costs and low transportation costs are required.

The production route with the lowest LC is centralised production in China with transport to Hong Kong. Although this route does not have the lowest electricity cost, the transportation costs are lower than for other production routes. Another likely production route is centralised production in Australia with fuel transported to Singapore.

4.4 What are the projected fuel costs?

Fuel cost projections

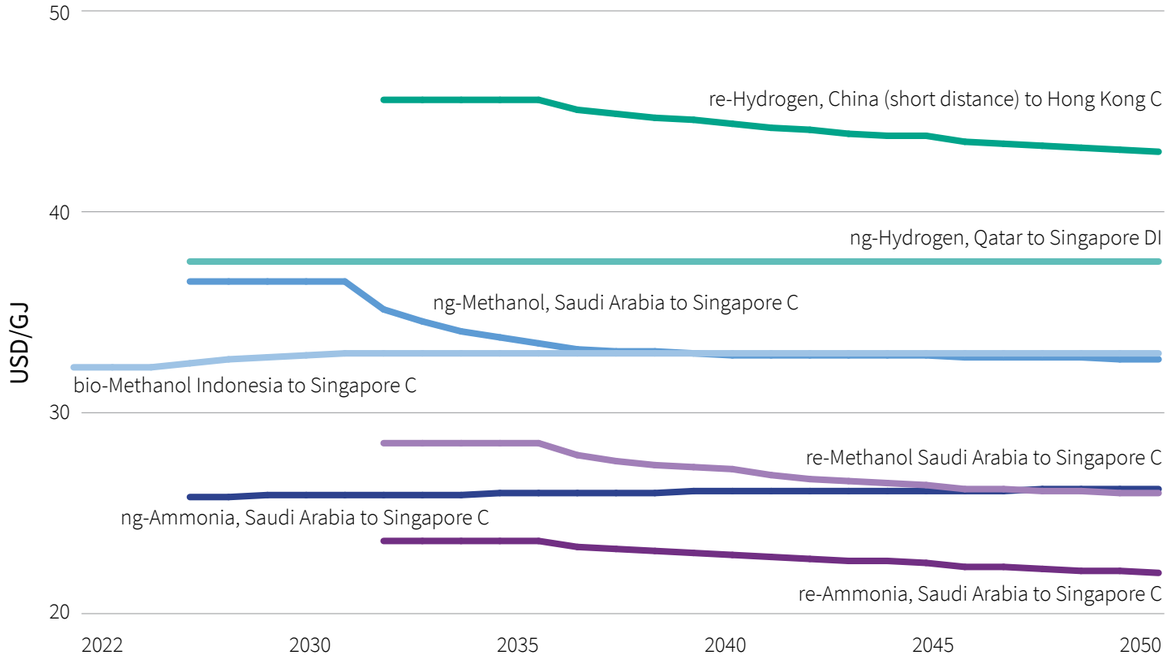
Local energy sources (renewable electricity, natural gas, UCO) are the key cost driver and the source of the main uncertainty. Nevertheless, we observe the following results.

The LC of bio-Methanol is fairly constant from 31 to 32 USD/GJ, as it is derived from production plants going live in 2022 and 2025. These are production costs; therefore, they do not take into account any supply-demand dynamics, and in the case of bio-Methanol, this could include demand-side competition emerging from other sectors that can tighten this market and risk higher prices over time.

The LC of ng-Methanol decreases from 36 to 32 USD/GJ. The LC of ng-Ammonia decreases from 28 to 25.5 USD/GJ, whereas ng-liquid hydrogen remains constant at just below 37 USD/GJ.

Fuels derived from renewable electricity have a lower LC than ng-fuels because the least cost production routes involve locations where the cost of renewable electricity is very low. Re-Methanol varies from 27 to 25 USD/GJ, re-Ammonia from 23 to 21 USD/GJ, and re-liquid hydrogen from 45 to 42 USD/GJ.

The cost effectiveness of re-fuels also depends on the assumption used to deal with the intermittent supply of renewable electricity. In contrast with ng-fuels which would essentially be steady state, re-fuels need to account for additional costs to deal with such intermittent supply. This analysis assumes a hypothetical hydrogen buffer storage for re-fuels, however, this is an area of uncertainty which would require more detailed analysis



Method highlights

The LC is estimated for each production route according to the development of production plants over time. For example, the LC was estimated for the ng-Methanol plant in 2025, and again in 2030 as capacity is increased, and so on.

Fuel cost projections are a function of these LCs. The fuel cost production is a weighted average of the LCs of all plants over time per unit of fuel produced. The fuel cost projection is specific to the selected fuel production routes and their development (i.e. the production routes yielding the lowest LCs). Since this fuel cost is specific to the 'most likely' production routes, they are not meant to represent a global average.

4.5 What are the key cost drivers for each fuel supply transition?



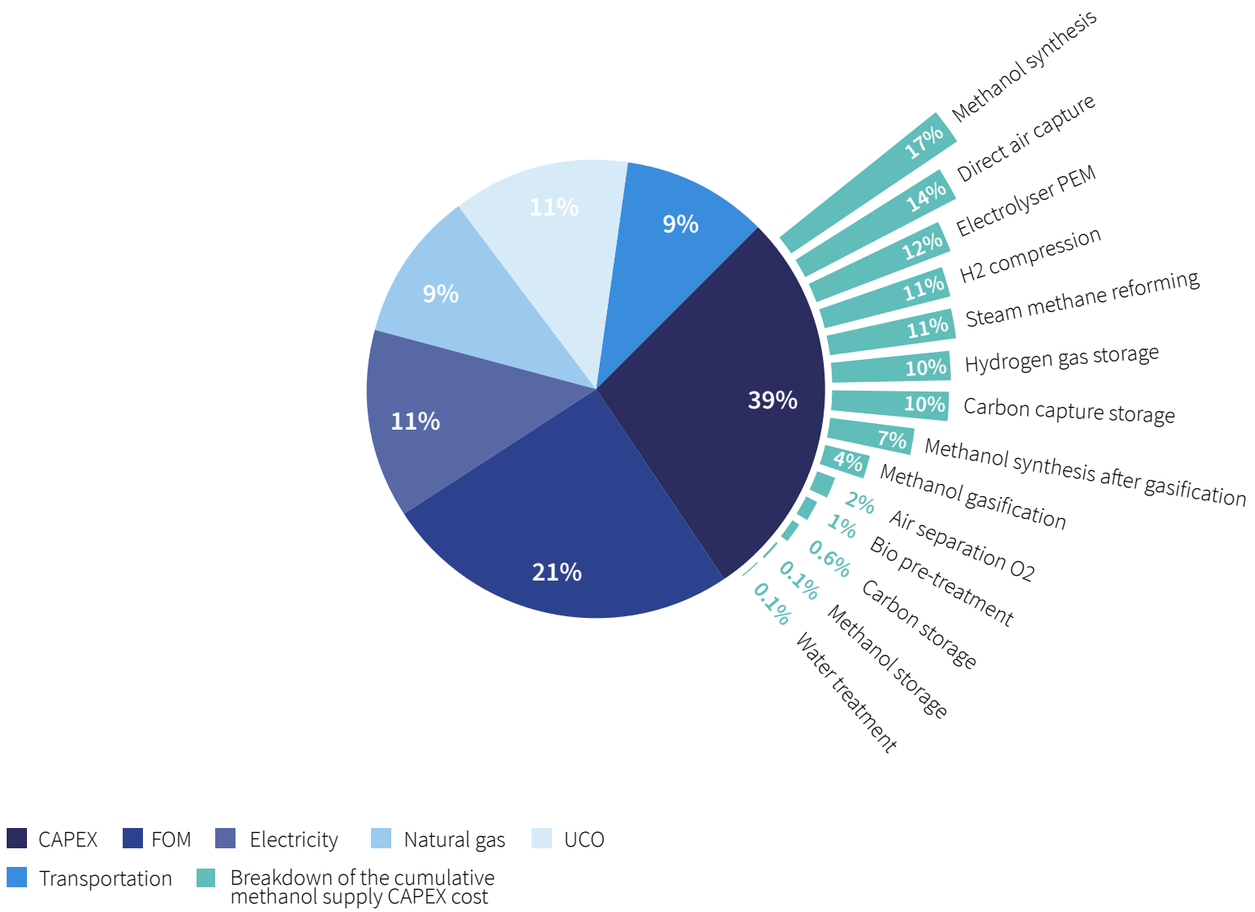
Closing the gap with policy and ‘targeted’ technological development

The fleet analysis has highlighted that the voyage costs associated with zero-carbon fuels are the major challenge for the economic viability of such fuels. These fuels are likely to be more expensive than the current marine fuels even with strong policy intervention.

The use of energy efficiency technologies on board ships is one way to reduce the voyage costs; however, it is crucial to understand the key cost drivers for the identified least cost fuel production routes to further close the gap with current marine fuels. Several factors can potentially reduce the gap in the short and long term. The analysis of the cost drivers of the identified production routes can highlight where effort should go into technology scale-up and development to reduce the overall fuel production costs. The cost drivers depend on the characteristics of the specific fuel production route.

Fuel supply total cost for the methanol transition

Breakdown of the cumulative methanol supply total cost (up to 2050) based on the identified three least cost production routes



Methanol supply cost

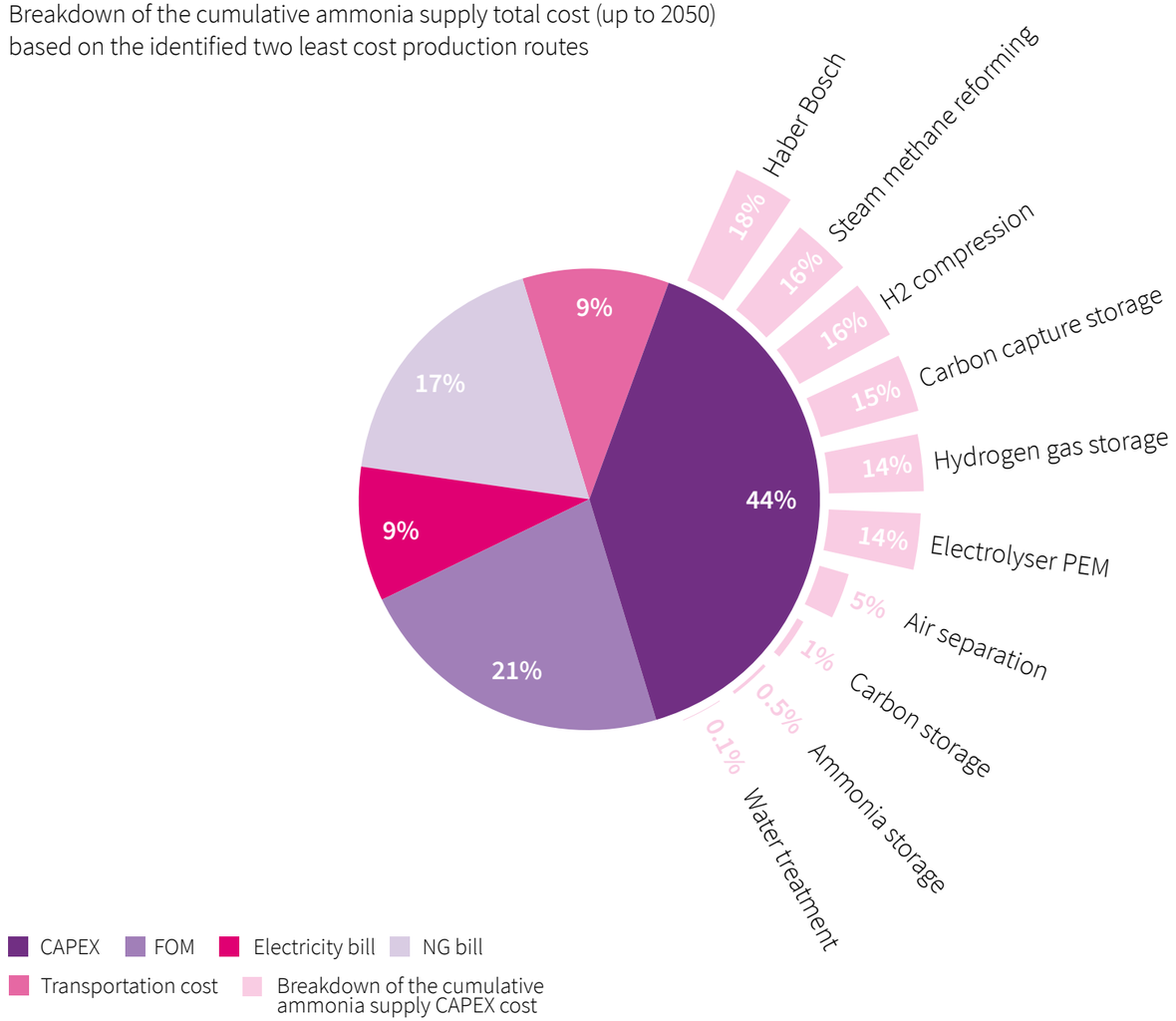
The cumulative fuel supply total transition costs (up to 2050) are estimated to be 41.4 bn USD. The methanol transition relies on ng-Methanol and then on re-Methanol in the medium to long term, and these fuels would be produced in locations where the cost of the energy sources (natural gas and renewable electricity) is expected to be very low (such as Saudi Arabia). In addition to keeping track of the expected costs of the energy sources, further fuel supply cost reduction opportunities could come from focusing on reducing the CAPEX of key technologies and processes.

The cumulative CAPEX represents about 39% of the total cumulative cost. Looking at the breakdown of cumulative CAPEX, we estimate that methanol synthesis, DAC, electrolyser and SMR equipment would represent over 54% of the cumulative fuel supply CAPEX of this transition.

Production process	unit	2020	2030	2040	2050
Electrolyser	USD/GJ/yr	37.48	30.62	25.02	20.67
Methanol synthesis	USD/GJ/yr	24.80	21.31	18.52	15.74
Direct air capture	USD/teCO_2/yr	1273.35	503.11	295.62	186.94
Carbon capture storage	USD/teCO_2/yr	207.81	199.91	192.30	184.99

Fuel supply total cost for the ammonia transition

Breakdown of the cumulative ammonia supply total cost (up to 2050) based on the identified two least cost production routes



Ammonia supply cost

The cumulative fuel supply total transition costs (up to 2050) are estimated to be 26.9 bn USD. The ammonia transition relies on ng-Ammonia and re-Ammonia. As for the methanol transition, ammonia fuels are produced in locations with a very low expected cost of the energy sources (natural gas and renewable electricity). By reducing the CAPEX of key technologies and processes, we could further bring down the ammonia supply cost and therefore its potential future price.

For ammonia, Haber-Bosch and SMR represent about 36% of the cumulative CAPEX, followed by hydrogen compression and storage and CCS.

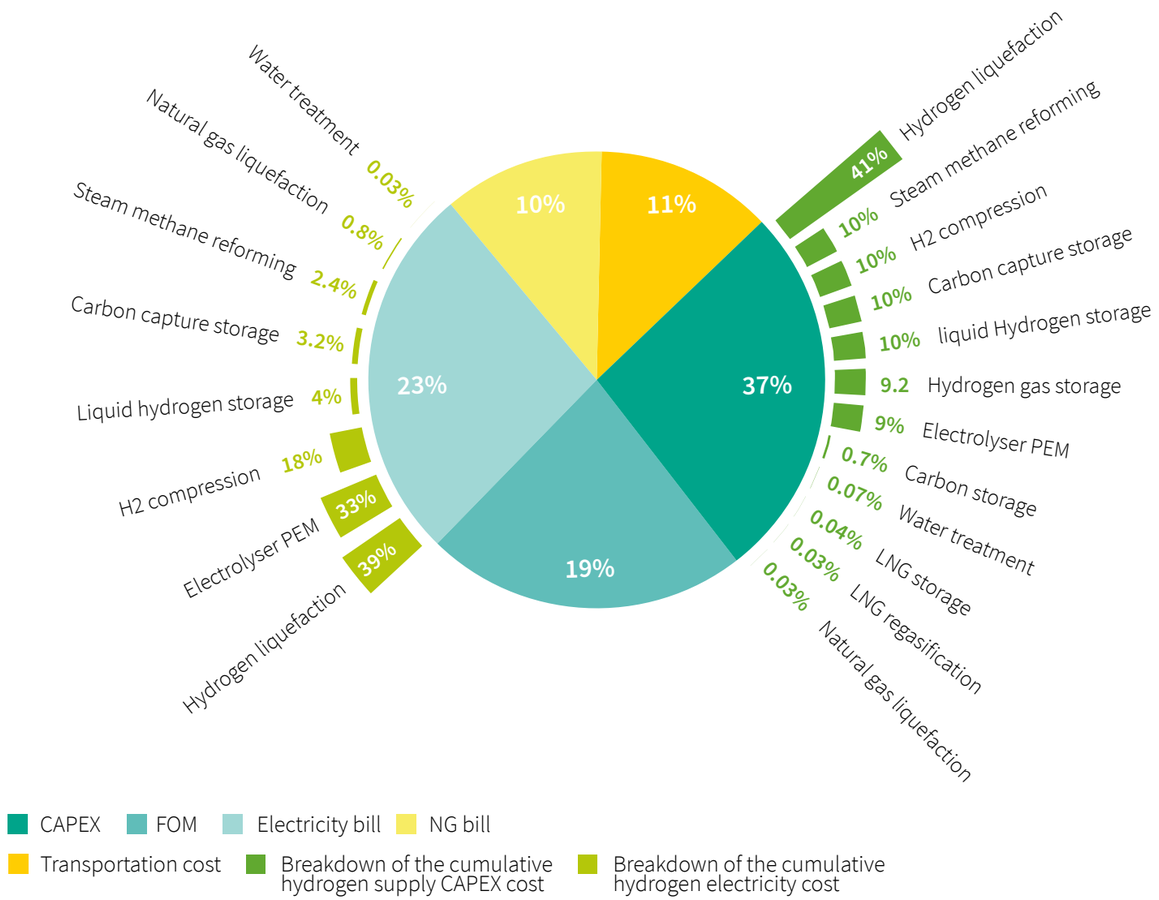
The technologies and processes associated with ng-Ammonia have a major impact because ng-Ammonia represents about 75% of the cumulative overall demand of ammonia.

As per the analysis of the FTC, there are several costs that fall outside the remit of this analysis; however, they are considered less material. One exception could be the potential safety costs for storing and bunkering ammonia and hydrogen at ports.

Production process	unit	2020	2030	2040	2050
Electrolyser	USD/GJ/yr	37.48	30.62	25.02	20.67
Hydrogen gas storage	USD/GJ	3909	3800	3581	3472
Haber Bosch	USD/GJ/yr	14.44	14.44	14.44	14.44
Carbon capture storage	USD/teCO_2/yr	207.81	199.91	192.30	184.99

Fuel supply total cost for the hydrogen transition

Breakdown of the cumulative hydrogen supply total cost (up to 2050) based on the identified two least cost production routes



Hydrogen supply cost

The cumulative fuel supply total transition costs (up to 2050) are estimated to be 43.7 bn USD.

In the hydrogen transition, in addition to CAPEX, the cost of renewable electricity is one of the main drivers, accounting for 23% of the cumulative fuel supply cost.

The least cost production route is based on sourcing both relatively low electricity costs (but not the lowest) and relatively low transportation costs. The breakdown of the electricity costs suggests that hydrogen liquefaction, together with the electrolyser and hydrogen compression and storage, could represent about 94% of the cumulative electricity costs. Improving the efficiency of these processes would bring the hydrogen supply cost down further.

Reducing CAPEX could reduce the future price of hydrogen. Cumulative CAPEX represents about 37% of the total cumulative cost. Breaking down CAPEX, liquefaction of hydrogen is the process that by far contributes the most, namely 41% of cumulative CAPEX.

Production process	unit	2020	2030	2040	2050
Electrolyser	USD/GJ/yr	37.48	30.62	25.02	20.67
Hydrogen gas storage	USD/GJ	3909	3800	3581	3472
Hydrogen liquefaction	USD/GJ/yr	44.87	44.87	44.87	44.87
Carbon capture storage	USD/teCO_2/yr	207.81	199.91	192.30	184.99



Conclusions

The combined analysis of the evolution of a fleet and the required fuel supply for different plausible transitions allows us to switch the focus away from debating the fuel of choice for the entire shipping industry, and instead delve deeper into understanding the fuel transition of choice for a specific fleet.

Comparing fuel versus fuel limits the debate to the characteristics of individual fuels and by doing so, the industry remains hugely uncertain around which fuel to invest in to achieve decarbonisation. Instead, an analysis focused on transitions for both the fleet and the fuel supply has the potential to highlight the costs involved, but also a series of considerations and steps needed to reach the end decarbonisation goal and to flag any risks and opportunities along the way. Different fuels may also be required at different points along a specific transition, with multiple fuels working in tandem to achieve the end goal of decarbonisation. An understanding across the supply chain of how these transitions could play out will generate the needed confidence for all stakeholders involved to commit to a long-term decarbonisation plan.

Key findings from containership feeders case study

Coordinate efforts between the fleet and the fuel supply side

This analysis has focused on a specific fleet and it has given a concrete example of how the fleet energy transition can take place in conjunction with the development of the required fuel supply. To unlock decarbonisation, it is important to understand what the cost drivers are and how material they are across the entire supply chain so that a system solution that works for the specific ecosystem can be identified.

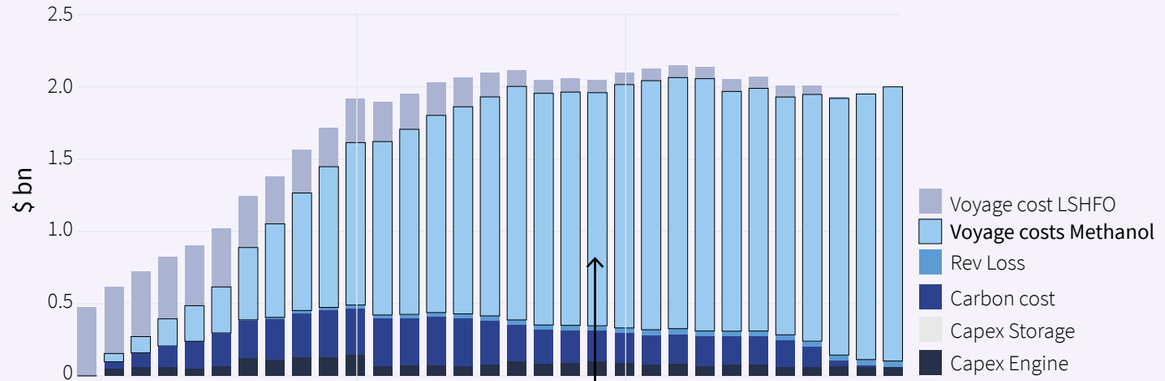
Focusing on a specific fleet allows us to analyse how the Fleet Total Cost (FTC) may evolve. This example (upper chart) for the methanol transition shows how the voyage cost associated with the use of net-zero methanol gradually increases over time. This highlights the importance of improving the technical and operational efficiency of zero-emissions vessels; however, it also highlights the impact of fuel supply cost. As the transitions consider different fuel production routes, this analysis allows us to identify what to focus on in the fuel supply to reduce the overall cost of the transition.

Ensuring that the costs of the chosen energy sources are in line with the forecast (e.g. decreasing trend of renewable electricity costs) is the first step. However, this analysis has identified that where energy sources are relatively low cost, CAPEX becomes one of the major contributors to the total cost of fuel supply (lower chart). Therefore, targeting effort on reducing both CAPEX and OPEX of key technologies and processes can significantly reduce the fuel production costs, fleet voyage costs, and, ultimately, the cost premium for the customers.

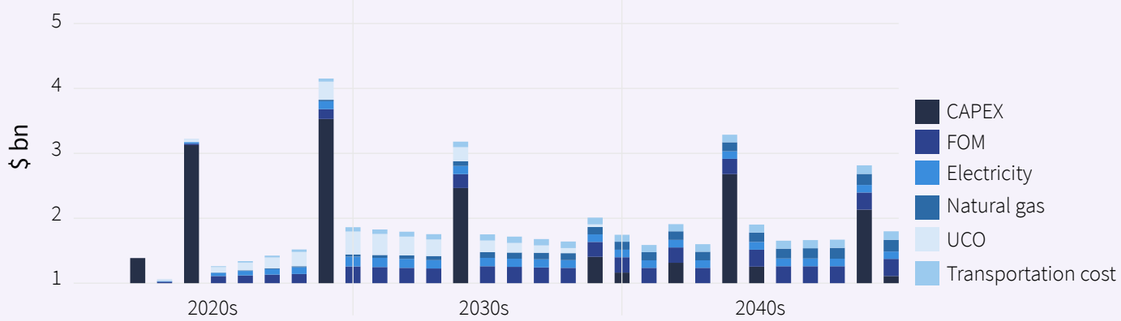
The analysis of the costs involved in both the fleet and fuel supply side gives the order of magnitude of the investment required over time. Understanding how these costs may evolve in the long term for all transitions provides further insights to build confidence and therefore reach coordinated commitment across the stakeholders involved. This analysis can form the basis of a more detailed business case where the uncertainty associated with each transition can be further analysed to identify the most resilient energy transition.

Example for the Methanol transition[19]

Fleet total cost breakdown



Fuel supply total cost breakdown



Different fuel supply options may yield similar emission reductions

Overall, the three transitions analysed have similar emissions reduction trajectories (approximately 79 million tons of net CO2 emissions up to 2050). The main difference is that the use of bio-Methanol allows for earlier emissions reduction in the methanol transition (approximately 1.7 million tons of net CO2 emissions saving up to 2030 compared to the ammonia and hydrogen transitions).

Each transition requires a complete supporting fuel infrastructure to be in place. The types and number of fuels in the fuel mix dictates how the fuel supply will need to scale. Both the ammonia and hydrogen transitions would use a two-stage approach that begins with the development of ng-fuels infrastructure and then moves to the development of re-fuels infrastructure.

In contrast, the methanol transition uses a three-stage approach: bio-Methanol followed by ng-Methanol followed by re-Methanol. The three-stage approach has the benefit of allowing the fleet to begin the transition earlier via a more gradual transition; however, this is more costly and complex. In the three-stage methanol transition, the investment case is less clear, as investors must find a balance between confidence in the longevity of a transition and the need to decarbonise earlier.

Balance the benefits of early results with long-term planning

A trade-off exists between efforts to start to decarbonise the fleet earlier along with a smoother transition versus the long-term planning approach that attempts to find the solution with lowest overall cost. This balance must be found while providing a growing supply of a fuel through different feedstock routes without major price fluctuations.

In the case of the three-stage methanol transition, the prompt availability of sustainable bio-Methanol makes up most of the fuel produced in the first decade. This enables an immediate drop in the fleet's emissions while allowing ng-Methanol and re-Methanol to absorb the entire demand of the fleet more gradually as the transition continues.

Although the first decade of the methanol transition requires a relatively high investment in the bio-Methanol plants, for a much smaller volume of fuel produced compared to later decades, this investment is evenly shared between OPEX and CAPEX. Later decades see similar levels of overall investment, albeit weighted more towards OPEX in order to focus on procuring the feedstock rather than pressure to build the plants to keep up with growing demand.

This limits the investment shock down the line, in both the fuel supply infrastructure and also for the fleet where a sudden drive to build or retrofit vessels and the associated potential overload on shipyards can be avoided.

The benefits of early decarbonisation, however, are balanced by the exposure in the short term to high OPEX costs – specifically through the impact of the expensive and constrained bio-waste feedstock needed to feed the sustainable bio-Methanol production routes.

In contrast, the two-stage ammonia and hydrogen transitions require the construction of a larger plant in the first decade, with more pressure to scale quickly. Delaying investments to later in the transition like this may result in competition for energy sources that may have a stronger market elsewhere, e.g. hydrogen for heating or renewable electricity for the power sector. The benefit, however, for the ammonia transition in particular is that should risks be successfully avoided, this would likely be the lowest cost transition overall.

Different transition strategies unlock specific supply investments

A given fuel transition (e.g. ammonia, methanol or hydrogen), is likely to determine the fuel production routes with the lowest cost. For re-Methanol and re-Ammonia, the least cost production route will originate in locations with very low costs of renewable electricity, whereas the lowest cost production route for re-Hydrogen requires both low electricity costs and low transportation costs.

After analysing several fuel production routes, we have concluded that for each fuel, the likely least cost production route is mainly driven by two factors: 1) the cost of local energy sources, and 2) transportation costs.

Middle East countries and Australia are among the locations with good potential for low cost production of methanol and ammonia, while for nghydrogen, it is important to reduce the cost of hydrogen transportation in one of two ways: either by locating production close to consumption (e.g. producing in China or the Philippines) or by importing the energy feedstock and converting to fuel close to consumption (e.g. producing in Qatar or Australia).

Identify co-location fuel supply synergies to cut costs

The development of a fuel supply infrastructure, including the production plant, pipelines, distribution networks, expertise and workforce, represents a large part of the overall energy transition commitment. This study found that the least cost production routes for ng-methanol, ng-Methanol, ng-Ammonia, re-Methanol share the same location (i.e. Saudi Arabia or Australia). This creates an opportunity to co-locate production, potentially driving further synergies and cost reductions. Therefore, in locations where both natural gas and renewable electricity are forecast to be competitive, there may be significant economic advantages realised in co-location.

Co-location can also contribute to the longevity and resilience of the investment in a particular plant, absorbing a large amount of the risk of potential failure should the feedstock fuel become uncompetitive. This is a known risk, as the fossil fuel industry has experienced cyclic downturns and periods of price volatility. Reducing the reliance on any single feedstock could also lower the investment risk of the fleet transition, where a narrowed range of fuel price projections would increase the confidence level behind fleet investment decisions.

ng-fuels may conceal hidden risks

For the ng-fuels production routes, the natural gas feedstock price drives the overall cost. This may conceal hidden risks because the expected trend is that the price of natural gas may increase over time, making ng-fuels less attractive. In addition, ng-fuels may still produce residual carbon emissions and methane leakage inherent in the production process, risking the achievement of net zero.

On the upside, ng-fuels could alleviate pressure on creating supply infrastructure for zero-carbon fuels produced from renewable electricity as these would otherwise need to develop at scale more quickly. Conversely, this could unduly lock in shipowners to a fuel that still includes more residual carbon emissions and methane leakage and an increasing reliance on a feedstock which is expected to increase in price. This is slightly more relevant for the ammonia and hydrogen transitions rather than the methanol transition because the ammonia and hydrogen transitions use more ng-fuels than the methanol transition.

Additional work to compare transitions without ng-fuels (e.g. leapfrogging directly to re-fuels) could enhance our understanding of these risks in terms of both GHG emissions and costs.





Voyage costs dominate fleet costs

Fuel total costs (FTC) up to 2050 are lowest for the ammonia transition ($44.5 billion), followed by methanol ($51.5 bn) and then hydrogen ($69.4 bn). This is equivalent to 5%-64% more than the fossil fuel baseline ($42.3 bn including carbon cost). Voyage costs dominate the fleet's total cost, representing between 71%-82% of the cumulative FTC depending on transitions – the cost of zero-carbon fuels outweighs all other main cost components.

Among the transitions, the ammonia transition has the lowest total voyage cost driven by its lower estimated fuel price. The dominance of the voyage costs means that improving vessel efficiency and voyage optimisation becomes more and more important to reduce the cost of decarbonisation.

Both retrofits and newbuilds needed to meet 1.5C trajectory

To meet a net-zero target by 2050 and achieve a smooth transition that both fuel supply and shipbuilding capacity can meet, the analysed fleet cannot fully decarbonise through natural scrappage and renewal strategies alone. Even if all age-driven renewals adopt zero-carbon fuels as they become available, considerable fossil fuels-related emissions would remain in 2050.

Retrofitting is therefore necessary to cut emissions in line with the target. Approximately 30% of the transition is achieved through retrofitting. For a methanol transition, this is spread out over a slightly longer period, whereas for ammonia and hydrogen, it must be met over a shorter time frame. This highlights that vessels built in the 2020s based on conventional fuel may need to be designed for early retirement or to be retrofit ready.

The required fleet turnover and the fleet age profile put constraints on the candidate vessels for retrofitting. Examination of the age distribution of candidate vessels for retrofitting reveals that some vessels could be at risk of early scrappage in cases where retrofitting happens late in the vessel's life.

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(13) 'Fleet Fuel Transition' definition = the way a fleet executes the energy transition through a series of steps (changing from one fuel to another) that could involve several fuels

(14) https://www.iea.org/reports/carbon-capture-utilisation-and-storage-the-opportunity-in-southeast-asia t

(15) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816018/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs.pdf

(16) (a) The cumulative FTC includes a carbon price increasing linearly over the period, starting at $0/mt today, increasing to $101/mt by 2030, $194/mt by 2040 and $288/mt in 2050 (b) "Fossil Fuel" Transition: this is a comparative transition assuming no decarbonisation efforts were made, for use as a cost benchmark against each fleet fuel transition. It assumes there are no retrofits, and all newbuilds are LSHFO ships

(17) Fuel production route = How a fuel is produced, where, and how it is distributed

(18) (a) Natural gas in Saudi Arabia and Qatar is priced at $1.2 per million BTU, and increases to $4.7/million BTU by 2050. Saudi Arabia is seen to have the biggest carbon storage potential in the Middle East, with the CCUS storage assumed to be located in Ghawar Field for these production routes

(b) Natural gas prices in Australia start at $6.72 per million BTU, which increases to $9.14/million BTU by 2050. Northern Carnarvon has been identified as a potential basin for carbon storage, selected due to proximity to existing LNG plants in NW shelf

(19) Voyage costs are a function of fuel production costs. Over 2025-2030, 71% of the total fleet cost is driven by voyage costs, and this share ramps up to 95% of total fleet costs over 2045-2050

(20) Notes: DAC = direct air capture; NG reform = natural gas steam reformer; NG liquef = natural gas liquefaction plant; LNG regas = LNG regasification unit. Hydrogen and nitrogen compression processes included in electrolyser, NG reforming and air separation processes

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A review of progress leading to Carbon-Free shipping.

Dr Mohan Anantharaman, Australian Maritime College (UTAS);
M.Anantharaman@utas.edu.au

Dr Rabiul Islam, Australian Maritime College (UTAS); rabiul.islam@utas.edu.au

Prof. Faisal Khan, Memorial University, Canada; fikhan@mun.ca

Dr Vikram Garaniya, Australian Maritime College (UTAS); v.garaniya@utas.edu.au

ABSTRACT

Exhaust emissions from ships have been a burning issue for the maritime world. The International Maritime Organisation (IMO) has always been proactive in dealing with this matter. IMO works with many maritime community stakeholders, including Flag state, Port state, Classification societies, shipbuilders, ship owners, and engine manufacturers, to achieve an amicable solution to combat such major issues in the best interest of the maritime world. IMO's top priority at present is to reduce the GreenHouse gas (GHG) emissions from international shipping. The target is to reduce GHG emissions by 50% in 2050 compared to the emissions figure of 2008. This paper aims to review the different strategies employed by diverse stakeholders of the maritime industry to achieve this ambitious GHG emissions reduction target, weigh its pros and cons, and provide recommendations to enhance the protection of the maritime environment.

Key words: Greenhouse gas (GHG), Emissions, Maritime, Shipping.

1. INTRODUCTION

Exhaust gas emissions from ships and their abatement is a dynamic topic confronted by the maritime industry. The International Maritime Organisation (IMO) [1], is the United Nations specialised agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships [2, 3]. The Marine Environment Protection Committee (MEPC) addresses the environmental issues under IMO's remit [4].IMO has always been proactive in dealing with this matter. In 1997, a new annex was added to the International Convention for the Prevention of Pollution from Ships (MARPOL). The regulations for the Prevention of Air Pollution from Ships (Annex VI) seek to minimise airborne emissions from ships viz., oxides of sulphur (SO_x), oxides of nitrogen ($NO_{x)}$, Ozone-depleting substances (ODS), Volatile Organic Compounds (VOC) and shipboard incineration as they contribute to local and global air pollution and environmental problems. Annex VI entered into force on 19 May 2005, and a revised Annex VI with significantly tightened emissions limits was adopted in October 2008, which entered into force on 1 July 2010. To restrict emissions of NO_x from ships engines, IMO adopted the NO_x technical code in 1997 [5]. The revised NO_x technical code 2008 is covered in Regulation 13 of the MARPOL, entered into force on 1 July 2010. Emissions from SO_x and particulate matter (PM) are dealt with in Regulation 14 of MARPOL, which limits the sulphur content in the fuel oil to a maximum of 0.1% in the Emission Control Area (ECA) and a maximum of 0.5% outside ECA [6].

International attention to global warming was first drawn by scientists as early as the 1960s and '70s. When IMO amended MARPOL in 1997, it also adopted resolution 8 on Carbon dioxide (CO_2) emissions from ships[7]. MEPC was invited to study feasible strategies to reduce CO_2 emissions. The Kyoto Protocol adopted in Kyoto, Japan, 1997contains provision for reducing Green House Gas (GHG) emissions from ships [8]. Of all GHG emissions, CO2 is the most significant because of its abundance, atmospheric lifetime, and associated warning liability that changes the amount of heat energy trapped within the atmosphere [9].

Interestingly no reference to IMO is made in the 2015 Paris Agreement on Climate Change or the decisions to implement the agreement, including the pre-2020 ambition [10] of IMO GHG studies in 2000. Subsequent studies were conducted in 2009 and 2014. The final study in 2014 concluded that the international shipping emissions in 2012 could be 796 million tonnes, which is approximately 2.2% of the total anthropogenic CO_2emissions. The initial reaction for the first time a reduction in GHG emissions from international shipping, which it says should peak as soon as possible and to reduce the total amount of GHG emissions by at least 50% by 2050 compared to 2008, while at the same time pursuing efforts towards phasing them out entirely [1]. IMO was a participant at the recently held conference at Glasgow on climate change (COP26) in November 2021. According to Climate Action Tracker (CAT), the shipping industry's 2030 and 2050 commitments are critically insufficient and highly insufficient, respectively [11]. Further, CAT observes that IMO continues to move at a snail's pace, failing to adopt meaningful measures to cut international shipping emissions at recent meetings. Hence it is necessary that IMO need to vastly exceed its target to get itself on a Paris compatible pathway.

2 LITERATURE REVIEW

Ships transport more than 80% of world trade volume and about 70% of trade value[12]. A thorough literature review was conducted to investigate relevant research done on the topic of GHG emissions from ships. Also, it was considered prudent and opportune to learn from strategies employed by sister transport industries like road, aviation, and rail to mitigate GHG emissions and look at the feasibility to adopt the same to the shipping industry.

Joung et al. [12] looked into IMO's initial strategy for reducing GHG emissions and its follow up actions towards 2050 and discussed decarbonisation of international shipping by using innovative technology and alternative fuel. It was concluded that international shipping should focus on next-generation eco-friendly propulsion ships such as hydrogen fuel-cell, ammonia, and biofuels. Also, it is advised that member states of IMO establish a national strategy (or National Action Plan, NAP) to prepare short, mid-term, long-term measures, and systematic approaches to implement the IMO GHG reduction strategy to relevant sectors.

According to a study by Habibi [13], ships are the single largest source of port-related pollution, causing emissions approximately ten times greater than those from the port's own operations. It is vital to reduce the ship's emissions in port to alleviate pollution and the related benefits to enhance the good quality of life for people. Also, ship's engines employed in ports to generate electricity for hotel services emit NO_x, SO_x and particulate emissions, which are again detrimental to human life. Styhre et al. [9], in their study on GHG emissions from ships, did case studies on ships berthed in ports in four continents. Winnes et al. [14] used a model developed by IVL Swedish Environmental Research Institute for the purpose of quantifying GHG emissions (as CO_2 equivalent) from ships in the port area. The study concluded that to decrease GHG emissions, strict policies and regulations related to alternative fuel and ship

design need to be taken on at the international level. Also, international terminals with large container ships could have an onshore power supply (OPS) to reduce CO_2 substantially.

Shi [15] considered Market-Based Measures (MBM) to reduce GHG emissions from ships. It is very controversial whether MBM s should be adopted to further the reduction of GHG emissions from international shipping. To date, Governments and observer organisations proposed 10 MBMs and agreed on the need to undertake an impact assessment of the MBM proposals, focusing on consumers and industries in developing countries, to be discussed in the future [16]. There has been discussion on global data collection at IMO to address the reduction of GHG emissions from shipping for some time. In May 2015, IMO agreed to a three-step approach that includes data collection, data analysis and decision making. However, not much progress has happened in this regard. Aiming to reduce CO2 emissions from ships, the European Commission developed a proposal for EU Monitoring, Reporting and Verification (MRV) adopted in July 2015[17]. The next herculean task for IMO will be to transfer the MRV regulation into a global data collection system. Although MBM is still a dilemma, various studies have predicted that certain MBM should be adopted as a supplementary method to reduce GHG emissions in addition to other current energy efficiency methods employed by IMO.

Nepomucen et al.[18] in their study evaluated the implementation of maritime transport mitigation measures. To mitigate GHG emissions, IMO adopted policies in 2011 defining Energy Efficiency Design Index (EEDI), a mandatory requirement for new ships and Ship Energy Efficiency Management Plan (SEEMP), which voluntarily encourages ship owners in operation to use Energy Efficiency Operational Indicator (EEOI). Lindstal et al.[19] and Faber et al.[20] studied some mitigation measures which resulted in negative Marginal Abatement Costs (MAC), which provides economic returns to ship operators, in addition to the reduction of emissions. The authors' study in [18] concluded that the market effectively implements measures with negative MACs more than those with positive MACs.

The challenges to the decarbonisation of the international shipping sector are a matter of huge interest to the community worldwide. Because of the involvement of many member states, it is challenging to reach an early agreement in these operational matters. Edurado et al. [21]focused on the integrated assessment models (IAMs), where the IMAGE model was used to meet IMO’s target for 2050. In their research, Zhang, H[22] specified that as we are approaching towards a green shipping, we have to adopt the IMO regulations, which are still being drafted. It is suggested that a complete understanding of the common but differential responsibility principle (CBDR) by all parties is essential to reach a feasible and amicable solution to adopt the principle to move forward towards our goal of green shipping.

Liquid natural gas (LNG) has been the preferred option for cruise ships since it complies with the present IMO regulations. LNG is a much-preferred option to other fossil fuels with its low sulphur content and low NO_X emissions. However, the ship's engine's methane (CH4) emissions nullify the GHG emissions [21]. There is a suggestion that there should be a holistic approach to reducing GHG emissions rather than focusing solely on CO_2 emissions. It is also important to assess the impact of mandatory GHG emissions regulation on the least developed countries and small island developing states [22]. Styre. L and Winners H[23], in their study, considered emissions from ships in ports, which are much different from emissions at sea. However, since many cities are in the close vicinity of ports, reducing emissions from ships in port will result in less pollution of the cities, thereby causing less harm to the health of human life in the cities.

Prissi et al.[24] studied the aviation sector's approach to reduce GHG emissions from international aviation. The highlight of the study included the goal of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which uses the life-cycle assessment (LCA) approach to reduce GHG emissions from international aviation. The LCA method is the first internationally adopted method for quantifying GHG emissions from aviation [25],[24],[26]. LCA is the tool that quantitatively assesses the emission savings by a specific alternative fuel for aviation [27]. It is suggested that the CORSIA method can serve as a template for international shipping and other transport and non-transport sectors [24]. A useful study on the GHG emissions from aviation in certain EU countries was undertaken by application of multiple-criteria statistical methods [28]. This could be useful to study GHG emissions from shipping.

Renewable jet fuel can significantly reduce aviation-related GHG emissions, provided the right feedstock and conversion technology are used [29].O'Connell et al. [30] in their study considered an alternative to aviation fuel for reducing GHG emissions. The study looked at various biofuel alternatives. Various types of vegetable oils were looked at, and it is interesting to note that palm oil is typically cheaper oil compared to other vegetable oils and is likely to provide the cheapest GHG emissions reduction as an alternative aviation fuel [29]. Staples et al. [30] also looked at quantifying CO_2emissions reduction from aviation by using alternative jet fuels (AJF) and using a scenario-based analysis. AJF could contribute to GHG reduction in the aviation industry, provided significant incentives are available. Also, the aviation industry's CO_2 reduction goals will require offsets from other industries [30]. Not all AJFs provide substantial GHG reduction over petroleum jet fuel. Many feedstocks and pathways provide minimal, if any, carbon savings [31].

A few research papers dealing with GHG emissions from rail transport was considered. One research calculated the life cycle GHG emissions of Shanghai Metro based on actual observed data. The study concluded that on account of advances in technology and efficiency, the emissions in China are much lower than in other Asian countries[32]. A vital study related to human factors contribution to rail decarbonisation[33]. The research expressed that a socio-technical systems model could offer significant advantages in reducing costs and improving the efficiency of the decarbonisation process.

3. DECARBONISATION OF SHIPPING

In the past two decades, the world has seen enormous efforts by various industries to reduce GHG emissions, and the shipping industry has been no exception in its contribution towards the achievement of a greener future. In this section, we shall look at the guidelines provided by IMO for the reduction of GHG emissions, followed by the thoughts, advice and actions of academic researchers on the IMO strategies, the classification societies, and the shipbuilding industry.

3.1. IMO's strategies on reduction of GHG emissions

In the last decade, IMO adopted the first international mandatory measure to improve ships' energy efficiency to reduce emissions [34]. In July 2011, the IMO introduced new regulations for existing ships and buildings to improve energy efficiency. These regulations came into force in January 2013. One of the key factors was introducing a factor termed the Energy Efficiency Design Index (EEDI), which indicates a ship's energy efficiency, calculated based on guidelines and information available in the EEDI technical file. The second key factor was the

introduction of a Ship Energy Efficiency Operation Plan (SEEMP) that forms part of the ship's Safety Management System (SMS). The SEEMP is to be developed considering guidelines adopted by IMO. After an initial survey by the administration, the ships will be provided with an International Energy Efficiency Certificate (IEEC), provided they comply with the IMO regulations.

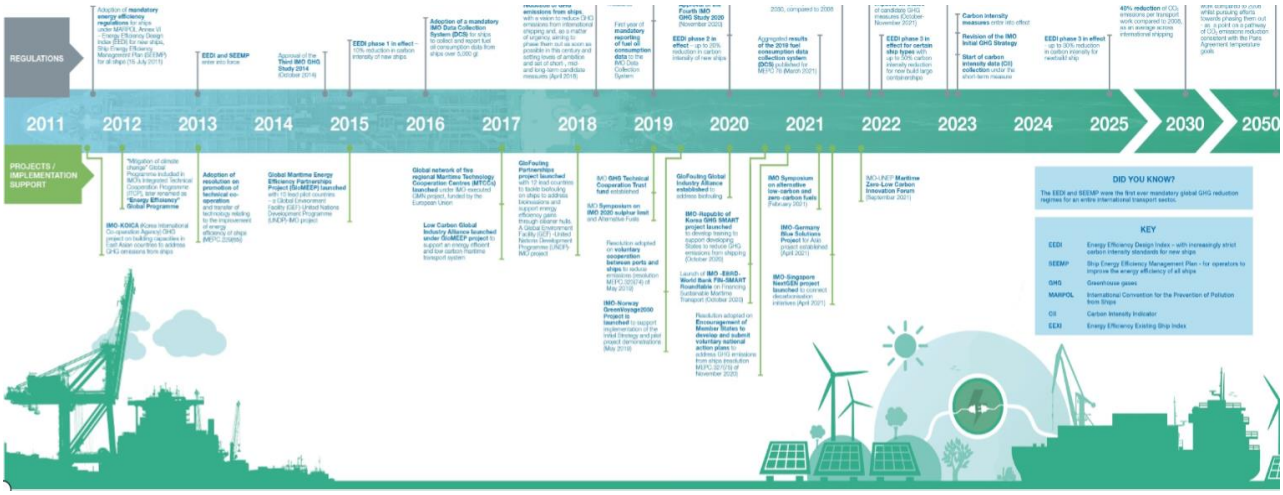


Figure 1: A decade of action to cut GHG emissions from shipping (Courtesy: IMO)

In 2018, IMO established an initial strategy to reduce GHG emissions. The main goals of this strategy were twofold. One was to reduce the GHG emissions from international shipping by at least 50% by 2050 compared to their level in 2008. The second was to reduce CO_2 emissions across international shipping by at least 40% by 2030 and further towards 70% by 2050 compared to 2008 [35]. IMO considered a short-mid-long-term strategy to meet the above goals, considering the already formed EEDI and SEEMP regulations.

The short-term strategy will require ships to calculate their Energy Efficiency Existing Ship Index (EEXI) by considering technical and operational measures. Based on the EEXI, the ships have to establish an annual carbon intensity indicator (CII) and CII rating. Carbon intensity links the GHG emissions to the amount of cargo carried over distance travelled [36], the ships will be rated for their energy efficiency (as A, B, C, D, E - where A is the best). Ships with ratings A and B may receive incentives from Administration, Port Authorities, and other appropriate stakeholders. IMO recognises that the path for decarbonisation is long and requires the collective approach of all stakeholders to achieve this ambitious mission. This amendment included in Annex VI of the MARPOL will come into force in November 2022, and the first annual reporting for EEXI and CII will begin in 2024.

The mid-long-term strategies were approved by MEPC in June 2021, which essentially comprised a Work Plan divided into three phases. Phase I was the initial collation and consideration for measures, Phase II being assessment and selection of measures to develop further, followed by Phase III, which will be the development of measures to be finalised with an agreed target date [37].

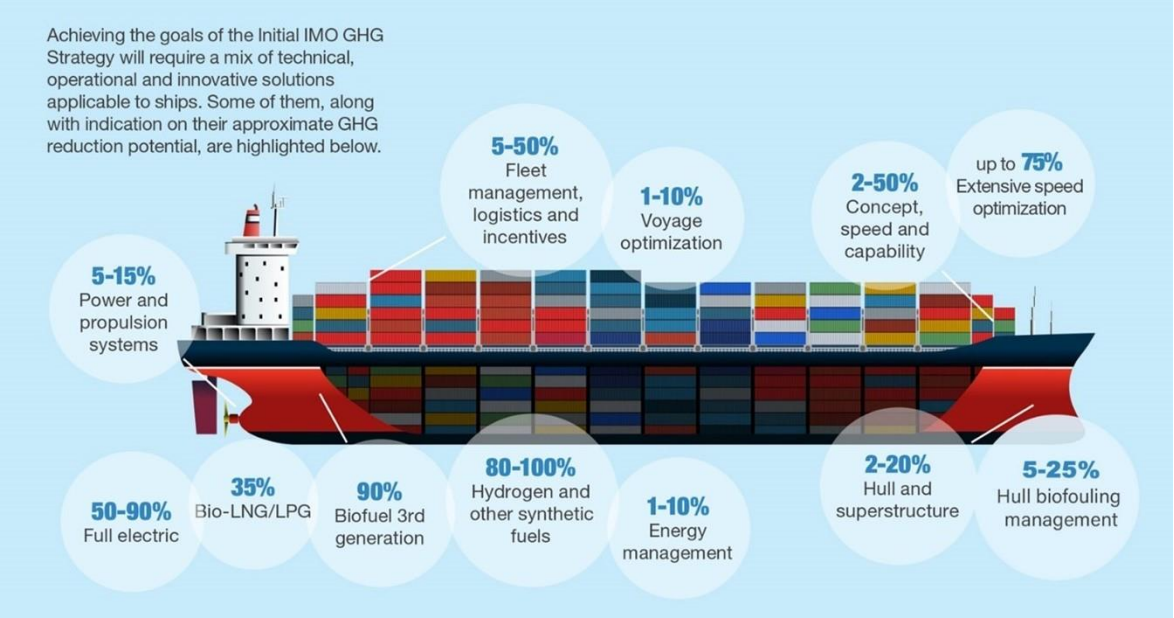


Figure 2: A wide variety of design, operational and economic solutions (Courtesy: IMO)

IMO's initial strategy for reducing GHG emissions also considered support for small island developing states (SIDS) and least developed countries (LDC). The impact factors on these states and countries included but were not limited to graphic remoteness and connectivity to main markets, cargo value, transport costs and socio-economic progress and development. The argument mainly looked at the disproportionately negative impact and addressed it appropriately. The four steps in this process would involve an initial impact assessment to be followed by submission of commenting documents, a comprehensive response to the documents and a final comprehensive assessment as required by MEPC [35].

3.2. Decarbonisation by the use of low carbon fuels

Usage of zero-carbon or very low carbon fuel is vital for decarbonisation. When considering alternative fuels, it is essential to consider many important factors including but not limited to availability, infrastructure, life cycle assessment of emissions, the viability of cost, onboard storage ships, training of personnel and safety aspects. Considering the above, IMO deemed it absolutely necessary to have a collective and collaborative response from all the players of the shipping industry. To facilitate this action, IMO held a symposium in February 2021 [38]. The symposium presented major players from the shipbuilding industry, classification societies, port administration, fuel suppliers, academia and more. Some important lessons learnt from the symposium is highlighted below.

CMA ships have developed an ambitious program for a new generation of vessels, which use LNG technology that allows the use of organically produced biomethane made from agricultural and domestic waste. Bio-methane is a renewable energy that emits up to 80% less CO_2 than conventional fuel. Though this is an immediate efficient step for the energy transition, there is a high potential for improvement and challenge for onboard and off-shore crew training[39].

A study by a leading shipping company advocates the use of methanol as a clean, cost-effective marine fuel solution for the future [40]. The decarbonisation pathway to methanol to meet

IMO 2050 goals can be twofold. One will be the electro-fuel pathway, where renewable electricity is used to extract hydrogen from water by electrolysis and carbon dioxide is captured from the exhaust stream from the atmosphere. The second pathway is the biomass pathway, where the organic matter undergoes fermentation that is processed in a reactor and formed into bio-methanol [41]. When tested on a vessel's main engine, Biofuel has shown zero CO_2 emissions. Results from a vessel showed a daily savings of 68.51 metric tonnes of CO_2 equivalent besides being a good alternative fuel with reduction of emissions when used in all areas of sailing[42]. Toki Nakamura, in his work, studied the expectations from a shipowner on using Ammonia (NH_3) as marine fuel for zero-emission ships [43]. It was argued that Hydrogen (H_2) and NH_3 is the key to CO_2 reduction. It is expected that by 2050 45% of the marine fuel would consist of H_2 and NH_3. Also, depending on the engine output size, larger ocean vessels will be propelled by NH_3, and relatively smaller inland water vessels will be propelled by H_2 fuel cells. A new biofuel based on biomass residue(lignin) and alcohols(methanol or ethanol) is under development stage, but its scalability and infrastructure for supply are being addressed [44]. One of the ongoing projects on green technology by a leading shipping company is powering the world's first Very Large Crude Carrier (VLCC) using LNG, which will be equipped with two tanks each of 3500m^3 capacity[45]. Also, another project being developed is an ammonia fuel solution for a 23,000 TEU container ship. It is argued that the close alternative to ideal fuel is ammonia being carbon-free and easily reformed to H_2 and N_2.

Further, ammonia can be stored and transported as a liquid at relatively low pressure or high temperature and has a low flammability risk – 15-25% in air. A study by the Korean Maritime Transportation Safety Authority (KOMSA) revealed the "Green New Deal" development to achieve net-zero emissions. This project provides a marine testbed where the various developed technologies are tested to prove their feasibility [46]. The International Wind Association Network studied the application of wind power to propel vessels and mentioned that large vessels like VLCC and Bulkers are fitted with wind-assisted systems to achieve significant savings in fuel [47].

3.3. Classification societies' input on decarbonisation

Classification societies are independent non-governmental bodies that maintain technical standards for the construction and operation of ships and offshore structures. They are an important stakeholder in the maritime industry that sets relevant standards and conduct surveys to ensure that the ships continuously comply with these standards during their operational life. They are experts in insurance and risk management and advise ship owners and engine builders on maritime safety and pollution prevention. In this section, we shall look into the input of the major classification societies on the subject of decarbonisation.

Det Norske Veritas (DNV)

DNV is a leading classification society that has done extensive studies on decarbonisation. The key highlights of the maritime forecast to 2050 presented by Hmamer l.S [48] states that shipowners must identify their own decarbonisation pathway to manage carbon risk. Another study by DNV has highlighted methanol as a good alternate fuel, successfully used by a leading shipping company on their tanker, with no major failures of the main engine [49]. Methanol has a low cetane number which lowers the self-ignition quality of the fuel, hence requiring a

small amount of pilot duel (95% methanol and 5% pilot fuel). A leading marine engine manufacturer is developing a two-stroke engine for ammonia as a fuel. It is claimed that ammonia is a viable solution for the decarbonisation of shipping, but it should be ensured that there are no other emissions in the bargain [50]. The engine is still developing and is likely to be delivered by 2024. Though ammonia is toxic and energy density almost half of the present fuels being used, it is still a better option than hydrogen and can be a future option for cargo ships with modified internal combustion engines and low-pressure fuel tanks[51]. A vital study on the use of Hydrogen as an alternate fuel was studied by DNV that mentions Hydrogen has the potential of becoming a zero-emissions solution for longer distances and larger energy needs in shipping. A concise handbook by DNV covers the safety, implementation, regulatory framework, bunkering aspects, engineering and more on Hydrogen as an alternate fuel for shipping [52].

Lloyds Register of Shipping (LRS)

LRS is a major classification society that has extensively studied decarbonisation [53]. LRS has considered a two-way approach to decarbonisation, one which comprises the maritime challenges and trends encountered by the fleet and the second being the global challenges encountered by the fuel suppliers[54]. Decision-makers consider the output derived from each outcome, compare the same and identify a viable solution. LRS considered it necessary to move from a generic ship or generic fuel supply to a more specific detailed analysis that forms a system solution and a better approach for a business plan. In doing so, LRS has considered newbuilds and retrofits separately and analysed the impact of alternative fuels on these ships. This approach provides a deeper understanding of the fuel choice for a specific fleet to facilitate a viable business plan for the shipping organisation.

American Bureau of Shipping (ABS)

ABS is a renowned classification society that provides guidance on alternate fuel options to ship owners [55]. As per IMO, the low flash point gaseous fuel includes liquid natural gas (LNG) and liquid petroleum gas (LPG). Such fuels should possess characteristics defined in the International Code of Safety for Ship Using Gases or Other Low-flash point Fuels (IGF). The calculated methane number (MN) of the LNG indicates the combustion performance. Normal operation down to an MN of 65-70 is now possible on many engines. Low MN numbers can cause knocking problems in engines [56].

Liquid Natural gas (LNG)

LNG is a mixture of several gases, mainly composed of methane (CH_4) with a concentration that can vary between 70-99 per cent by mass, depending upon the origin of the natural gas. Other hydrocarbon constituents commonly found in LNG are ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}). Small amounts of other gases, such as nitrogen (N_2), may also be present. When liquified at approximately -162^{o}C, the volume required for natural gas is reduced to about 1/600th of that required when stored in the gaseous state. In this condition, LNG is transported as liquified gas on ships, and any heat ingression to the tanks lead to constant boil-off gas (BOG) generation. This BOG can be used as a fuel to propel the main propulsion engine. The heating value of LNG will vary between 49.1-49.9 MJ/kg. To deliver the same energy content, the volume of LNG will be 1.8 times the volume of fuel oil [56].

Ethane (C_2H_6)

Ethane is a colourless, odourless gas that can be liquified to -89^{o}C at atmospheric pressure. The heating value of ethane is 47.8 MJ/kg. To deliver the same energy content, the volume of LNG will be 1.4 times the volume of fuel oil [56].

Liquid petroleum gas (LPG)

LPG is a hydrocarbon fuel that is a mixture of propane (C_3H_8) and butane (C_4H_{10}). The heating value of LPG ranges from 45.7-46.3 MJ/kg. To deliver the same energy content, the volume of LPG will be 1.5 times the volume of fuel oil. LPG is transported in pressure vessels around 18 bar or semi-pressurised/refrigerated tanks at 5-8 bars and -10 to -20^{o}C [56].

Methanol

Methanol (CH_3OH), also known as methyl alcohol, is a clear, odourless, colourless chemical compound that is water-soluble and biodegradable. It is liquid at atmospheric pressure with a boiling point of 65^{o}C. Its energy density is 19.9 MJ/kg. To deliver the same energy content, the volume of methanol will be 2.4 times the volume of fuel oil. Methanol also burns with an invisible flame, requiring special fire detectors, fire extinguishing systems and operational procedures [56].

Hydrogen(H_2)

The heating value of hydrogen is the highest of all potential fuels at approximately 120.2 MJ/kg. However, even when liquified, its energy density per unit volume is significantly lower than distillates. To deliver the same energy content, the volume of hydrogen will be 4.1 times the volume of fuel oil. That means compressed or liquified storage of hydrogen may only be practical for small ships [56].

Ammonia (NH_3)

In large quantities, ammonia can be transported in LPG carriers and has a boiling point of -33oC [56]. The typical heating value of ammonia is 22.5 MJ/kg. To deliver the same energy content, the volume of ammonia will be 2.4 times the volume of fuel oil.

4. DEVELOPMENT OF MARINE ENGINES TO COMBAT GHG EMISSIONS FROM SHIPS.

In this section, the author considered the research output from academia and solutions from the engine manufacturers.

4.1. Research output from academia

Ni et al. [57] studied alternate fuels on marine engines that play a significant role in marine transport. Stringent emission limits from ship's engines have been formulated by IMO. A term emission factor (EF) is used to determine emissions from ships engine measured as g/kWh either in the laboratory or from the exhaust manifold on ships. It was concluded that EF is always higher at low loads. Further switching over to clean fuels like biodiesel methanol and LNG appears to be a promising solution to reduce exhaust emissions from ships.

McCullum et al. [58]looked at greenhouse gas emissions from aviation and marine transportation and their potential mitigation. The study concluded that in the near to medium term, emission reduction in marine transport could be achieved by slower marine vessel speeds, optimised routing, reduced port time and improvement in shipping operations. Larger

ships, new combined-cycle or diesel-electric engines, and optimised propeller designs should reduce emissions in the long term.

Bauman et al. [59] reviewed the state-of-art technologies, measures and potential for reducing GHG emissions from ships. The studies concluded that the marine sector has many technological and operational measures at its disposal, but no one single measure in itself is sufficient to reach considerable sector-wide reduction. Reduction over 75% is achievable by swift adoption and a combination of many individual dependent and independent measures.

4.2. Solutions from engine manufacturers

Leading engine manufacturers have also been very proactive when it comes to the reduction of exhaust emissions from engines. They have been taken measures to achieve a reduction limit less than the one prescribed by the IMO regulations.

MAN Energy solutions[60] have provided a range of measures to reduce emissions from ships. Vessels with conventional propulsion can meet the IMO NOx and SOx emission limit by combining technologies that include injection systems, turbochargers, control and after-treatment system. A Selective Catalytic Reactor (SCR) helps to reduce NO_x emissions up to 90% and simultaneously reduces the specific fuel oil consumption (SFOC) by 2.5g/kWh. MAN Energy solutions also provide LNG supply and bunker systems for ships, reducing emissions, increasing fuel efficiency and power density, and keeping ships' operation economical.

The use of advanced digital technology enhances efficient engine operation and reduction of emissions. MAN has also developed hybrid propulsion by combining combustion engines with battery power that optimises engine operation while reducing emissions. Methanol may be available for maritime use in 2024, as per MAN.

Another leading engine manufacturer Wartsila [61], has provided practical solutions for the maritime reduction of GHG emissions. The manufacturer has developed a propulsion system for a ferry based on a dual-fuel engine and batteries. The principal source of fuel will be LNG but will also be able to use Bio LNG, a totally renewable fuel that can reduce CO_2 emissions up to 90% compared to conventional marine fuels, with no emission of particulate matter (PM), and close to zero levels of nitrogen oxides (NO_x) and sulphur oxides (SO_x). Also, digital solutions based on artificial intelligence is adopted to detect potential faults before they can actually happen.

Wartsila is also considering the feasibility of using ammonia as a primary fuel in a dual-fuel engine where LNG is an alternate fuel. The test will be carried out on an offshore supply vessel (OSV). Methanol has been successfully used on another vessel to fuel the main propulsion. Hydrogen has also been tested on some gas engines, and research and development work is still in progress. Storage and hydrogen supply still remains a challenge at this juncture [62].

Air lubrication system is a modern technology that Wartsila is testing on a large container vessel. The system essentially creates a carpet of microbubbles that coat the entire flat bottom of the vessel. This carpet effectively reduces frictional resistance between the hull and the water, thus reducing fuel consumption, thereby reducing emissions [63]. A layer of slime as

this as 0.5mm covering 50% of the hull area can increase the GHG emissions in the range of 20-25% [64].

5 CONCLUDING REMARKS

GHG from International shipping is to be reduced at least by 50% in 2050 compared to 2008, which appears to be an ambitious target by IMO. Unfortunately, there is criticism by CAT, which remarked at the recent COP26 that IMO is moving at a snail's pace in its attempt to curtail GHG emissions reduction from shipping and steps taken by IMO are very much insufficient.

Ships, when in ports, emit significant emissions, which needs to be curtailed to provide a better quality of life for people. Large ships could have the shore power supply to reduce CO2 emissions in port.

It is suggested that a full understanding of the common but differential responsibility principle (CBDR) by all parties is essential to reach a feasible and amicable solution to adopt the principle to move forward towards our goal of green shipping. IMO deemed it absolutely necessary to have a collective and collaborative response from all the players of the shipping industry. GHG emission reduction strategy will require a mix of technical, operational, and innovative solutions. Near to medium term emission reduction in marine transport could be achieved by slower marine vessel speeds, optimised routing, reduced port time and improvement in shipping operations, but no one single measure in itself is sufficient to reach considerable sector-wide reduction. It is suggested that the CORSIA method can serve as a template for quantifying GHG emissions for international shipping.

Usage of zero-carbon or very low carbon fuel is a vital step for decarbonisation, and it is suggested that international shipping should focus on next-generation eco-friendly propulsion ships such as hydrogen fuel-cell, ammonia, and biofuels. Palm oil is the cheapest vegetable oil and is likely to provide the cheapest GHG reduction as an alternate fuel. Bio-methane is a renewable energy that emits up to 80% less CO_2 than conventional fuel. Methanol is seen as a clean, cost-effective marine fuel solution for the future. It is expected that by 2050 45% of the marine fuel will consist of hydrogen and ammonia. Also, depending on the engine output size, larger ocean vessels will be propelled by NH_3, and relatively smaller inland water vessels will be propelled by H_2 fuel cells. To deliver the same energy content, the volume of LNG will be 1.8 times the volume of fuel oil, and the volume of hydrogen will be 4.1 times the volume of fuel oil. The heating value of LNG will be 1.1 times of fuel oil, whereas hydrogen has a heating value nearly thrice as that of fuel oil. Maritime stakeholders suggest the necessity to move from a generic ship or generic fuel supply to a more specific detailed analysis that forms a system solution and a better approach for a business plan.

Air lubrication system is a modern technology that is being tested by shipbuilders on a large container vessel, which will significantly reduce GHG emissions.

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SESSION 11

Ship Design

Naval architecture at UNSW Canberra

Maritime industry research past, present and future - Collaborations between academia and industry

Nav archs (you gotta) fight for your right (to margins)!

Development of an Australian sovereign shock testing and assurance capability

Naval Architecture at UNSW Canberra

Warren F. Smith[1], **David Lyons**[1]

[1]UNSW Canberra, Canberra, ACT, AUSTRALIA
emails: w.smith@adfa.edu.au, david.lyons@adfa.edu.au, navarch@adfa.edu.au

ABSTRACT

The delivery of new naval architecture Bachelor of Engineering (BE) Honours programs by UNSW Canberra at the Australian Defence Force Academy has begun in 2022. The degrees target navy and civilian students in a plan of study that is "grey-ship" focused. The programs should attract and excite those that are specifically interested in warship design and construction.

Given the significant history of the discipline at UNSW Sydney, this might be seen as a transfer geographically from Sydney to Canberra, but it also represents a conscious effort to tailor the program for Navy, delivering the requisite foundational skills development in the discipline in support of the Defence White Paper (2016)[1], the Defence Strategic Update (2020)[2], and the Naval Shipbuilding Plan. Imbedded within the Australian Defence Force Academy, UNSW Canberra represents a unique institution in the context of the Australian higher education landscape and positioning the relatively small program here provides opportunities for it to thrive.

Provided in this paper is an overview of the academic undergraduate program structure, and our aspirations for it. The expected broadening of related activities in the postgraduate and research spaces are also discussed. Particular attention is given to describing the maritime flavoured research opportunities anticipated to be developed in parallel with the teaching. The multidisciplinary yet tight community that is UNSW Canberra, provides strengths that can be leveraged into the naval architecture domain. Examples include multidisciplinary design optimisation (MDO); autonomy, as related to surface and sub-surface vessels and impact dynamics, as related to ship survivability and vulnerability.

Terminology

In the context of this paper the current usage of UNSW is adopted:

University Program *A defined plan of study comprising a range of core and elective courses that leads to the award of a degree. A standard Engineering degree is planned to span a 4-year period of full-time study and requires the accrual of 192 units of credit.*

University Course *A discrete block of study in which students enrol, are assessed and are given a grade. A standard engineering program comprises 32 courses (core and elective). A full-time load is nominally 8 courses per year, 4 courses per semester, in a 2-semester system (as at UNSW Canberra).*

[1] https://www.defence.gov.au/about/publications/2016-defence-white-paper
[2] https://www.defence.gov.au/about/publications/2020-defence-strategic-update

Units of Credit *Each standard course carries 6 Units of Credit (UoC) where each UoC represents approximately 25-30 hours of student engagement (includes all related activities such as lectures, tutorials, assignments, exam preparation). 192 units of credit are required for a BE degree.*

BACKGROUND

A new offering in the Australian higher education sector is the discipline of Naval Architecture (NA) at UNSW Canberra, imbedded at the Australian Defence Force Academy (ADFA). Two undergraduate Bachelor of Engineering (BE) programs represent phase 1 of the enterprise, but it is expected that related postgraduate and research activities will naturally develop. The first specialised NA third Year undergraduate courses are being taught in Semester 1, 2022, with the programs built on a common 1st and 2nd year foundation with Mechanical (and Aeronautical) Engineering. It is anticipated that the first graduates will be awarded their NA degrees in December 2023. This reflects a program plan that we refer to as a 2 + 2 model, one that facilitates students transferring to UNSW Canberra having undertaken the first two years of an accredited Mechanical (or Aeronautical) Engineering four-year degree program at another Australian tertiary institution. Exact course credits for transferees will be managed on a case-by-case basis. It should be noted that this is how the program ran at UNSW Sydney for nearly 60 years and it aligns with the plans that the Australian Maritime College (AMC) also executes.

Each of the five engineering disciplines at UNSW Canberra: civil, electrical, mechanical, aeronautical, and naval architecture offer two BE degree programs, the “Standard”, and a “CDF” (Chief of Defence Force) variant. The CDF program is an elite research focused degree offered to students entering the program with an Australian Tertiary Admission Rank (ATAR) greater than 98 (top 2% nationally). The CDF scholars then also need to maintain a high level of performance in their university studies to remain in the program. While acknowledging the existence of the CDF program, the concentration of this paper will be on the Standard.

A complementary paper providing a broader historical and situational perspective for the UNSW Canberra initiative was recently published in the Australian Naval Architect [1]. From this paper, one key point is the institutional connection with the previously successful and highly respected UNSW Sydney program. Its closure in 2017 (the last course was taught in 2018) was primarily for budgetary reasons. As described in [1], “*the historical record of UNSW Sydney shows that 413 Naval Architecture graduates have been produced with a long-term average of 8 graduates per year. While UNSW Canberra anticipates ramping up to an average of 10-15 graduates per year, this will take a few years to achieve … It is to be noted that the different (operating and funding) conditions of the ADFA environment do not threaten small class sizes such as these, as they did in Sydney.*”

A second key point is to acknowledge Navy’s request for, and sponsorship of, the NA developments at UNSW Canberra in support of the current Defence White Paper, the continuous naval shipbuilding plan, and the requisite foundational skills development in the

discipline. ADFA, and therefore also UNSW Canberra, exist to provide high-quality university education for both military and civilian students in a military environment.

A third key point is our fostering of a collaborative relationship with AMC as the other Australasian institution, established in the 1980's, delivering NA graduates to the sector. Again, as more fully described in [1], "*it is not in our interest to duplicate the facilities of Australia's premier maritime experimental organisation. Rather, we plan to visit and utilise and expose* (our) *students to AMC's facilities* (during their 4th Year)*, through a cooperative agreement that has been negotiated in principle*", details of which are being defined in 2022 for their first execution in 2023.

ACADEMIC PROGRAM

Program Structure

The structure of courses for the Standard Program (4484) is mapped in Table 1 with the specialist 3rd and 4th year NA courses bolded and highlighted. The differences for the CDF version (Program 4485) see ZEIT2501, ZHSS3750 and ZEIT3753 being substituted with research-based variants addressing the same respective knowledge domains. Also, in the CDF program, ZEIT4500 and ZEIT4501 project (thesis) courses are expanded from 6 to 12 units of credit each with the associated loss of the two technical electives. While other engineering programs at UNSW Canberra are less prescriptive than NA, having more elective choice, NA itself can be viewed as a "mega" elective. Note that it is a requirement of all UNSW undergraduate degrees to include two broadening general studies courses (ZGEN's).

A distinction of the UNSW Canberra NA program content is that it is "grey-ship" focused. Certainly, the laws of physics and the impact of the environment do not differentiate between military maritime vessels or those serving a commercial or recreational purpose. However, the examples discussed in our classrooms will lean towards military applications. That said, students will grow in their general awareness and appreciation of all ship types and the challenges a naval architect faces in delivering all capabilities.

The grey-ship focus is also underpinned by the sponsorship of Navy as a customer for the program at ADFA in a unique military environment within the Australasian Higher Education sector. It is also supported explicitly through the office of Head Naval Engineering (HNE).

While much is being spoken of in relation to the RAN's acquisition of a nuclear-powered submarine, the program will generally target and emphasise surface ships and the associated threshold concepts involved. Many of these can in due course be applied to submarines but this extension in detail is likely to be the scope of future postgraduate offerings and activities.

The Program Learning Outcomes as documented in the 2022 University Handbook[3] are shown in Table 2. In general, across all programs, UNSW aspires to develop globally focussed graduates who are rigorous scholars, capable of leadership and professional practice in an international community. It follows for accreditation purposes by Engineers Australia (EA), that all graduating students demonstrate their attainment of the Stage 1 Competencies. It is also worth noting that the quality of UNSW Engineering education ranks in first place in Australia across all three major ranking systems (2021 QS World University Rankings, 2022 Times Higher Education World University Rankings, and 2021 Global Ranking of Academic Subjects).

Table 1 – The Standard Naval Architecture BE Program (Program 4484)

Yr	Sem	BE (Nav Arch) (Honours)	
1	1	ZPEM 1303	Engineering Mathematics 1A
		ZPEM1307	Computational Problem Solving
		ZPEM1503	Engineering Physics 1A
		ZEIT1504	Introduction to Mechanical, Aeronautical and Naval Architecture Engineering
1	2	ZPEM1304	Engineering Mathematics 1B
		ZEIT1102	Introduction to Programming
		ZEIT1501	Engineering Practice and Design
		ZEIT1503	Engineering Mechanics
2	1	ZPEM2309	Engineering Mathematics 2A
		ZEIT2500	Thermofluids
		ZEIT2501	Mechanical and Electronic Design
		ZINT2501	Engineering Materials and Chemistry
2	2	ZPEM2310	Engineering Mathematics 2B
		ZEIT2503	Fluid Mechanics
		ZEIT2504	Mechanics of Solids
		ZGEN	
3	1	ZEIT3501	Engineering Materials
		ZGEN	
		ZEIT3750	**Naval Architecture Practice, Ship Hydrostatics and Stability**
		ZHSS3750	**Building the Fleet: History, Politics and Naval Technology**
3	2	ZEIT3506	Managing the Development of Engineered Systems
		ZEIT3751	**Hydrodynamics of Ships and High Speed Craft**
		ZEIT3752	**Ship Structures**
		ZEIT3753	**Design of Ships and High Speed Craft**
4	1	ZEIT4500	Engineering Project A
		ZEIT4750	**Ship Design Project A**
		ZEIT4752	**Ship Propulsion and Marine Engineering**
			Technical Elective
4	2	ZEIT4501	Engineering Project B
		ZINT 2100	Introduction to Cyber-Security: Policy and Operations
		ZEIT4751	**Ship Design Project B**
			Technical Elective

[3] https://www.handbook.unsw.edu.au/undergraduate/programs/2022/4484?year=2022

Table 2 – Naval Architecture (Honours) Program Learning Outcomes (Program 4484)

PLO1	Relate a quantitative, theory-based understanding of the sciences and rationally apply comprehensive knowledge of the fundamental principles underpinning maritime engineering, with advanced knowledge of both Naval and Ocean vehicle design, hydrodynamics, ship structures, and/or on-board systems and equipment specific to the naval architecture discipline, using critical thinking and judgement
PLO2	Appropriately select and apply the mathematical, statistical, programming and computational tools and techniques which underpin naval architecture
PLO3	Demonstrate a comprehensive understanding of ship design, construction, performance, maritime systems and sub-systems aboard surface ships and submarines, and articulate directions of research and knowledge development in naval architecture
PLO4	Synthesise ship design practice, contextual factors, norms and accountabilities in and the limitations on naval architecture
PLO5	Define, conduct experiments on and apply problem solving, design and decision-making methodologies to identify complex problems in both the ship design and construction industries and the wider maritime sector whilst concurrently considering the implications of the solution in a global and sustainable context using appropriate engineering methods and tools
PLO6	Demonstrate proficiency in applying systematic engineering synthesis and design processes, and critically evaluating and effectively communicating the results and implications to all audiences
PLO7	Operate in collaborative environments, as leader or member of interdisciplinary teams
PLO8	Review personal performance, demonstrate independent initiatives and leadership as a means of managing continuing professional development and lifelong learning

Naval Architecture Courses

As identified in [1], *"what is particularly unique to our program is the inclusion of a compulsory contextual course in semester 1, 3rd year, titled "ZHSS3750 Building the Fleet". It is presented by the School of Humanities and Social Science, and aims to provide students with a historical, political, strategic, tactical, and cultural perspective of why the Navy looks the way it does. The other seven courses provide for a contemporary technical education on things naval architectural, with a structure similar to the former program at UNSW Sydney."*

The normal full time student load is 4 x 6 Unit of Credit courses per semester, 8 courses per year. A description of each of the 8 unique NA courses as documented in the handbook follows.

ZEIT3750 Naval Architecture Practice, Hydrostatics and Stability

The Practice component of this course introduces ship terminology and the role of international and Australian independent and statutory authorities concerned with ship classification, naval and commercial standards, vessel registration, safety and survey; vessel stability measurement and assessment, and the professional practice of the naval architect. Excursions may include visits to drydock and harbour facilities, consultancies and the conduct of an inclining experiment. The Hydrostatics and Stability component covers ship geometry, hydrostatic particulars, intact and damaged stability, subdivision, launching and grounding. A practice-based introduction to relevant software is provided.

ZHSS3750 Building the Fleet: History, Politics and Naval Technology

This course examines the technological, political and strategic factors that have shaped the development of warships and ship design and continue to do so today. It will survey the key

developments in naval and maritime technologies over the past 200 years, setting them into their broader contexts. This will provide a grounding for a more focused exploration of the historical, political, strategic, tactical, and cultural factors that frame decision making regarding Australian naval construction. The course aims to develop the students' understanding of the contexts which shape the decisions over the design and construction of warships.

ZEIT3751 Hydrodynamics of Ships and High-Speed Craft

Introduction to ship and High-Speed Craft hydrodynamics, resistance, seakeeping and model testing, followed by the study of ship motions, powering and manoeuvrability/steering.

ZEIT3752 Ship Structures

Methods for the first principles analysis of global and local loading and response are treated alongside rules-based ship structural design and scantling determination with the aid of naval codes and classification society software. Familiarisation with material properties, welding and composite processing precede a more detailed investigation of fatigue and fracture, particularly of structural connections.

ZEIT3753 Design of Ships and High-Speed Craft

This course introduces the preliminary ship design and construction process with emphasis on naval ship types and requirements. Methods for the initial estimation of vessel performance, dimensions, weights/centres and volumetric capacity are practised before undertaking ship geometry definition using software tools to generate preliminary hull lines and general arrangement drawings. Requirements for load lines, freeboard and commercial vessel tonnage admeasurement are presented, followed by ocean environment and seakeeping considerations. The case of IMO High Speed Craft design, regulation and operation is specifically considered. A typical ship specification document is presented as an exemplar.

ZEIT4750 Ship Design Project A

In response to a nominated design brief, all essential ship design tasks are individually completed to a preliminary stage in Ship Design Project A: Principal particulars; hull lines; general arrangement; estimate of weights and centres; resistance calculation; machinery selection; performance prediction and structural design, culminating in a presentation. To assist with the design project, advanced structural design considerations are addressed, namely optimisation, vibration, noise, shock, slamming, whipping, risk and drawing practices.

ZEIT4751 Ship Design Project B

In response to a nominated design brief, all final ship design tasks are individually completed in Ship Design Project B: Principal particulars; hull lines; general arrangement; estimate of weights and centres; stability; resistance; machinery; performance prediction and structural

design, culminating in the production of a consolidated final design report, presented and defended in-class at the end of semester.

ZEIT4752 Ship Propulsion and Marine Engineering

This fourth-year course equips students with knowledge and skills required to analyse and design marine thermo-fluid engineering equipment used on board a variety of ship types. This knowledge can then be applied to obtaining effective engineering design solutions for these systems, so that they can meet their functional purposes within international statutory and regulatory frameworks.

BEYOND THE CORE NAVAL ARCHITECTURE COURSES

While the eight core discipline courses represent 25% of the formal course work for the degree, students are indirectly addressing questions of relevance to NA throughout the other 75% in the materials, mechanics, structures and thermo-fluids courses. In the thermo fluids stream, delivered to mechanical, aeronautical and NA students, they are exposed to concepts of buoyancy, metacentre, boundary layer, and frictional resistance amongst others. Similarly, the materials and structures courses address relevant failure modes such as fatigue, brittle fracture, buckling and yield and the relevant impacts of corrosion and stress concentration. It is expected that the final year thesis topics chosen by individual students would also relate to the discipline and contribute to the relevant research directions being pursued within the School. Even without a NA degree being available, previous students have pursued maritime projects with recent examples included in references [2-18]. Current thesis projects in 2022 relate to developing our flume, pool, and open water testing capabilities, and the continuation of work with the hybrid submersible UAV, through design optimisation.

It follows that the two technical electives provide opportunities for NA application of specific topics. The documented set of electives listed within the program include:

- ZEIT3502 Vibration and Control Engineering
- ZEIT3701 Heat Transfer and Refrigeration
- ZEIT4003 Computational Fluid Dynamics
- ZEIT4006 Structural Integrity Analysis
- ZEIT4014 Impact Dynamics
- ZEIT4503 Applied Thermodynamics and Propulsion
- ZEIT4504 Electrical and Mechanical Plant
- ZEIT4603 Finite Element Methods
- ZEIT4702 Microcontroller-based Instrumentation

FIELD TRIPS

It is planned that each student undertakes three significant NA field trips allowing them to gain an appreciation and understanding of NA practice. In Semester 1 of third Year, there will be a trip to Sydney which will include visits to Garden Island Dockyard, a naval architecture consultancy, a classification society, and the conduct of an inclining experiment. In Semester 1 of fourth Year, while not aligned with any one course but to the entire program, there will be a trip to Tasmania, to Launceston (AMC) and Hobart (Incat and related sites). This AMC-centred trip represents a mandatory 15-day work experience block during which experiments in the towing tank and seakeeping basin will be conducted and familiarisation with other AMC facilities will be achieved. A training cruise will also be conducted on AMC's *Bluefin* (or alternatively on one of Navy's assets). The third trip will target attending the biennial INDO Pacific International Maritime Conference and Exhibition. Other opportunities as they arise will be taken to visit shipyards, maritime organisations, navy bases and ships.

THE STUDENT BODY

As stated earlier, UNSW Canberra anticipates ramping up to an average of 10-15 graduates per year, but it is expected that this will take a few years to achieve, as the knowledge of the opportunity at UNSW Canberra is spread through secondary schools and the maritime sector. For all involved, staff and students, it represents a fantastic staff / student ratio and a close-knit learning community.

Specifically, with the program's "grey-ship" focus, it should attract and excite those that are specifically interested in warship design and construction. The year cohorts may comprise both uniformed and civilian students. While ADFA is a military base established in 1986, and originally operated predominantly at the undergraduate level, training and educating only Midshipmen and Officer Cadets, today it is open to civilian students (some conditions apply).

More broadly, there is a range of categories of students now able to study at UNSW Canberra and pursue a NA education. Those in uniform may be either a Training Officer (TO – Officer Cadet or Midshipmen) in the Australian Defence Force, a mature age student serving in the ADF (with a variety of ranks who would then belong to the Advanced Student Squadron), or a member of a foreign military gaining training and education at ADFA. Those that are civilian may be Defence sponsored under the Defence Civilian Undergraduate Scholarship (DCUS) scheme or they may be regular fee-paying non-defence students with Commonwealth support.

To arrive at ADFA, School Leavers aspiring to join the ADF must apply:

- through Defence Force Recruiting (DFR) for ADF positions (culminating in Service based Officer Selection Boards), and
- to UNSW Canberra via the Universities Admission Centre (UAC).

Civilian students seeking a DCUS scholarship would have a similar two-step process of application while fee-paying students would only need to apply via UAC.

Those wishing to take advantage of the previously described 2 + 2 opportunity would need to apply for transfer to UNSW Canberra through the UNSW Student Administration processes.

STAFFING AND STAKEHOLDERS

The authors represent the core staff for the discipline, and both are graduates of the UNSW Sydney NA program. Warren has been an academic at UNSW Canberra, since 1998. This followed a 20-year career serving in a range of naval architectural roles with the Department of Defence (Navy). While predominantly teaching design-based courses within the Mechanical and Aeronautical programs, Warren has provided a maritime flavour in the School over the years. With the decision to stand up a full naval architectural discipline, Warren is the inaugural Program Coordinator and has turned his full attention to its success. David accepted an offer to transfer to UNSW Canberra in September 2020. He had been the Program Coordinator for NA at UNSW Sydney, assuming that role from Phil Helmore in 2015. Following the closure of the UNSW Sydney NA program, from 2018-2020, David taught mechanical design, composite materials engineering and capstone final year projects at UNSW Sydney. Prior to joining the University, David enjoyed a lengthy career in industry as a practicing naval architect, chartered engineer and business manager.

Additional staff will be recruited, and a range of part-time and casual contributions will be made by professionals engaged from across the sector.

We approached potential stakeholders through a survey in early 2021 and received responses from Navy, Class Societies, Government, and Industry. Responses were received from:

- Head Navy Engineering, HNE, (as the Program Sponsor);
- Naval Construction Branch (Navy/CASG);
- Navy Education, Navy People Branch;
- Lloyds Register;
- DNV;
- Transport for NSW, Maritime;
- Austal Ships;
- Australian Maritime Technologies (AMT);
- International Maritime Consultants Pty. Ltd., and
- Thales Australia.

The invitation remains open to other experts and organisations that would like to contribute to the quality of the naval architecture programs at UNSW Canberra.

LOCAL RESOURCES

We already have a few ship models, and tanks to float them in, a sample of which is shown in Figure 1. This collection will naturally grow. We also have Armfield fluid benches, flow tables and their ship stability rig for demonstration. All current SEIT[4] School facilities including wind tunnels, material testing laboratories, student workshops and computer rooms are also available.



Figure 1 – Set up for a Model Inclining Experiment with an Armfield Hydraulics Bench (back left) (Photo – Warren Smith)

In terms of major infrastructure supporting NA demonstration and research activities, the primary facilities being developed are the School's two flumes. Projects in 2022 are adding wave making, carriage and ship model instrumentation capabilities. These will underpin the conduct of resistance, powering and seakeeping model tests. The flumes are depicted in Figure 2, with the original in the foreground and the newly installed unit with white frame, currently under construction.

Beyond the School, the ADFA and Duntroon aquatic pools have been used for experiments in the past and there is potential to leverage use of the ADFA Boatshed and its assets at Yarralumla Bay on Lake Burley Griffin, to facilitate an open water lake test facility. Undergraduate student thesis projects are being undertaken in 2022 to further explore and build model test capabilities in these pool and open water environments.

In addition to the software that is generally available in the School (including Dassault 3D Experience (CATIA), MATLAB, ANSYS for FEA and Star CCM+ for CFD), the prime discipline-based naval architecture software is Maxsurf, which is introduced to students in ZEIT3750.

[4] School of Engineering and Information Technology

Packages such as Rhino, Navcad Hydrocomp and/or the Wolfson Unit's Marine Design Software may be acquired.

Finally, with the closure of NA at UNSW Sydney, the UNSW Library NA holdings will be consolidated in Canberra during 2022.



Figure 2 – UNSW Canberra Flumes supporting Civil Engineering and Naval Architecture
(new white flume under construction – expected commissioning mid 2022)
(Photo – Warren Smith)

RESEARCH POSSIBILITIES

It is reasonable that our current preoccupation is on preparing to teach the new courses described earlier. However, the mature and thriving enterprise we aspire to build must in parallel develop research capability, as it will underpin the teaching, provide avenues for projects, and build reputation and esteem. We will always welcome higher degree research (HDR) students, that is, those studying for PhD's and Masters degrees. Some examples of past and current HDR students working in the domain include [19-22]. New students are expected to join in 2022.

Looking forward (as discussed in [1]), with the existing multidisciplinary nature of the School and UNSW Canberra more widely, we expect to align with existing research strengths, bringing a maritime flavour to them.

"For example, strengths in the following can be leveraged:

- *Optimisation and Design, as related to ships, boats and submarines and systems;*

- *Fluid & Fluid-structure Interaction, as related to numerical (CFD) simulations, model tests and full-scale trials;*
- *Trusted Autonomy, as related to surface and sub-surface vessels; and*
- *Advanced Materials and Impact Dynamics, as related to ship survivability and vulnerability issues."*

TO CONCLUDE

As expressed in [1]:

- We are excited to be creating a high-quality undergraduate NA program that is grey-ship focussed.
- We have welcomed our first students in 2022 and we anticipate producing our first graduates in 2023.
- We look forward to growing relevant research and postgraduate coursework opportunities.
- We reside within a strong multidisciplinary environment which has a unique relationship to Defence.
- We appreciate and acknowledge Navy's support and particularly that of the Head Navy Engineering (past and present).
- We appreciate the cooperation of AMC in support of our planned field trip to visit and use their facilities.
- We appreciate the engagement of our stakeholders, and we invite all those interested to come aboard.
- We are keen to answer any questions arising – now and in the future! – from stakeholders and prospective students.

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Maritime Industry Research Past, Present and Future – Collaboration between Academia and Industry

Douglas Potts, Australian Maritime College, douglas.potts@utas.edu.au

Michael Woodward, Australian Maritime College, michael.woodward@utas.edu.au

Jonathan Binns, Australian Maritime College, Jonathan.binns@utas.edu.au

Zhi Leong, Australian Maritime College, zhi.leong@utas.edu.au

Adam Waldie, Adam.Waldie@thalesgroup.com.au

Norman Dong, Norman.Dong@thalesgroup.com.au

Hayden Marcollo, AMOG Consulting, hayden.marcollo@amog.consulting

Chris White: christopher.white@amc.edu.au

Damien Guihen, damien.guihen@utas.edu.au

Jen Smit, jennifer.smit@utas.edu.au

ABSTRACT

In 2016, the Defence White Paper and its compendium of associated strategic policy and force structure plans specifically called on industry and academia for innovation and research supporting capability development. It also called for the generation of sovereign industrial capability in areas such as shipbuilding, submarine sustainment, and test and evaluation. All Australian universities and industry have taken this call very seriously, which is evident within the undersea applications most relevant to the design, build, operation, and maintenance of submersible vessels.

The Australian Maritime College (AMC) at the University of Tasmania (UTAS) has the most comprehensive suite of maritime industry research facilities within Australia. The cavitation tunnel, the towing tank and the model test basin have unique capabilities, extending the reach of our research arms. But it is the combination of the suite of facilities, the directed education and the training together with working closely with an ecosystem of industry partners, that provides the means to solve industry problems.

This paper describes an overview of example projects based within the AMC (the past) with direct relevance for the maritime Defence industry. Examples of past use of cross disciplines to provide capability life-cycle analysis with direct industry relevance include activities such as:

- submersible autonomy training program design for Defence;
- experimental and numerical determination of bluff body/free surface operation.

The paper then describes one specific current project:

- The acoustic test facility of the Oceania Underwater Test and Evaluation Centre (OUTEC);

The paper will then focus on elements for the future:

- Increasing the capacity and capability of maritime engineering facilities;
- Increasing multi-disciplinary research through multi-university collaborations;
- Increasing and cementing secure ICT facilities

Keywords: maritime industry; research & development; autonomy; hydrodynamics

INTRODUCTION

This paper has been constructed from descriptions of four projects currently underway based at the Australian Maritime College (AMC), University of Tasmania (UTAS). Each of these four projects has direct relevance to submersible vehicles, each providing key capabilities to enable their development. But the most significant factor that is common across all four projects is that they depend on collaboration between industry, government and academia. Each of these sectors brings unique capability and capacity, the combination provides solutions to the identification and execution of R&D needed to produce regionally superior, sovereign capability.

SUBMERSIBLE AUTONOMY TRAINING

AMC has an outstanding track record in the provision of training for Autonomous Maritime Systems (AMS) and has been training Navy personnel in the operation of both Autonomous Underwater Vehicles (AUVs) and Un-crewed Surface Vessels (USVs) since 2017. In July 2020, AMC was selected by Navy Training Force as its preferred training provider to continue delivering AMS training until 2023. This agreement supports the introduction of autonomous systems as part of SEA1778 (Task Group MCM) and 1770 (Rapid Environmental Assessment – Maritime).

AMC's AMS training is allowing Navy to effectively transition its workforce towards maritime autonomy in both surface and subsurface domains. With AMC's support, Navy is growing the knowledge, skills and experience required to accept, introduce, and operate the robotic and autonomous systems selected under future projects. The Navy RAS-AI Strategy 2040, states that RAS-AI adoption inside Navy will require 'training and workforce transformation; research & development; and building collaborative partnerships…..' The continued use of AMC to provide AMS training not only supports future project outcomes but will also significantly contribute towards the implementation of the RAS-AI Strategy 2040.

Following extensive consultation with Navy Training and Project SEA 1778 and 1770 staff, AMC has a developed a suite of AUV and USV training courses. The AUV related courses are:

- Basic AUV Operator Course;
- AUV Mission Controller Course (MCC);
- AUV Technical Course;
- Autonomous Marine System – Underwater Vehicles.

Each of these courses develops skills and capabilities from the introductory level through to advanced mission planning and fault finding. The qualifications can be performed stepwise independently or as part of micro-credentialling to provide credit towards graduate certificates and masters programs.

The proposed USV related courses are:

- Small Vessel Master Course (SVMC);
- USV Operator Course;
- Autonomous Marine System – MCM Application Course (Towing).

AMC has further increased the scope and diversity of our AMS training through the inclusion of a 2-day introductory or awareness level AMS Fundamentals Course. The AMS Fundamentals Course being only 2-days in length is highly suitable to increase the awareness and develop an initial understanding of Robotics and Autonomous Maritime Systems across a large percentage of Navy's workforce.

A flow chart outlining AMC's AMS training continuum for Navy candidates is shown in Figure 1 with RAN personnel undergoing training shown in Figure 2.

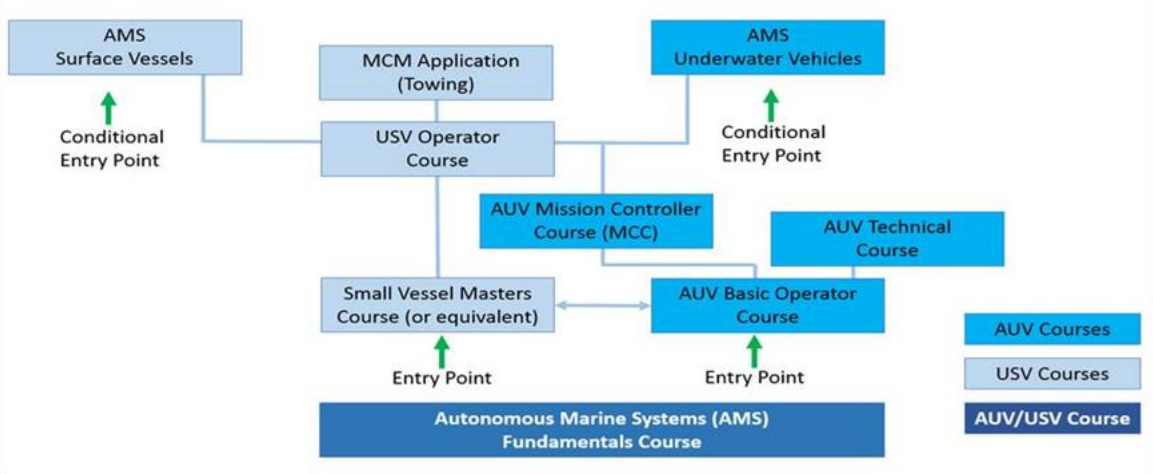


Figure 1 Flowchart showing the interrelationship between the course offering in the autonomous systems space

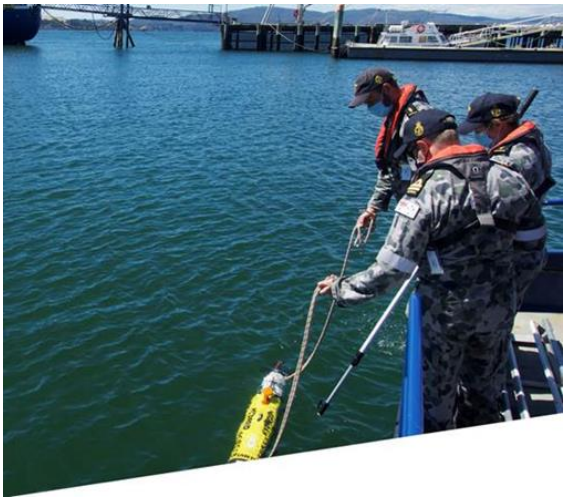


Figure 2 Hands-on training is essential to providing skills and capability for successful deployment. RAN personnel shown at the AMC's Beauty Point facility initiating missions for submersible platforms

Since commencing AMS training in 2017, post-course feedback survey results by Navy personnel show very strong agreement (80-100%) that course was useful to future career prospects.

The use of education to underpin deeper R&D has always been a part of the AMC. In the climate of skills and capability development to produce regionally superior platforms, this element is even more important.

EXPERIMENTAL AND NUMERICAL DETERMINATION OF BLUFF BODY AND FREE SURFACE INTERACTIONS

Bluff body hydrodynamic analysis is a difficult problem due to length and time scale variations. It is further complicated when a free-surface is introduced creating two interacting domains and the potential for multiphase flows. See for example the images in Figure 3 which show two bluff bodies being towed at small velocity variations.

Bluff body free surface flows are, important to engineering, for example every bridge pylon that has ever experienced a tidal flow. However, with the complexity of the system a typical engineering approach would be to simply apply higher than usual safety factors.

Defence industry is interested in fluid interaction with bluff bodies due to geometric requirements trumping hydrodynamic efficiency. For example, large arrays of sensors require very specific arrangement relative to the oncoming flow and interfaces between submerged vessels and the air above, having severe space and mechanical operational restrictions. These design requirements drive the use of very bluff bodies used at speeds that produce significant non-linear wakes. Characterising the flow over such bluff bodies directs the design in terms of the hydrodynamic forces, induced vibrations and effects on signature production.

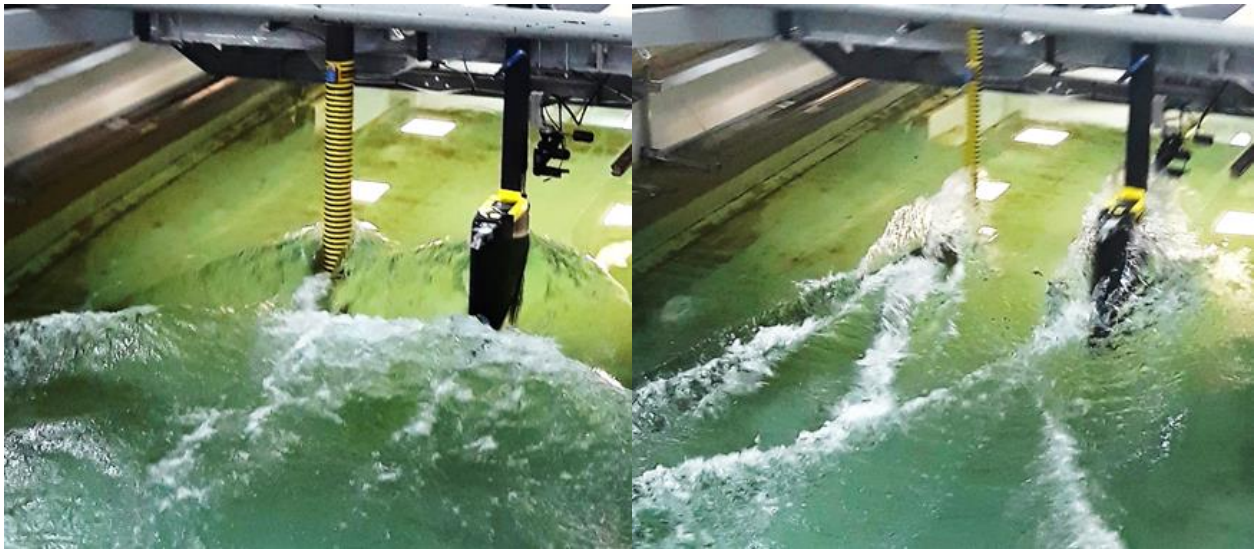


Figure 3 Experimental demonstration of bluff bodies in a free surface. (Left) is the lowest velocity, (right) the highest. The amount of spray generated requires significant variations in length and time scale

Significant work has been conducted on experimental methods relating to the manner in which structures vibrate [1, 2] and the interaction of the subsurface boundary with the flow regimes of

importance [3, 4]. By non-dimensionalising this data, design engineers can produce baseline parameters from which to progress designs. The detailed flow field shown in Figure 3 requires the specific shape and subsurface boundary condition to be replicated. This is not possible in an experimental approach.

To progress the designs of such shapes, numerical experiments can be performed such that closer representations of the lower boundary condition and intended geometry can be analysed. Such numerical work has only been computationally possible in the last 20 years due to the high demand on computing resources [5-7]. Bringing this work to a realisable state, capable of producing design results has taken the combined collaboration of industry, government and academia [8].

OUTEC (OCEANIA UNDERWATER TEST AND EVALUATION CENTRE) ACOUSTIC TEST FACILITY

The role of any experimental research facility is to be positioned to verify as-yet unknown scientific questions while at the same time remain true to its core competencies. That is, by developing research facilities that are flexible and adaptable but still have a clear specialisation visible to the client audience. To achieve this goal, Thales together with the support of the Australian Maritime College (AMC) and AMOG have undertaken a detailed study of the technical and commercial viability.

Thales Australia CEO Chris Jenkins announced that the initiative was part of the organisation's commitment to work collaboratively with leading Australian SMEs and universities to deliver high technology, leading-edge solutions for Defence, see Figure 4.

The envisaged capability has a particularly strong synergy with the University of Tasmania strategic plan, that strives to build locally based but globally competitive and sustainable enterprises. The unique research capability will support the Australian Naval Shipbuilding program, create jobs in the local community, and provide indirect regional economic impact.

AMC has both a baseline of experimental facilities and staff with core and world recognised competencies in experimental hydrodynamics. Tasmania has as part of its unique geography, large and deep natural and dammed bodies of water in uniquely "quiet" locations. In this context, quiet refers to several aspects including low population resulting in low human activity, distance from road induce vibration and free from powerline electromagnetic signatures. The objective of OUTEC is to capitalise on this synergy, by offering a unique and novel open-water hydrodynamic testing capability.

A review has been conducted to identify the most suitable locations. This included aspects such as geography and current usage of the lakes, logistics and access, security and noise/disturbance aspects of the surrounding environment together with evaluating and measuring the associated environmental conditions. In parallel, meetings/communications have occurred between parties of interest, such as Hydro Tasmania (the power company responsible for the dams on the lakes), a Heritage Association, local government and local community representatives.

Following the initial studies, suitable candidate lakes were identified, and more detailed hydro-acoustic surveys are currently underway; conducted using the AMC capability in Autonomous Underwater vehicles.

To assure the long-term viability of the proposed capability, complementary diversification studies are being undertaken by AMC. For example, AMC participated in a project led by Adelaide University to research the viability of an Australian free-running submarine research platform. AMC has started investigations into the viability of conducting surface ship manoeuvring experiment using free-running models; with a student project looking at digital-twin models for battery-driven platforms. Complementary work is also being undertaken in partnership between AMC and the Australian Antarctic Division to research the hydrodynamic behaviour of towed devices that will be deployed behind the new Icebreaker RSV Nuyina; with jointly funded PhD places in position. Each of the above is intended to build a critical mass in capacity and capability when building competency for the lake testing.

Notwithstanding, the core purpose and activity of OUTEC is to support the Department of Defence's Naval Shipbuilding Plan through developing sovereign capability. This will be achieved in the short-term through the testing and calibration of Thales underwater acoustic technologies including Sonar hydrophones, transducers and arrays. Capitalising on these commercial activities and built competencies, the longer-term objective includes the realisation of unique hydro-acoustic theoretical and experimental research capabilities and the positive community impact that this can bring.

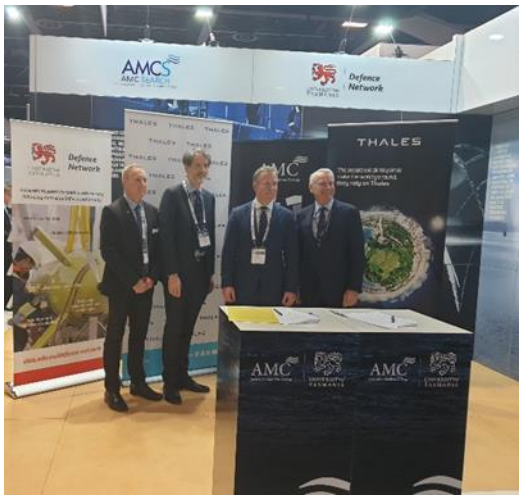


Figure 4 The leadership of the University of Tasmania, Thales and the Tasmanian State Government announcing the initial stages leading to the OUTEC in late 2019

THE FUTURE OF MARITIME ENGINEERING FACILITIES – INCREASING CAPACITY AND CAPABILITY AND SHORING UP ICT

Education, training, research and consultancy all play key parts in engaging with industry. But it is bringing all the parties together, in the one place, at the one time that will cement these relationships and drive our capability on.

The Defence and Maritime Innovation and Design Precinct (DMIDP) is designed to help the Australian Government to deliver on its Naval Shipbuilding Enterprise, by supporting the high value testing and evaluation needs of the RAN, as well as contribute enhanced R&D to maritime

industries. The Australian Government has committed $30M to Phase 1 of the Precinct, with further stages on the horizon, ensuring both sustainment and enhancement of current capability.

The Australian Maritime College (AMC), Australia's national institute for maritime education, training and research, has a suite of the Southern Hemisphere's best maritime-related research facilities which will enable critical design inputs into the building of 57 Naval vessels over the next thirty years.

Every state in Australia has a role to play and Tasmania has a unique position to provide significant input in the regeneration of Australia's naval capabilities. The intention from the outset has been for the Precinct to be a venue where contractors, Government agencies and diverse industry stakeholders come together to conduct tests and look at the design issues they are facing - marking out the way forward for better design, operated more efficiently together with greater safety. One of the earlier engagement workshops was held in Launceston, Tasmania, and included representatives from industry, government and academia, see Figure 5 for the end of workshop photo.

An immediate outcome of the engagement workshops conducted throughout the generation of the plans for the Precinct was that the University can provide a conduit between Defence and Industry in terms of realising new ideas through capability, but also in terms of providing access to high grade infrastructure.

To maintain sovereign capability, the Precinct's main task is to increase capacity of the existing facilities at the AMC and to initiate the build program for new facilities. At AMC's Newnham campus, these plans include three key projects harnessing advances in hydrodynamic testing facilities specifically targeted at the R&D questions required from submersible vehicles: a proposal for a second cavitation laboratory, a new 200 m long towing tank and a collaborative user space and Industry Hub. It is the third of these facilities that this paper will focus on as it encompasses the aspirations for providing a blended environment for academics, Defence and Industry alike.

The Precinct Industry Hub and common user facility includes a generalist secure area within the first floor which will allow secure accommodation for allied Defence and maritime industry entrepreneurs and established businesses. Signifying a change in the more usual campus landscape, the incubator is imagined as a hive of activity, offering start up 'bootcamps' for innovative businesses, collaborative open areas, conference space and seminar areas. The lower floor provides access to accredited spaces for secure work, along with specialist areas for PhD students and other University organisations requiring access to Defence secure environments. Interest from local and national businesses is increasing as the value proposition offered to industry stakeholders looking to engage with Defence are clear. Firstly, being able to benefit from proximity to the AMC's researchers, allows for close collaboration on identifiable industry 'problems', leading to research scenarios that can be as much industry lead as research driven. Secondly, industry has the opportunity to participate in co-working spaces with other Defence industry stakeholders, providing a space to seek collaborations while simultaneously 'keeping an eye on the competitors. And thirdly, the common user facility will provide immediate access to Defence secure networks, provisioned with zone 2 and zone 4 spaces that allow for secure networking and collaboration with other industry primes as well as with Defence.

In summary, the provision of industry hubs as portals for universities to engage with both government and business are not a new idea – from the mid 2000's, business incubators have been seen as a way of fostering innovation and reinvigorating the domain of applied research on campuses. As a mechanism for generating revenue, there is much to be gained for universities challenged by new funding models and for industry there is the promise of positive connections and proximity to cutting edge research along with attractive tenancy terms. And, as Margaret Weatley identifies "innovation is fostered by information gathered from new connections… from active collegial networks, and fluid open boundaries. Innovation arises from ongoing circles of exchange, where information is not just accumulated or stored, but created. Knowledge is generated anew from connections that weren't there before" [9, 10].

The DMIDP Industry Hub will be a portal for continuing the connections with Defence and maritime industry we have already established, with the aim of broadening the reach and relevance of our partnerships and consultancies.



Figure 5 Participants at an early engagement workshop in October 2018, co-designing the future of a Newnham based Defence Precinct

THE FUTURE OF UNIVERSITIES HOSTING DEFENCE AND DEFENCE INDUSTRIES ON CAMPUS.

As the DMIDP is developing its proposed suite of capabilities and working with DSTG to codesign a business case to procure additional nationally significant testing and evaluation infrastructure, consideration is being given to the sustainment of these relatively large-scale projects; specifically the identifiable operating costs in terms of personnel and other operating expenditures. In developing nationally significant facilities, universities must take care not to duplicate assets; rather, to focus on existing capability and research strengths that provide specific and defence and industry needs.

Establishment of a sovereign capability framework to ensure that multiple complementary 'centres of excellence' can be maintained at each of our leading institutions will be key to the future of integrating Defence and industry on Australian campuses. It is envisaged the DMIDP will provide a useful exemplar for creating other defence focused research centres of excellence on Australian campuses.

As such, the DMIDP will be strategically positioned to provide Australia's Centre of Excellence for Maritime Engineering and Hydrodynamics.

CONCLUSIONS

The use of world class facilities has been explained in direct reference to maritime defence projects. These projects have brought a broad range of support for the research conducted. The future for advanced experimental and numerical analysis for Australia with direct industry relevance will continue to be integrated with both education and associated training.

Supporting national capability must be carried out with an eye to creating complementary centres-of-excellence, with Government cognisance of the true cost of sovereign capability and ensuring maritime related testing and evaluation facilities can continue to provide value across the defence and maritime sectors.

ACKNOWLEDGEMENTS

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Nav Archs (You Gotta) Fight For Your Right (To Margins)!

Levi Catton, Gibbs & Cox Australia (levi.catton@gibbscox.com.au)

ABSTRACT

Warship design and build is technically complex, involving highly integrated engineering products that form an essential contribution to the national security of their sovereign nation.

Warship prototypes are a luxury that most nations simply cannot afford, so it's imperative that every effort is made to get the design right first time, especially as the service life of a warship is typically 25 years. Our choices have long term consequences.

Margins are needed to 1) address uncertainty in acquisition; 2) ensure adequate reserve levels of safety throughout the service life of the program; and 3) provide capacity for technology upgrades to ensure warships remain effective in an evolving threat environment.

Unfortunately, in past and present naval programs around the world we continue to observe chronic optimism whereby margins are traded off for up-front capability delivery on the assumption that a little margin will be OK, and Nav Archs are trying to stretch the laws of physics to stay in distant touch with appropriate margining policy.

In order to maximise the chances of success, Nav Archs must learn from previous programs and this learning involves the application of and adherence to appropriate margining practices throughout the design, build and sustainment phases.

The purpose of this paper is threefold;

1. Act as a reminder to Nav Archs – (You Gotta) Fight For Your Right (To Margins)!

2. Show that proper margins are an actual warfighting asset, worth paying for up front

3. Highlight the importance of disciplined data collection and learning to benefit our successors

INTRODUCTION

Warships form an essential contribution to national security, and our choices in warship programs have significant long-term consequences. Warship design and build is also technically very complex, involving highly integrated engineering products with in the order of 1-2 million parts. Warships are developed through long and complex design and construction processes, and have long service lives, ranging between 15 and 50 years. There are a range of major uncertainties over the course of this Capability Lifecycle (CLC), which we seek to prepare for in what we hope is an intelligent way.

To address these uncertainties we use a range of hedging and de-risking measures. One of the primary measures is to incorporate a range of technical margins into the design. Margins are applied with the intention to 1) mitigate uncertainty in acquisition processes; 2) ensure adequate reserve levels of safety throughout the service life of the program; and 3) provide capacity for technology and capability upgrades to ensure warships remain effective and competitive in an evolving threat environment.

The extent to which margins achieve these effects is correlated to the amount of margins applied and how effectively they are managed. The more margin available, the greater uncertainty the margin is able to cover. Since margins are instantiated through physical characteristics like size, weight, and system capacity, margins cost money, and also compete for these parameters with the baseline warfighting capability of the ship at delivery. In acquisition there is typically a direct tension between the application of margins on the one hand, and cost and delivered capability objectives on the other hand.

In past and present naval programs around the world we observe unrealistic optimism in relation to the definition of margin positions (Reference 1), whereby margins are traded off for up-front capability delivery on the assumption that a little margin will be OK. Historical and current data shows that margins continue to be consumed more or less at trend rates, which are in some cases not supported by the margins we are designing into new ships. This means that some classes fall into technical margin deficits well before the end of the service life, and a range of quite drastic measures have to be taken to address this. This pattern is exhibited in allied navies, as well as being a central characteristic of Australian surface combatant programs over the last three decades, and will likely continue to be a challenge going forward.

Given this context, there are a few questions we can usefully ask:

1) How are we advocating for and enforcing the application of correct margin budgets?

2) What are the long-term consequences of lower than required margin budgets?

3) Do we understand what the correct margin budgets are?

MARGIN BUDGETTING

Ship design is an iterative process in which key design parameters are balanced against one another as the various design elements, such as hull geometry, structure, propulsion system, energy storage, combat and payload systems, etc. are refined. The key parameters governing

vessel margins are locked in relatively early during the design process. Therefore it is important to establish a clear set of appropriate margins requirements, along with effective monitoring and enforcement processes, at the outset of design activity.

There are different types of margins applied at various stages of the CLC, by different parties within each program, to manage various types of uncertainty. These different margins are applied in varying amounts across different design characteristics, systems and services. Ultimately, each margin applied at various stages of the CLC contributes to ensuring that the capability required by Navy is delivered and remains available and relevant throughout the service life of the class.

While weight and stability margins are often a key consideration, it is also typical and important to apply and manage margins across a range of systems and characteristics such as HVAC, chilled water, electrical power, data and signal processing capacity, structure, and space. The planned application of margins across different margins types, when documented, is known as a margin budget.

PURPOSES AND TYPES OF MARGINS

There are three main categories of purpose for which we apply margins to naval ship designs: mitigating uncertainty in acquisition; ensuring safety throughout the service life; and providing capacity for technology upgrades in an evolving threat environment.

Mitigating Uncertainty in Acquisition

The acquisition phase faces the most diverse set of uncertainties, and a range of margins are included in the design for use during this phase. Regarding terminology, this paper uses terms in current use in Australian surface combatant circles, however different countries and marine design sectors do use different terms to describe the same fundamental concepts. As always, it's prudent to check your counterparty understands terms the same way you are using them!

Design Margin During design, the designer faces uncertainty around design characteristics. This uncertainty is gradually retired as the design evolves and matures towards a production baseline. To address this uncertainty, the designer applies margin to account for the difference between early design estimates of the system that is intended to meet the requirements (at a low level of confidence), and the out-turned production baseline that is expected to meet the requirements (at a moderate level of confidence). The amount of design margin should address the amount of development risk and design uncertainty in the program. A highly developmental program will require a wider and deeper suite of margins compared with a program based on incremental change to an existing well-understood in-service design.

Build Margin During production, the shipbuilder faces uncertainty related to how accurately their supply chain and their own shipbuilding processes can produce the design and deliver the design characteristics and performance in the physical ship. Additionally, ship designs are complex and include errors, so the shipbuilder also faces uncertainty related to the producibility of the design and the quality and accuracy of the production data. The shipbuilder applies margins to address these uncertainties. Again the amount of margin

applied must account for the level of uncertainty in production processes and production design maturity. If the designer and builder are the same enterprise, design and build margins are sometimes combined and termed DBM. This is poor margin budgeting practice, as the design and build divisions of the enterprise are separate entities and need to have clearly separated margin budgets to address the different risks that those divisions face. Following expiry of warranties, unused design margin and build margin are rolled into Capability Upgrade Margin (CUM) or In-Service Growth Margin (IGM).

Performance Margin Some performance parameters are considered particularly critical for the capability, particularly at risk of achievement (likely due to a demanding or developmental requirement), or represent some other special risk. Typical examples include signature performance, and top speed. Performance margins can be applied by the designer to mitigate the risk that the customer requirement is not met, or may be specified by the customer as a mandated additional risk mitigation to the designer's margins. On occasion the customer may not disclose the absolute performance requirement to the designer, but will propose a requirement with a margin built in to further hedge risk in the designer's margins.

Contract Modification Margin (CMM) Due to the complexity of naval ships, and the typically long development time from initial requirements establishment to delivery, there is often some changes in requirements or Government Furnished Material (GFM) allocations during the acquisition phase. The customer may include margins to account for these uncertainties during design and build. Unused CMM at delivery is rolled into CUM or IGM.

Ensuring Safety Throughout the Service Life

During the in-service phase, the ship must remain within safe operating limits with respect to structural strength, stability, and provision of critical services. This need is addressed by the application of In-Service Growth Margins (IGM).

In-Service Growth Margins The customer includes margins at the design stage to allow for unplanned, unattributable or uncontrolled changes that typically occur during the service life. These changes occur as a result of obsolescence management, general sustainment activities, accumulation of unconfigured equipment, progressive degradation of system performance over time, accumulation of coatings, etc. These changes can be forecast based on historical data, and various standards offer recommendations on the amount of margins to apply in early design for different ship types, based on analysis of technical records from current and previous classes.

Providing Capacity for Technology Upgrades in an Evolving Threat Environment

During the in-service phase, the ship must remain relevant to and competitive with the evolving threat environment. If the ship is not a credible threat to adversary actors expected within the allocated mission portfolio, it cannot be expected to perform those intended missions with a reasonable probability of success and therefore loses its primary purpose and value as a military asset. If the ship is not able to defend itself against the expected threat environment at a reasonable level of risk, it should not be operated in that threat environment and again loses its value as a military asset.

The threat environment evolves in proportion with technological development of sensors and effectors, which have refresh cycles in the order of 2-5 years and lifecycles in the order of 1-2 decades. Ships as a complete system have refresh cycles of 1-2 decades and lifecyles of 2-4 decades. This means that ships need to be able to receive new technologies throughout the service life, while remaining within design safety limits and service capacities. This need is addressed by the application of CUM.

Capability Upgrade Margin The customer includes margins to address the uncertainty around technology development, the changing threat environment over the life of the vessel, and the consequent probability of needing to add equipment or change the configuration to remain competitive and effective in the evolving threat environment. The amount of margins applied for capability upgrade depends on the type of missions the ship performs, the expected pace of technology development associated with the threat environment, forecasts of the types of systems that will be needed to address expected changes in the threat environment. CUM should also address the level of uncertainty in such assessments. There may be general consideration of a substantial mid-life re-fit as part of this allocation.

FIGHT FOR YOUR RIGHT TO MARGINS!

How are we advocating for and enforcing the application of correct margin budgets?

The Zero-Sum Game

After the concept design is chilled, management of the margin budget becomes a quasi zero-sum game. It's about as hard to find extra margin in the design late in the design schedule as it is to find extra money in the budget late in the design schedule. Any overconsumption of margin during acquisition is likely to deplete the available customer margins required to upgrade and sustain the vessel through life and maintain the relevance and effectiveness of the class.

As a result of this zero-sum situation, margin consumption issues can quickly become challenging. It is not unusual for a margin consumer in the active phase of a project (e.g. design or build) to consume over their budget, and common themes that go along with this situation can be colloquially summarised as follows:

The margin consumers' claim	**Translation**	**Outcome**
We will find a way to make up the margin deficit through other mitigating changes	We should spend more budget (we don't have enough) to recover the deficit	Some of the deficit might be recovered with a cost penalty
Later consumers will find a way to make up the difference through other mitigating changes (with suggestions)	Someone else should spend some of their budget (they have plently) to recover our deficit	Some of the deficit might be recovered with a cost or other penalty
Later consumers don't actually need all the margin in their budgets because they can do fine with less (with justifications)	The next phase is less important than our phase The next phase is less informed than us as to what they need	The deficit is passed on right through the next phase because they actually need their margin budget. Little to no deficit is recovered.

The margin consumers' claim	Translation	Outcome
Later consumers will simply have to do with less budget	We don't care about the next phase	The deficit is passed on right through the next phase because they actually need their margin budget. Little to no deficit is recovered.

Budget Discipline

In the context of the potentially contested margins management environment, a clear policy on authorities and consequences for margins use and misuse is critical to enforce constraints. It is also critical to provide oversight throughout acquisition in order to assess and mitigate any risk to the margin budget and delivery of customer margins.

In some situations the margin budget is treated as a second order constraint compared with customer functional requirements. Is this attitude justified in terms of best capability outcomes over the whole CLC? We need to carefully consider the assumptions and requirements that lead to any margin over-consumption. Commitment bias (i.e. biased towards what we have committed to as a documented requirement) and ambiguity bias (i.e. biased towards what we know we need now rather than what we might need in the uncertain future) can and do lead to requirements fixation. It can be the case that the rationale or requirement driving a margin over-consumption is actually less important than delivering that quanta of margin to address uncertainty in the service life. A design engineer with a margin challenge should consider testing this with the customer, and not blindly follow a functional requirement as the superior objective, at the cost of the margin budget. Customers can also continue to review the relative level of priority of margin requirements in comparison with other functional requirements as design proceeds. This might avoid achieving a tactical gain while suffering a strategic loss.

Budget discipline is as hard in design management as it is in financial management, and perhaps even less successfully exhibited. In a complex design environment such as ship design, the designer's first instinct should be that a solution outside the budget is not the solution. As a cultural norm this instinct is not always well established in ship acquisition and sustainment activities, where we are just as likely to believe that there is margin to cover a difference between budget and solution. We can also be too quick to permanently borrow someone else's margin budget. This behaviour may arise from the bias that since margin is a conservative hedge against uncertainty, others' need to use all their budgeted margin probably won't arise, whilst our need has been realised, and is actual and immediate and therefore justified. Finally, over-consuming margin when we haven't met our margin budget is of course the easiest course of action, and therefore a fairly popular approach!

Although it is essential to ensure margins are available to accommodate upgrades throughout the CLC, it is equally important to avoid consuming margins inefficiently because they are available. Therefore it is critical to establish a well-structured margins management system to control the use of margins not only through acquisition but throughout the service life (Reference 2).

MARGINS ARE THE FUTURE CAPABILITY

What are the long-term consequences of lower than required margin budgets?

We can reasonably assume that unattributable margin consumption will proceed generally in accordance with the relevant historical evidence and the derived trends indicated in standards. These trends are well-established and it is unrealistic to suggest that next time it will be different, without major changes in typical and entrenched operating and support patterns. In general, ISG margin shouldn't be assumed to be significantly variant to historical trends without a significant base of evidence as to how ship management would be performed differently.

This leaves CUM as the main variable quantity in the equation. So, at a basic level, margin budgets lower than indicated by evidence are likely to result in CUM getting sacrificially compressed. This is a significant capability risk. Ships are delivered with a certain required set of capabilities, but these are not the capabilities they need for competitive operations in the latter part of their service life. CUM is likely to be required to realise the capabilities required in the future. So how do we balance the importance of future needs compared with the importance of current needs?

Firstly, we need to acknowledge present bias – a dominant human decision heuristic is that a present known thing is more important than a future uncertain thing.

Secondly, in margin budgeting, as in managing many uncertainties, we would take a typical risk costing approach, in which the greater the uncertainty, the greater the hedge is required to cover that uncertainty. The required size of this hedge is accelerating with the rate of technology development and disruption. So, in assessing future capability uncertainty to budget our IGM, we need to consider the rate of change of uncertainty in the threat environment. Some current and near-future technological and operational concepts which are likely to disrupt typical design assumptions for surface combatants include:

- Long-range and persistent weaponised Autonomous Underwater Vehicles (AUV)
- Crewed / uncrewed teaming
- Advanced passive radars
- Directed energy weapons
- Hypersonics
- Quantum computing
- Quantum radars
- Cheap, pervasive, high-performance acoustic sensing, along with the AI/ML capacity to process the data volume
- Distributed lethality
- Non-carbon fuels

Compared with technology developments during the last c. 50 years of warship design, sensor and effector development and technology disruption continues to progress at a rapid rate, with major disruptors observable, and the probability of other unknown disruptors we don't yet observe, within one ship service life into the future. Dealing with the capability uncertainty in the second half of the service life may actually be strategically more important than

addressing the known capability advantage we need to achieve in the first half of the service life. Additionally, the rate of technological development may suggest that CUM will become increasingly important into the future compared with recent historical trends.

Margins are the warfighting asset for the second half of the service life, and should be considered equally important as the warfighting systems established in the delivery baseline. The logical extension of this assertion is that CUM should be deliberately traded off against cost and delivery capability as an equally important factor during acquisition. When we trade CUM away for delivery capability, we make the implicit judgement that either 1) the future capability upgrade need will not require as much margin as first thought (which is contradicted by Australian surface combatant history); or 2) addressing threat competition in the first half of the service life is more important than in the second half of the service life (which is contradicted by the technological outlook).

In relation to the first case above, we sometimes observe an assumption that future capability will be more efficient and have a smaller footprint or service demand that that which it replaces. Hence the capability upgrade provides its own margin. This argument is not uncommon but it does not get played out in the growth data or the observed scope of upgrade programs. Firstly, because capability upgrade is rarely capability neutral; more new capability tends to be added. Secondly, because it is expensive and time consuming to remove old capability and so often it stays, or the new technology is developmental so there is a desire to hold onto the old until the new is proven. In general, we should not reasonably expect upgrades to provide their own margin.

Accordingly, during acquisition we should continue to actively consider rebalancing delivery capability in favour of increased CUM, even if this materially increases capability superiority risk in the delivery baseline.

LEARNING FROM EXPERIENCE

Do we understand what the correct margin budgets are?

Cost Considerations

Technical margins are an established, and in relative terms, very cost effective means to treat uncertainty and assure utility and relevance throughout the lifecycle of a system. They are particularly important for finely balanced, high value, complex systems like naval vessels.

While the application of margin is a significant cost factor in ship acquisition, the relative cost is much lower compared with remediation activities after delivery. As an example we can observe this in the Adelaide class and ANZAC class upgrade programs. These experiences suggest that we should budget considerable margin for major changes during the life of surface combatants.

Building substantial margins into the ship during acquisition is radically cheaper and technically less constrained than seeking to develop additional margin during an upgrade project, which will present more constrained and typically less satisfactory technical outcomes for much greater cost. Accordingly, more aggressively prioritising the provision of substantial ISG and CUM at delivery is likely to materially reduce CLC total cost of ownership.

Mod-Repeat Trend Requires Larger Margin Budgets

In a modified-off-the-shelf or mod-repeat program, the modifications against the original design intent represent in additional complicating factor in margin budgeting. The recent popularity of mod-repeat acquisition strategies in NATO+2 navies reflects the perception that this strategy helps to control technical and program risk, which is true if certain conditions and boundaries are respected. Cole (Reference 3) addressed the question of the relative value presented by an off-the-shelf approach to naval acquisition.

The extent of modification applied in such programs can vary significantly, from reasonably modest changes (e.g. Hobart), to very significant changes (e.g. Hunter and CSC, DDG Flight III) to fundamental re-design (e.g. Constellation). In a mod-repeat program the "mod" aspect is often equal to or greater in scope than a major mid-life upgrade of the parent class. Since ships are not typically designed to accommodate more than one major upgrade, it is almost inherent in the acquisition strategy that the margin budget is going to be placed under significant pressure, unless very substantial secondary remediation changes are included in the modification design. Constellation is an example of this situation.

In all cases, the mod-repeat acquisition strategy places major additional stress on the margin budget, over and above the existing tensions in the original margin budget of the reference design. The current trend in surface combatants to mod-repeat reference designs makes the establishment of a generous margin budget in any new design or major re-design an even more foundational objective for designers. Based on experience we can be confident that customers will continue to require more capacity from platforms and drive platforms to their capacity limits.

Data Collection

Another area where the enterprise can benefit from an increase in discipline and consistency is in the collection and management of margins data.

There is an opportunity to collect and maintain margins data across the naval enterprise through efficient, broad-based access to a common, accurate and consistent set of margins data, covering both the active fleet and current acquisitions. This database would serve as a historical record of margin consumption, margin decisions and margin requirements for each ship in each class, and allow future regulatory and acquisition activities to benefit from experience on past and current programs, and establish margin requirements based on a reliable base of objective evidence.

EVOLVING OUR APPROACH TO MARGIN MANAGEMENT

There are a range of opportunities available to develop the approach we take to margins management in the naval enterprise. We can consider actions across four general categories: margins management culture; policy framework and standards; margins definition and management; and engineering capability (Reference 4).

Margin Management Culture

It is important to establish a strong culture of margins management and preservation across the naval enterprise. With regards to margins management, an effective organisational culture adopts a number of fundamental attributes to deliver safe and competitive platforms with sufficient margin availability through the service life.

Leadership Responsibility Leadership understands margin tradeoffs for capability versus in-service growth. Leaders ensure that effective margins management is prioritised and promoted across the organisation. Leadership behaviour demonstrates that margins are an essential element of capability delivery, sustainment and overall safety. Leadership endorse and support the continual development of processes and policies that serve as the framework for effective margins management throughout the capability lifecycle. Leaders are provided with clear, accurate and concise information necessary to make appropriate decisions.

Decision Making Authority and responsibility for margins decision making is specific and well defined. Delegated authorities follow the established process and make decisions using a consistent and systematic approach to evaluate key factors and risks. A systematic approach is used to collect and store high-quality information from all relevant sources to inform current and future decisions. Decisions which lead to the consumption of margin are recorded and preserved to influence future decision making.

Continuous Learning The organisation systematically collects and evaluates margins data, requirements and decisions to record lessons learned and identify opportunities for improvement. Lessons learned and resultant opportunities are shared across programs to support continuous learning and improvement. Effective training is provided to operators, practitioners and leaders, to ensure all members of the organisation are equipped with the necessary skills and knowledge, and are aware of their individual responsibility in regard to margins.

Communication Leaders frequently communicate and reinforce the expectation that margins are prioritised to address uncertainty. Clear communication lines across stakeholders ensure that margins information and decisions that affect margins are flowed throughout the organisation as well as across programs. Key stakeholders including the designer, builder, sustainment organisation and customer are transparent and communicate key information impacting margins in a clear, timely and effective way.

Proactivity The organisation is proactive in the management of margins. Teams consider and manage risk to margins as a priority. This includes strong cultural awareness and clear processes to reduce unnecessary or uncontrolled growth that impact upon margin availability. Operators understand the importance of maintaining control of the platform configuration and actively seek to minimise unrecorded impacts to the configuration baseline. Teams recognize and plan for future challenges by forecasting margin risk and implementing recovery solutions to address the risk prior to it being realised.

Policy Framework and Standards

Margins management policy, and any subordinate standards, would describe a systematic approach to margins management that is supported by a common framework implemented

across the naval enterprise. Conformance with margin policy and standards is promoted as a priority by leadership, linking to the development of a proactive margins management culture.

A common margins management framework would take account of the differences in various projects and ship classes. The framework would provide a clear baseline of consistent margins principles, but is tailorable (within limits) to suit the needs and characteristics of the class. A robust policy framework would instantiate the following principles:

Common approach to margins management across enterprise A review of current margin management practice and policy (Reference 4) observed that there are inconsistencies and misalignments in existing margins requirements. There is opportunity to introduce measures such as a singular set of margin definitions, a more prescriptive approach to margin assessment and measurement, and a more robust and prescribed margin budgeting process.

Common Margins Documentation and Deliverables To achieve a common baseline of good practice, a standardised suite of margins deliverables would be developed and implemented in the form of templates included as annexes to ANP-4801 (Reference 5). These templates would then be tailored by projects (within limits) to meet project requirements, and used to govern margins application and management in that project. A Margins Management Plan would set out the margin budget as an agreed baseline, and define how change is implemented against that baseline. A Margins Usage Report would record all changes on a periodic basis.

Common Roles and Responsibilities Currently, margin related roles and responsibilities vary across the naval enterprise. A consistent set of roles and responsibilities relating to each margin, as well as defined roles for margins management and assessment could be implemented across the Maritime Domain. A Margins Working Group could be established within each project, with consistent functions and processes.

Margins Definition and Management

The framework set out in the policy must be enacted through the requirements, tools and processes used in each program. The following principles could be considered in establishing these processes:

Consistent Margin Requirements Managed throughout CLC Margin requirements need to be considered as early as possible in the Risk Mitigation and Requirements Setting Phase. This is because decisions made during this phase have the most significant impact on margins availability through life (Reference 5). A minimum set of standard margin requirements should be included in the Request for Tender (RFT) phase to ensure an assessment of margin compliance is made as early as possible in the acquisition process. To ensure the full suite of possible margins is considered for inclusion in the requirements set, a comprehensive margins checklist could be used.

Assessment of Tenderer Margin Positions The most significant contributor to successful margins outcomes over the CLC is ensuring that adequate margins are included within the design from the beginning of the acquisition process. This is because the key characteristics that fix the physical limitations of the platform, and essentially set the available margins

within the design, are established early in the design process. This is true regardless of the acquisition strategy, be it a developmental design based on RAN requirements, or a MOTS design based on an existing reference ship. Therefore, it is important that the tender process ensures margin availability is prioritised as a key assessment objective and outcome. This could be achieved by, for example, increased technical engagement between customer and contractor SMEs in the form of detailed exploratory workshops, and co-modelling activities by embedded customer representatives.

Standardised Growth Forecasting and Margin Risk Prediction Some projects forecast margin consumption out to End of Life (EOL) to anticipate risks and challenges related to margin availability. To facilitate a common approach to growth forecasting and margins risk prediction a standard toolset could be developed and applied.

Management of Change Proposals to Reduce Growth Rates A typical priority for surface ship management is to manage the approval of margin consumption through the standard Engineering Change Proposal (ECP) and contract Change Proposal (CCP) processes. This can lead to a fundamentally reactive approach to margins management whereby strict growth reduction measures and options to recover margin are typically only enacted as margins become tighter. In comparison, management of submarine platforms by some navies demonstrates that actively controlling growth by implementing clear targets for recovering margin, or reducing the impact to margin, during change can slow the rate of growth and increase margin availability through life. Implementing a proactive approach to growth reduction using a goal based process to minimise impact to margin will ensure greater margin availability throughout the service life.

Engineering Capability

Establishing appropriate engineering capabilities would help provide an improved margin position from acquisition by supporting thorough and consistent requirement definition, specialist engineering assessment, and access to accurate timely information for decision makers.

Specialist Margins Design and Engineering Team A number of in-service classes and acquisition projects face challenging margin positions, for which remediation action may be required. These remediation actions typically require complex design engineering and analysis. This requires an engineering capability equipped with appropriate naval design skillsets, tools and processes to deal with the level of design and engineering analysis necessary to develop resolved design solutions to margins challenges. The tools, skills, techniques and approaches that would be applied to margin remediation design engineering tasks are generally common with other whole-ship design engineering tasks. Therefore, this concept aligns with the mandate arising from the Naval Shipbuilding Plan (Reference 6) to develop Australia's naval design engineering capability in support of delivery of the maritime elements of the Force Structure Plan.

CONCLUSIONS

The ultimate purpose of all margins is to ensure that the capability needed by Navy is delivered and remains available and competitive throughout the service life. Margins archive

this by mitigating uncertainty in acquisition; ensuring safety throughout the service life; and providing capacity for technology upgrades in an evolving threat environment.

Unfounded optimism and present bias are challenges in margining practice across various previous and current NATO+2 naval programs. Margins are difficult to recover once in deficit, and under-margining is dangerous to program objectives when viewed over the CLC. Discipline is a foundational characteristic needed in the engineering management of margins.

A well-structured margins management system is critical to control the use of margins across margin-consuming stakeholders through design, production and service. The foundation of a robust margins management system is a margin budget which clearly sets out all margin allocations and describes who is authorised to use what margins and when.

Robustly managing a ship margin budget across the CLC requires:

1) An evidence-based understanding of the types and amounts of margins required through the various phases of the CLC
2) A clearly documented margin budget, which sets out the amounts of margins, how they are measured, how they are allocated to the different phases of the CLC, and who is authorised to consume them
3) A clearly documented margins management policy which sets out treatment and enforcement measures for budget exceedance
4) A culture of margin budget discipline throughout acquisition and sustainment

Naval acquisition and sustainment professionals need to fight for margin discipline and margin preservation. Margins are future capability and as such, need to be treated with the same priority as existing warfighting capability.

The costs of remediating a deficient margin position during the service life are much higher than a healthy margin budget established early and maintained with discipline. Based on recent surface combatant history, provision of generous margin budgets is a significant opportunity to reduce total cost of ownership. The trend of Mod-repeat acquisition strategies indicates that even higher margin allocations are required in new designs which may later become reference designs. This is something to be reviewed carefully during tender stage if this acquisition strategy is to be pursued.

In order to maximise the chances of long-term success in the technical management of our naval fleet, the enterprise must learn from previous programs. This learning involves disciplined collection, management and analysis of margins data across the fleet; and adherence to appropriate margin setting and margin management practices throughout the acquisition and sustainment phases.

There are a range of opportunities to develop our approach to margin management by improving our margin management culture; establishing and enforcing a consistent policy framework and standards; establishing and enforcing consistent margins definitions and management processes; and improving our specialist engineering capability with relation to ship margins engineering.

Considering recent history, the future threat environment, and taking a CLC view of ship projects, we would be prudent to focus more priority on the provision of generous margin budgets, with the expectation that significant changes will be required over the service life of the ship. Improvement of margin outcomes will allow increased platform availability through life, simpler and cheaper platform management, extended platform service life where required, and an increased ability to maintain capability competitiveness.

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Development of an Australian Sovereign Shock Testing and Assurance Capability.

Warren Reid, Thornton Tomasetti Pty Ltd. wreid@thorntontomasetti.com

ABSTRACT

Royal Australian Navy (RAN) frontline combatants are expected to be able to survive, as much as possible, the rigours of war including attack by above and below water weapons. From the perspective of mines and torpedoes, Australia has performed ad hoc shock testing of complete platforms and combat equipment for many years on the numerous overseas designed platforms that make up the RAN fleet. With the reinvigoration of the Australian naval ship building industry, the opportunity exists to develop a more extensive and coordinated sovereign capability in naval platform and equipment shock testing and assurance.

This paper outlines the authors thoughts on the development of a sovereign shock testing capability here in Australia, especially in the development of a heavy and medium-weight shock testing capability to support the shock qualification and assessment of existing & future RAN frontline combatants. It is proposed to take the existing ad hoc shock testing capability from a Tier 1 level up to a Tier 3 level. Tier 3 brings together four shock assessment capabilities: (i) equipment and systems shock testing, (ii) full scale ship shock testing, (iii) modelling & simulation, and (iv) shock standards and requirements development, into a coordinated program where each would be fully integrated with the other. The aim should be to gradually reach a Tier 3 level capability over the next two to four years.

INTRODUCTION

The Sovereign Industrial Capability Priority Implementation Plan [1] outlines the important requirement for test evaluation, certification, and systems assurance within the Defence sector. The document details four industrial capabilities as critical. This paper aims to address the development of a sovereign capability in relation to underwater shock survivability of naval platforms covered by critical capabilities number three and four, being Joint Force Capability Assurance, and Complex Systems Test and Evaluation Capabilities respectively.

The detail in this paper lays out the author's thoughts to develop a sovereign capability for assessing and improving the shock survivability of Royal Australian Navy (RAN) platforms to weapon attack from the testing, evaluation, certification, and systems assurance perspective. The plan assesses the opportunities in terms of the Naval Ship Building Plan [2] and how to potentially bring together all aspects of current discreet industry capabilities into a coordinated sovereign national capability. The main focus is on aspects of the capabilities to survive

underwater weapon attack; however, the principles can be applied to other aspects of RAN platform survivability such as air blast and fragmentation aspects from missile and other above water weapons attack.

NAVAL SHIP BUILDING INDUSTRY VISION

Within the Australian Defence sector, the RAN have generally acquired "Off-the-shelf" designs for their surface combatants and submarines since at least World War II. Although Off-the-shelf, the designs have generally been modified to take Australian government furnished equipment such as weapons and combat systems. Once a batch of class were produced then there was generally no follow up program or continuous ship building approach. This meant that there was generally a sporadic naval ship building industry that was reluctant to invest in the local environment for fear of the reduction in work programs which invariably arrived at the end of each build.

In the 2016 Defence White paper [3] the Australian Government announced an initiative to generate a Naval Ship Building Industry to support a rolling build program for Australian naval platforms. The first platform announced as part of the rolling ship building industry was 12 of the Attack Class submarines, although these have now been cancelled. The next platform announced as part of the rolling ship building industry was the Hunter Class Frigates due to commence production in 2021 and based on the UK T26 "Global Combat Ship" design. The main difference between the construction of these platforms and previous combatants is that these platforms are expected to evolve over construction of the class with considerable opportunities for Australian Industry to invest and be comfortable in the knowledge that this will truly be a rolling ship building industry and not suffer periods of inactivity that many involved in Defence industry saw as unsustainable.

NAVAL SHIP BUILDING SOVEREIGN SHOCK CAPABILITY

In 2017 Vice Admiral Tim Barrett – Chief of Navy, proclaimed that the future RAN needs to be able to "Fight and win at sea" and "lethality at sea is the business of the Navy" [4]. There are two parts to lethality (i) to be effectively lethal against an adversary, but just as importantly (ii) not to have an adversary apply equally lethal force against our navy. In order to resist lethal force at sea, the RAN needs to have capable platforms that can survive attacks from adversaries. In below water warfare, maximising survival from underwater shock loading events is critical. This is generally achieved through a shock testing and assurance program.

Australia's shock testing and assurance capability can best be described as haphazard in its current form, going back more than 50 years. The main reason for this is that Australia has traditionally built overseas combat platform designs with the associated shock requirements being specified by the country of origin of the design. Numerous past platforms have either

being US or UK designs and therefore there have been some shock machine designs from these countries utilised here in Australia, e.g., the US based medium-weight shock machine (MWSM).

However, over the past 35 years, numerous non US/UK designs have been built here in Australia with the aforementioned shock machines often utilised for shock testing components that were retrofitted to these designs, or for government furnished equipment that was fitted to "Australianise" the platform. This evolution of the shock performance of Australian combatants has often been misunderstood with test machines used to generally "test" equipment, with no consideration for the performance variations that platforms provided due to their basic design differences, nor an understanding of the threats for which platforms were likely to be exposed. Subsequently, there has been a haphazard mix of testing machines here in Australia. Some old machines still exist, and some new ones have been built, or evolved to be used to shock test and qualify equipment for past and current platforms. There has been limited understanding of general shock testing requirements to ensure that all naval platforms achieved at least a minimum, or even better, a level of shock performance that enabled the platform to survive regional threats, or a basic understanding of what level of performance most platforms had in certain wartime scenarios.

In the late 1990s, DSTO with the Naval Technical Bureau, improved some of these issues by generating an Australian shock standard, which eventually came into doctrine as the DEF(Aust) 5000 shock requirements [5] for RAN platforms. The Standard has had little use over the past twenty years mainly because platforms such as the ANZAC FFGs and Hobart Class DDGs have been built to overseas designs with very little Australian local capability development. Where there has been Australian content, the shock testing and assurance process has generally been difficult to apply due to the reliance on the original shock testing requirements from the country of origin of the design. This is not to demean the standard or the technical regulators, but generally there has been a non-understanding of how to apply the standard within Projects (and against other international standards) and confusion regarding the capabilities of testing machines here in Australia.

If we call the shock testing and assurance capability described above as Tier 1, then the development of an Australian shock testing and assurance capability should be viewed as achievement of a Tier 2 capability. A Tier 2 capability within Australia should be considered to achieve the following:-

- Assessment of all current and future naval platforms having shock loading performance requirements to be assessed against the current Australian shock testing standard for their relevant performance against Australian shock levels and the equivalency of those levels against any other shock standards utilised for those platforms. The shock performance of naval platforms against various regional threat weapons also needs to be better specified and understood to ensure that appropriate and cost-effective shock testing and qualification is applied. Every Australian frontline combatant having shock performance requirements needs to go

through first of class shock testing to ensure that the platforms are “combat ready” and that this capability is achieved/monitored throughout the life of the platform.

- The capabilities of all shock testing machines in Australia and their capabilities assessed against the Australian shock standard. Any limitations of each machine should be identified to ensure that they are not utilised to test equipment or systems at levels that cannot be attained, at structural frequency response levels that are not appropriate for that platform or tested at too high shock level which may result in systems failure or overdesign.
- Any identified gaps in the Australian industry shock testing capability need to be filled to ensure that an increased local content of shock qualified equipment and systems for RAN platforms is achieved.
- Sufficient industry training to ensure that all industry players understand the shock requirements of Australian platforms and the appropriateness of testing capabilities here in Australia.

Once Tier 2 is achieved, then a Tier 3 shock testing & assurance capability should be aspired to. Tier 3 would involve significant use of modelling and simulation to ensure that even though shock standards have been specified, the actual performance of the platform in a shock loading scenario can be accurately modelled and “tweaking” of the performance of underperforming systems can be achieved. Tier 3 could also involve a series of threat weapon performance requirements be specified for a platform and then the whole platform is modelled and simulated (a digital twin) to ensure that every piece of equipment and system performs up to an appropriate level. This would ensure that equipment is not over designed, therefore potentially allowing increased weight margins and full platform vulnerability models to be achieved. The outputs from these models can then be utilised by operational planners to understand the capabilities of the platform as best as possible and not put the platform at too much risk by knowing it’s full shock performance capability.

As an example, in the UK a Tier 3 level has been achieved. The UK Tier 3 capability brings a range of industry participants together into a capability that utilises four pillars to provide the UK MoD with the confidence it needs to place its frontline combatants in harm’s way knowing that they have done the best they can to maximise the survivability and safety of crew in a cost-effective manner. The aim is to take Australia to this same Tier 3 level and give operational planners the appropriate confidence and knowledge to make decisions when deploying RAN platforms.

Australia should aim to utilise overseas experience in shock capability development knowledge to enable Tier 2 to be achieved as part of the ship building industry over the 2022/23 period. Once achieved, the aim would be to then take the capability to the Tier 3 level sovereign capability by 2024/25.

Timelines for achievement of a Tier 3 Capability through development and oversight of each of these pillars will depend upon available funding to develop new capabilities and drawing

together of existing capabilities here in Australia. It is suggested that an industry leader in the field could manage, develop, and coordinate the Tier 3 Capability as a trusted partner in conjunction with the Directorate of Naval Engineering, and Capability Acquisition and Sustainment Group. This would ensure that all the shock requirements of the naval ship builders here in Australia are coordinated and not piecemeal, nor competing against each other for resources.

ACHIEVING A NAVAL PLATFORM SOVEREIGN SHOCK CAPABILITY

It is proposed that there are four pillars required for achieving a Tier 3 shock testing and assurance capability here in Australia:

1. Equipment & Systems Shock Testing,
2. Full Scale Ship Shock Testing,
3. Modelling & Simulation,
4. Shock Standards and Requirements.

To reach a Tier 3 level, all four pillars need to be put in place and intimately linked to each other.

Pillar 1: Equipment & Systems Shock Testing

For Pillar 1, heavy-weight testing capabilities will need to be achieved through development of relevant deck shock fixtures (DSF) and Floating Shock Platform (FSP) testing to develop processes to ensure that RAN platforms can meet Australian and other International Standard requirements. Australia has had little to no capability in heavy-weight equipment shock testing in the past. The Defence Science and Technology Group (DSTG) has recently built a FSP to accommodate heavy-weight testing up to approximately 27 tonnes equipment capacity. An explosive commissioning trial is due to be performed on the FSP in May 2022, with a DSF being constructed by Thornton Tomasetti to replicate typical surface ship deck frequencies, for instance such as those for the Hunter Class Frigate. This capability will enable Australia to certify a broad range of heavy-weight systems and rafted lightweight systems to any of the international and Australian based standards in the future. Directorate of Naval Engineering is also purchasing an equivalent airgun based FSP testing system [6] which should be ready for use in late 2022. Figure 1 shows an image of a heavy-weight barge explosive trial, Figure 2 shows the Australian constructed FSP, whilst Figure 3 shows a typical Deck Shock Fixture.



Figure 1. UK explosive barge testing at Thornton Tomasetti's Limehillock facility.

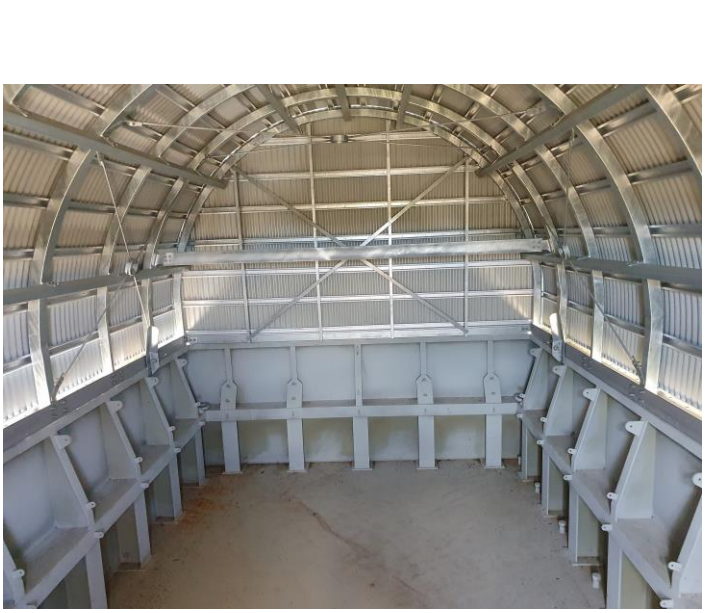




Figure 2. Australian Floating Shock Platform (courtesy of DSTG).

In terms of medium-weight testing capabilities from approximately 800 kg up to 3000kg, Australia has had limited testing capability in the past with a US 901E specification medium-weight shock machine (MWSM) that was based at St Mary's in NSW up until about 5 years ago. Unfortunately, the machine has now been disposed of, however, it was only ever designed to test equipment to the US Mil-S-901E standard [7] and was therefore not suitable or used to test to other international standards. To fill this gap, Thornton Tomasetti is bringing in a portable

JASSO airgun testing machine [8] to cover and extend the medium and light-weight shock testing regime from a minimal mass up to approximately 5 tonnes mass. JASSO should be available by mid-2022 to allow for new builds such as the Hunter Class Frigate Projects and for upgrade and refit Projects such as the Collins Class Submarines, ANZAC Frigates and Hobart Class Destroyers. Figure 4 shows the JASSO portable shock testing machine. JASSO is fully adjustable for full asymmetric sine wave acceleration and pulse duration by adjusting air pressure within the seismic airgun and adjusting platen impact materials on the impact table where equipment is mounted.



Figure 3. Floating Shock Platform Deck Shock Fixture.



Figure 4. JASSO, portable medium-weight equipment shock testing machine, with airgun firing system on the right. JASSO is subject to patent protection: United Kingdom Patent No. 2567314B applies with Patent Pending in Australia - Australian Patent Application No 2018333032 applies.

There is sufficient lightweight shock testing capability already in Australia and these should continue to be used where appropriate. Typically, this capability consists of drop towers, lightweight shock testing machines and various servo hydraulic testing machines. However, care needs to be exercised in the use of these machines for achieving complex wave form responses as typically seen on naval platforms. Asymmetric sine wave loadings are typically

observed on naval platforms resulting from the impinging shock wave on the platform and the inherent energy release within the structure after the shock loading has stopped. Unless all the elements of the shock loading and unloading are simulated in a test, then loadings at specific frequency responses may be missed, which subsequently means that the equipment has not being tested to a level at which failure may occur during an actual ship shock test. Figure 5 shows a typical drop tower and light weight shock machine.

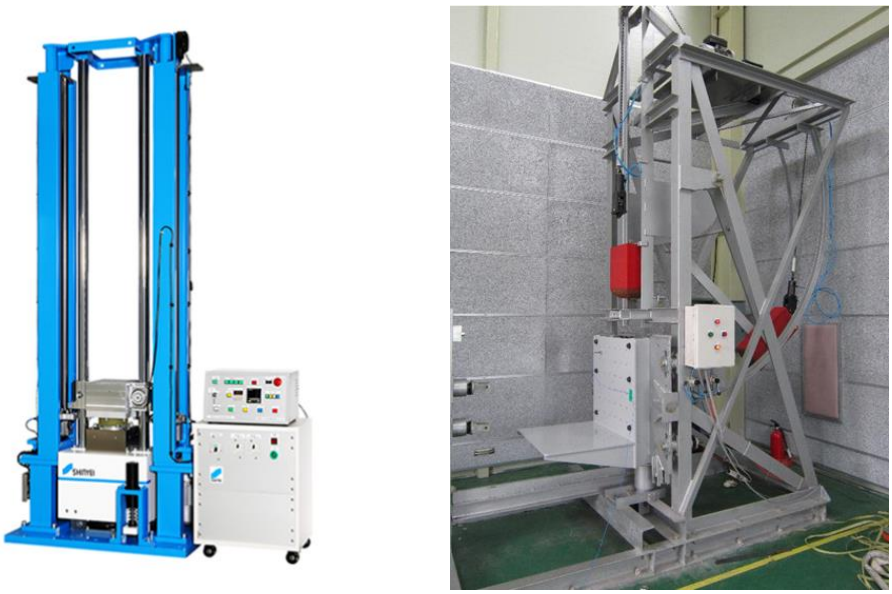


Figure 5. Drop tower on left and lightweight shock machine on right that are typically used for shock testing equipment up to a few hundred kilograms.

In all of the above equipment testing methods under Pillar 1, the Directorate of Naval Engineering would have oversight of the testing processes and how each test meets the requirements of the various standards that equipment needs to be certified against.

Pillar 2: Full-Scale Ship Shock Testing

For Pillar 2, Australia has performed limited explosive based full-scale ship shock testing (FSST) of naval platforms in the past. FSST allows the complete performance of first of class platforms to be assessed, so that subsequent platform shock related issues can be corrected. However, it is highly unlikely that future explosive charge shock testing in Australian blue waters will be allowed due to environmental restrictions and the threat to ocean mammals. Explosive testing costs in blue water are also prohibitive and similar results can be achieved utilising seismic air guns at a fraction of the cost. The Directorate of Naval Engineering is currently assessing the opportunities to perform future FSST testing with Australian owned airgun shock testing infrastructure, which would also allow testing of platforms and training of ship crews prior to operational deployments. Figure 6 shows full-scale ship airgun testing against decommissioned naval platforms.



Figure 6. Air gun shock testing of full-scale naval platforms (top), with air gun string modules (bottom).

Pillar 3: Modelling & Simulation

The development of numerical modelling and simulation capabilities over the past forty or so years has allowed significant advancement in the survivability performance assessment of naval platforms. Simulations of platform performance under dynamic loading conditions are now so sophisticated that they can be considered a replacement for shock testing in many situations. Ultimately however, failure of system components is very difficult to predict so testing is still required. In order to develop shock modelling & simulation capabilities here in Australia, it will be a matter of recruiting and training skilled staff and transferring technology know how and

adoption of appropriate cyber security measures to store and run digital twin models here in Australia. Local recruitment of staff to develop and run assessments of digital twin survivability models needs to be done in conjunction with guidance from overseas expertise to ensure appropriate standards are maintained and the latest updates to modelling software are utilised.

An Australian sovereign capability in shock modelling & simulation will allow future modifications to new or existing platforms to be assessed, prior to construction of the platforms. This should reduce expensive reengineering of systems, foundations, and structures after failure to meet shock testing requirements. Figure 7 shows the extent of digital twins that can now be developed for full platform survivability assessments. An example of full numerical models are the EPSA and FLEX codes developed by Thornton Tomasetti. Full platform and detailed sub-system models can accurately reflect dynamic loading responses through having been developed and validated against experimental data over many years. Supplementing the full numerical models are algorithm-based codes such as Purple Fire [9] by SCL, which allows full vulnerability and survivability assessments of naval platforms.

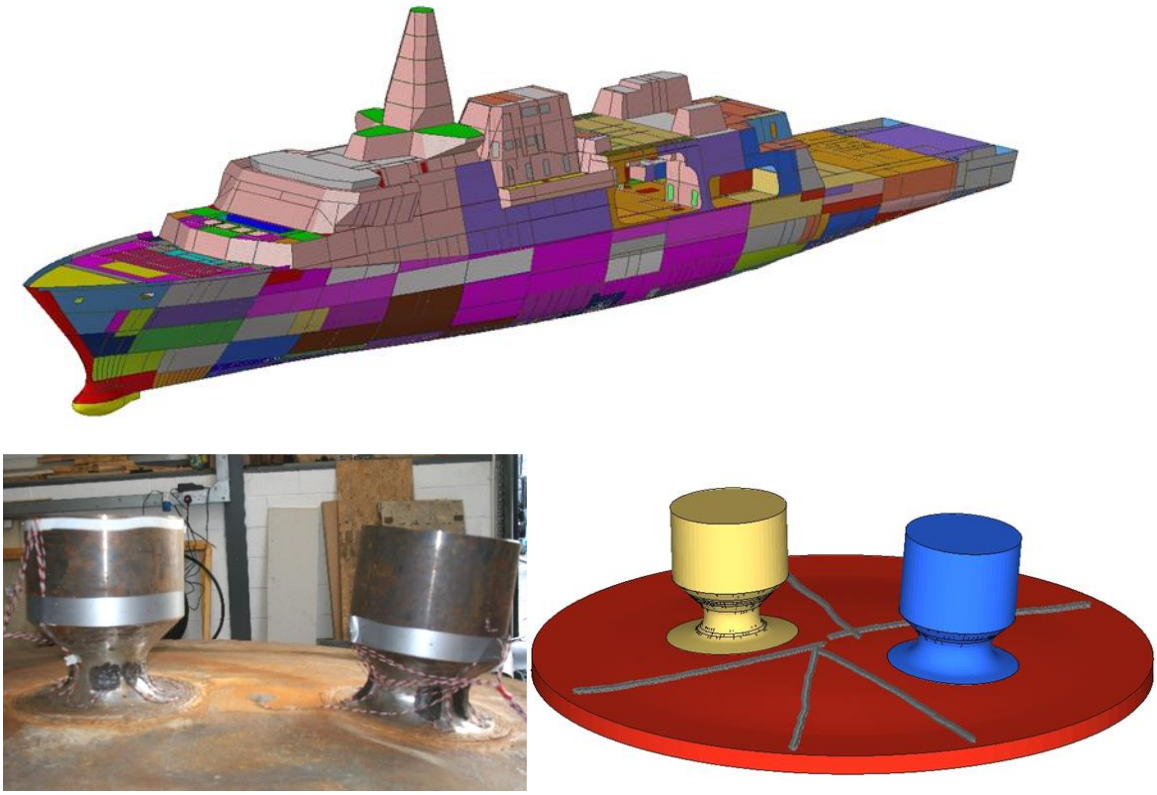


Figure 7. Full ship model (top), and detailed sub system models (bottom) that allow accurate modelling and simulation of dynamic loading events typically found during naval platform vulnerability events.

Pillar 4: Shock Standard Requirements

Development of shock standard requirements needs to be continuous to better reflect the expectations of the RAN in terms of the future operational scenarios of platforms. Updating of standards is especially important so that the full shock and overall survivability requirements of all combat platforms are fully understood and reflected in Navy doctrine. This will also allow accurate certification of systems and sub-components in existing platforms. The aim should be to have an updated version of the Australian Standard by the end of 2023, which would also include an accurate equivalency with all relevant international standards. Modelling & simulation along with shock testing become integral inputs to the shock standard development process and in turn the standards then drive work programs in these two areas. Figure 8 shows a comparison of equipment shock testing responses against a nominal shock standard using shock spectral analysis.

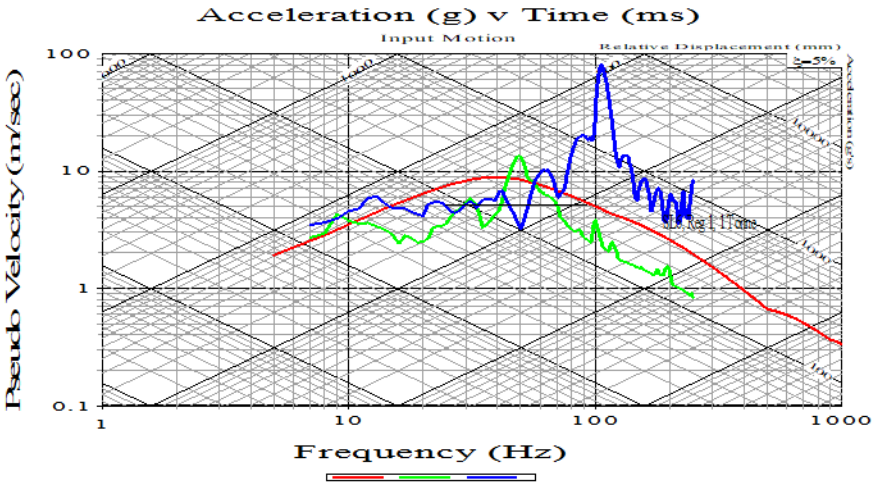


Figure 8. Typical shock standards comparison using shock response spectra of equipment and systems test responses versus a nominal shock standard requirement.

SUMMARY

This paper aims to address the development of an Australian sovereign shock testing and assurance capability in underwater shock survivability of naval platforms in relation to the Sovereign Industrial Capability Priority Implementation Plan [1].

To achieve an Australian sovereign shock testing and assurance capability four fundamental pillars will need to be put in place:

1. Equipment & Systems Shock Testing,
2. Full-scale Ship Shock Testing,
3. Modelling & Simulation,

4. Shock Standards and Requirements.

By establishing these four pillars and intimately linking them together, Australia should be able to move from its current limited Tier 1 capability up to a world class Tier 3 capability over the next two to four years. In 2022, capability development work programs in heavy and medium-weight shock testing are already in place to take Australia from a Tier 1 to a Tier 2 capability.

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SESSION 12

Submarine Hydrodynamics

Hydrodynamic issues associated with out-of-plane loads on the turning of a submerged submarine
Refereed

Captive model experiments to determine the hydrodynamic loads for a submarine operating near the free surface
Refereed

Manoeuvring performance of a submarine with different sail designs

Enhancing the propulsive performance of a ducted propeller for a full scale BB2 underwater vehicle
Refereed

Hydrodynamic issues associated with out-of-plane loads on the turning of a submerged submarine

Howan Kim[1], M Renilson[2], and D Ranmuthugala[3]
[1] Australian Maritime College, University of Tasmania, Australia
[2] Pacific ESI, Australia
[3] Defence Science and Technology Group, Department of Defence, Australia
Email: martin@renilson-marine.com

ABSTRACT
The presence of a sail and casing on the upper part of a modern submarine results in an asymmetry, which causes a vertical force and pitch moment on the boat. When the submarine is travelling in a straight line these can easily be balanced by small control plane angles. However, when turning in the horizontal plane, both the vertical force and the pitch moment can significantly increase due to the vortex structures generated by the sail at an angle of incidence to the flow. This requires larger plane angles on both the forward and aft control surfaces to counteract these out-of-plane loads.

Understanding the out-of-plane loads acting on a turning submarine when executing a level turn is important to ensure that the boat can be controlled for operational and safety reasons. The authors have previously suggested that these out-of-plane effects can be estimated by considering the flow over the submarine experiencing pure sway. However, recent work by the authors has found that the influence of pure yaw is also significant, and can have the opposite effect to that of pure sway.

Thus, the factors which influence the controllability of a submarine when executing a turn in the horizontal plane are complex. These need to be fully understood in order to ensure that the control surfaces and autopilot are designed accordingly. This paper discusses these factors and their varying effects on the submarine's behaviour, with examples such as the pressure distributions acting on the turning boat.

1. INTRODUCTION

The presence of a sail and casing on the upper part of a modern submarine results in an asymmetry, which causes a vertical force and a resulting pitch moment on the boat as illustrated in Figure 1.1. This hydrodynamic force and moment can be represented by the terms: Z'_* and M'_* in the equations of motion, as discussed in [1]. This can easily be counteracted by small 'balance angles' on the submarine's control planes.

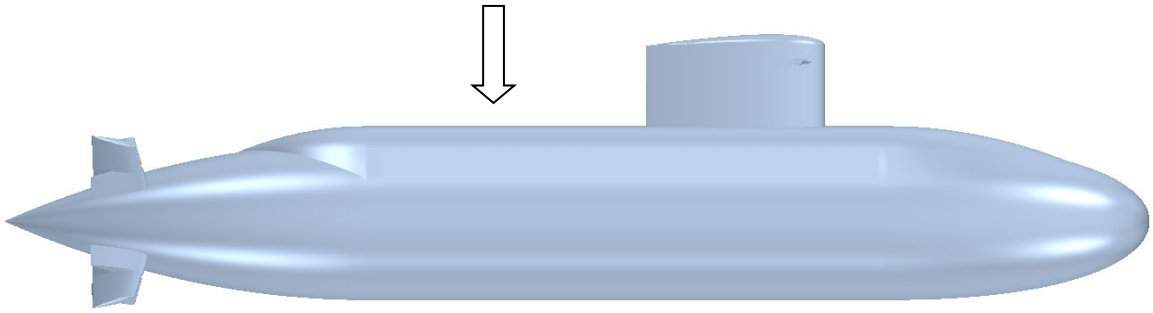


Figure 1.1 Schematic of out-of-plane force acting on the submarine

When the submarine is turning in the horizontal plane, both the vertical force and the pitch moment can be significantly increased due to the vortex structures generated by the sail at an angle of incidence to the flow as shown in Figure 1.2 [1],[2]. This requires larger plane angles on both the forward and aft control surfaces to counteract these out-of-plane loads [3].

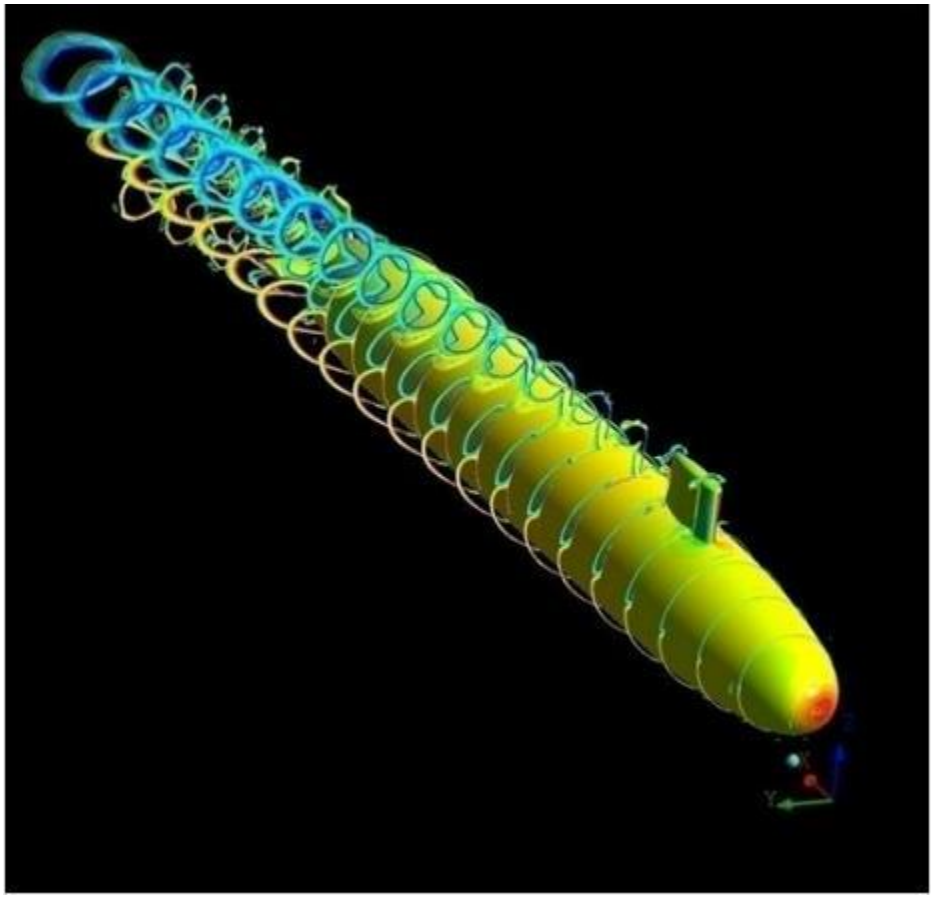


Figure 1.2 Flow around a turning submarine [1]

Understanding the out-of-plane loads acting on a turning submarine when executing a level turn is very important to ensure that the boat can be controlled for operational and safety reasons [1]. This is also important when considering the design of the Aft Control Surfaces (ACSs).

2. EQUATIONS OF MOTION

The hydrodynamic forces acting on a submarine can be expressed in terms of the velocities and accelerations of the boat in six degrees of freedom, as explained in [1]. The submarine motion is described in a body fixed axis system, as shown in Figure 2.1, with the origin located at the submarine's centre of gravity.

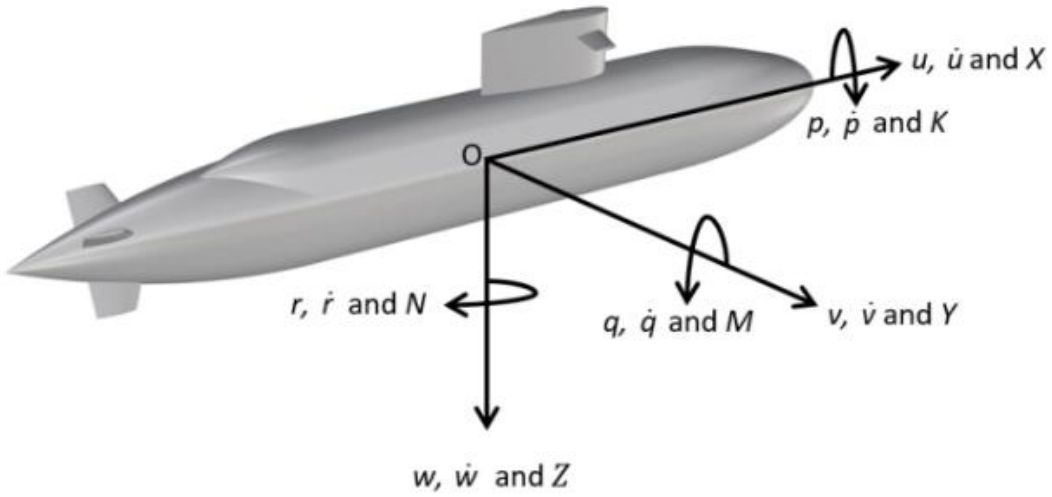


Figure 2.1 Body fixed axis system of the submarine with the origin (O) located at the boat's centre of gravity

The positions, velocities, and accelerations about these axes are defined in Table 2.1.

Table 2.1 Axis, load and displacement definitions (see Figure 2.1)

Motion	Displacement	Velocity	Acceleration	Force/Moment
Surge	x	u	$\dot{u}$	X
Sway	y	v	$\dot{v}$	Y
Heave	z	w	$\dot{w}$	Z
Roll	φ	p	$\dot{p}$	K
Pitch	θ	q	$\dot{q}$	M
Yaw	ψ	r	$\dot{r}$	N

The non-dimensional heave force (Z') and pitch moment (M') are calculated as given in equations 2.1 and 2.2.

$$Z' = \frac{Z}{0.5\rho U^2 L^2} \tag{2.1}$$

$$M' = \frac{M}{0.5\rho U^2 L^3} \tag{2.2}$$

where ρ the density of the fluid, L is the length of the submarine and U is the magnitude of the free-stream velocity.

The six degree-of-freedom equations of motion of the submarine about the axis system in Figure 2.1 are given in [4]. From these the hydrodynamic heave force and pitch moment on the submarine due to a steady turn (where $w = p = 0$ and $r \neq 0$, $v \neq 0$) can be obtained from equations 2.3 and 2.4 respectively.

$$Z = \frac{1}{2}\rho L^4 Z'_{rr} r^2 + \frac{1}{2}\rho L^3 Z'_{vr} vr + \frac{1}{2}\rho L^2 [Z'_* u^2 + Z'_{vv} v^2] \quad (2.3)$$

$$M = \frac{1}{2}\rho L^5 M'_{rr} r^2 + \frac{1}{2}\rho L^4 M'_{vr} vr + \frac{1}{2}\rho L^3 [M'_* u^2 + M'_{vv} v^2] \quad (2.4)$$

In equations 2.3 and 2.4 the hydrodynamic coefficients relating to the asymmetry causing a heave force and pitch moment when the submarine is travelling in a straight line are: Z'_* and M'_* respectively. The other hydrodynamic coefficients are those which are used to represent the heave force and pitch moment due to the turn and are described in [1].

3. FLOW AROUND A SUBMARINE IN A TURN

As noted in Section 1, the presence of the sail and the casing results in an asymmetric flow around the submarine when it is in a turn [1],[2],[5]. This will result in an out-of-plane force and moment, as discussed. A typical flow pattern for a submarine in a turn is shown in Figure 3.1.

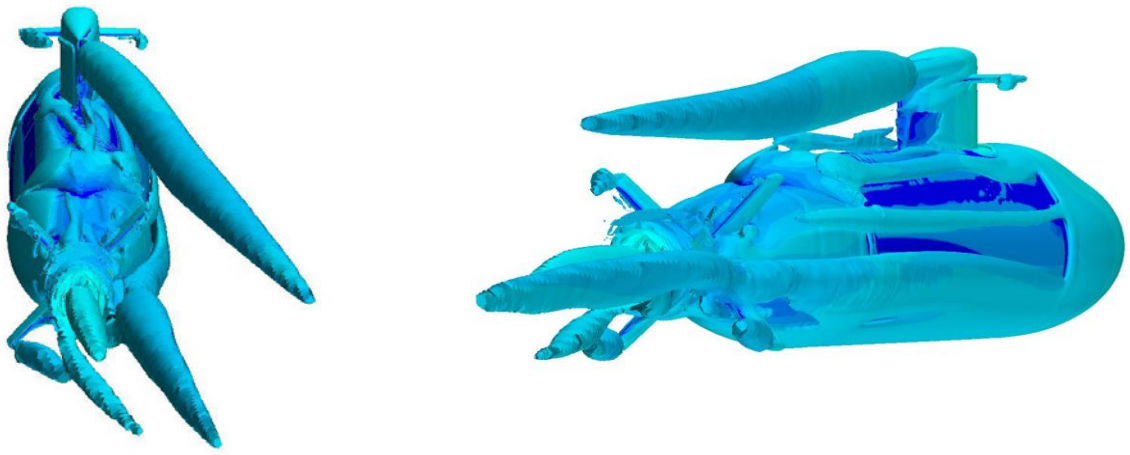


Figure 3.1 Q plots showing the flow structure around the BB2 submarine geometry during a turn. Vortical structures are shown as isosurfaces at Q-criterion=0.8 coloured with axial velocities. Unpublished results from [7]

The non-axisymmetric flow shown in Figure 3.1 results in a difference in pressure along the top of the submarine (Figure 3.2a), where the flow is strongly influenced by the presence of the casing and the sail, in contrast to the bottom of the submarine. The result is an out-of plane-force along the length of the boat, dependent on the geometry of the casing and sail, as shown

in Figure 3.2b. As can be seen from this figure, there is no out-of-plane force on the axisymmetric body (BH).

The addition of the casing alone (HC) results in a downward force just aft of the bow where the forward section of the casing intersects the hull, an upward force just aft of that section, and an upward force towards the stern where the casing ends. This is likely to be manifested in a small net upward force and a small bow down trimming moment.

On the other hand, the further addition of the sail (HCS) shows a large downward force aft of the sail. This will result in a large downward force and a bow up trimming moment, often referred to as: 'stern dipping'. The downward force aft of the sail is due to the generation of the tip vortex at the top of the sail as shown in Figure 3.1 and the bound body vortices on the hull that generates a circulation around the hull, which in turn results in a downward force on the hull aft of the sail. A detailed description of the mechanism involved in creating this downward force is given in [2].

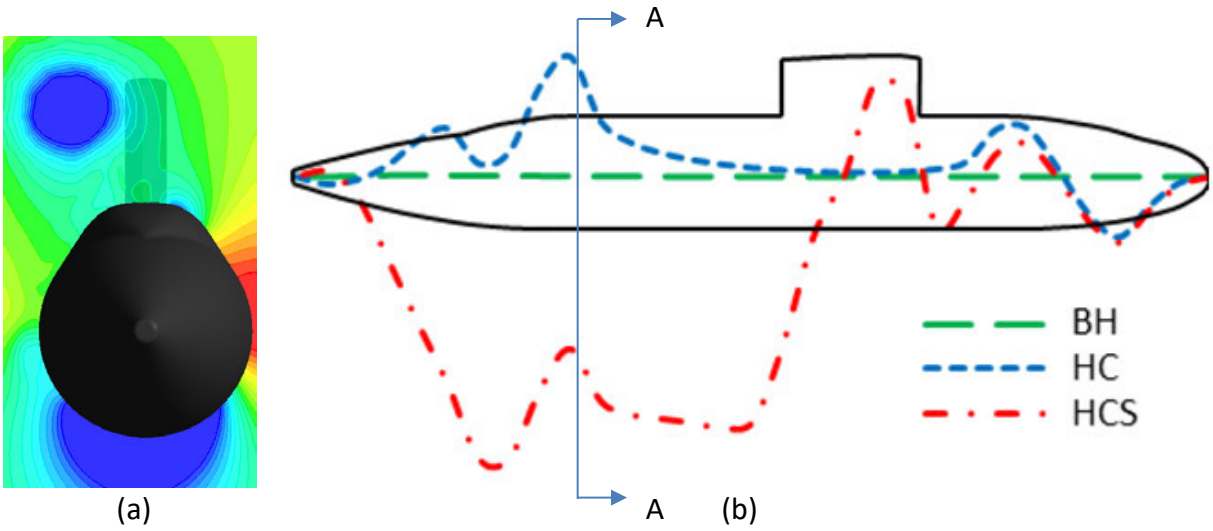


Figure 3.2 (a) Pressure contours on the submarine hull with sail and casing during a turn to port on Plane A-A, looking from the stern (blue to red increase in pressure). (b) Non-dimensional heave force Z' distribution along the longitudinal axis of the submarine hull (BH: Bare hull; HC: Hull and casing; HCS: Hull, casing and sail). (From: [5])

4. GEOMETRY

To further study this phenomenon, the BB2 generic submarine geometry [6] that represents a typical SSK submarine was modelled and simulated undergoing a steady turn in a horizontal plane. The BB2 submarine consists of a hull with a casing, a sail with sailplanes, and ACSs in an X-plane configuration. The current study employed the model scale BB2 with a scale factor of 18.348. A schematic of the hull, with its dimensions are shown in Figure 4.1.

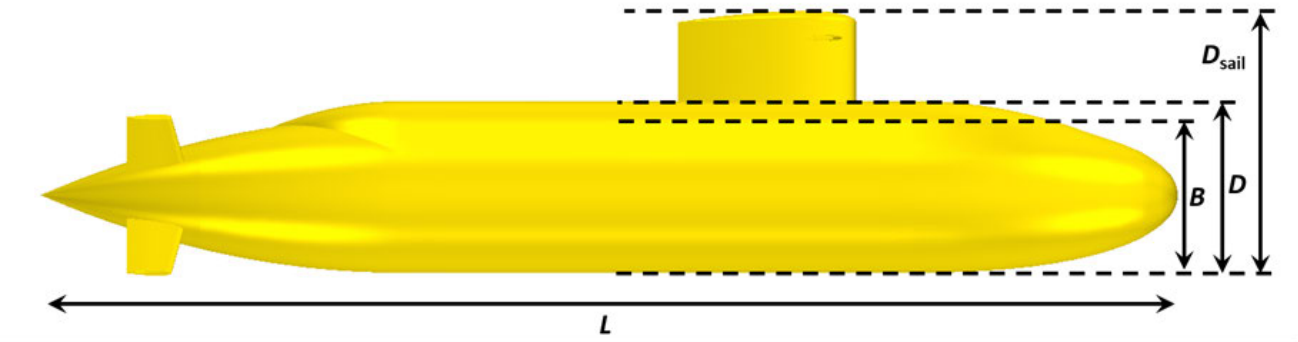
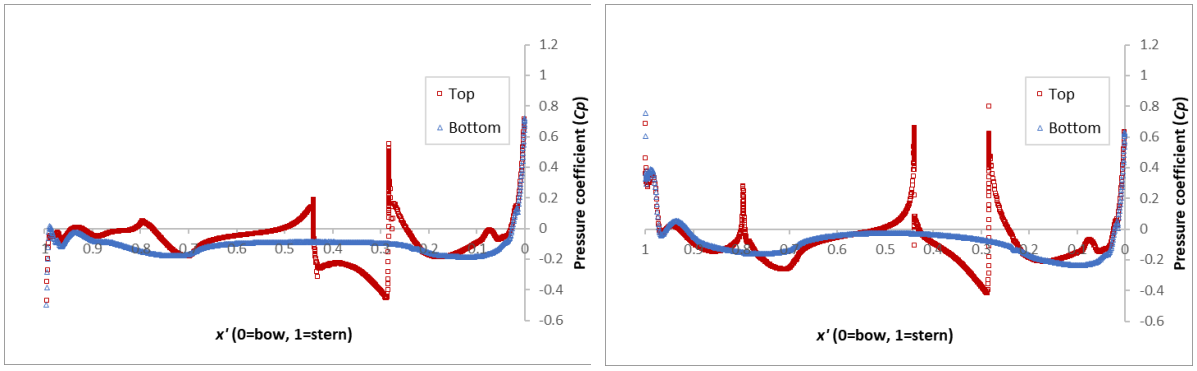


Figure 4.1. BB2 generic submarine geometry with the following dimensions: Length (L) = 3.826m; Hull diameter (B) = 0.523m; Depth from deck (D) = 0.578m; Depth from sail tip (D_{sail}) = 0.883m.

5. OUT-OF-PLANE FORCE AND MOMENT

Figures 3.1 and 3.2 illustrate the situation when the submarine is in a turn. When turning the submarine experiences both a sway velocity, *v*, and a yaw velocity, *r*. In order to understand the relative importance of the sway velocity and the yaw velocity on the out-of-plane force and moment during a turn the pressure coefficients at the top and the bottom of the submarine hull were obtained using simulations as discussed in [7]. These are shown in Figure 5.1. Figure 5.1a shows the case for pure sway ($v \neq 0$; $r = 0$), while Figure 5.1b represents the case for pure yaw ($v = 0$, $r \neq 0$). The values of non-dimensional sway velocity, *v'*, and non-dimensional yaw velocity, *r'*, correspond to typical values in a turn [4] [7].



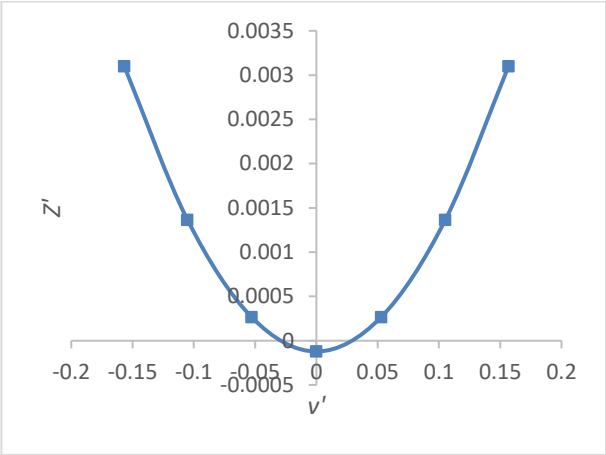
(a) pure sway at $v' = 0.158$ and $r' = 0$ (b) pure yaw at $v' = 0$ and $r' = 0.555$

Figure 5.1 Pressure coefficient at the top and bottom of the BB2 generic submarine hull in: (a) pure sway, (b) pure yaw. Bow located at x = 0.

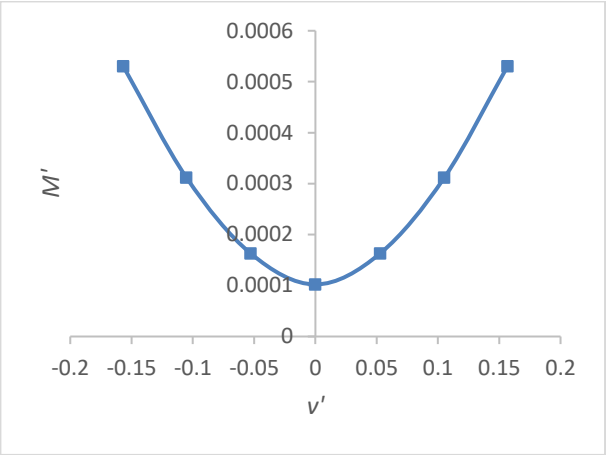
As seen from Figure 5.1, the main difference between the pure sway and the pure yaw cases is in the pressure coefficient along the top of the hull. For the pure sway case (Figure 5.1a) the difference in pressure aft of amidships will result in a net downward force, and bow up moment, as expected. However, this is not as pronounced for the pure yaw case given in Figure 5.1b. Thus,

simplified descriptions of this phenomenon (such as that given in [1], for example) may not adequately explain the situation.

In order to further analyse this effect, the force and moment can be obtained as functions of non-dimensional sway velocity, *v'*, and non-dimensional yaw velocity, *r'*. The results are presented for the BB2 geometry in Figures 5.2 and 5.3.

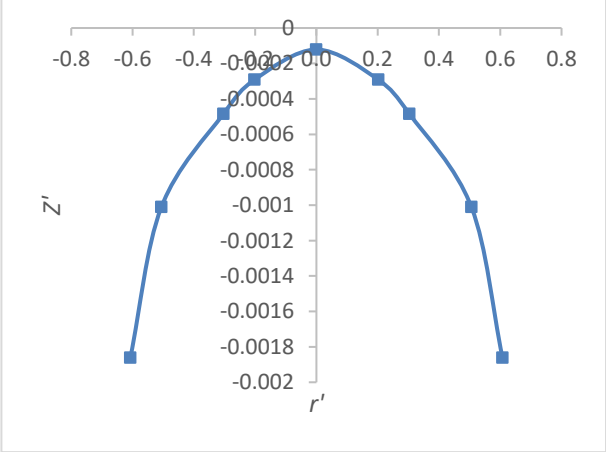


(a) heave force as function of sway velocity

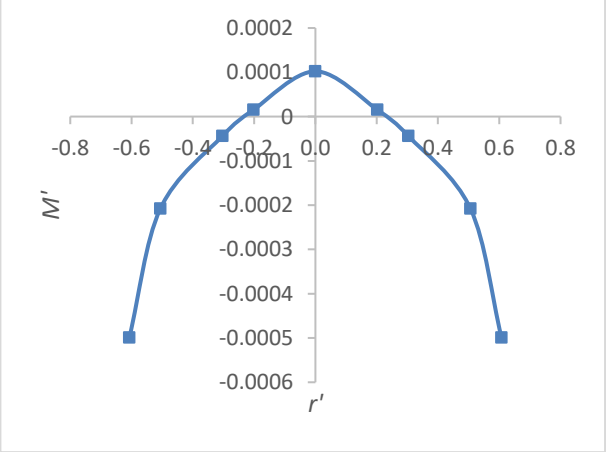


(b) pitch moment as function of sway velocity

Figure 5.2 Non-dimensional heave force and pitch moment as function of sway velocity



(a) heave force as function of yaw velocity



(b) pitch moment as function of yaw velocity

Figure 5.3 Non-dimensional heave force and pitch moment as function of yaw velocity

The results from Figures 5.2 and 5.3 can be used to obtain the required hydrodynamic coefficients for equations 2.3 and 2.4, as shown in Table 5.1.

It was assumed that the values of Z'_{vr} and M'_{vr} are small and so they were neglected.

The coefficients in Table 5.1 can be used in equations 2.3 and 2.4 to predict the heave force and pitch moment in a typical turn, with the results presented in Tables 5.2 and 5.3.

Table 5.1 Out-of-plane hydrodynamic coefficients for the BB2 generic submarine during a turn

Non-Dimensional Coefficient	Value
Z'_*	-1.20E-04
Z'_{rr}	-4.30E-03
Z'_{vv}	1.30E-01
M'_*	1.00E-04
M'_{rr}	-1.50E-03
M'_{vv}	1.77E-02

Table 5.2 Non-dimensional heave force on the BB2 generic submarine during turns

	Rudder angle = 20°	Rudder angle = 30°
Sway velocity, *v'*	1.44E-01	1.50E-01
Yaw velocity, *r'*	-5.93E-01	-6.31E-01
Heave force due to sway velocity	2.72E-03	2.95E-03
Heave force due to yaw velocity	-1.51E-03	-1.71E-03
Total heave force, *Z'*	1.09E-03	1.12E-03

Table 5.3 Non-dimensional pitch moment on the BB2 generic submarine during turns

	Rudder angle = 20°	Rudder angle = 30°
Sway velocity, *v'*	1.44E-01	1.50E-01
Yaw velocity, *r'*	-5.93E-01	-6.31E-01
Pitch moment due to sway velocity	3.70E-04	4.01E-04
Pitch moment due to yaw velocity	-5.28E-04	-5.97E-04
Total pitch moment, *M'*	-6.03E-05	-9.89E-05

6. DISCUSSION

It is shown in Table 5.2 that, for the BB2 generic submarine geometry, the heave force due to sway velocity is positive (downwards) whereas the heave force due to yaw velocity is negative (upwards), with the contribution due to yaw velocity being about half of that from the sway velocity. Thus, the overall heave force is positive (downwards). Note that the total heave force in the turn is not simply a sum of the forces due to sway velocity and yaw velocity independently, because of the additional complexity of the steady state coefficient, Z'_*, in equation 2.3.

Table 5.3 shows that there is a similar issue with the pitch moment. The pitch moment due to sway velocity is in the positive direction (bow upwards) whereas the pitch moment due to the yaw velocity is in the negative direction (bow downwards). These are of similar magnitude, with the resulting pitch moment being of a small negative value (bow downwards). Again, the steady state term (M'_*) also has a significant influence, which is why the total pitch moment is not simply the sum of that due to sway velocity and yaw velocity independently.

The results summarised in Tables 5.2 and 5.3 illustrate the complex nature of this phenomenon, and go some way to explain the discussion in [8] with regard to this phenomenon,

"The most common form of this complex interaction is for the submarine to pitch up and sink in depth, the so called 'stern dipping' tendency. Not all submarines behave in this way, …… No simple explanation can be offered, except that the different actions could be due to the configuration of the casing on the hull as they have been found to be more pronounced in boats with a substantial casing, rather than those which are more nearly axisymmetric."

Earlier work by the authors, and summarised in [1], focussed on the contributions due to sway velocity alone, which led to the conclusion that the force will always be downwards and the pitch moment always bow upwards. It is now clear that this is not always the case, and hence a greater understanding of this phenomenon is required for any particular proposed geometry.

7. CONCLUDING REMARKS

The presence of a sail and casing on the upper part of a modern submarine results in an asymmetry, which causes a vertical force and a pitch moment on the boat when it is turning.

Earlier work by the authors, which focussed on pure sway alone, suggested that the vertical force will always be downwards, and that the pitch moment will always be upwards – the so called, 'stern dipping' tendency. However, in order to better understand the phenomenon when a submarine is in a realistic turn, with both sway and yaw velocities, the current investigation also included the influence of yaw velocity. It has now been shown that the effect of yaw velocity is significant, and can have the opposite effect to that of pure sway velocity.

The relative influence of the sway and yaw velocities will influence the behaviour of the submarine in a turn. It is likely that this will depend on the submarine geometry, and to better understand this issue further work is required using different hull, casing and sail configurations.

8. ACKNOWLEDGEMENTS

The authors thank Zhi Quan Leong for the contribution to the work described in this paper.

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Captive model experiments to determine the hydrodynamic loads for a submarine operating near the free surface

Alexander Conway*, Chetan Kumar†, Adam Rolls* and Jonathan Duffy*

*Australian Maritime College, University of Tasmania
†Maritime Division, Defence Science and Technology Group, Australia
e-mail: a.conway@utas.edu.au

ABSTRACT

Due to operational requirements, submarines operate near the free surface for extended periods of time, for example during transit in shallow waters. However, the free surface has a significant impact on the hydrodynamic forces acting on the submarine which can cause it to either broach the surface or descend if control is insufficient. Due to the typically low operating speeds for near surface operations, these changes in hydrodynamic forces can be greater than the forces generated by the submarine's control surfaces. Therefore, it is critical to accurately predict the changes in pitching moment, heave and surge forces at typical speeds and depths to ensure the trim tanks and control surfaces can effectively control the submarine safely throughout the mission.

This paper presents the findings from a captive model experimental program at model scale for a 1.69m BB2 generic submarine model in calm water at the Australian Maritime College Towing Tank facility. A depth which was representative of periscope depth and two depths of increasing distance from the free surface were tested at a range of forward velocities. It was shown that the free surface creates an upwards heave force and bow up pitching moment on the submarine which is relative to the submerged depth and forward velocity. The data generated will be used to validate numerical tools and thus, further study the behaviour of submarines operating close to the free surface.

INTRODUCTION

Submarines operating near the free surface typically operate at relatively slow speeds due to operational and hydrodynamic reasons such as stealth and powering. However, slow speeds have a negative impact on the vessel's manoeuvrability and control. This reduction in control, combined with the changes in hydrodynamic forces as a result of free surface interaction, can result in a loss of control. Therefore, it is critical to understand the changes in hydrodynamic forces and moments to ensure safe operation whilst operating near the surface.

The free surface effect is directly related to both the speed and depth of the submarine [1]. The depth (d) is the distance from the horizontal centre line of the submarine to the equivalent flat free surface and is presented in the non-dimensional term H^* as shown in equation (1) where D is the maximum diameter of the submarine's hull. The submarine's

velocity is non-dimensionalised with respect to length using Froude number (*Fr*) (equation (2)) where *V* is the boat speed, *L* is the model length and *g* is acceleration due to gravity.

$$H^* = \frac{d}{D} \tag{1}$$

$$Fr = \frac{V}{\sqrt{gL}} \tag{2}$$

Whilst there have been several studies investigating the free surface effect using both experimental and numerical methods, more investigation is required for fully appended submarines at a range of speeds and depths. These investigations have used various submarine hull shapes including the Joubert [2] and SUBOFF [3]. Others have shown that the increase in surge force due to the wave making resistance at H*=2.0 is greater than 50% [4] whilst at H*>3.0, the wave making resistance in negligible at typical submarine snorkelling speeds [5].

This paper presents the methodology and results from an experimental program at model scale using the BB2 generic submarine shape [6] at the Australian Maritime College Towing Tank (TT) facility. A total of three depths were tested at four different forward velocities in calm water. This data will be used to validate the numerical simulations investigating the behaviour of submarines operating close to the free surface.

EXPERIMENTAL SET UP

Model Details

The model used during this experimental program was the DSTG BB2 generic submarine model (Figure 1). The model is 1.69m in length, 0.232m in diameter and derived from a NACA-0018 for the first 0.07*L*, a parallel midbody and a tail cone. The model has a casing, sail (NACA-002) with two horizontal sail planes (NACA-0015) and X-form aft control surfaces [6].

In order to mount the model to the carriage, a stern mounted sting configuration was utilised which resulted in a truncated tail cone at 0.95*L*. The horizontal sting exited the model through the truncated aft and attached to a vertical pylon which was rigidly mounted to the carriage, see Figure 1.

Two coordinate systems are used in this publication, as shown in Figure 1. The first coordinate system (blue) is used for the loads measurement, which is located at the longitudinal centre of buoyancy on the hull's central axis. The secondary axis system (red) is used for the surface wave measurements, which is located at the nose of the model. As can be seen in Figure 1, the direction of the z axis is reversed between the two axis systems.

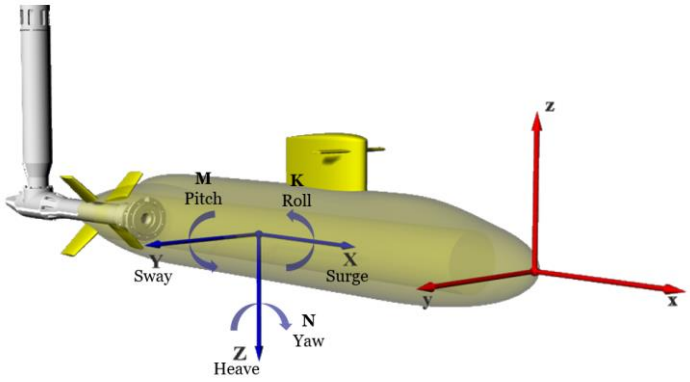


Figure 1: The BB2 generic submarine model geometry (yellow) and sting mounting arrangement (silver) with coordinate systems for loads (blue) including moments and free surface elevation (red)

Metrology

The model was constructed using resin infused fibreglass from a CNC cut mould. As the construction method can result in variations to the model accuracy, the dimensional accuracy was verified using a 3D laser scan. The standard deviation of the out-of-tolerance compared to the reference CAD file was found to be 0.3mm. The results from the 3D laser scan are shown in Figure 2, where red indicates a raised section of hull and blue represents a hollow in the skin.

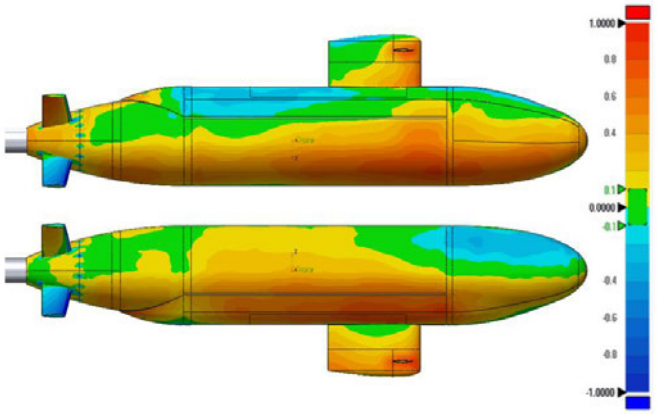


Figure 2: Comparison of the CAD file to the 3D laser scan showing dimensional variations for: (top) starboard and (bottom) port sides of the BB2 generic submarine model. All dimensions in mm

Turbulence Stimulation

The model length and forward velocities tested during this experimental program resulted in Reynolds numbers in the laminar flow regime. Thus, Hama trip strips were used to trip the flow from laminar to turbulent flow along the length of the model. Hama trips have a regular saw tooth pattern of constant thickness (Figure 3). Based on the findings from a

previous study [7], a Hama trip of thickness 0.52mm was installed at 6% of the model length from the bow and a 0.87mm thick Hama trip was installed on the sail, 5% of the sail length from its leading edge. It was shown in [7] that the selected Hama trips effectively generate a turbulent boundary layer for the entire length of the model whilst minimising parasitic drag.



Figure 1: Hama trip strips installed on the BB2 submarine model's (left) bow and (right) sail

Loads Measurement

The hydrodynamic forces and moments were measured via two Kistler 3-axis load sensors, which were internally mounted and rigidly connected to a machined strong-back as seen in Figure 4. The aft mounted sting configuration results in the internal pressure equalising to the external pressure towards the aft end of the model. If significant, this internal pressure can exert a force on the model affecting the surge measured. Therefore, two pressure sensors were installed inside the model to measure the internal pressure. This can be used to apply a correction factor for numerical prediction models if the internal pressure is significant. The internal pressure recorded during these experiments was not found to be significant with respect to surge force, and therefore, no surge force correction was required.

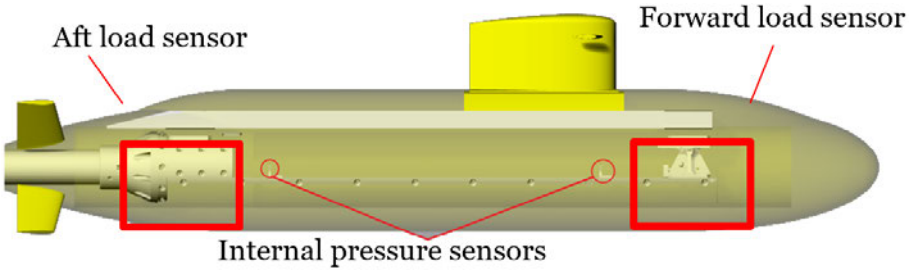


Figure 4: BB2 submarine model showing the location of the forward and aft load sensors and internal pressure sensors

The load sensors were calibrated as a single unit using a custom-designed frame in which single and complex forces and moment were applied to the model. The calibration matrix was calculated using a 6x6 matrix [*C*] as shown in equation (3), where [F] is the 6x1 matrix of input forces and moments, $[V - V_0]$ is a 6x1 matrix with the transpose function (*T*) applied that is a combination of the forward and aft load sensor voltages (*V*) minus the initial voltage offset (V_0).

$$[C] = [F] \cdot [V - V_0]^T \quad (3)$$

Wave Measurements

The free surface elevation was measured using two different measurement techniques, two-wire resistive wave probes (S1-S5) and ultrasonic wave probes (M1-M4). The five individual two-wire resistive wave probes were used as static wave probes and at fixed locations in the TT. This wave probe array measured the free surface elevation along four transverse locations. The ultrasonic wave probes were installed underneath the carriage and used as moving wave probes at fixed locations relative to the model at prescribed *x/L* locations. The location of both wave probes, relative to the model, can be seen in Figure 5. The mounting method for the static wave probes and ultrasonic wave probes is shown in Figure 6.

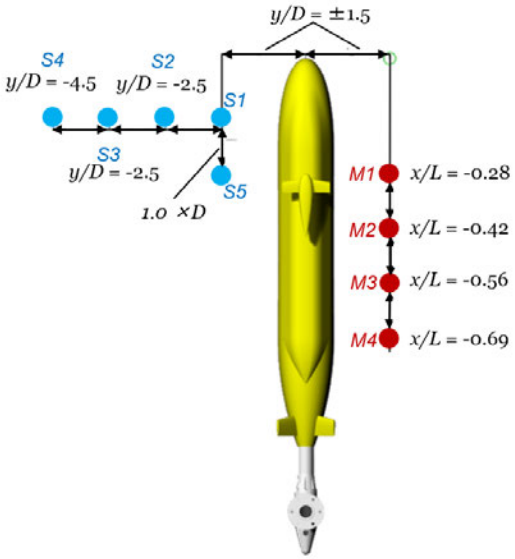


Figure 5: Layout and location of the stationary two-wire resistive (S1- S5) and the moving ultrasonic (M1- M4) wave probes attached underneath the carriage. *D* is the model diameter and *L* is the model length



Figure 6: (Left) static wave probes mounted at fixed locations on tank wall and (right) ultrasonic wave probes installed underneath the carriage at fixed x/L locations parallel to the model

Experimental Uncertainty

Both the systematic uncertainty and the random uncertainty were calculated. The systematic uncertainty was calculated by applying a range of complex load checks using the calibration rig, as seen in Figure 7. This involved applying loads simultaneously and determining the residual between the applied and measured forces. The systematic uncertainty was found to be approximately 1% when the maximum expected force was applied.

The random uncertainty was estimated by multiple runs (a total of 15) throughout the experimental program at the same depth and speed (Fr = *0.19* and *H** = 2.57). The standard deviation was calculated from those repeated runs and the values for two standard deviations are presented in Table 1.

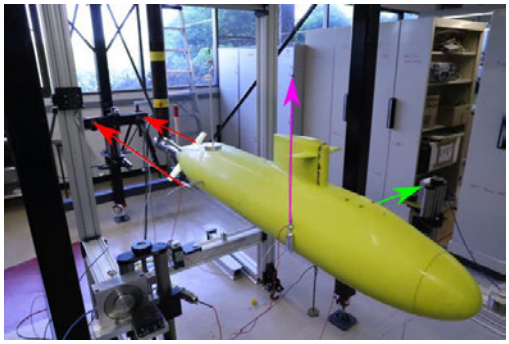


Figure 7: Example of a complex load check where surge (red arrows), heave (pink arrow) and sway (green arrow) loads are applied simultaneously

Table 1: Two standard deviations for random uncertainty calculated from 15 repeat runs

	X(N)	Y(N)	Z(N)	K(Nm)	M(Nm)	N(Nm)
2σ	±0.042	±0.079	±0.061	±0.003	±0.052	±0.020

Test Matrix

Three depths were tested throughout this experimental program which represented a typical periscope depth and two incremental depths in which the free surface effect would still be significant. Four forward velocities were tested at each depth such that a better understanding of near surface effects as a function of speed and depth could be obtained. A summary of the test matrix is presented in Table 2.

Table 2: Test matrix for runs completed in this experimental program

H*	Froude number (*Fr*)
1.71 2.14 2.57	0.19, 0.22, 0.27, 0.32

RESULTS AND DISCUSSION

Force and Moment Data

The force and moment data were non-dimensionalised with respect to length and plotted against Froude number, as defined in equation (2). The surge, heave and pitch coefficients are shown in equations (4) - (6) where *X'* and *X* are the surge coefficient and surge force, *Z'* and *Z* are the heave coefficient and heave force, *M'* and *M* are the pitch coefficient and pitch moment, ρ is the water density, *V* is the forward velocity of the model and *L* is the model length.

$$X' = \frac{X}{\frac{1}{2}\rho V^2 L^2} \tag{4}$$

$$Z' = \frac{Z}{\frac{1}{2}\rho V^2 L^2} \tag{5}$$

$$M' = \frac{M}{\frac{1}{2}\rho V^2 L^3} \tag{6}$$

Figure 8 to Figure 10 show the surge, heave and pitch coefficients plotted against Froude number for all three depths tested. Figure 8 shows the surge coefficient and the experimental uncertainty. Due to the relatively small loads measured in the surge axis, the uncertainty results in each depth fall within the uncertainty of both other depths for each Froude number. Therefore, it is difficult to make a conclusive statement about the effect of the free surface with respect to depth for the range tested. However, there is a positive gradient trend of the surge coefficient with respect to Froude number indicating a change in magnitude of the free surface effect. Due to the small range of speeds tested, there was no resistance hump noticed.

The heave coefficient, Figure 9, shows a clear trend for both speed and depth with respect to the free surface effect. A decrease in heave coefficient indicates an increase in upwards force. Therefore, when the heave coefficient is analysed with respect to depth, there is a significant increase in the upwards force between *Fr* = 0.19 and *Fr* = 0.27. This is due to the well-known venturi effect [8] which increases the velocity of the flow between the submarine and the free surface due to a decrease in total volume, resulting in a suction force towards the surface. As shown by these results, modelling the venturi effect and free surface interactions is useful for planning submarine operations near the surface. Additionally, understanding the depth and velocities at which this upwards heave force becomes significant is critical to maintaining control of a submarine operating close to the free surface. It can also be seen there is minimal change in heave coefficient when increasing the Froude number to *Fr* = 0.32. This is hypothesised to be a result of the interaction between the vertical pylon, which is connecting the horizontal sting to the carriage, and the surface wave generated by the BB2 model. This is also noticed when analysing the free surface elevation plots.

Like the surge coefficient, the pitch coefficient results, Figure 10, are within experimental uncertainty for each depth tested for a given Froude number due to the small moments recorded.

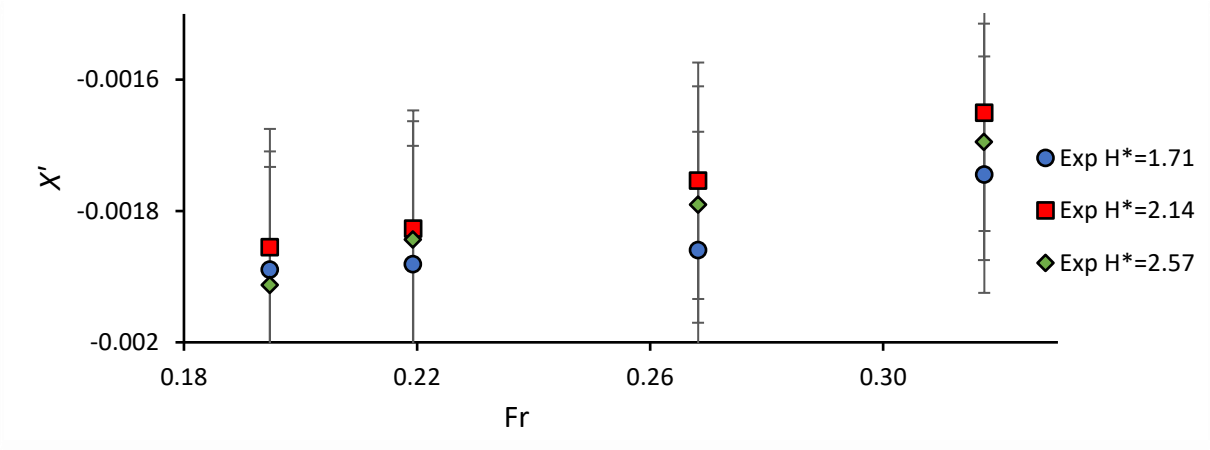


Figure 8: Surge force coefficient (X') plotted against Froude number (Fr) comparing the free surface effect at different depth (H*) values for the BB2 generic submarine

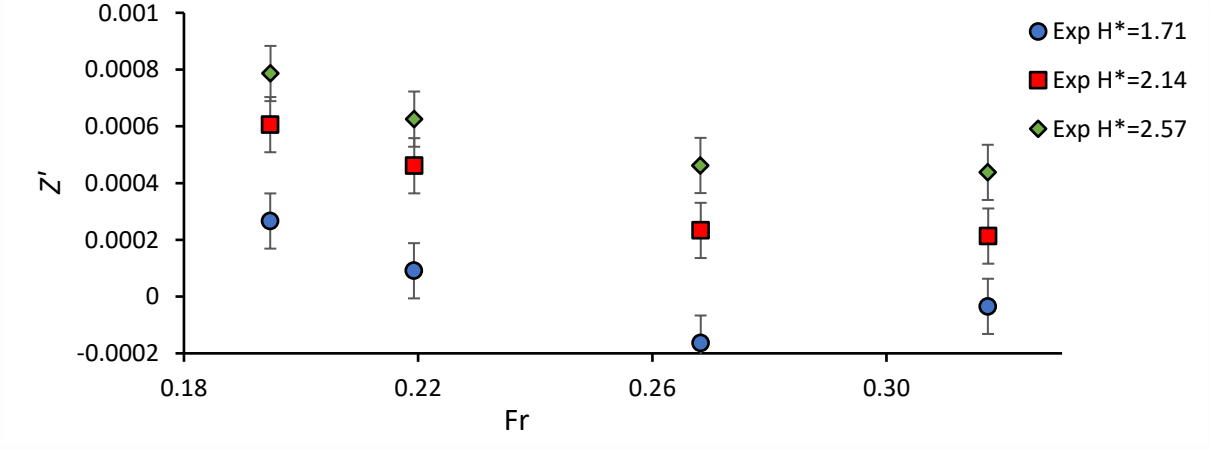


Figure 9: Heave force coefficient (*Z'*) plotted against Froude number (*Fr*) comparing the free surface effect at different depth (*H**) values for the BB2 generic submarine

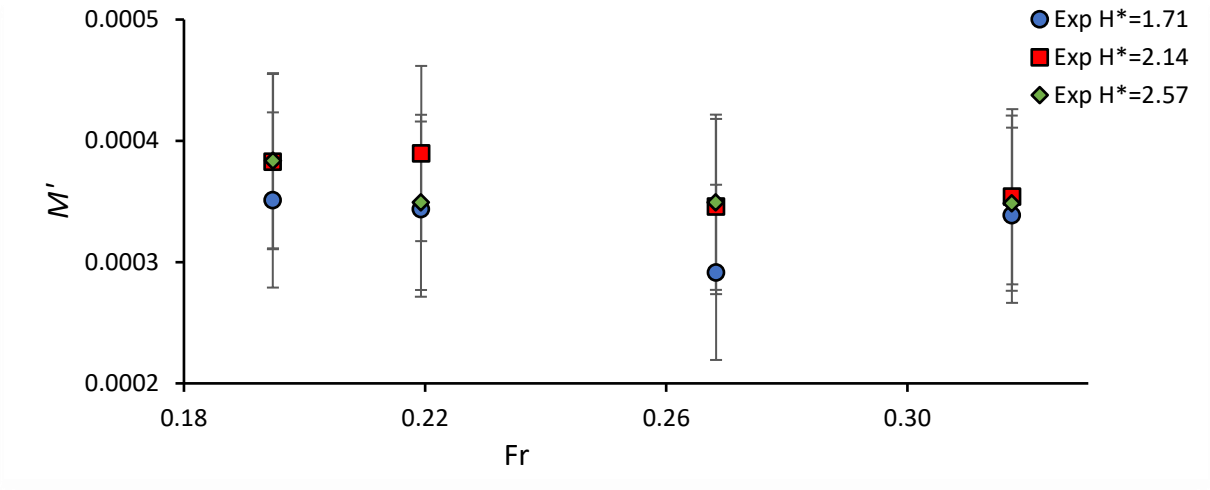


Figure 10: Pitch moment coefficient (*Z'*) plotted against Froude number (*Fr*) comparing the free surface effect at different depth (*H**) values for the BB2 generic submarine

Free Surface Data

Figure 11 to Figure 13 present the free surface elevation against the longitudinal position. The free surface elevation is non-dimensionalised with respect to submarine diameter, λ/D, where λ is the free surface elevation and *D* is the submarine diameter. As discussed in the model details section and shown in Figure 1, the bow of the model is at the longitudinal position x/L = 0 with the stern of the model at *x/L* = -1. As the wave profile was in a steady-state condition, the moving ultrasonic wave probes captured the surface elevation at a fixed location (M1 – M4 in Figure 5) next to the model. The static wave probes (S1 – S5 in Figure 5) were synchronised in time with the carriage. Therefore, through converting time to the known location of the carriage, the wave elevation could be calculated relative to the model position providing a continuous line for the surface elevation. Figure 11 shows the comparison between the static and moving wave probes at the transverse location *y/D* = 1.5 (S1) at the longitudinal positions for the moving ultrasonic wave probes shown in Figure 5. As seen, both wave probe methods provide excellent results relative to each other.

Figure 12 shows the dissipation of the wave profile as the transverse distance from the model is increased at a constant Froude number (*Fr* = 0.32) as expected. The plot in Figure 13 represents the free surface elevation at the three depths tested for the S1 static wave probe at a constant Froude number (*Fr* = 0.32). As can be seen, whilst the wave length remains the same, the wave amplitude increases with decreasing submergence depth, indicating a strong correlation between depth and wave height. Additionally, at H* = 1.71, there is a change in wave profile at the aft end of the model. As briefly mentioned in the surge coefficient discussion, this is due to the pressure field and bow wave generated by the vertical pylon mounted to the sting interacting with the wave profile generated by the model. As such, the hydrodynamic interactions from the vertical sting must be considered when using this experimental dataset to validate numerical simulations.

The final free surface elevation plot presented in this paper shows the change in surface elevation with respect to speed. Figure 14 plots the non-dimensional surface elevation for a

constant depth, H^* = 2.57, at the four Froude numbers tested. Similar to the trend discussed from the heave coefficient, there is significant reduction in the changes to the free surface elevation as the Froude number reduces, indicating a reduction in free surface effect. However, it is clear that at all the speeds and depths investigated, there is still an interaction with the free surface.

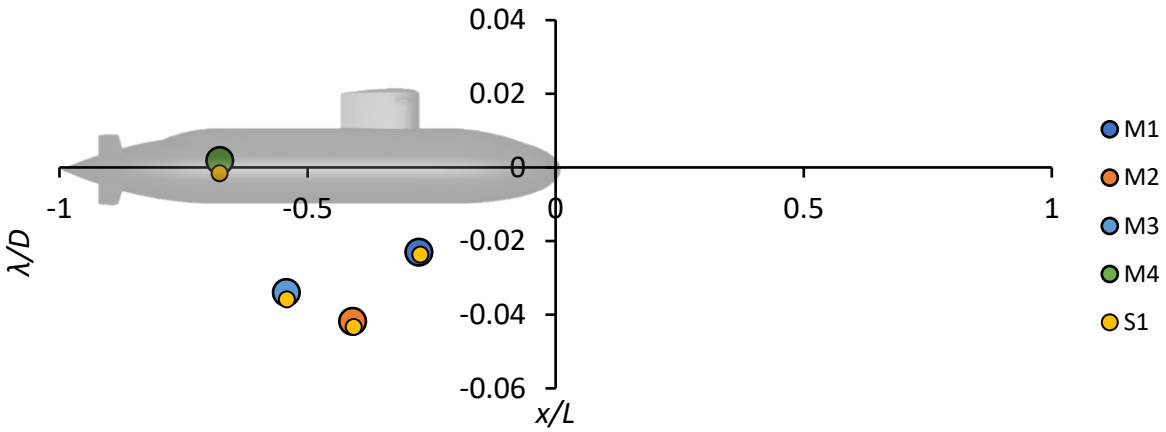


Figure 11: Comparison in wave elevation between static (S1) and moving wave probes (M1, M2, M3, M4) at y/D = 1.5, Fr = 0.32 and H^* = 1.71

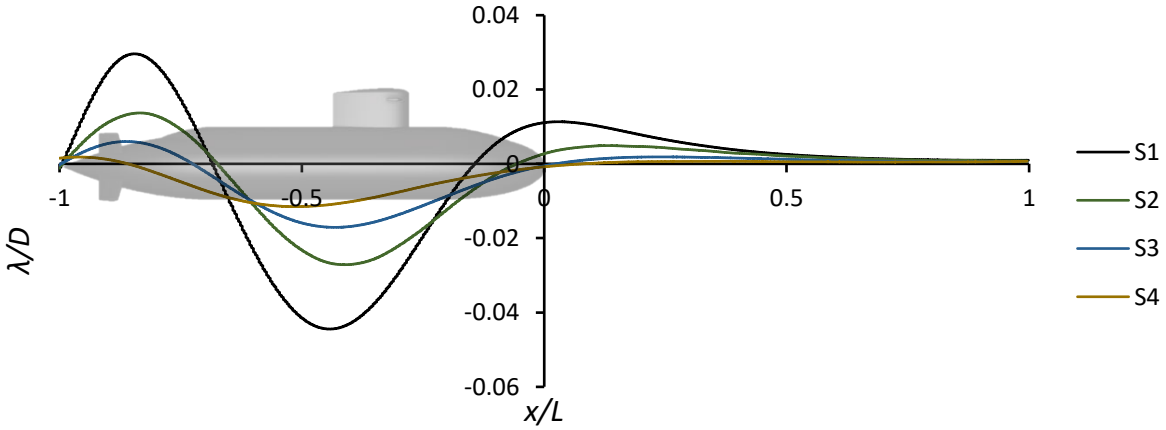


Figure 12: Non-dimensional free surface elevation (λ/D) plotted against longitudinal distance (x/L), for static wave probes (S1-S4) at Fr = 0.32, H* = 1.71

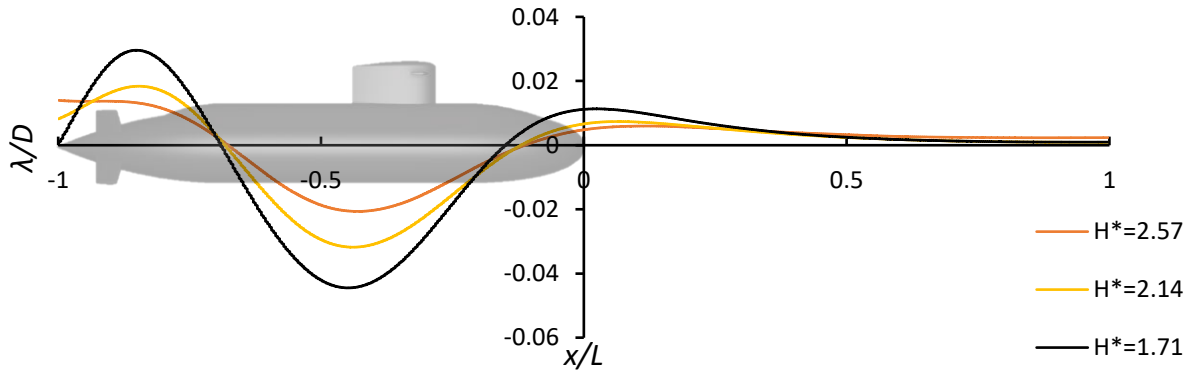


Figure 13: Non-dimensional free surface elevation (λ/D) plotted against longitudinal distance (x/L), for the three depths (H*) at static wave probe (S1) and Fr = 0.32

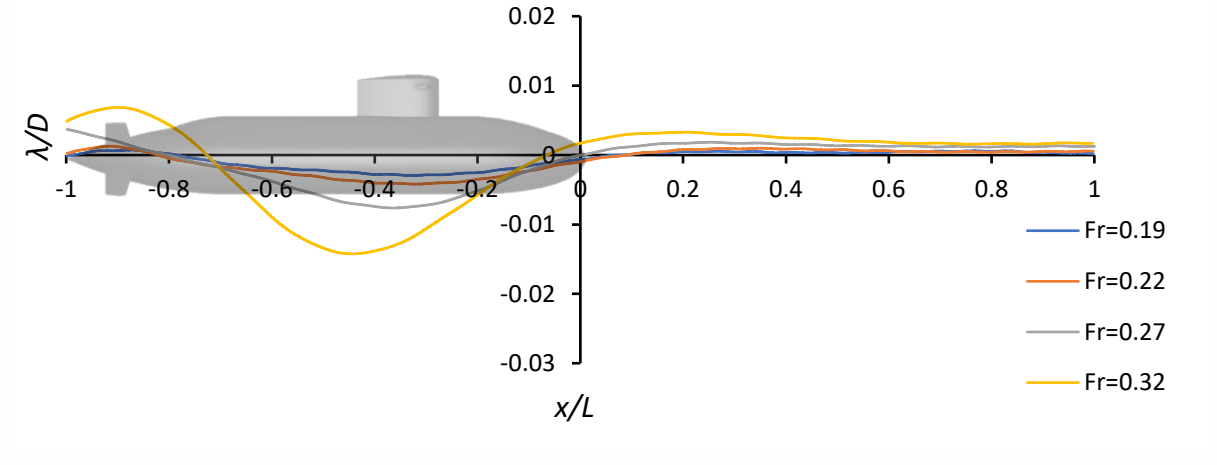


Figure 14: Non-dimensional free surface elevation (λ/D) plotted against longitudinal distance (x/L), for the four speeds (Fr) at static wave probe (S2) and H^* = 2.7

CONCLUSIONS

The experimental program presented in this paper investigated the hydrodynamic interaction between the BB2 submarine model and the free surface in the Australian Maritime College Towing Tank. Understanding this interaction and the relationship between depth and speed on the forces and moments experienced by the submarine is critical to maintaining the vessel's safety and control when operating close to the surface. The surge, heave and pitch coefficients were presented along with the free surface elevation at a range of speeds and depths that represent the typical operating conditions of a submarine near the free surface.

The heave coefficient and wave elevation plots showed a strong correlation between speed and depth with respect to free surface interaction. Reducing the forward velocity reduced the impact from the free surface interaction, as did increasing the submergence depth. It was also shown that the free surface effect was significantly reduced for the deepest (H^* = 2.57) and slowest speed (Fr = 0.19) tested, however, it was concluded that the free surface interaction was still recorded. If the depth and velocity is essential at which there is no

longer an interaction with the free surface, further investigation at slower speeds and/or deeper depths will be required.

This experimental data will be used to validate numerical simulations which will then be used to investigate additional depths and speeds at full scale to further understand the critical depth and speed that free surface interactions have an impact on the submarine's performance.

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Manoeuvring Performance of a Submarine with Different Sails

Gregory Seil[1] **Gregory.Seil@dst.defence.gov.au**
Alexander Cameron[2] **Alexander.Cameron@dst.defence.gov.au**

[1] Maritime Division, Defence Science and Technology Group
[2] QinetiQ Pty Ltd

ABSTRACT

Previous studies conducted by the Defence Science and Technology Group (DSTG) investigated the effect of different submarine sail designs on the out-of-plane loads and hydrodynamic flow structures of the generic Joubert submarine. In this study, deeply submerged manoeuvring simulations of the generic BB2 submarine are performed using the same sail designs to investigate their impact on manoeuvring performance. This provides a greater understanding of the influence of these design changes on the safe operational performance of a submarine. The simulations are performed using the DSTG Maritime Vehicle Simulation Model (MAVSIM), a six-degree of freedom computational model for assessing the dynamics, manoeuvring and control behaviour of underwater vehicles.

To enable these simulations, the hydrodynamic coefficients associated with each sail design are calculated using a body build-up technique similar to the Bohlmann method. This technique calculates coefficients directly from geometry and represents significant time and cost savings over conventional computational fluid dynamics (CFD) methods. Validation is performed against manoeuvring simulations using hydrodynamic coefficients calculated from CFD and shown to be in good agreement for undertaking rapid parametric studies.

This paper demonstrates how the above technique can be applied in conjunction with a manoeuvring model to investigate manoeuvring performance. The results from this study show how different submarine sail designs affect manoeuvring performance and provide insight, from a hydrodynamic perspective, into the benefits of each design. This technique provides for rapid parametric studies and can be applied to other geometric features in order to provide further insights and understanding of underwater vehicle design choices.

INTRODUCTION

The prediction of submarine manoeuvring performance is important for determining the safe operating envelope of the boat [1]. Such predictions are typically enabled by computational or experimental models that allow performance to be assessed without the cost or risk associated with full-scale trials. These methods can also be used for investigating the effect of specific design changes on manoeuvring performance.

The stability, controllability and manoeuvrability of the submarine is primarily determined by the size and shape of the hull and its appendages, propulsor characteristics, buoyancy, mass and inertial properties. The sail, which is required in order to house the masts and periscopes for use when at or near the surface [2], also provides a bridge for commanding the boat when it is on the surface. It is typically the largest appendage on the boat and has a significant effect on manoeuvring performance. In particular, the sail generates a lifting force and a trailing vortex system which affect the development of out-of-planes forces and moments, leading to the so-called 'stern-dipping' tendency [2]. In order to maintain depth and trim during manoeuvres, which is desirable for operational reasons, this stern-dipping effect must be compensated for by additional movement of the control surfaces beyond that required for execution of the particular manoeuvre (e.g. a steady turn). Under certain circumstances the out-of-plane forces and moments can be of sufficient magnitude that the control surfaces reach their physical limits, leading to dynamic instability. The design of the sail is therefore critical to the safe operating envelope of the boat and must be assessed using manoeuvring studies.

Previous studies conducted by the Defence Science and Technology Group (DSTG) [3] investigated the effect of different submarine sail designs on the out-of-plane loads and hydrodynamic flow structures of the Joubert submarine [4]. The Joubert submarine is the predecessor to the DSTG generic submarine (BB2) [5]. The BB2 is representative of a conventional submarine (SSK). An axisymmetric hull, both with and without casing, was also investigated. Whilst the work provided useful insight into differences in the underlying hydrodynamic loads and flow structures for different configurations, the associated manoeuvring performance was not investigated.

In this paper, the work of [3] is extended into a comparative study of manoeuvring behaviour. The BB2 was selected as the baseline geometry due to its improved straight-line stability compared to its predecessor. The primary focus of this paper is on comparing how the presence of appendages, namely the casing and the sail, affect the manoeuvring performance of the boat relative to the basic axisymmetric hull with aft control surfaces. The impact of sail design on manoeuvring performance is also examined. Due to the brevity of this paper, attention will be focused on turning circle manoeuvres.

HULL AND SAIL GEOMETRY

The baseline geometry for this study is the BB2, shown in Figure 1. The BB2 has a full scale overall length of 70.2 m, a maximum hull diameter of 9.6 m, a volume of 4349.7 m^3 and a wetted surface area of 2143.5 m^2.

The following five configurations were studied:

1) Hull: Axisymmetric hull and aft control surfaces of the BB2.
2) Casing: Hull, casing and aft control surfaces of the BB2.
3) BB2: Hull, casing, sail and aft control surfaces of the BB2.
4) Low Profile: Hull, casing and aft control surfaces of the BB2, with the low aspect ratio sail of [3].
5) Blended: Hull, casing and aft control surfaces of the BB2, with the blended sail of [3, 6].

The geometry of the five configurations are compared in Table 1. The sails of the Low Profile and Blended configurations are shown in Figure 2.

For the configurations with sails, no sailplanes have been modelled, as the short span of the sail of the Low Profile configuration makes the use of sailplanes impractical. The sails of the Low Profile and Blended configurations have been positioned such that the average quarter chord lengths are at the same axial position as the BB2 sail (67.9% of the overall length of the boat when measured from the stern).

Table 1: Comparison of total volume (∇_{Total}), sail volume (∇_{Sail}), span (b) and aspect ratio for the different configurations. Note that the volume has been non-dimensionalised by the length of the boat (L) and the sail span by the maximum diameter (D) of the hull. Aspect ratio is based on the planform area (A_P) of the double 'wing'.

	∇_{Total}/L^3 [× 10^{-2}]	∇_{Sail}/L^3 [× 10^{-4}]	b/D [× 10^{-1}]	$2\,b/A_P$ [× 10^{-1}]
Hull	1.156	-	-	-
Casing	1.228	-	-	-
BB2	1.257	2.836	5.833	10.84
Low Profile	1.258	2.941	3.125	4.152
Blended	1.276	4.800	5.818	8.478

The sail of the Low Profile configuration has 53.6% of the span of the BB2 sail, but similar volume. The BB2 sail and the Blended sail have similar span, but the Blended sail has 69% greater volume.



Figure 1. DSTG generic submarine BB2 with control surface notation and sign convention.

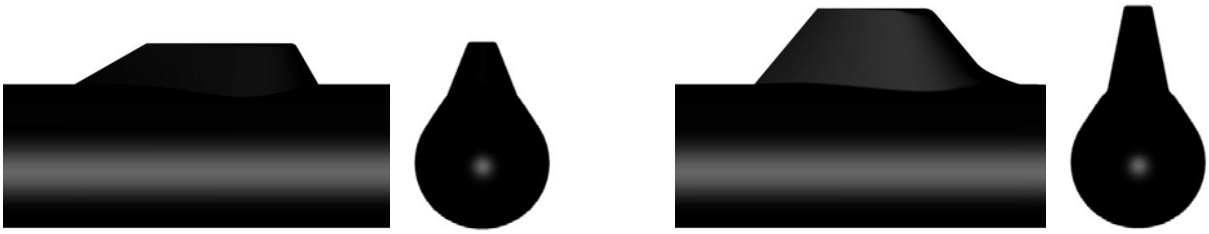


Figure 2. Side and frontal views of sail for Low Profile configuration (left) and Blended configuration (right). Aft control surfaces are not shown in these frontal views.

HYDRODYNAMIC AND MANOEUVRING MODELLING

In this study, manoeuvring simulations are performed using the DSTG Maritime Vehicle Simulation Model (MAVSIM) [7]. MAVSIM is a six-degree of freedom, time-domain computational model for assessing the dynamics, manoeuvring and control behaviour of underwater vehicles. Within MAVSIM, hydrodynamic loads are calculated using the coefficient-based model described by [8]. These are combined with the hydrostatic equations and equations of motion defined by [9] and solved in the time domain to determine the motion of the boat.

In MAVSIM, the linear (u, v, w) and angular (p, q, r) velocities are measured relative to a body-fixed coordinate system located at the centreline of the hull and midships. In this axis system the x axis is collinear with the centreline of the hull and points toward the bow, the y axis points to starboard and the z axis completes the right-handed system. The position of the boat relative to an inertial Earth-fixed coordinate system is (x, y, z) and its orientation is given by the Euler angles (ϕ, θ, ψ). These angles describe the boat's orientation in roll (ϕ), pitch (θ) and yaw (ψ). Both body-fixed and earth-fixed coordinate systems share the same origin at zero time and are shown in Figure 3.

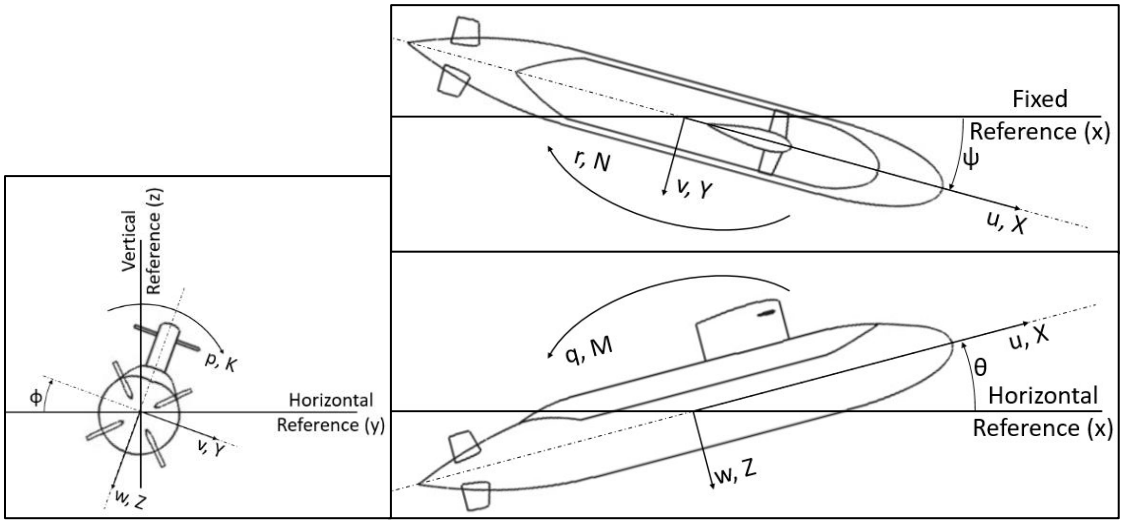


Figure 3. Body-fixed and earth-fixed coordinate systems from aft view (left), side view (bottom right) and top view (top right).

The vehicle parameters required by MAVSIM for the baseline BB2 configuration are primarily sourced from [10]. This includes the definition of a proportional-derivative (PD) controller for control in the horizontal plane (using lateral position and heading angle) and vertical plane (using depth and trim angle). With the exception of buoyancy and centre of buoyancy, these same parameters are used for each configuration. By default, MAVSIM assumes neutral buoyancy with a fixed centre of gravity. In order to undertake a systematic comparison between the configurations considered here, the same transverse stability (the vertical distance [BG] between the centre of gravity [G] and the centre of buoyancy [B]) as that of the baseline BB2 configuration was maintained. In the case of BB2, the centre of gravity was assumed to be located on the

centreline of the hull. The centre of gravity was then determined for the other configurations using B and a constant BG. Propulsor rpm is adjusted for each simulation so that each configuration achieves the same steady speed prior to execution of the selected manoeuvre.

The coefficient-based model used in MAVSIM typically requires a large number of coefficients to characterise the hydrodynamic loads acting on the vehicle. These can be obtained using computational fluid dynamics (CFD); however, the computational expense of using CFD to determine the hydrodynamic coefficients can often be difficult to justify, despite the relatively high fidelity of CFD. Semi-empirical approaches can instead be used for such purposes, and different methods have been considered previously by DSTG [11]. Whilst these approaches lack the fidelity of CFD, their advantage lies in the ability to rapidly evaluate different designs.

The hydrodynamic coefficients for this study were calculated using a modified and extended version of Bohlmann's model [12]. The Bohlmann model uses a semi-empirical body build-up approach to calculating the hydrodynamic coefficients. The Bohlmann model was modified to provide hydrodynamic coefficients for use with the equations of Gertler-Hagen [8] that are implemented in MAVSIM.

RESULTS

Validation of Methodology

Prior to performing simulations using the different sail configurations, the manoeuvring performance of the fully-appended BB2 using the modified Bohlmann model was validated against simulations performed with hydrodynamic coefficients calculated using CFD. The CFD coefficients are for a model-scale Reynolds number of 5.2×10^6 based on the length of the boat [10].

Three different manoeuvres were considered: a horizontal turning circle, a horizontal zig-zag and a vertical zig-zag. For the turning circle and horizontal zig-zag manoeuvres the controller remains active in the vertical plane to maintain a constant depth (z) with zero trim angle (θ). For the vertical zig-zag manoeuvre the controller remains active in the horizontal plane to maintain zero lateral displacement (y) and zero heading angle (ψ). The manoeuvres are shown in Figure 4 – Figure 6. In the figures, only deflections of the upper starboard (d_1) and upper port (d_4) aft control surfaces are shown. Positive deflections correspond to a downward deflection of the trailing edge of the control surface (see Figure 1). Due to the control methodology, the deflection of the lower port and lower starboard control surfaces will be equivalent to the upper starboard and upper port control surfaces, respectively. Angle of attack is defined as $\alpha = \tan^{-1}(w/u)$ and it denotes the angle of the longitudinal body axis from the projection into the principal plane of symmetry of the boat's velocity relative to the fluid. Angle of drift is defined as $\beta = \sin^{-1}(-v/U)$, where U is the total speed of the boat, and it denotes the angle to the principal plane of symmetry from the moving boat's velocity vector relative to the fluid [13]. Where relevant, results are non-dimensionalised using the commanded velocity and the boat length.

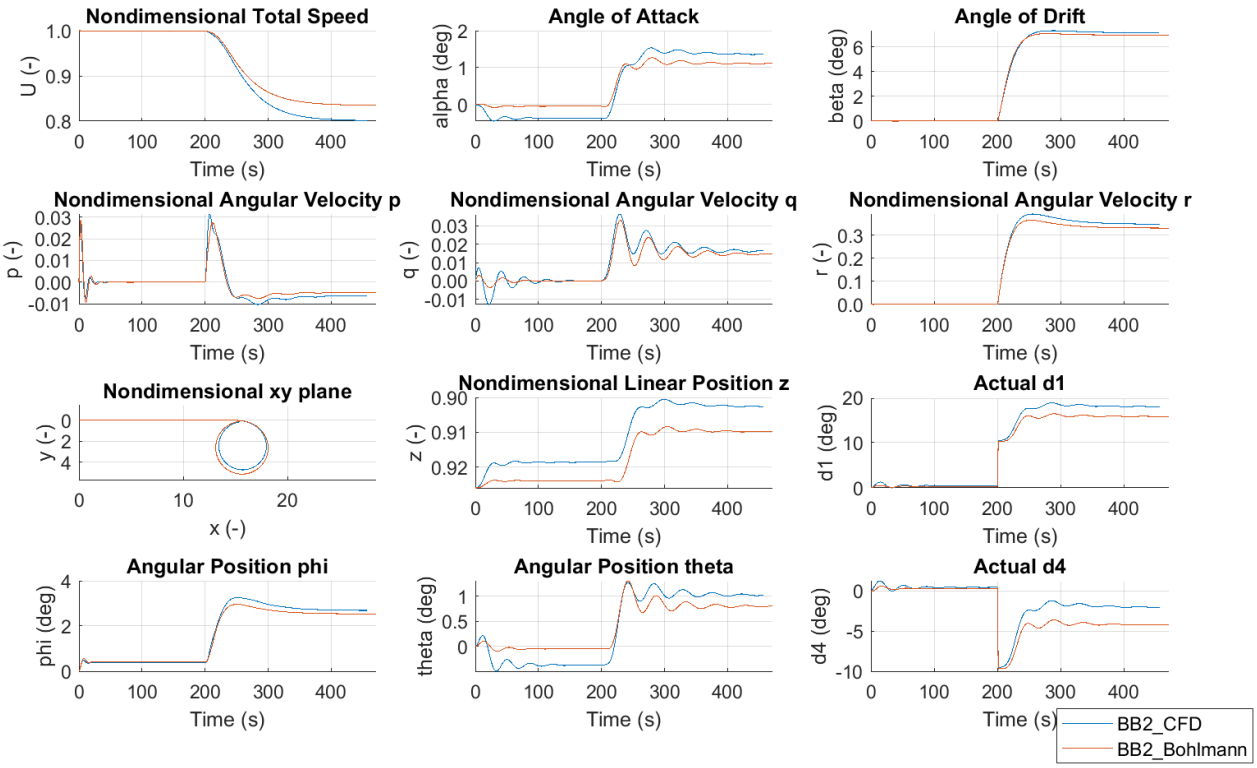


Figure 4. Comparison of turning circle manoeuvre for BB2 with coefficients calculated using CFD and Bohlmann method.

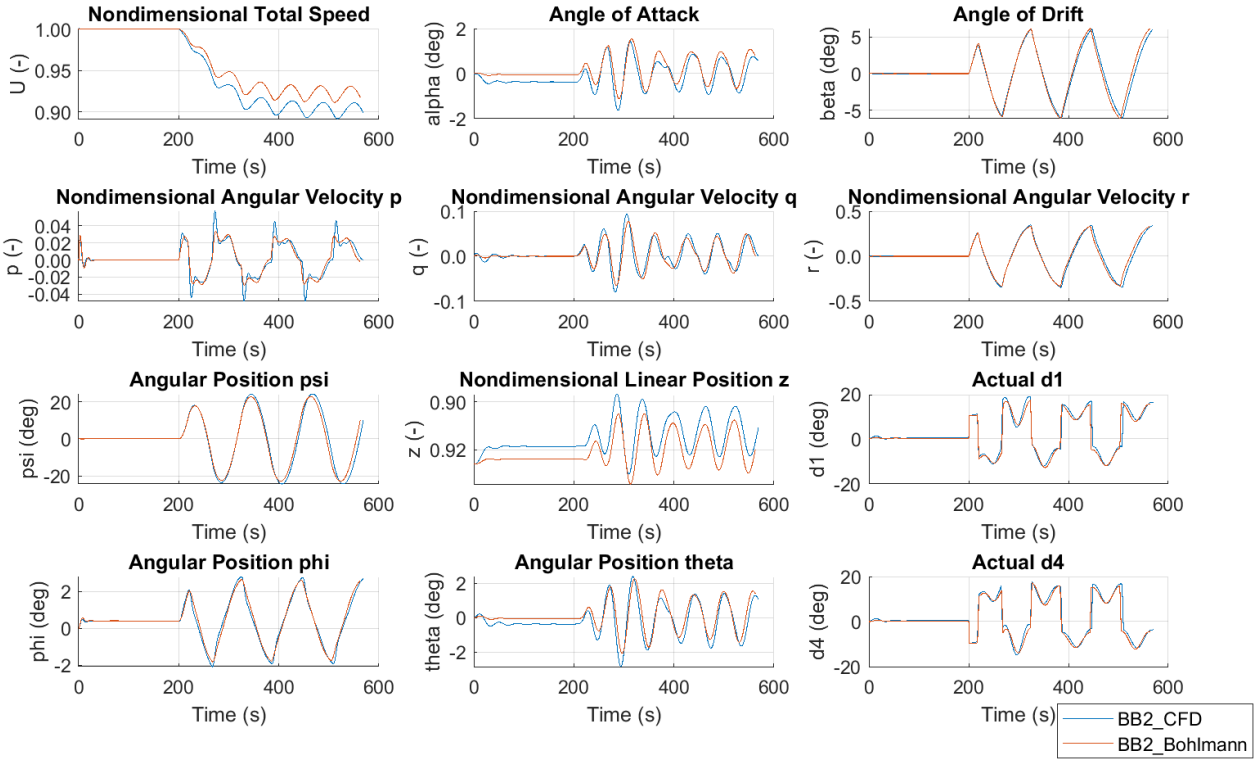


Figure 5. Comparison of horizontal zig-zag manoeuvre for BB2 with coefficients calculated using CFD and Bohlmann method.

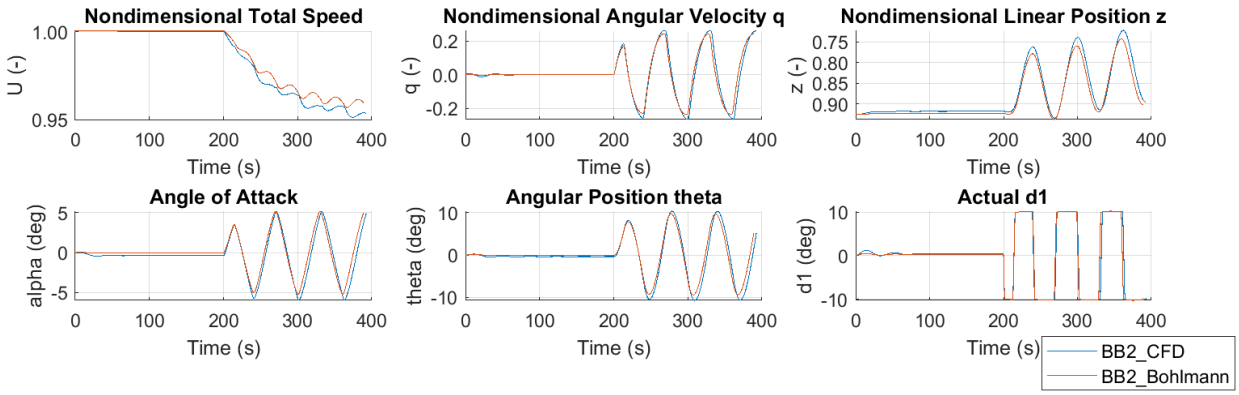


Figure 6. Comparison of vertical zig-zag manoeuvre for BB2 with coefficients calculated using CFD and Bohlmann method.

The results predicted by the modified Bohlmann model are in very good agreement with the manoeuvring results predicted using coefficients based on CFD, showing similar states and aft control surface deflections.

Both the horizontal and the vertical zig-zag manoeuvres show good agreement with minimal phase shift. For the case of the horizontal turning circle, the most noticeable difference is the larger tactical diameter and a less pronounced drop in boat speed for the Bohlmann results. This may be attributed to predicted hydrodynamic coefficients for the control surfaces which result in lower control surface effectiveness.

All manoeuvres showed a difference in the steady depth and trim positions prior to execution of the manoeuvre. This is caused by differences in the straight-ahead resistance and pitching moment coefficients between CFD and the modified Bohlmann method.

Comparison of Manoeuvring Performance of Different Configurations

Having established that the predicted hydrodynamic coefficients using the modified Bohlmann method produce acceptable results, the comparative manoeuvring performance of the five configurations described previously was examined. These results are shown in Figure 7 for the case of a horizontal turning circle. Table 2 summarises these results using a variety of key metrics.

Table 2: Comparison of turning circle key metrics for different configurations. Where relevant, results are non-dimensionalised using the commanded velocity (U) and the boat length (L).

Geometry Configuration	Advance $[\times \frac{1}{L}]$	Tactical Diameter $[\times \frac{1}{L}]$	Steady Speed $[\times \frac{1}{U}]$	Steady Yaw Rate [rad/s]	Steady Roll Angle [deg]	Steady Trim Angle [deg]
Hull	4.279	6.582	0.818	0.251	0.893	1.002
Casing	3.769	5.412	0.780	0.292	0.490	1.094
BB2	3.471	4.894	0.805	0.332	2.510	2.931
Low Profile	3.933	5.940	0.821	0.278	1.599	2.208
Blended	3.630	5.246	0.817	0.313	2.571	2.910

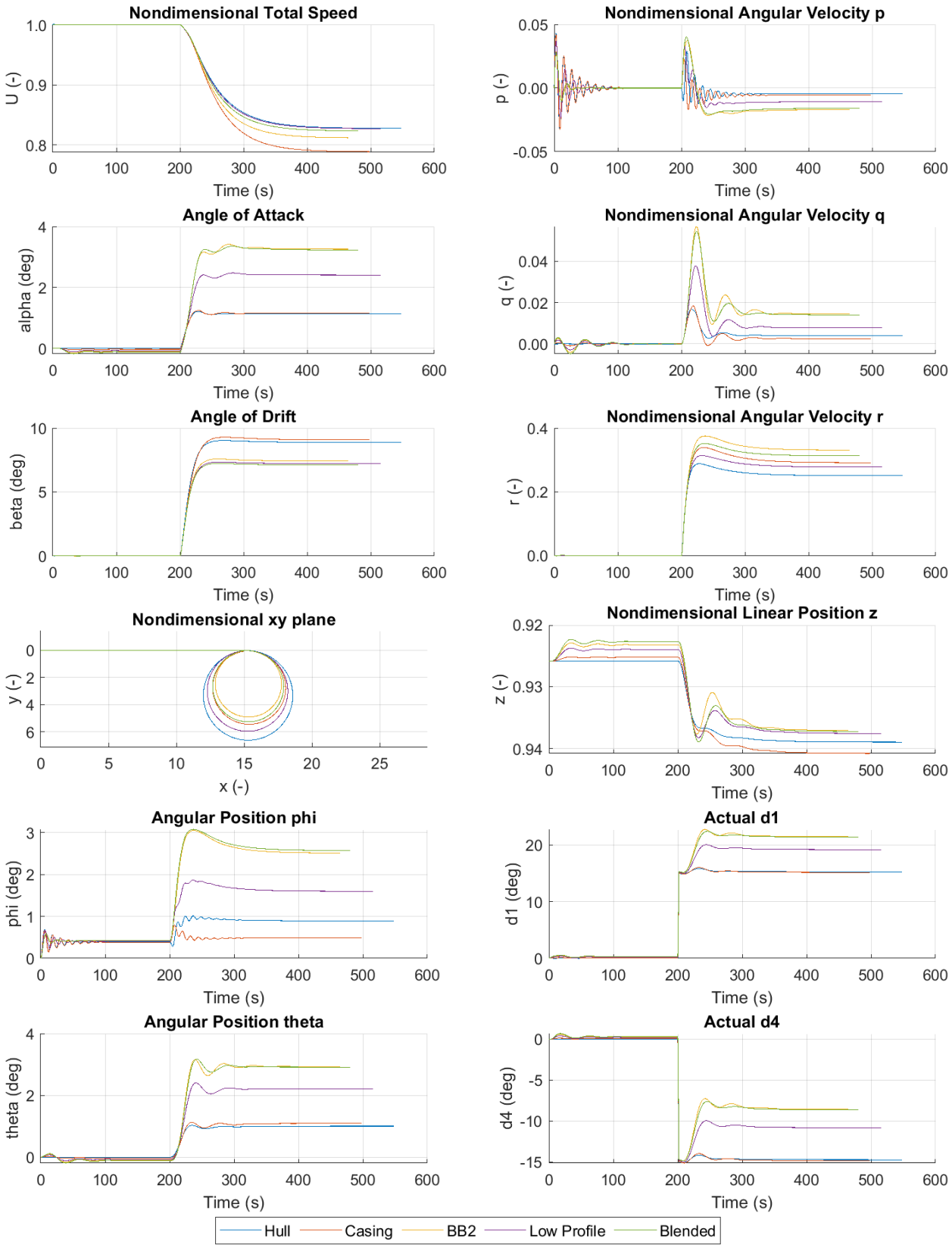


Figure 7. Comparison of turning circle manoeuvre for different configurations.

In the simulation the turn is initiated at 200 seconds with the deflection of the aft control surfaces. The stern-dipping tendency is clearly evident for the configurations with a sail over the period of 200 - 230 seconds, where an increase in depth (z) and a pitch-up behaviour (increased θ) is observed. The tendency is most pronounced for the Blended and BB2 configurations and least for the Low Profile configuration. Of the configurations with a sail, the BB2 and Blended configurations experience the most pronounced roll angle (ϕ) over the course of the turn and the Low Profile configuration the least. There is little difference in steady roll angle and trim angle between the BB2 and Blended configurations. After approximately 230 seconds, the pitch angular velocity (q) reduces as the aft control surfaces counteract the stern-dipping effect. Stern-dipping is also evident for the configurations without a sail, although to a lesser extent than for configurations with a sail. For configurations without a sail the control surface deflections remain essentially constant, whereas they can be seen to change for the configurations with a sail. By 350 seconds all configurations have achieved steady motion (within 5% of their final value) in all 6 velocity components.

The BB2 configuration has the smallest tactical diameter, followed by the Blended configuration which has a 7.2% greater tactical diameter. As expected the Low Profile configuration has the largest tactical diameter of the configurations with a sail, being 21.4% greater than that of the BB2 configuration. The Hull configuration, which has no sail, has the largest tactical diameter of all of the configurations and is 34.5% larger than the value for the BB2 configuration. The tactical diameter of the Casing configuration suggests that the presence of the casing results in a significant reduction in the tactical diameter of the turning circle, relative to the basic axisymmetric hull with aft control surfaces.

The drop in speed during the manoeuvre shows interesting behaviour. The greatest speed drop occurs for the Casing configuration, which is somewhat counter-intuitive. However, it must be noted that the drag on the boat is related to the incidence of the boat, its rotational velocity and the deflection of the aft control surfaces. Relative to the Hull configuration, the Casing configuration undergoes a greater yaw angular velocity (r). Since the aft control surface deflections and drift angles are similar for the Hull and Casing configurations, it is the difference in yaw angular velocity which produces the difference in drag, and hence speed drop, between these configurations. The greater speed drop of the Casing configuration relative to the configurations with sails may be attributed to the difference in drift angle. The control surfaces push the Casing configuration to a greater drift angle which produces more drag and pulls the boat into a relatively tight turn, but at the cost of a reduction in boat speed.

DISCUSSION OF RESULTS

The stern-dipping behaviour is directly correlated with the lift and circulation produced by the sail and is, in general terms, consistent with the expected results based on the hydrodynamic heave force and pitching moments of [3]. In other words, the stern-dipping behaviour of the BB2 and Blended configurations is similar and both are more pronounced than the Low Profile configuration.

For the cases without a sail, a stern-dipping type of behaviour was also observed. In these cases there is no sail with an associated trailing vortex system altering the crossflow about the hull and generating out-of-plane forces and moments. However, for both these configurations the centre of gravity lies below the origin of the body-fixed coordinate system. During a turn, this generates a pitching moment arising from inertial forces, which results in a similar trim behaviour to the sail-induced stern-dipping. For the case of the Casing configuration, this mechanism also applies (albeit to a lesser extent than the Hull configuration) in addition to hydrodynamic forces arising from the asymmetry of the geometry when it undergoes coupled rotation and drift in a turn.

All configurations displayed roll behaviour during the turn. For the configurations with a sail, this effect is driven by the lift and position of the sail and therefore follows similar trends to the stern-dipping. Specifically, the roll angle of the BB2 and Blended configurations are similar, and both are larger than the Low Profile configuration. For the configurations without a sail the roll behaviour is caused by the same inertial forces which cause stern-dipping. This is smaller for the Casing configuration due to its higher centre of buoyancy (and hence centre of gravity).

CONCLUSIONS

The influence of casing and sail design on the manoeuvring performance of a generic conventional submarine was investigated for a horizontal turning circle manoeuvre. The stern-dipping in the initial part of the turn was clearly evident for the configurations with a sail, with the magnitude of this tendency related to the lift produced by the sail. A greater pitch angle during the course of the turn was associated with greater sail lift. Maintaining depth control while undergoing stern-dipping requires greater control surface deflection; this makes the turn more expensive, both in terms of noise and propulsion energy, for sails with greater lift.

The influence of the sail lift on the turning circle was evident, with greater sail lift associated with a smaller tactical diameter. Elimination of the sail and the use of an axisymmetric hull resulted in a significant increase in tactical diameter, relative to the configurations with a sail. On the other hand, the addition of the casing to the axisymmetric hull was shown to produce a dramatic reduction in tactical diameter relative to the tactical diameter of the axisymmetric hull, but this came at the cost of greater speed drop in the turn, relative to the configurations with a sail.

The results demonstrated that both the sail and inertial forces provide strong contributions to the roll behaviour of the vehicle.

The work presented in this paper highlights some of the design considerations and potential trade-offs in submarine sail design which are difficult to quantify without manoeuvring simulations.

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Enhancing the propulsive performance of a ducted propeller for a Full-scale BB2 underwater vehicle

Kenshiro Takahashi[*†] **and Chris Gargan-Shingles**[†]
[*]Naval Systems Research Center, Acquisition, Technology & Logistics Agency, Tokyo/Japan
[†]Maritime Division, Defence Science and Technology Group, Melbourne/Australia
kenshiro.takahashi@defence.gov.au

ABSTRACT

The hydrodynamic performance and acoustic signature of underwater vehicles are of vital importance when they are deployed as underwater defence systems. An excellent propulsion candidate for such vehicles is the ducted propeller, which when properly designed can deliver improvements in areas such as delivered thrust, propulsive efficiency, acoustic signature, and cavitation suppression. Therefore, a study has been conducted on wake-adapted ducted propellers fitted to a full-scale underwater vehicle. In an earlier study, the effect of duct length on the self-propulsive performance was investigated considering the space required by the struts to mount the duct on the hull. A monotonic adverse trend of the duct length for the self-propulsive performance was demonstrated, and it was observed that propulsive efficiency decreased for longer ducts. In this regard, the present study aimed to improve the propulsive efficiency for a longer-ducted propeller and investigate the effect of struts fitted in the upstream of the blades on the hydrodynamic performance. A set of simulations was performed to evaluate the open-water performance of the ducted propeller using CFD for each pitch ratio, and an efficiency plot was created to optimise the propeller pitch and diameter. The self-propulsive performance was improved by approximately 20 %. The effect of the struts on the delivered power was limited. The dominant harmonic of unsteady propeller thrusts was reduced compared with that of the previous ducted propeller design. There was limited variation in the unsteady propeller thrusts between the cases with and without the struts.

NOMENCLATURE

A_E	expanded area [m^2]	R_e	Reynolds number
A_O	disk area [m^2]	R_P	propeller radius [m]
$A_{k,l}$	coefficient	R_T	hull resistance [N]
B	beam [m]	$R_{T\ towed}$	hull resistance without propulsion [N]
$B_{k,l}$	coefficient	t	thrust deduction fraction
B_P	power coefficient	T	propeller thrust [N]
$C_{0.7R_P}$	chord length at 70% radius [m]	T_b	blade thrust [N]
C_f	frictional coefficient	$(T_b)_N$	amplitude of the Nth harmonic of the propeller thrust [N]

C_F	frictional coefficient of the hull according to the ITTC-1957 model-ship correlation line	$(T_b)_{N=0}$	circumferential average of the propeller thrust [N]
d	boss diameter [m]	T_d	duct thrust [N]
D_{deck}	keel to deck [m]	u_τ	frictional velocity [m/s]
D_P	propeller diameter [m]	V	ship speed [m/s]
D_{Pf}	propeller diameter [feet]	V_A	advanced velocity [m/s]
D_{sail}	keel to top of sail [m]	V_{Ak}	advanced velocity [knots]
J	advance coefficient	$\bar{V}_x$	circumferential average of the axial velocity [m/s]
k	coefficient order	w	Taylor wake fraction
K_Q	torque coefficient	y^+_{min}	non-dimensional initial layer thickness
K_T	thrust coefficient	Z	number of blades
K_{Tb}	blade thrust coefficient	δ	speed ratio
K_{Td}	duct thrust coefficient	η	propulsive efficiency
l	coefficient order	η_H	hull efficiency
L_{OA}	overall length [m]	η_o	open-water efficiency
n	propeller rotational speed [rps]	η_R	relative rotative efficiency
n_m	propeller rotational speed [rpm]	θ	angular position on the propeller disk, positive clockwise looking upstream [°]
$O.W.$	open water	ν	kinematic viscosity [m^2/s]
P	propeller pitch [m]	ρ	Fluid density [kg/m^3]
P_D	delivered power [HP]	$(\phi_T)_N$	phase angle of the N^{th} harmonic of the propeller thrust [°]
Q	propeller torque [N·m]	Δ_{min}	initial layer thickness [m]
Q_H	propeller torque [HP·s]		

1 INTRODUCTION

Underwater vehicles are specialised platforms required to achieve a wide variety of mission objectives. Improving the hydrodynamic performance of such vehicles is critical in enabling mission success. Although there are numerous factors that influence hydrodynamic performance, proper design and operation of the propulsion system is key. In this regard, the marine propeller hydrodynamics has been extensively studied, and superior performance has been achieved through appropriate design evolution. Ducted propellers are expected to exhibit advanced hydrodynamic performance of underwater vehicles, with significant benefits over open propellers. Specifically, an accelerating duct can achieve higher propulsive efficiency owing to the thrust generated by the duct. In contrast, a decelerating duct is used to suppress cavitation by increasing the pressure inside the duct. Nevertheless, the performance of ducted propellers fitted to underwater vehicles is unclear, as such propellers are typically fitted for highly loaded propulsion required for vessels such as tugboats and low-speed tankers. Furthermore, the scale effect on the hydrodynamic performance is significant in underwater vehicles, and it should be considered in the design process to predict the actual

performance. The design parameters should be adapted for the specified vehicle, and therefore the hydrodynamic performance of ducted propellers in the wake of a full-scale underwater vehicle should be analysed.

This study is based on previous work in a series of numerical studies on a wake-adapted ducted propeller fitted to a full-scale BB2 underwater vehicle, which involved the fundamental design and analysis on the propulsive performance. A benchmark study of a five-bladed propeller with an accelerating duct was performed using computational fluid dynamics (CFD) for a full-scale BB2 underwater vehicle operating at the self-propulsive condition by Takahashi and Shingles (2021a). The propeller pitch and diameter were optimised using an existing design chart, and a comparison was made between the hydrodynamic performance at full-scale and that at model-scale. In the study conducted by Takahashi and Shingles (2021b), the effect of duct length on the self-propulsive performance was investigated considering the space required by the struts to mount the duct on the hull. A monotonic adverse trend of the duct length for the self-propulsive performance was demonstrated, and it was observed that propulsive efficiency decreased for longer ducts. In addition to the increased frictional drag on the duct owing to the large wetted surface area, the design parameters were optimised for the benchmark duct length (the ratio of the duct length to the propeller diameter is 0.5), contributing to the lower propulsive efficiency of the longer-ducted propellers. Consequently, the present study aimed to improve the propulsive efficiency for a longer-ducted propeller and investigate the effect of struts fitted upstream of the blades on the hydrodynamic performance. A design chart was developed using CFD to optimise the propeller diameter and pitch ratio for the ducted propeller. The propulsive performance and unsteady propeller thrusts were computed, and compared with those of the previous propeller. The dominant harmonics in the unsteady propeller thrust were determined via Fourier series. The nominal wake in the propeller plane was analysed to correlate the velocity profiles and blade load fluctuations.

2 METHODOLOGY

The BB2 underwater vehicle, which is a modern generic SSK-class underwater vehicle based on the concept design by Joubert (2004, 2006), was used for this study. The vehicle comprised of a hull, sail, sail planes, casing, and stern planes, as shown in Fig. 1. Table 1 lists the principal parameters of the BB2 underwater vehicle for full scale. A five-bladed propeller was selected, and the blade section profile was determined based on the study by Oosterveld (1970). The accelerating nozzle no. 19A was chosen for the previous and present ducted propellers, with its geometry and design charts available in the public domain. The accelerating nozzle provides additional thrust enhancing propulsive efficiency (Oosterveld 1970). The ratio of the duct length to propeller diameter (L_n/D_P) was 0.8, and it was selected accounting for the space required by the struts to mount the duct on the hull.

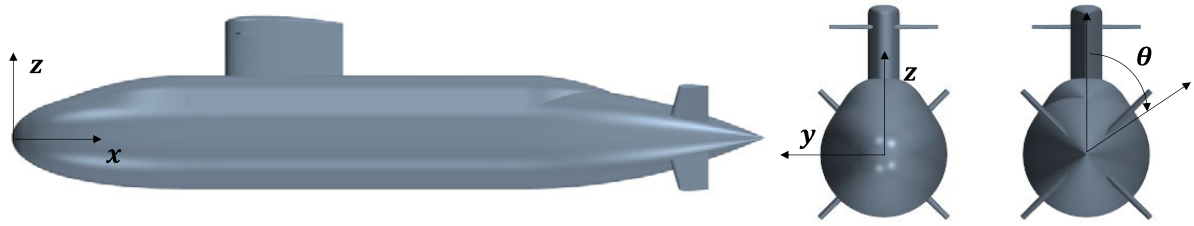


Fig. 1: Geometry of the BB2 underwater vehicle.

Table 1: Principal parameters of the full-scale BB2 underwater vehicle.

Parameters	Values
Overall length, L_{OA} [m]	70.2
Beam, B [m]	9.6
Keel to deck, D_{deck} [m]	10.6
Keel to top of sail, D_{sail} [m]	16.2

The CFD package STAR-CCM+2020.2.1 was used for the computations. STAR-CCM+ utilises a finite volume method solver, and the continuity and Reynolds averaged Navier–Stokes equations were used as the governing equations. The k–ω shear stress transport turbulence model (Menter 1994) was employed, and a second-order scheme was used in space and time. An unstructured trimmed mesh was employed. Prism layer meshes were generated on the hull and blade surfaces to ensure that y^+_{min} was 30 at an expansion rate of 1.15 for full-scale self-propulsive simulations. Here, y^+_{min} is the non-dimensional initial layer thickness. y^+_{min} for the hull surface was estimated using the equations based on Takahashi and Sahoo (2019):

$$y^+_{min} = \frac{\Delta_{min} \cdot u_\tau}{\nu}, \tag{1}$$

$$u_\tau = \sqrt{\frac{1}{2} V^2 C_F}, \tag{2}$$

$$C_F = \frac{0.075}{(\log R_e - 2)^2}, \tag{3}$$

$$R_e = \frac{V \cdot L_{OA}}{\nu}, \tag{4}$$

where Δ_{min} is the initial layer thickness [m], u_τ is the frictional velocity [m/s], ν is the kinematic viscosity [m^2/s], V is the ship speed [m/s], C_F is the frictional coefficient of the hull according to the ITTC-1957 model-ship correlation line, and L_{OA} is the overall length [m]. y^+_{min} for the blade surface was calculated using Eq. (1) and the following equations:

$$R_e = \frac{C_{0.7R_P}\sqrt{V_A^2 + (0.7\pi n D_P)^2}}{\nu}, \tag{5}$$

$$u_\tau = \sqrt{\frac{1}{2}(V_A^2 + (0.7\pi n D_P)^2) C_f}, \tag{6}$$

$$\frac{0.242}{\sqrt{C_f}} = \log_{10}(R_e \cdot C_f), \tag{7}$$

where $C_{0.7R_P}$ is the chord length at 70% radius [m], V_A is the advanced velocity [m/s], n is the propeller rotational speed [rps], D_P is the propeller diameter [m], and C_f is the frictional coefficient. Mesh refinement was implemented near the propulsion unit, and the total number of cells was approximately 33 million. Figs 2 (left) and 3 illustrate the computational domain and volume cells used for the self-propulsive simulations.

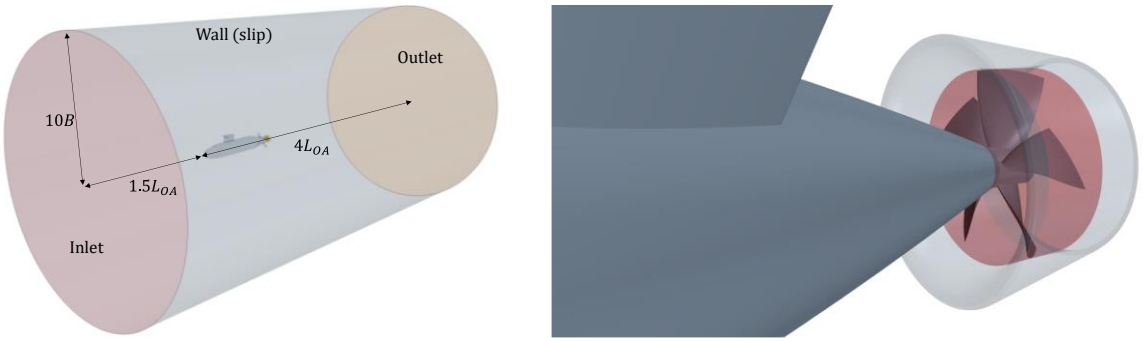


Fig. 2: Computational domain (left) and sliding mesh region (right).

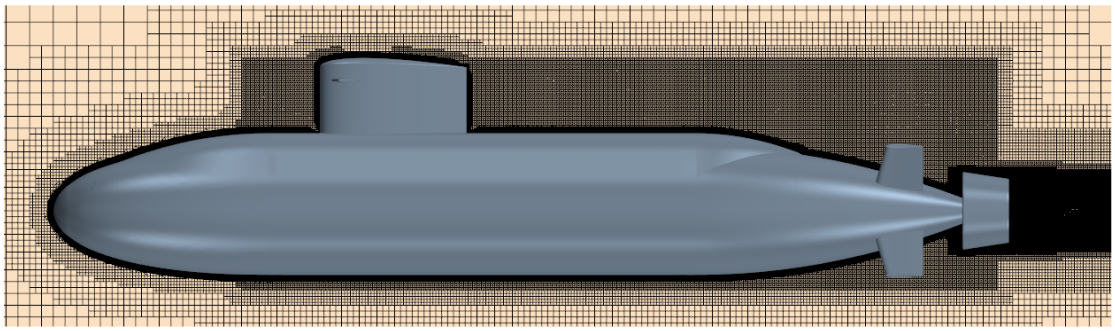


Fig. 3: Volume mesh at y = 0 plane (33 million cells).

Unsteady simulations modelling the actual geometry of the propulsion unit were performed at V = 5.144 m/s (10 knots). A sliding mesh method was used to rotate the propeller blades, as shown in Fig. 2 (right). The time-step size was equivalent to the time periods corresponding to propeller rotations of 1.0 degree, and an inner iteration number of five was employed. Several simulations were performed to determine the self-propulsive point via trial and error until the imbalance between the hull resistance R_T [N] and propeller thrust T [N] was less than 1.0% based on the ITTC Recommended Procedures and Guidelines (2014). Fig. 4 shows the iteration histories of R_T and T for the present propeller at n = 1.051 rps, where T_b is the blade thrust [N] and T_d is the duct thrust [N]. A steady simulation was performed in the first period to achieve iterative evolution by using the moving reference frame method. Thereafter, the unsteady simulations were performed for the duration of five propeller rotations, and the time-averaged values for the fifth rotation were used for the analysis.

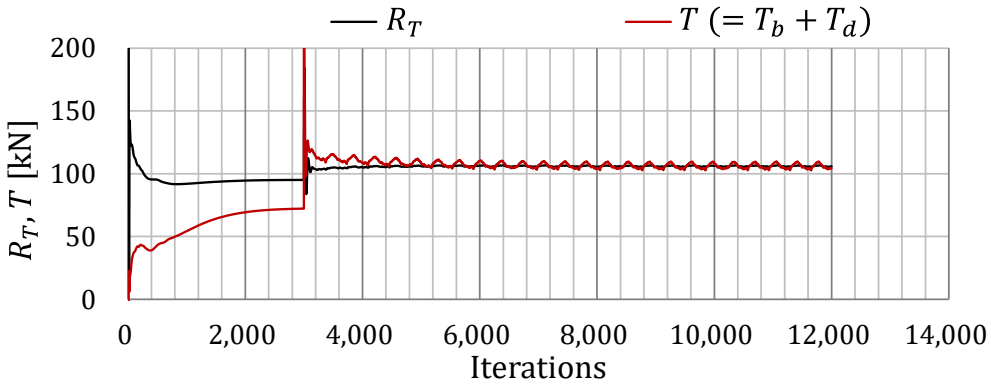


Fig. 4: Iteration histories of R_T and T for present propeller at V = 5.144 m/s.

3 PROPELLER DESIGN

A set of simulations was performed to evaluate the open-water performance of the ducted propeller using CFD for pitch ratios in the range of $1.0 \leq P/D_P \leq 2.4$ to develop a $B_P - \delta$ design chart. B_P is the power coefficient and δ is the speed ratio defined as (Carlton 2012)

$$B_P = \frac{P_D^{1/2} n_m}{V_{Ak}^{2.5}}, \tag{8}$$

$$P_D = 2\pi n Q_H, \tag{9}$$

$$\delta = \frac{101.27}{J}, \tag{10}$$

$$J = \frac{V_A}{nD_P}, \tag{11}$$

where P_D is the delivered power [HP], n_m is the propeller rotational speed [rpm], V_{Ak} is the advanced velocity [knots], Q_H is the propeller torque [HP·s], and J is the advance coefficient. The computed thrust coefficient K_T and torque coefficient K_Q were expressed as polynomials of J and P/D_P based on Oosterveld (1970) as follows:

$$K_T = \sum_{k=0}^{6} \sum_{l=0}^{6} A_{k,l} \left(\frac{P}{D_P}\right)^k \cdot J^l, \tag{12}$$

$$K_Q = \sum_{k=0}^{6} \sum_{l=0}^{6} B_{k,l} \left(\frac{P}{D_P}\right)^k \cdot J^l, \tag{13}$$

where $A_{k,l}$ and $B_{k,l}$ are the coefficients, k and l are the coefficient orders and vary from 0 to 6. Fig. 5 illustrates the computational domain using the periodic boundaries and volume mesh for the propeller open-water simulations, and Fig. 6 shows the $B_P - \delta$ chart developed, where η_o is the open-water efficiency defined as

$$\eta_o = \frac{K_T}{2\pi K_Q} \cdot J. \tag{14}$$

The propeller diameter D_P and pitch ratio P/D_P were selected for the full-scale BB2 underwater vehicle under self-propulsive conditions for the ship speed V = 5.144 m/s (R_e = 2.66×10^8) using the chart.

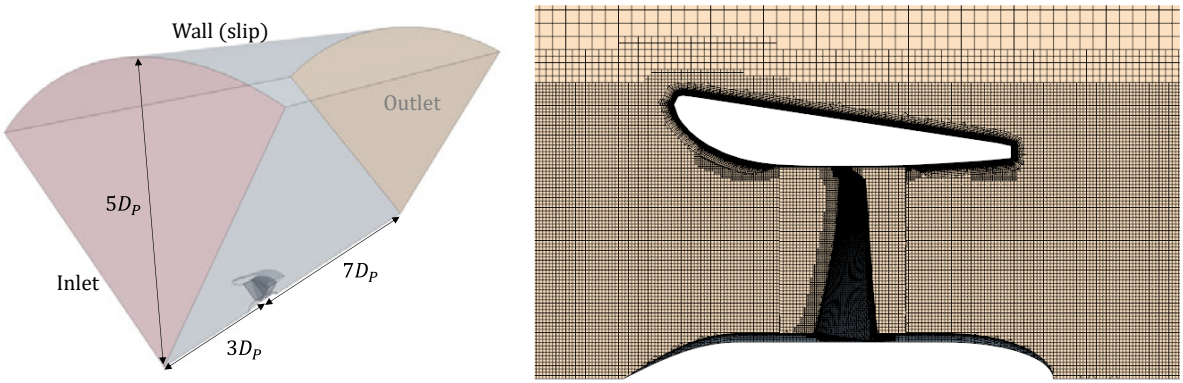


Fig. 5: Computational domain periodic boundaries and volume mesh (5.8 million cells) for open-water performance.

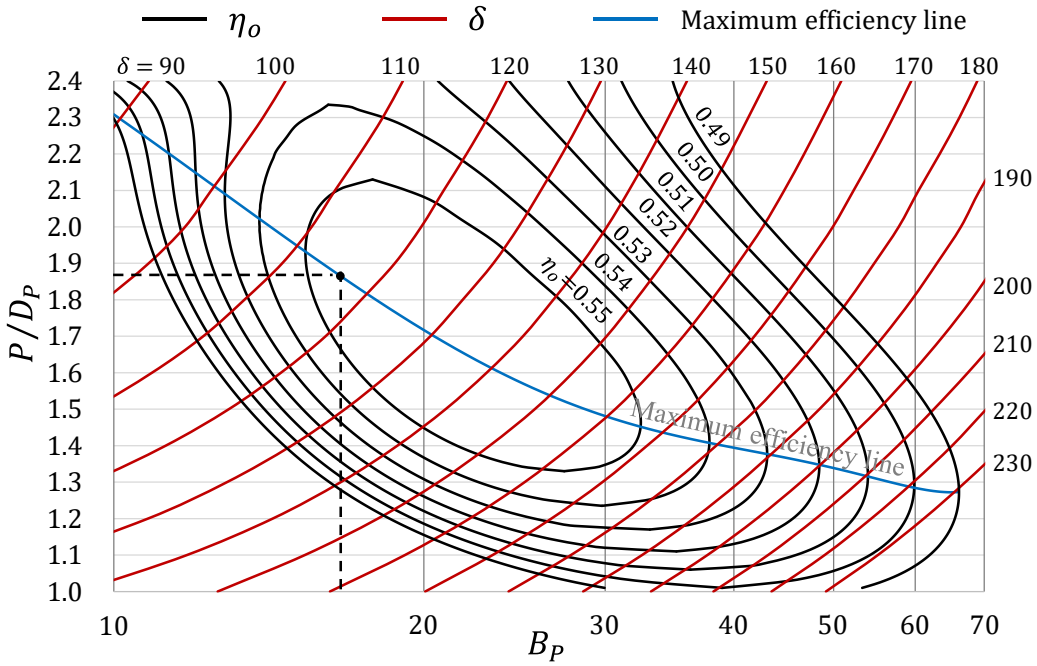


Fig. 6: $B_P - \delta$ design chart developed using CFD.

The power coefficient, B_P (= 15.3) was calculated using the values of P_D, n_m, and V_{Ak} at the self-propulsive condition obtained in an earlier study (Takahashi and Shingles 2021b). Subsequently, the required speed ratio δ (= 117) for the B_P value was noted at the point of intersection of the constant B_P line and the maximum efficiency line. Then, the optimum propeller diameter D_{Pf} [feet] was calculated as follows (Carlton 2012):

$$D_{Pf} = \frac{\delta \cdot V_{Ak}}{n_m}. \tag{15}$$

Finally, P/D_P was determined from the intersection in the $B_P-\delta$ chart. Table 2 lists the design parameters of the present propeller in conjunction with those of the previous propeller. Herein, A_O is the disk area [m^2] and R_P is the propeller radius [m].

Table 2: Principal parameters of ducted propeller.

Parameters	Present propeller	Previous propeller
Number of blades, Z	5	
Propeller diameter, D_P [m]	3.54	4.33
Pitch ratio, P/D_P	1.87	1.36
Boss ratio, d/D_P	0.215	
Expanded area ratio, A_E/A_O	0.75	
Skew at 0.7R_P	0	
Rake	0	
Nozzle	No. 19 A (L_n/D_P = 0.8)	

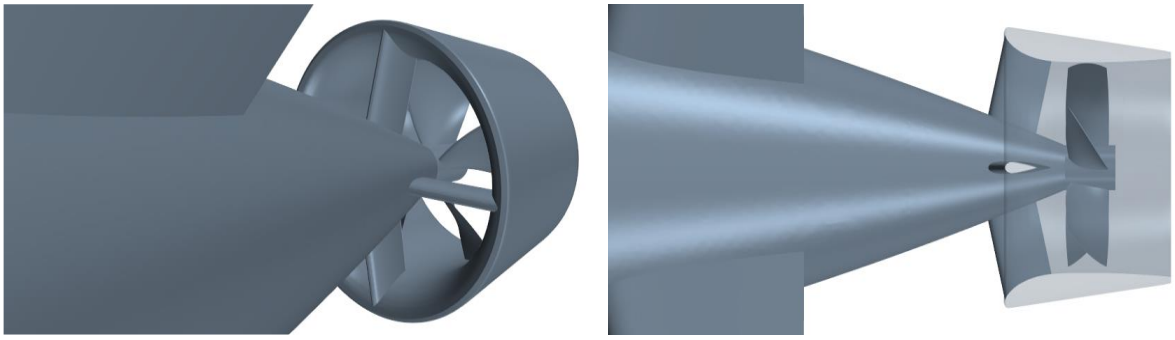


Fig. 7: Struts of the ducted propeller.

The accelerating nozzle no. 19A (L_n/D_P = 0.8) was employed for the previous and present propellers. The duct of the previous propeller was elongated from the original duct length (L_n/D_P = 0.5) to provide space for struts to mount the duct on to the hull; however, the actual geometry of the struts was not modelled in that study (Takahashi and Shingles, 2021b). By contrast, four struts fitted upstream of the blades were designed in the present study, and their effect on the hydrodynamic performance was investigated. NACA 0024 was employed for the section geometry, and the chord length was equal to 0.25D_P. The struts were inclined backward from the root to the tip at a constant angle based on Groves et al. (1989). Four struts were fitted in a cruciform configuration, as shown in Fig. 7. The computer-aided design (CAD) geometries of the duct, blades, and struts were developed using a commercial software, CAESES 4.4.2.

4 RESULTS

4.1 Open Water Performance

Error! Reference source not found. illustrates the propeller open-water performance, where K_T and K_Q are defined as

$$K_T = K_{Tb} + K_{Td}, \tag{16}$$

$$K_{Tb} = \frac{T_b}{\rho n^2 D_P^4}, \tag{17}$$

$$K_{Td} = \frac{T_d}{\rho n^2 D_P^4}, \tag{18}$$

$$K_Q = \frac{Q}{\rho n^2 D_P^5}, \tag{19}$$

where K_{Tb} is the blade thrust coefficient, K_{Td} is the duct thrust coefficient, ρ is the fluid density [kg/m^3], and Q is the propeller torque [N·m]. The coefficients of the present propeller globally shifted to higher J owing to the higher pitch ratio. In the following self-propulsive analysis, the duct was considered as part of the propulsion unit based on the International Towing Tank Conference (ITTC) Recommended Procedures and Guidelines (2008), and the open-water curves were employed for the thrust identity method.

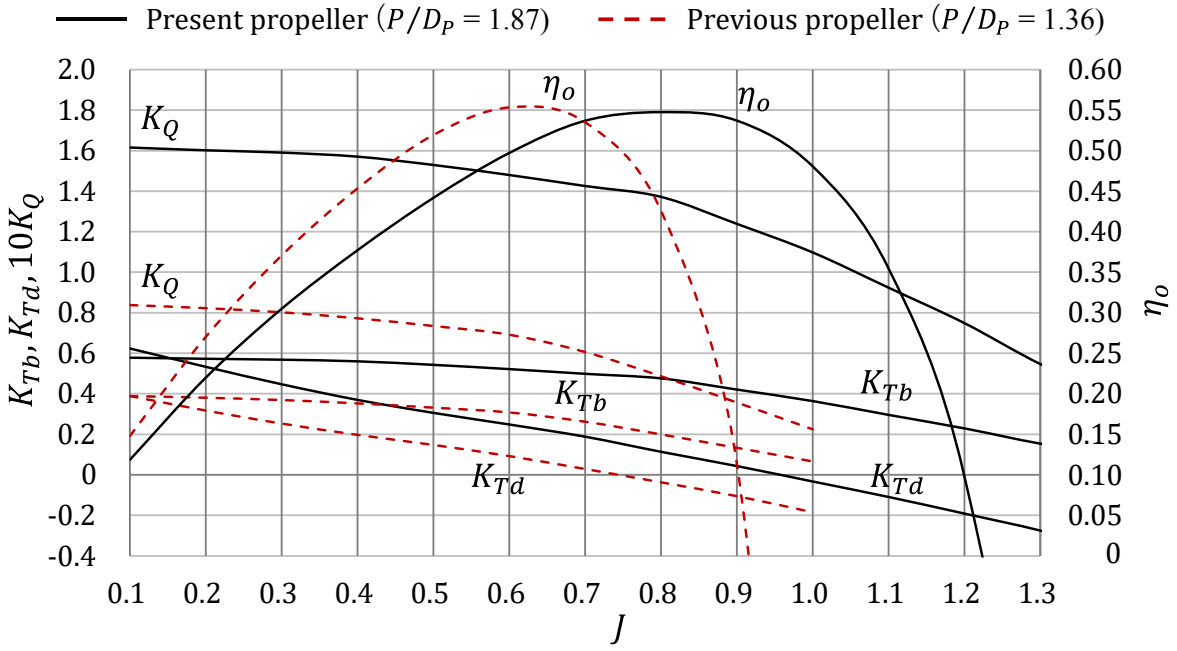


Fig. 8: Propeller open-water performance.

4.2 Propulsive Performance

Table 3 lists the self-propulsive performance computed for the present and previous propellers without the struts at V = 5.144 m/s (R_e = 2.66×10^8). Herein, w is the Taylor wake fraction, t is the thrust deduction fraction, η_H is the hull efficiency, η_R is the relative rotative efficiency, and η is the propulsive efficiency. Coefficients are defined as follows:

$$w = \frac{V - V_A}{V}, \tag{20}$$

$$t = \frac{T - R_{T\,towed}}{T}, \tag{21}$$

$$\eta_H = \frac{1-t}{1-w}, \tag{22}$$

$$\eta_R = \frac{K_{Q\ in\ O.W.}}{K_Q}, \tag{23}$$

$$\eta = \eta_o \cdot \eta_H \cdot \eta_R, \tag{24}$$

$$T = T_b + T_d, \tag{25}$$

where $R_{T\ towed}$ is the hull resistance without propulsion [N], and $O.W.$ denotes open water. $R_{T\ towed}$ (= 72.1 kN) was obtained by performing a steady simulation under the same condition (V = 5.144 m/s) without the propeller to determine the thrust deduction fraction.

Table 3: Full-scale self-propulsive performance without the struts at V = 5.144 m/s.

Parameters	Present propeller (D_P = 3.54 m, P/D_P = 1.87)	Previous propeller (D_P = 4.33 m, P/D_P = 1.36)
R_e	2.66×10^8	
K_{Td}	0.236	0.075
K_{Tb}	0.359	0.181
K_{Tb}/K_T	0.603	0.707
$10K_Q$	1.073	0.437
n [rps]	1.051	1.067
V_A [m/s]	2.95	3.38
J	0.792	0.731
w	0.427	0.343
t	0.320	0.314
η_H	1.187	1.044
η_o	0.548	0.506
η_R	1.267	1.311
η	0.824	0.689

The thrust and torque coefficients increased due to the smaller propeller diameter for the present propeller. By contrast, the difference in n was only 1.5%. w increased by approximately 25% due to decreased V_A caused by the propeller rotating in the reduced velocity region in the vicinity of the tail-cone. The variation in t was insignificant; t increased by only 2%. These results support that the higher η_H for the present propeller was obtained due to the higher w and limited increase in t. η_o increased by 8% for the present propeller. The expanded area, A_E, of the present propeller was approximately 33% lower than that of the previous propeller. The increase in η_o could be partially attributable to the reduction in A_E, due to the lower frictional drag on the blades. However, the maximum η_o was almost equivalent for both the present and previous propellers as shown in Fig. 8. Hence,

the increase in η_o for the present propeller was primarily attributable to the shift of the advance coefficient at the self-propulsive point towards the apex of the η_o curve. By contrast, η_R decreased by 3%. Therefore, η $(= \eta_o \cdot \eta_H \cdot \eta_R)$ improved by 20% due to the higher η_H and η_o compared with that of the previous propeller. The delivered power P_D was computed at V = 5, 10, 15, and 20 knots with and without the struts and compared with that of the open propeller (MARIN 7371R); a six-bladed stock propeller used in earlier studies by Carrica et al. (2016), Pontarelli et al. (2017), and Takahashi and Shingles (2021a), which is called an open propeller in contrast to a ducted propeller. Fig. 9 shows P_D and the differences between ducted and open propellers as a function of the ship speed V. P_D for the ducted propeller was smaller over the range of V tested, and reduction in P_D was significant at higher V. This is significant as a reduction in P_D means that less power needs to be delivered to the propeller to drive the boat at a given speed. P_D for the propeller with struts slightly increased owing to the extra resistance. However, P_D with the struts remains approximately 4–7% lower than that for the open propeller.

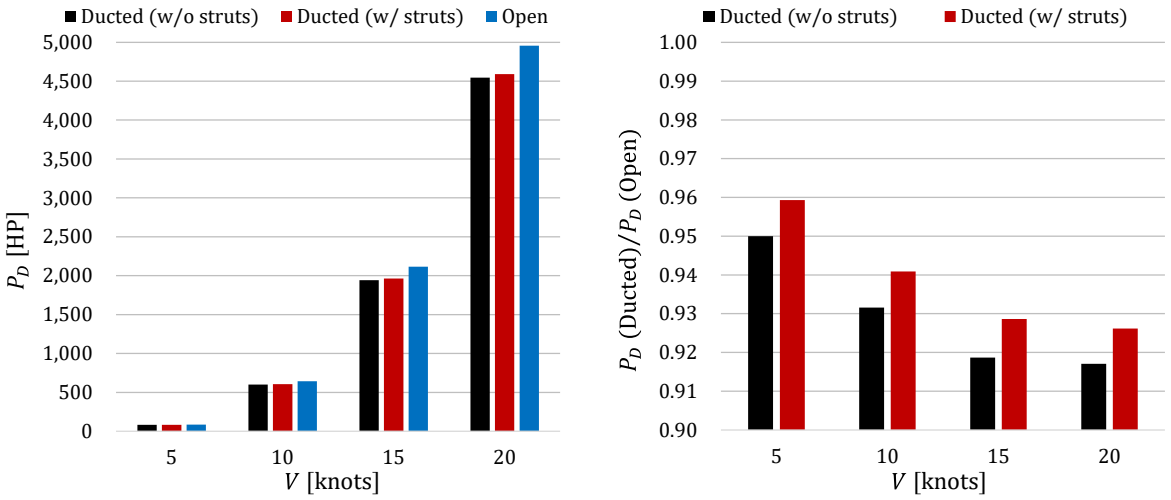


Fig. 9: Delivered power as a function of ship speed V.

Although the propulsive efficiency was improved for the present ducted propeller, the pressure on the suction side of the blades is lowered due to the smaller diameter and higher propeller pitch. The decrease in expanded area for the present propeller is also likely to increase the risk of cavitation due to the increase in the loading of each blade. However, the non-dimensional cavitation number increased for the present propellers due to the smaller propeller diameter and rotational speed compared with those for the previous propeller. The increase in the cavitation number delays the cavitation inception for the present propeller. Furthermore, the ratio of K_{Tb} to K_T was lower for the present propeller, suggesting that the blades produced a lower proportion of the thrust at the self-propulsion condition, reducing the likelihood of cavitation. The cavitation performance of the ducted propeller will be evaluated quantitatively in a future study.

4.3 Unsteady Propeller Thrust

The circumferentially non-uniform wake from a hull causes periodic variations in the blade angle of attack, resulting in fluctuations in the blade loading. The unsteady loading produces unsteady propeller thrusts which are transmitted through the propeller shaft and bearings, and produce undesirable vibration and noise (Boswell and Millar 1968). Hence, the computed unsteady propeller thrusts were analysed using the Fourier series (Jessup 1990) in this study:

$$T_b(\theta) = (T_b)_{N=0} + \sum_{N=1}^{100} (T_b)_N \cos[N\theta - (\phi_T)_N], \tag{26}$$

where $(T_b)_{N=0}$ is the circumferential average of the propeller thrust [N], $(T_b)_N$ is the amplitude of the N^{th} harmonic of the propeller thrust [N], θ is angular position on the propeller disk, positive clockwise looking upstream [°], and $(\phi_T)_N$ is the phase angle of the N^{th} harmonic of the propeller thrust [°]. The coefficients were calculated by fitting a curve to the data plots using the least-squares method.

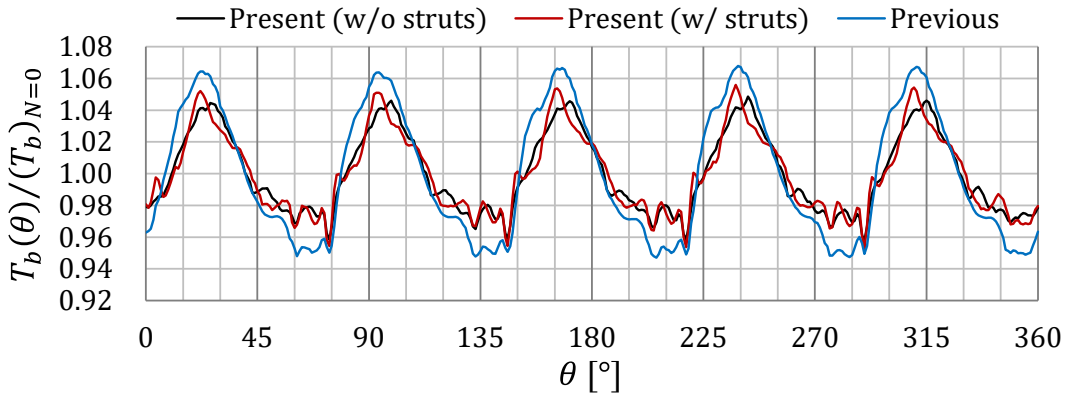


Fig. 10: Time histories for unsteady propeller thrusts.

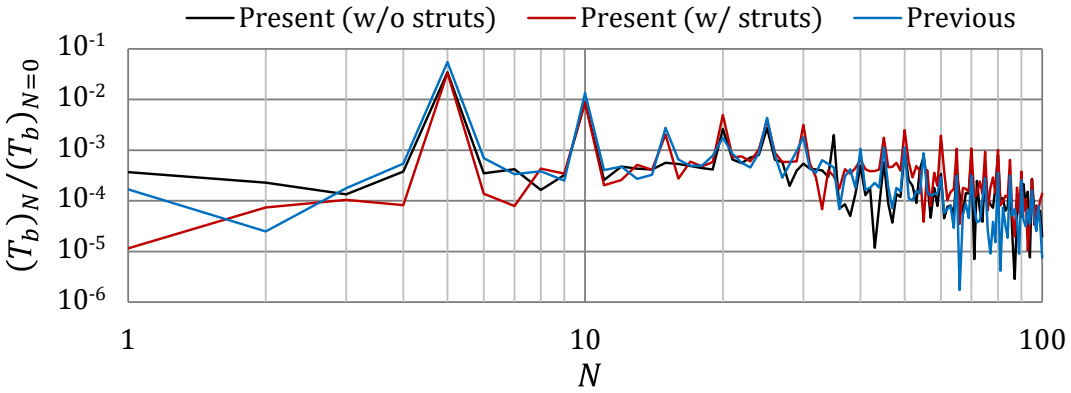


Fig. 11: Amplitudes of the first 100 harmonics for propeller thrusts.

Fig. 10**Error! Reference source not found.** illustrates the time histories of the unsteady propeller thrusts. Five peaks, corresponding to the number of blades, were obtained, and the thrust fluctuations for the present propeller were lower compared with those of the previous propeller. Fig. 11 shows the amplitudes of the first 100 harmonics normalised by $(T_b)_{N=0}$ for propeller thrusts. The 5^{th} harmonic $(T_b)_5$ is the most significant, followed by the 10^{th}

harmonic $(T_b)_{10}$. Although minor peaks were observed at N = $5k$ (k = 3, 4, 5…), the amplitudes were less than 0.5% of the circumferential average values. The dominant harmonics $(T_b)_5$ and $(T_b)_{10}$ for the present propeller were decreased by 30–40%. No significant difference in $(T_b)_5$ and $(T_b)_{10}$ was observed for the present propeller with and without the struts.

Fig. 12 shows the time history of one-blade loads. Lower blade loads occurred when the blade passed through the top, crossing the wake of the sail. Additionally, higher blade loads occurred at $\theta \approx 15°$ and 315° due to the low-velocity wake caused by the necklace vortices. Similar blade-load fluctuations were present in the numerical results obtained by Chase (2012). The fluctuations for the present propellers were reduced for $\theta \approx$ 0–90° and 270–360°. Additional-positive four peaks in the one-blade load were observed for the present propeller with struts. The additional peak at θ = 345° was smaller than those at θ = 75°, 165°, and 255° with the vertical strut mounted in the downstream of the sail and casing producing a different wake pattern at the propeller plane. Fig. 13 shows the amplitudes of the first 100 harmonics normalized by the circumferential average values for the one-blade loads. The influence of the four struts were similarly observed in the amplitudes of the harmonics at N = 4, 8, 12, and 16; the amplitudes at N = 8, 12, and 16 increased whereas that at N = 4 decreased.

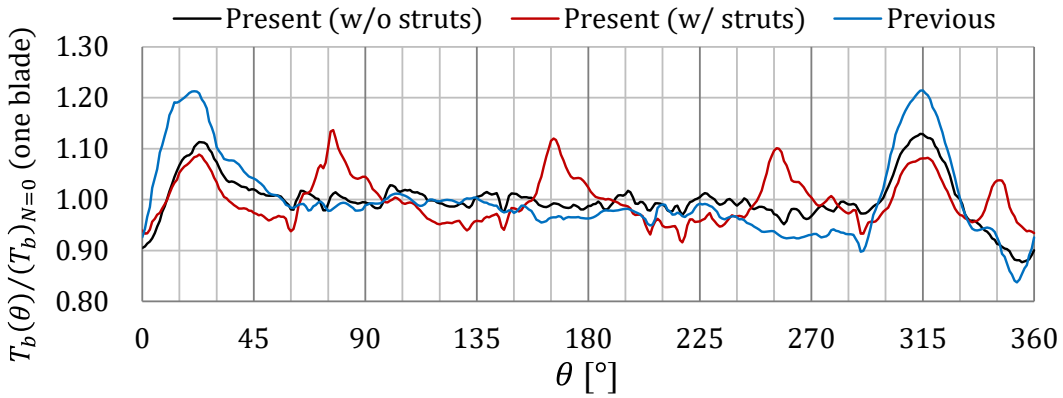


Fig. 12: Time histories for one-blade loads.

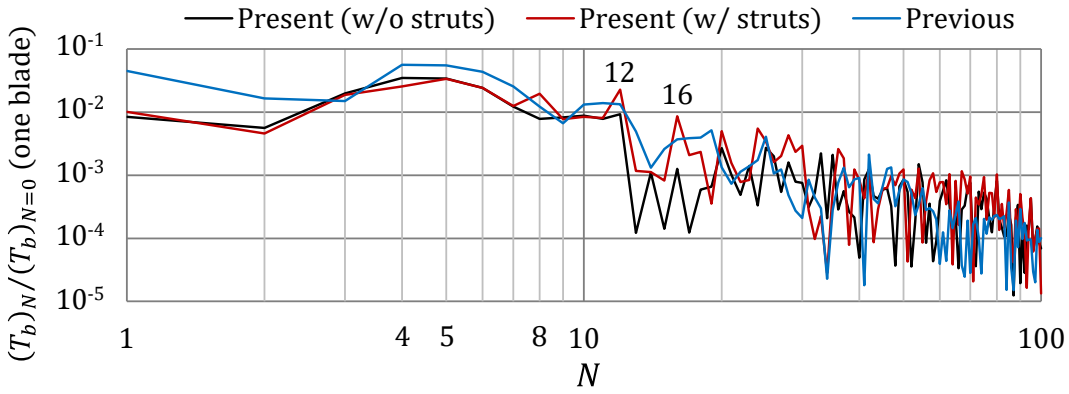


Fig. 13: Amplitudes of the first 100 harmonics for one-blade loads.

The nominal wake profiles in the propeller plane were analysed. Fig. 14**Error! Reference source not found.** shows the distribution of the axial velocity, $V_x(\theta)$, normalised by the

circumferential average of the axial velocity $\bar{V}_x$, for $0.7R_P$. Propeller dimensions at 70% radius locations are often used as reference values (ITTC–Recommended Procedures and Guidelines 2002, 2014). The axial velocities for the previous propeller are lower than those for the present model for $15° < \theta < 45°$ and $315° < \theta < 345°$. When the blade is exposed to these low-velocity regions, higher blade loads were observed due to a locally lower advance velocity and the resulting higher effective angle of attack for the previous propeller as shown in Fig. 12**Error! Reference source not found.**. Four negative peaks caused by the struts were observed at θ = 0°, 90°, 180°, and 270°, which supports the additional positive peaks in the one-blade load in the downstream of the struts (shown in Fig. 12**Error! Reference source not found.**).

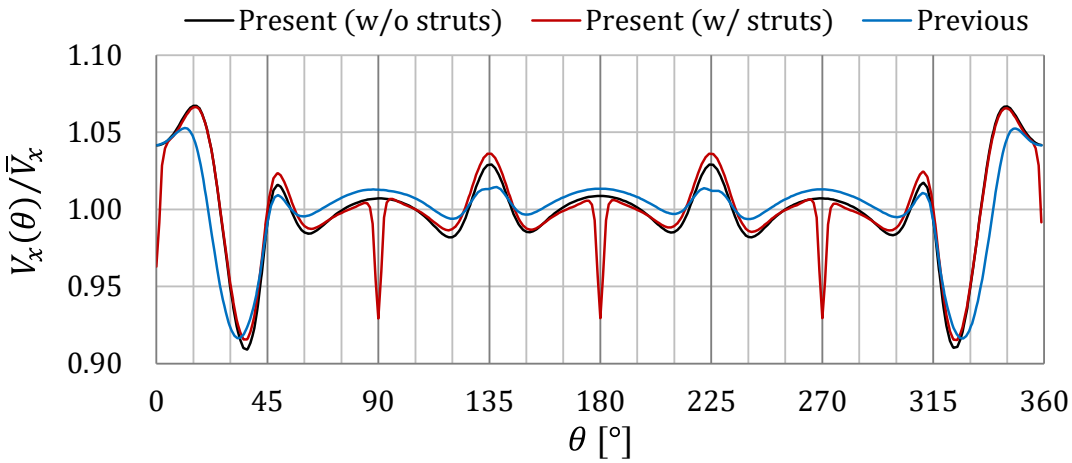


Fig. 14: Axial velocity distribution in the propeller plane for $0.7R_P$.

5 CONCLUSION

Numerical analysis on the hydrodynamic performance of ducted propellers for the BB2 underwater vehicle was undertaken to improve the propulsive efficiency for a longer-ducted propeller and investigate the effect of struts fitted upstream of the blades on the hydrodynamic performance. Compared with a previous ducted propeller design, the self-propulsive performance was improved by approximately 20 % with the re-optimisation of the propeller diameter and pitch ratio using a design chart developed with CFD. The effect of the struts on the delivered power was limited over the range of tested ship speeds. No significant difference in $(T_b)_5$ and $(T_b)_{10}$ for the unsteady thrust between the present propellers with and without the struts was observed. By contrast, additional fluctuations were observed for the one-blade load for the present propeller with the struts. These fluctuations are associated with the negative peaks of the axial velocity in the nominal wake at the propeller plane. In a future study, an experimental study will be performed to evaluate the cavitation performance of ducted propellers in a cavitation tunnel. Furthermore, the other design parameters such as the duct geometry and the radial distributions of pitch, skew, and chord length will be adapted to the inflow velocity profile to enhance the propeller performance comprehensively.

6 ACKNOWLEDGMENT

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SESSION 13

Shipbuilding

Production optimisation through a direct connection between project data and the workshop
Refereed

Production Optimization Through a Direct Connection Between Project Data and the Workshop

Rodrigo Perez Fernandez, Siemens Digital Industries, Universidad Politécnica de Madrid, rodrigo.perez.fernandez@upm.es
Raul Serrano Garrote, Siemens Digital Industries, raul.serrano@siemens.com

ABSTRACT

In the current workflow for the shipbuilding within the shipyard, the relationship between the CAD/CAM software and the production machines is carried out through exchange files. Once the 3D model of the project is mature enough, data is converted into production information and must be transferred to the machines in the workshops. That transfer of information to the plate and profile cutting machines, welding robots or pipe bending machines requires the generation of exchange files and the corresponding management as documentation of the project prior to be loaded into the corresponding production machine. These exchange files are usually text or XML files with a specific language depending on the machine manufacturer, which requires an initial effort to customize the CAD/CAM software to generate such files as well as the time and resources used in every project for the generation and management of that large number of exchange files.

One of the aims of the digitization of the shipyard is the simplification of processes and the optimization of the workflow by removing intermediate tasks.

Through this paper we will explore the different requirements and alternatives to improve the transfer of information between the production data stored with the rest of the ship project and the machines used to create manufactured items of the real ship.

This simplification in the process will avoid the inefficiencies associated to managing and processing a significant amount of information as a large number of files. And how it will reduce processing and lead times by simplifying the workflow.

1. INTRODUCTION

Shipbuilding is a continuous process of renewal. Shipowners are increasingly demanding more complex and efficient vessels to comply with international safety and environmental regulations as well as to meet their business objectives. These shipbuilding projects can only be successfully addressed in a timely manner if the construction processes are continuously analyzed and up to kept up to date.

In this context of continuous updating and improvement, the rapid development of the digitalization of the shipyard is one of the key points around which this developing is growing. Automation of processes, the use of tools with increasing technological complexity and the technological development of design software tools, allow the construction of ships in shorter times and with a technological complexity that would have been difficult to achieve a few years ago. But this modernization process will be successful only if, in addition to adopting technologically advanced manufacturing equipment and software, there is a correct and effective integration of all these systems, as well as efficient time and process management.

2. STATE OF THE ART

The nature of shipbuilding as a "heavy" industry means that this activity can potentially be particularly benefited by the introduction of automation means (robotized means, fundamentally) that bring optimizations into its production process. As a counterpart, it is widely known that robotization has traditionally been very beneficial especially to those processes of great repetitiveness (since robot programming is a complex aspect of its implementation), and that its application in areas where greater flexibility is demanded is apparently more complex; that is why it is worth considering what is the current state of these technologies and compare it with the current shipbuilding scenario.

However, in recent years this situation has begun to change, thanks to the incorporation of new concepts and technologies in the field of robotics, and specially thanks to the recent advances in sensors and fields such as artificial vision, that are allowing to evolve robotics towards a concept of intelligent, collaborative and flexible automation.

In a simple way, and applied to the industrial environment, artificial vision would be the process of automatically acquiring images and its subsequent analysis, with the purpose of characterizing an object, element, operation, process, activity, etc., through said process, and extract the necessary information that allows carrying out a specific task in relation to them. Artificial vision has many applications, such as the measurement of parts without contact, real time quality control, the recognition of workers, the identification and scanning of objects, etc., as well as those arising from their integration with other technologies. Following this argument, it is possible to develop capable systems, as for example:

- Prior to carrying out the welding work, recognize the parts and surfaces to be welded, scanning them to define an accurate 3D model of the elements to be welded.
- Using algorithms developed for this purpose, compare the extracted 3D image with the nominal values (2D drawings vs original 3D model) and establish and adjust the points that determine the welding trajectory. An operator could review and make adjustments later, but there would have been significant savings in the time needed to determine the spatial coordinates of the different points of the welding trajectory.
- As a result of the defined welding trajectory, the robotic welding process can be carried out, with a considerable saving in the time required to perform such an operation without this capability.

This type of applications is feasible with current technology (there is a wide range of cameras and vision sensors in the market, with different capacities and accuracies, as well as software and hardware tools with the capacity to develop this type of applications), so currently, the implementation of automation technologies in areas where flexibility is demanded is more a matter of delimitation of the problem to be solved, than the technology itself. This is the true essence of today's robotics, which endowed with intelligence and collaborative capacity thanks to the recent development of complementary technologies, has today a greater ability for providing improvements to different environments and situations than in previous times. That is why soon the robots for specific operations will integrate a series of systems (hardware and software) that will increase their versatility, and not only shipbuilders of bigger size, but smaller shipyards can benefit from them, at the same time that for the latter it is also possible to consider the development of specific innovations to meet their own requirements.

On the other hand, a common problem in the production of shipbuilding is to plan the production appropriately. The shipbuilding production process is often planned only roughly in weekly or even monthly slices, with detailed planning skipped completely or done by foremen for their team's

purpose. Feedback on problems in either delivery or production is not available promptly. Late time changes demanded by ship owners impose additional problems. As a result, the visibility of the actual status is often poor. Thus, acute problems are not detected in time making mitigation actions more expensive in terms of time or expenses than necessary. There are many research projects aiming on helping the shipbuilding industry to perform better planning of the manufacturing processes and thus reduce times and efforts. The base idea of these projects is enabling planners to run complete processes with reasonable effort. Planning the production once in terms of schedule and needed resources is common practice, but permanently updating the planning taking changes into account is rarely done.
In both cases, improve working planning and production machines (robots and equipment) need a set of exchange files, which are required to convert the information from the 3D model.

3. INEFFICIENCIES IN SHIPBUILDING PROCESSES

The shipbuilding market is demanding to the CAD Systems collaborative design solutions to overcome some challenges that have appeared in the last decade. In fact, the delivery times required by the shipowners are much shorter than in the past and therefore the engineering cycles. At the same time the amount of information for production has dramatically increased. Production requirements and constraints have to be taken into account at the very early stages of the design (Alonso, et al., 2013).
Every shipyard needs to somehow plan how a new vessel is going to be produced or manufacture. Many information items are relevant for this planning process, most notably the assembly structure of the vessel itself, production activities to perform, available manufacturing resources, and last but not least restrictions in terms of schedule and money. Similar to the design process of a vessel, this planning process is not only run once but needs to be performed on several stages of the vessel's lifecycle with different methods and reliability of available data. The planning is based on the current status of the design and production process plus estimation of real production times. The reliability of the estimations depends on the chosen method as well as on the underlying data. But even if a yard has perfect control over its processes and thus totally reliable estimates, external factors like purchase status or changes demanded by a customer necessitate running a new Deming cycle to take these changes into account.

3.1 Integration between 3D Model and Production

For 3D evaluation, monitoring progress, and checking the parts and materials, shipyards can integrate the 3D model with PLM/PDM or ERP systems. Linked documents and system parts, including dimensional drawings and piping parts, provide a rich context when they are efficiently visualized as separate parts and as an integral part of the vessels´ 3D model. In addition, a 3D model linked to task planning at the detailed work breakdown level, kitting packages, and BOM visualizes planning, retrieval of tasks (welding, grinding, painting), and resource planning.
Having a complete integration between 3D model and production, it would help to reduce many inefficiencies (delays and issues). Then, it is required to have a strong link between 3D model and planning and manufacturing execution systems, which could helps visualize the scheduling status of items and blocks (structure) or zone & systems (outfitting and electrical). Resource management systems are often focused on narrow tasks and reporting processes, leaving workshop staff without a direct link to the product they are producing and a significant amount of design and production-generated information.
Linking materials, fittings, and equipment with their digital counterparts in a 3D model provides additional benefits for integration. For work preparation and planning, the 3D model can be

integrated with work planning systems and ERP for work package kitting visualization and shipyard resource management. Any item can be found in the digital model using RFID or QR codes as well as all related data from integrated systems, as for example attributes, drawings, and instructions accessed on site. The shipyard can benefit from integrating 3D models with production systems, such as nesting and assembly controls. The hull production statuses for cutting, bending/pre-assembly, approval, and section assembly are visualized and monitored using a 3D model on a suitable device.

Some companies are using the concept of game development platforms in order to improve the current way of manufacturing the virtual world (3D model), including physics, materials, animation, etc. allowing the creation of photorealistic environments in which to have the Digital Twin of the product and the shipyard, as well as the workers and vehicles that interact in it. Once done, there is free way for simulation in this virtual environment. With these tools, it will be possible to analyse the different distribution and operation's options into the virtual world and test them under different conditions, like for example product assembly operations requiring the definition of operation strategies.

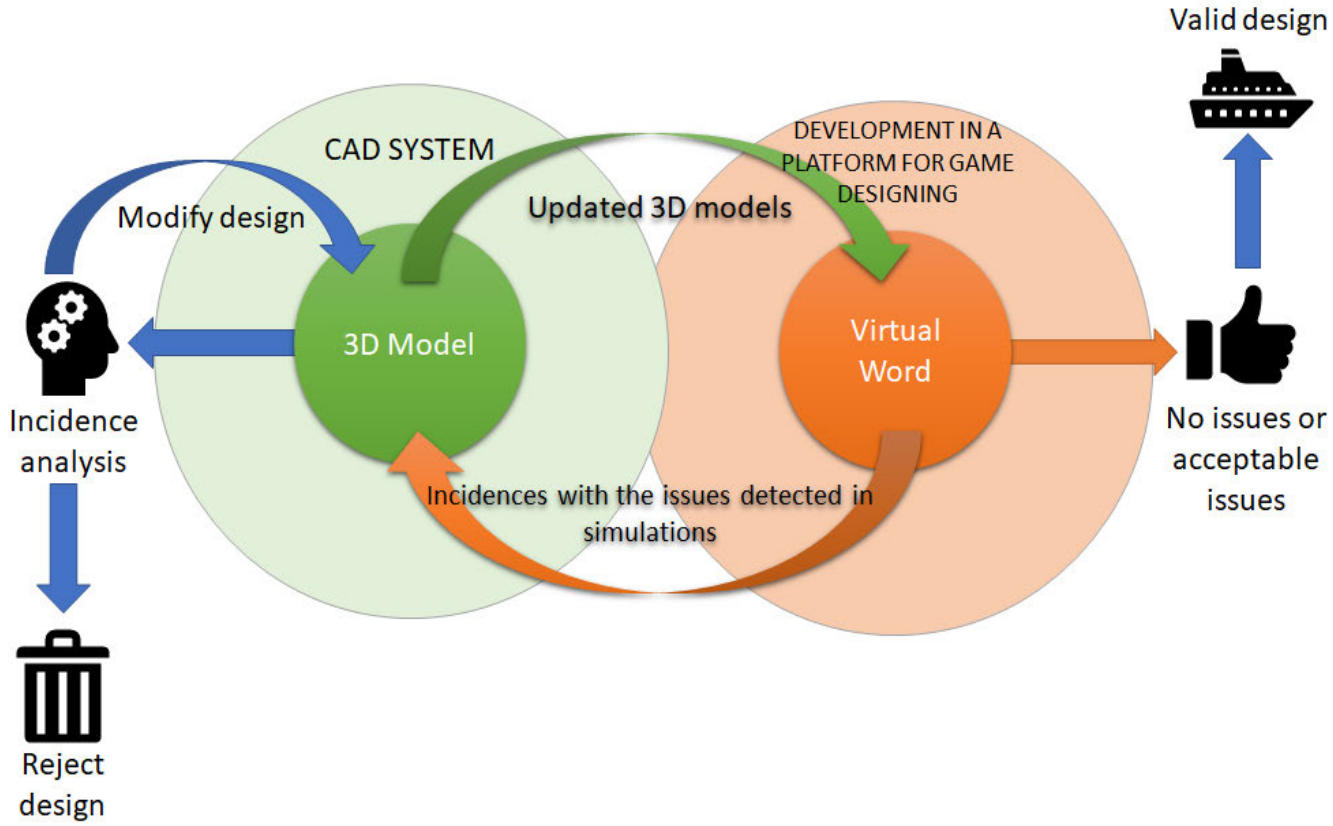


Figure 1. Diagram that explains how could be the workflow between the 3D Model of a CAD system and the applications designed with a game development platform (Perez and Peter, 2019)

The creation of the connection between the 3D CAD model of the product and the infrastructure in which the product is manufactured (see *figure 1*), and the game development platform, opens the door to endless possibilities, in addition to the simulation itself. In many cases, the core of the products that offers the implementation of Digital Twin and the access to Virtual Reality and Augmented Reality technologies is based on a Video Game development platform (Perez and Peter, 2019).

3.2 Change Control management

Currently CAD systems can automatically calculate welding lengths and welding type classification according to various criteria (position and assembly interim level), yielding welding reports and drawings.

CAD tools generally provide solutions to produce nested plates and profiles according to the standards of the yard, their means of production and manufacturing methods. CAD systems can be used to calculate the material take-off as well as to generate information for CNC machines, cutting patterns and statistics during the detailed design phase raw material.

The history of the issue begins at the beginning of the widespread adoption of computers in shipyards. Vendors set out to build software applications to accomplish specific tasks. These applications had a discrete functional focus and the programmers creating them put little to no thought into how these applications might work with other programs. It did not take long, however, for people to realize that the data needed increasingly came from other computer programs. However, it was natural to want to automate the transfer of information.



Figure 2. Idealistic representation of issues and misalignments during ship design stages

But that exposed a significant problem because the various programs that people wanted to integrate had incompatible infrastructure and the data structure differed greatly. This forced shipbuilders to use inefficient manual methods and complicated, unintuitive workflows in order to share data between applications (Marcos and Perez, 2014). Therefore, several organizations hired programmers to create custom integrations but ran into new difficulties. Custom integrations on a case by case or product by product basis proved to be very costly to implement and maintain. Thus, as it is tried to represent in *figure 2*, in frustration, companies looked for a different model.

3.3 Production planning

Production planning is done at different stages of the vessel's lifecycle, as shown *figure 3*. Even before signing the contract, some preliminary production planning is needed to figure out a realistic delivery date. Only a few basic parameters and the general arrangement plan are available at this time, therefore the preliminary planning must use expert judgement or empirical estimation based on historical data of previous vessels. The reliability of this estimation is driven by the amount, accuracy, and applicability of historic knowledge. This is quite a risk, as the delivery

date fixed in the contract relies on the estimated production times. Even if a yard is meticulously collecting data for future usage, a new ship type or production method may render this information useless for the vessel to estimate (Lee, et al., 2013).
During the design phase, the amount and reliability of input data increase permanently. Information like number, type, weight, and volume of sections is now available as input for a parametric estimation of needed resources and times. This results in a better fidelity compared to empirical estimation and is available 6-12 months ahead of production start. The resulting data is needed to allocated building places and docks as well start purchasing items with longer delivery time, so they are available in time for assembly.

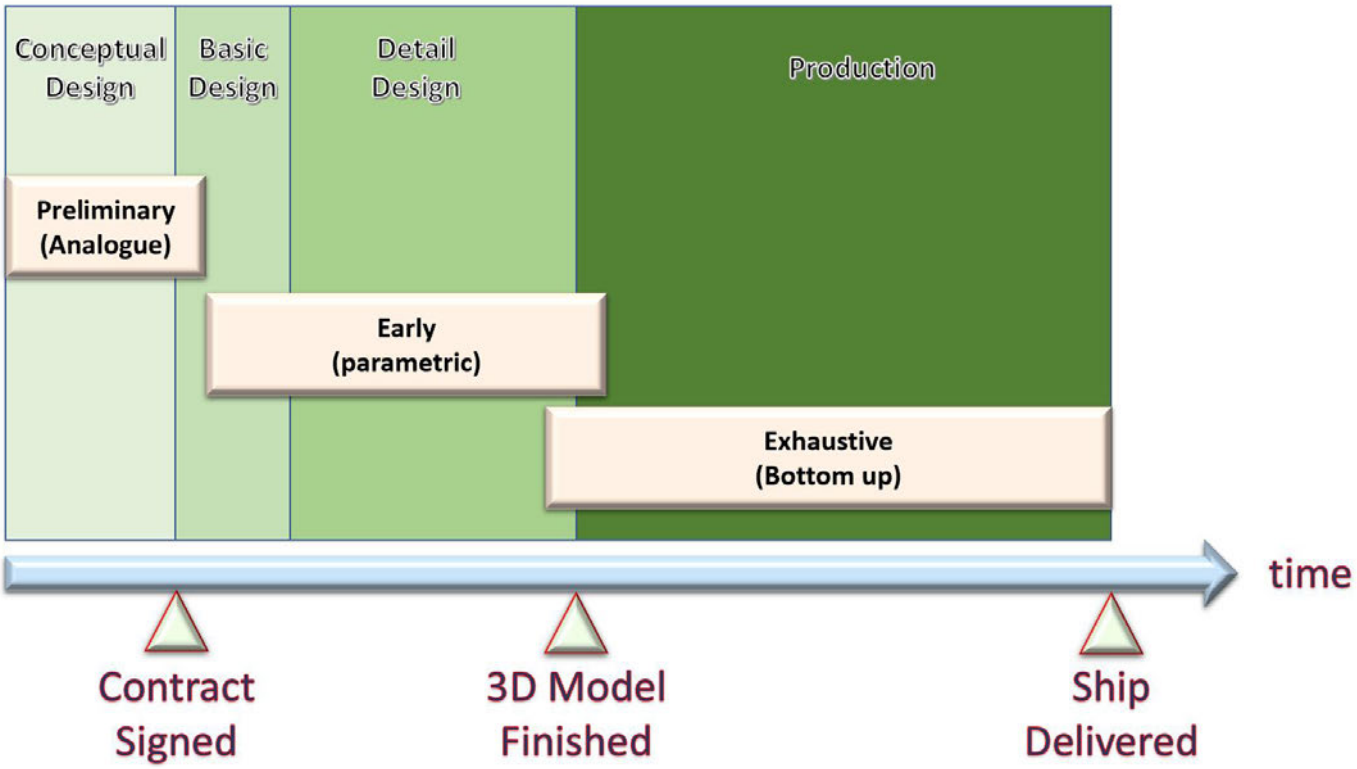


Figure 3. Vessel lifecycle and planning stages

In the late design phase, design is ready down to plates and stiffeners, supporting a bottom-up methodology offering the most accurate estimate. Depending on the ship size, planning horizon, and granularity of the estimation we need to handle millions of parts with their production or delivery status as input for the planning. As this is nearly impossible without dedicated tools support, this is the focus of the research project.

4. INTEROPERABILTY BETWEEN THE PROJECT DATA AND THE WORKSHOP MACHINES

The following discussion focuses on the production and manufacturing stages of the structural plates and profiles of the vessel, but most of considerations outlined here could be perfectly applicable to other disciplines of the vessel production process.

Transitions between the different stages of a project of a vessel are complex processes. The project data must evolve from a very initial and general stage of the Conceptual Design to a Basic Design and later to a Production Design that provides as much manufacturing information as

required to build the different parts in the workshops machines of the shipyard to build and assemble the real vessel.

This transformation among the different stages of the project means that main and general concepts developed during the early stages of the conceptual and basic design such as the hull, decks and bulkheads are broken down into millions of parts. Those parts are essentially plates and profiles. The definition of each of these parts must be completed with the required information to be manufactured and assembled. Ideally, it should be a linear process, where one stage starts where the previous one has been fully completed, but the demanding schedule to deliver the vessel, as well as the constant modifications in the design due to updates in the scope of the project or constrains posed by applicable regulations, cause the different steps to overlap.

There are different approaches to achieve a successful management of all the data required to provide information to the workshop machines of the shipyard, but the most efficient one (Perez et al., 2013) (Perez-Martinez and Perez, 2021) (Liu et al., 2016) is to focus all the design efforts to generate a single data model with all the design information in a single database generated by CAD/CAM application or by a PLM system.

Historically and due to the functional limitations of the different CAD/CAM applications existing in the market, several CAD and CAM applications are required to complete this process and often the output information of each design stage are not stored as a single entity but in several databases or set of files as independent stores of the different stages and information of the project. The management and coordination between those information stores increases the lead time of the project and often leads to misalignments in the data associated to different stages of the project. Therefore, a single data model created by a single CAD/CAM system capable of covering the different stages of the project must be considered as a key benefit for the successful execution of the project in a timely manner.

Once the 3D model built during the production stage design is mature enough, it becomes the baseline for a proper definition of the build strategy of the project: In addition to breaking down the Basic Design concepts into parts with fabrication information and details, the information must be rearranged to establish a build strategy capable of being adopted in the workshops of the shipyard. Build Strategy of the project includes all the information defined in the production model: its geometric definition as well as any additional information needed to build each of those plates and profiles but broken down into constructive units capable of being assembled in a berth or in a dry dock to build a vessel.

A powerful CAM tool to extract the information defined in the Build Strategy model of the project is a key factor for an efficient transition to the manufacturing stage of the project.

The use of CNC cutting machines for plates and profiles are widely implemented for several decades within the productive process of the shipyard.

During the last decade welding robots, SMWP and any other welding automation means has been widely implemented in the workshops of the shipyard, transforming long manual welding processes into automated and more efficient procedures.

For both types of manufacturing machines (CNC cutting machines and welding automation means) the degree of integration with the rest of the manufacturing process have been followed the same path but with a time gap of several years between them.

In both cases, the transfer of information from the Build Strategy CAD/CAM model to the manufacturer machine can be carried out in a similar way and we can divide the input data required by these workshop machines into two different main groups:

- Geometric information: shape and dimensions of the parts to be built or assembled.

- Input parameters for the cutting/welding processes (cutting sequences, zero points, fabrication planes)

Depending on the degree of integration between the CAD/CAM system used during the Design Stage of the project and the different machines available in the workshops of the shipyards, a significant part of the manufacturing information can be transferred from the Build Strategy model to the workshop machine. But if there is no such integration, additional third-party software is needed to transfer this data or to complete the data to be input in CNC cutting machines and welding robots.

Over the last few years, Manufacturers of those type of machines and third party software vendors are developing their own tools and functionalities to try to cover as much of the production process as possible and to easily load in their systems the information previously generated in the CAD/CAM system. Manufacturers and software vendors are making a major effort to update and upgrade the software associated with the management of the CNC cutting machines and welding robots to achieve a smooth transition from the CAD/CAM design model to the workshop. Those efforts are intended to adapt not only the user interface of the software associated to the machines but also incorporating new functionalities to compensate the lack of information transferred from the CAD/CAM system: Data to setup the machine operation must be defined in the machine itself by the software and interface provided or imported from the CAD/CAM system. The set of functionalities associated to that software includes the capability to import the geometric definition of the parts to be processed in neutral formats such as DXF drawings in 2D or STEP in 3D formats.

All these kind of software enhancements associated with cutting machines and welding robots shift the related workload from the design office to the workshop and break the consistency of the single project data model and can lead to duplicate definition tasks on both sides of the process.

4.1 CNC cutting machines

The Build Strategy model generated with the latest versions of CAD/CAM software is able to include all the manufacturing information necessary for the correct cutting process. Plates and profiles (including those define in curved areas of the vessel that need to be duly developed first) are associated to different building units (as assemblies of panels or interim products) and are also nested into large raw plates and profiles with their associated material specification and cutting information.

If there is not a direct connection of the Build Strategy (production) model with the CNC cutting machine, the geometry of the plates and profiles must be exported to an additional software capable of transforming the information received from the project into data that can be understood by the cutting machine. This software may be provided by the cutting machine supplier or by a third-party vendor. Such software processes the information received from the Production model to generate the data required by the CNC cutting machine.

Transfer of data from the production 3D model to intermediate software is done by means of neutral files such as DXF drawings. Those drawings contain the geometric information of the gross plate as well as the shape of the nested parts and may include additional manufacturing information defined or calculated by the CAD/CAM software. The manufacturing data may be transferred by means of layers and colors configuration in the dxf file. Those colors and layers are mapped in the intermediate software with the corresponding manufacturing attribute. All other information required for the cutting of plates and profiles and not transferred from the CAD/CAM model must be manually defined in the intermediate software or by the CNC machine operator.

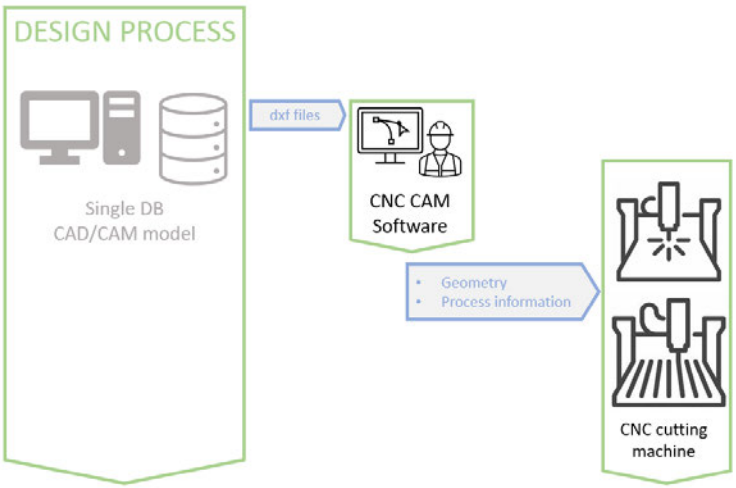


Figure 5: Use of intermediate CAM software prior to transfer the model information to the CNC cutting machine

As an alternative to the use of intermediate software, the information may be directly transferred from the Build Strategy data model to the CNC cutting machine by means of exchange files and avoiding intermediate steps. This direct process needs to adapt the data generated in the production model to a language understood by the CNC cutting machines. Those exchange files, usually in XML or plain text formats, are generated by a post-processor developed by the CAD/CAM supplier and are based on programming rules supplied by the CNC cutting machine manufacturer. The degree of customization of those post-processors is usually high and they are hardly reusable for another CNC cutting machine model even if it is supplied by the same vendor.

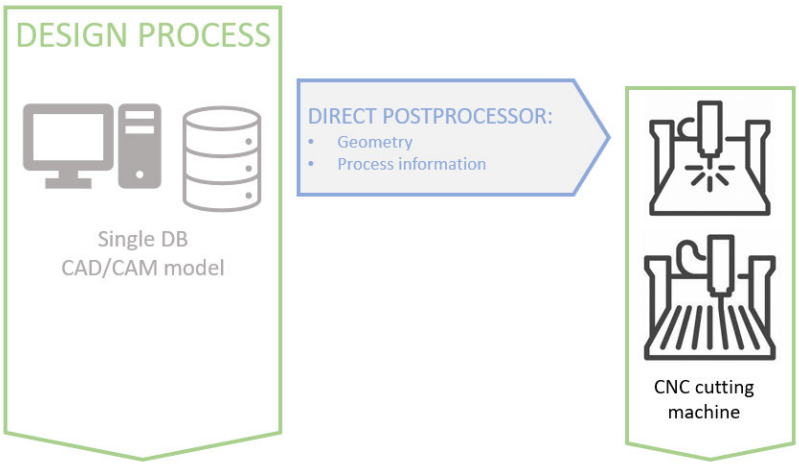


Figure 4: Direct transfer of the model information to a CNC cutting machine

The development of these postprocessors can involve a significant upfront investment that the shipyard sometimes refuses to face, but they allow for minimum interaction and a considerable time savings for machine operator to process the information in the cutting machine.

4.2 Welding Automation machines

For this kind of workshop machines, the development of direct postprocessors is not as widespread as for the CNC cutting machines. But as mentioned above, welding robots and SMWP manufactures have developed their own software applications to configure and run the operation

of those machines. That software includes tools to acquire the geometric information of the panels and interim products to be assembled by means of laser scanning devices. They also allow to import the geometric information by means of neutral format files, such as STEP files. In both cases, the acquisition of information is limited to the geometry of the parts to be processed. Even adopting the latest standards in terms of import capabilities for those neutral formats, such as STEP 242, they are not able to include much more information of the parts but a simple geometric definition as well as additional information related to the identification of the parts included in the file. No significant manufacturing information for the welding process setup is transferred from the CAD/CAM model.

That limitation means that the operator of welding automation machine needs to complete the manufacturing configuration of the welding task manually and none of the information defined or calculated by the CAD/CAM software is transferred.

As the information manually loaded in the welding robot must be defined for each panel or assembly to be processed, the time the welding automation machine is engaged with one unit is increased and the availability of the machine is reduced.

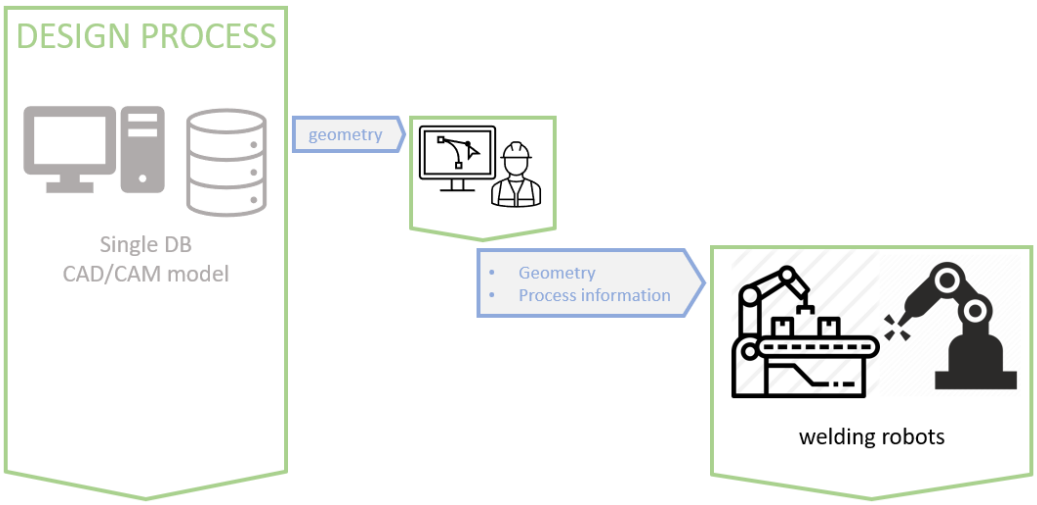


Figure 6: Use of intermediate CAM software prior to transfer the model information to the welding robot

There is a similar direct process to transfer of information from the CAD/CAM model to the welding machines as in the CNC cutting machines. This direct link leads to significant improvements in welding tasks:

- Geometry of the parts to be processed can be transferred from the CAD/CAM model to the machine using a direct interface without additional translations to intermediate neutral formats. It provides a more accurate definition of the geometry of the transferred model avoiding geometry inconsistences when the geometry is translated from the CAD/CAM model to the neutral format and from the neutral format to the one supported by the welding robot.
- Additional metadata is included with the geometry to provide instructions and input information for welding procedures.

By using a direct link, similar to a postprocessor used with the CNC cutting machines, the welding task configuration of an assembly can be defined in advance in the CAD/CAM system and stored as part of the build strategy information of the project. All the required information is transferred in

one go from the production model to the welding robot. This reduces the time required for the welding robot to be ready for operation, increasing its availability.

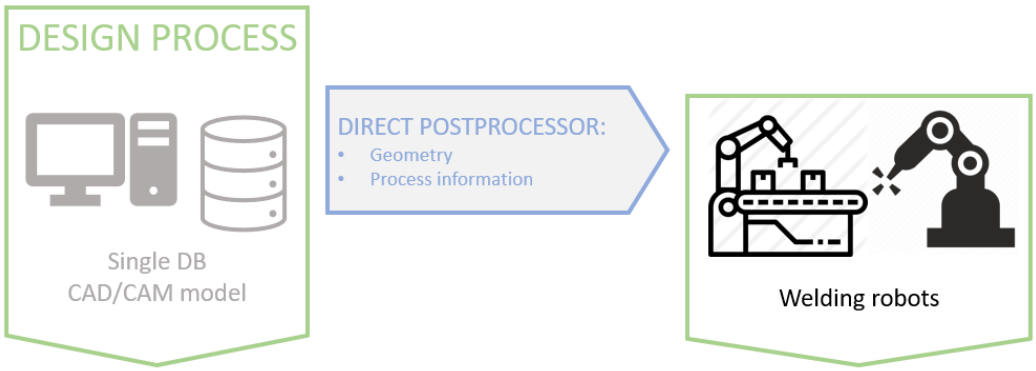


Figure 7: Direct connection to transfer the model information to the CNC cutting machine

4.3 Improvements in the management of the production process

In addition to the relevant improvements in the overall performance for the process of supplying information to the workshop machines, the use of a direct interface between the data stored in the build strategy model of the project and the workshop machines allows optimization in terms of production and manufacturing process management.

When the information for processing the parts on the workshop machines is defined within the build strategy model of the project, the data is defined for the whole construction unit instead of assembly by assembly. Subsequently, the information is transferred panel by panel according to the manufacturing schedule. This is a more efficient procedure, where the input parameters of the welding tasks, such as the definition of the zero point (starting point of the welding task) or the definition of the fabrication drawing of the assembly, are defined in advance.

As the manufacturing data is defined on the CAD/CAM model, they are stored in the building strategy model and are associated with the corresponding plates and profiles to be cut or in the panels to be welded. The exchange files are generated just when they are to be transferred to workshop machines and do not need to be stored as additional information. Build Strategy model is able to include the information on when the panel or the assembly has been processed, which simplifies the traceability of the process. It also avoids having an additional set of documentation to managed by the project.

5. FINAL CONSIDERATIONS

This paper has been intended to act as a brief summary of the main potential applications of some of the most important technologies included under the advanced manufacturing software and tools, developing an analysis that going from the general to the particular has intended to be illustrative of the reasons why this manufacturing interface is highly relevant to the shipbuilding business and is key to its improvement.

The work reflected in this paper leads to a summary of the most important facts:

- Behind the concept of advanced manufacturing there is a wide range of technologies capable of offering new possibilities for the improvement of manufacturing processes in the field of shipbuilding. The range of technologies is very broad, although nowadays it is possible to identify a number of major technologies, with the capacity to cover the entire shipbuilding process: 3D design and management tools, manufacturing process simulation technologies,

scanning and 3D printing, automation, virtual and augmented reality and the necessary complement of information and communication technologies.

- Each of the above technologies is implementable in an isolated or integrated manner, based on the needs of each organization. In this sense, technology is never the final goal, but the means through which to achieve operational benefits, and any implementation must start from a clear definition of needs and improvement goals, from which to evaluate the possible role of the technology available.
- 3D design and management technologies offer clear benefits in terms of error reduction, streamlining of change and reuse of information, although traditional 2D design systems are still highly efficient in the initial stages of development, which hinders the implementation of 3D tools in these stages, and therefore in the process as a whole. These tools are evolving, and it is worth making a close follow-up of them, so that each organization can determine from which point the migration to the complete 3D concept allows them to respond in all the stages of a project in an agile and effective way. Regarding the simulation technologies of manufacturing processes in the field of shipbuilding, there are specific application cases that are of great interest when evaluating their potential in terms of flexible planning of the activity, although they require a considerable level of information and digitalization.
- In the field of manufacturing, additive manufacturing and advances in robotization and automation can provide capacities not yet foreseen. Although by its nature, the 3D printing of large metallic structural elements is not foreseeable in the short or medium term, the existing and developing technologies seem to be potentially capable for the manufacture of vessels based on fibers and other plastic materials; In any of the cases, the possibilities of these technologies in supporting to the design and development of elements and small equipment is beyond doubt. In the field of automation, the current concepts of robotics (integrated with different technologies that provide flexibility and collaborative capacity) are evolving towards the possibility that robots can be effective tools not only in repetitive manufacturing, but in environments that demand greater flexibility.
- Virtual and augmented reality technologies are beginning to be implemented in the field of shipbuilding, with various possibilities ranging from the mere virtual recreation of environments and spaces, to the use of this technology as a tool for design (visualization and design correction), passing through its potential applications in fields such as maintenance.
- Information and communication technologies are a “must have” complement, not only to create fully digital environments where it is possible to transmit and share information no matter where, who and how, but to support the maximum exploitation of previous technologies, as well as to enhance the benefits of integration among all of them.
- As part of the process of continuous improvement in shipbuilding projects, it is necessary to identify the existence of duplicated or overlapping processes and work in the direction of simplifying these processes and for this purpose it is necessary to involve all the stakeholders of the manufacturing process: This is a task in which the shipbuilder must involve each and every one of the suppliers that provide their machinery as well as the CAD/CAM system.
- If CAD/CAM suppliers and welding automation manufacturers are able to achieve a similar degree of interoperability between their products similar to that between CAD/CAM systems CNC cutting machines, the benefits of adopting welding automation machines in the manufacturing processes of a vessel will be greatly enhanced in terms of efficiency. This would result in a faster deployment and development of welding automation in the workshop of shipyards.

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	*Definition*
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
CNC	Computer Numerical Control
DXF	Drawing Exchange Format
ERP	Enterprise Resource Planning
PDM	Product Data Management
PLM	Product Lifecycle management
SMWP	Stiffener and Mounting Welding Portal
STEP	Standard Template for Electronic Publishing
XML	Extensible Markup Language

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SESSION 14

Submarine Hydrodynamics

Near free surface behaviour of a submarine
Refereed

Promoting submarine stealthy by reducing submarine mast hydrodynamics
Refereed

Wakes of surface-piercing cylinders
Refereed

Near Free Surface Behaviour of a Submarine

Xavier Ling, Zhi Quan Leong, Jonathan Duffy, Christopher Chin, Michael Woodward
Australian Maritime College, University of Tasmania, Australia
Xavier.Ling@utas.edu.au

SUMMARY

A well-known but poorly understood issue with submarines operating at small submergence depths is the effect of the free surface on its hydrodynamic and manoeuvring characteristics. Generally, submarines are designed only to be marginally stable for ease of manoeuvrability with the assumption that most of their operations take place while deeply submerged. Thus, off-design operations such as high speeds at small submergence depths can make them unstable. When deeply submerged, the flow field of the submarine is assumed to be unaffected by boundary effects and this greatly simplifies stability and control requirements. However, travelling near the free surface invalidates this assumption. Submarines operating near the free surface experience a submergence depth and speed dependent heave force and pitch moment, which can significantly impact the stability of the submarine.

Small changes in submergence depth combined with the effects of speed can cause significant increases in the free surface induced forces and moments. This condition warrants further study as the resulting hydrodynamic forces can overwhelm the control system in maintaining the desired trim and depth. Hence, this paper presents an evaluation of the effects of the free surface on the hydrodynamics of the bare hull geometry of a submarine. The work was carried out using Computational Fluid Dynamics (CFD) simulation models validated against experimental data for selected conditions. The investigation covers a range of speeds, submergence depths, and length-to-diameter ratios. The results show that the effects of the free surface vary with speed and diminish rapidly with submergence depth.

1. INTRODUCTION

Underwater vehicles such as diesel-electric powered submarines or autonomous underwater vehicles are periodically required to operate at periscope depth for purposes such as snorting, communication, or other mission specific requirements. The shallow submergence depth induces free surface interactions that can alter the flow field surrounding the hull which changes the hydrodynamic forces and moments acting on the hull. The first and most apparent effect of an underwater vehicle travelling near the free surface is the generation of surface waves, much like the wake of a surface vessel. These surface waves are the result of the interaction between the pressure field generated by the hull and the free surface. The wave system generated by an underwater vehicle operating near the free surface is the combination of several waves that occur at different points along the length of the hull [1-4]. In addition, the energy required to generate surface waves can adversely affect the hydrodynamics of the vehicle. With a decrease in submergence depth, it is expected that the induced interaction effects on the vehicle will increase as the amplitudes of the surface waves increase.

The influence of the free surface on underwater vehicles has been the subject of numerous studies long before the advent of the modern-day diesel and nuclear submarines. The first of which was conducted by Havelock who calculated the resistance increase due to the free surface for various geometries including a sphere, oblate and prolate spheroids and ellipsoids [2-4] travelling at small submergence depths. It was shown that the resistance component exhibits distinct peaks due to the presence of the free surface with respect to Froude number and that the peaks diminish rapidly with an increase in submergence depth. More current investigations of near free surface geometries for real world applications involve underwater vehicles such as autonomous underwater vehicles (AUVs) or submarine-like axisymmetric shapes such as the SUBOFF [7, 8, 10] or the Joubert hullform [11]. The added resistance due to the free surface is now more commonly known as wave-making resistance and is attributed to the energy expended by the vehicle when generating waves as in the case of any surface vessel. However, for an underwater vehicle there are two extra components in the vertical plane worth considering for depth-keeping stability which are heave force and the pitching moment which also vary with Froude number [6].

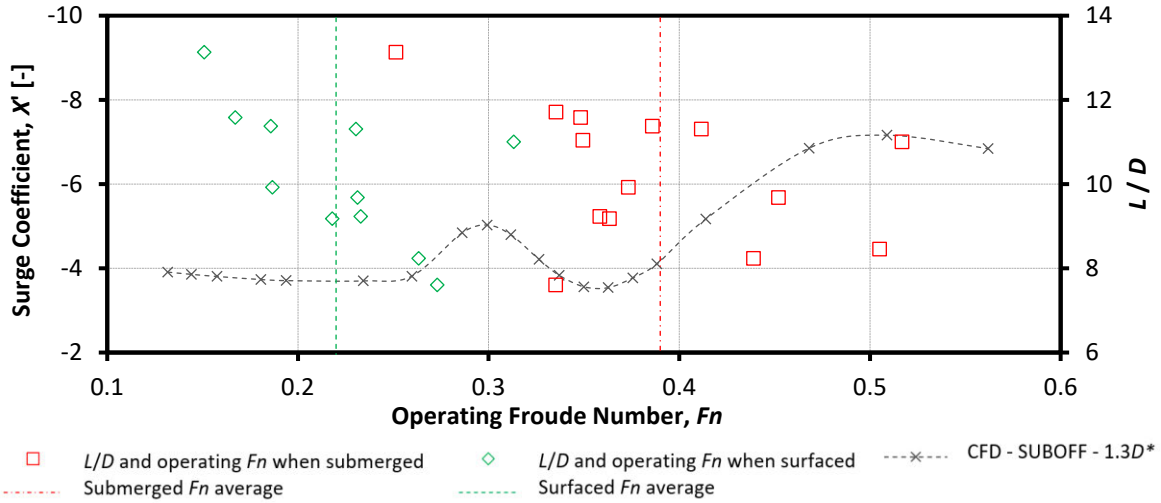


Figure 1: Primary axis shows surge coefficient, *X*' of the bare hull SUBOFF with *L*/*D* = 8.6 at a submergence depth of 1.3*D**. Secondary axis shows the *L*/*D* of various submarine geometries and their respective submerged and surfaced operating speeds.

In addition to the near surface interaction effects on an axisymmetric body at various submergence depths, the evolution of the interaction effects as a function of hull length to diameter ratio (*L*/*D*) for the bare hull geometry of a submarine has also been investigated numerically [5]. However, the test range was limited up to a Froude number of 0.24. As shown in Figure 1, the speed investigated only includes a very small section of the operational range of underwater vehicles. Hence, this paper acts to extend upon the methodology by Ranmuthugala et al [5] to investigate the free surface hydrodynamic interaction effects induced on an underwater vehicle over the full range of operational speeds including high speeds which are not typical near the free surface to provide an additional insight into the interaction behaviour. The hydrodynamic interaction is characterised using CFD and discussed in terms of the surge force, heave force and pitch moment acting on a vehicle as a function of Froude number, submergence depth and body length-to-diameter ratio, *L*/*D*. Near free surface operations of underwater vehicles and submarines entails increased manoeuvring difficulties especially when very shallowly

submerged. Even at low speeds, the free surface induces a destabilising heave force and pitching moment. Loss of control near the free surface can lead to detection, broaching of the free surface, and possibly injury for crew on board. Quantifying and understanding free surface effects will allow submarine operators to develop safe operational envelopes, where even when shallowly submerged, if the operational Froude number is sufficiently low, free surface effects (especially instability in the vertical plane) can be avoided.

2. SIMULATION SETUP

The bare hull configuration of the SUBOFF [7, 8] with the particulars presented in Table 1 was used throughout this study. The body-fixed coordinate system is shown in Figure 2 (Left) with its origin located at the longitudinal centre of buoyancy, x_{CB} of the SUBOFF, measured at 0.462 body lengths away from the nose. The submergence depth, D^* is given as the ratio of the distance from the free surface to the centreline of the SUBOFF, h to the diameter of the SUBOFF hull, D. This can be written as $D^* = h/D$ with h as shown in Figure 2 (Right).

Table 1: Geometric characteristics of the baseline SUBOFF of L/D = 8.6.

Description	Symbol	Value	Unit
Overall length	L	4.356	[m]
Diameter	D	0.508	[m]
Surface area	A_S	5.986	[m^2]
Volume	∇	0.698	[m^3]
Centre of buoyancy	x_{CB}	0.462L from nose	[-]

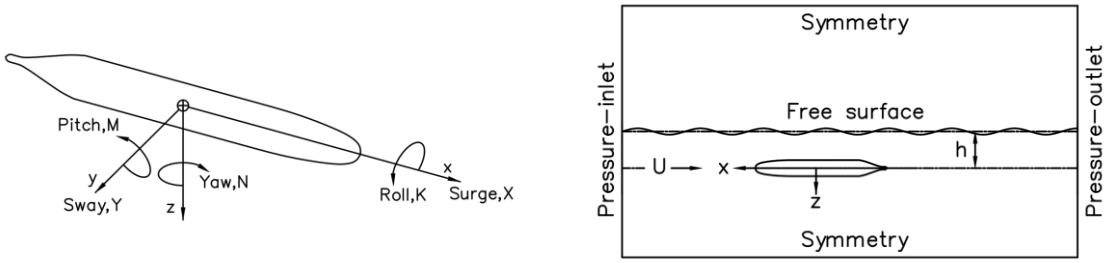


Figure 2: (Left) Coordinate system used in this study. (Right): Boundary conditions prescribed to the computational domain.

The test conditions were simulated using the commercial Computational Fluid Dynamics (CFD) code ANSYS Fluent with the Reynolds-averaged Navier-Stokes (RANS) scheme and the Baseline Reynolds Stress Model (BSLRSM) turbulence model. The computational domain was discretised using an unstructured CutCell mesh as shown in Figure 3. The computational domain used throughout this study is with the SUBOFF at 3.5 body lengths away from the domain sides, the inlet being 3 body lengths away from the nose of the SUBOFF, and the outlet 5 body lengths away from the stern. The fluid domain dimensions have been established to be independent of blockage effects [9]. Additionally, the boundary conditions for the computational domain are as such: the SUBOFF hull as a no-slip wall; the top and sides as free-slip walls; the bottom face as a no-slip wall; the upstream boundary as a pressure inlet; and the downstream boundary as a pressure outlet as shown in Figure 2 (Right).

2.1 GRID INDEPENDENCE STUDY

From previous studies [9] and work by the authors [12], the mesh requirements of the CFD simulation of an underwater vehicle moving near the free surface has been well established with respect to the turbulence model, the effect of mesh resolution, inflation layers around the hull (total thickness and y^+) and the free surface mesh resolution. The mesh model is shown in Figure 3 (Left). A grid independence study was conducted with the following parameters: submergence depth of 1.1D^*, Froude number of 0.512, and L/D of 8.6. At 7.8 million elements, predictions of all forces and moments were within 5% of the finest solution and at 13 million, predictions were within 1% as shown in Figure 3 (Right). The 13 million elements mesh model was preferred and was used for the remainder of this study.

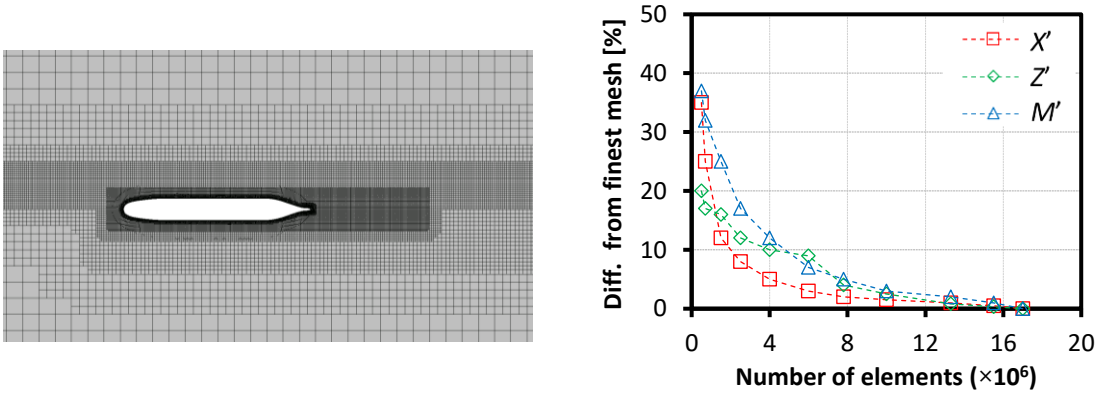


Figure 3: (Left) Vertical cut-plane of the SUBOFF mesh model. (Right) Percentage difference of the surge coefficient, X', heave coefficient, Z', and pitch coefficient, M' predictions from the finest 17 million mesh solution vs number of elements for the SUBOFF at a submergence depth of 1.1D^* and a forward velocity of 3.344 m s^{-1} (Froude number of 0.512), and L/D = 8.6.

3. CFD VALIDATION

The CFD model is validated via two experimental datasets: the bare hull SUBOFF [10] and bare hull Joubert hullform [11] undergoing straight ahead motion near the free surface. The geometries are shown in Figure 4 (Left). The SUBOFF data is limited to resistance while the Joubert data provides the relevant forces and moment in the vertical plane Note that for the CFD simulations, the SUBOFF geometry (L/D = 8.6) is used and is subsequently compared against both the experimental SUBOFF and Joubert datasets (L/D = 8.5). To the knowledge of the authors, no current experimental data exists for the vertical force and moment of a near free surface SUBOFF, and thus, experiments conducted using the Joubert are still used for the purposes of validation for heave and pitch coefficient of the SUBOFF. Hence, both experimental data sets were required to validate the CFD model as the geometries used are comparable in shape and L/D. The non-dimensionalisation of the hydrodynamic coefficients is defined as such for surge, heave, and pitch respectively:

$$X' = \frac{X}{0.5\rho U^2 S};\ Z' = \frac{Z}{0.5\rho U^2 S};\ M' = \frac{M}{0.5\rho U^2 S L};$$

where X is the surge force, Z is the heave force, M is the pitch moment, ρ is the fluid density, U is the forward velocity, S and L are the surface area and length of the SUBOFF and Joubert models respectively. The validation was conducted at a submergence depth of 1.3D^* over a range of Froude numbers with the comparison shown in Figure 5. For surge coefficient, CFD accurately predicts the two peaks at *Fn* = 0.30 and 0.50 and the trough at *Fn* = 0.40. The numerical simulations are shown to be capable of capturing the distinct peaks and troughs of surge, heave, and pitch coefficients of both the SUBOFF and the Joubert with respect to Froude number. For surge coefficient, the CFD predictions were within 5% agreement of Wilson-Haffenden [10] and an overprediction of 10% is seen when compared to Dawson [11]. The percentage difference for heave coefficient is 17.5% and for pitch coefficient, a difference of 10.1% was observed. It is noted that the experimental data from both Wilson-Haffenden [10] and Dawson [11] are not corrected for the sting and support strut effects which induce an uncertainty to the percentage difference reported. Attempts to address these effects within this study were not conclusive due to the lack of verifiable information available regarding the sting and support structure.

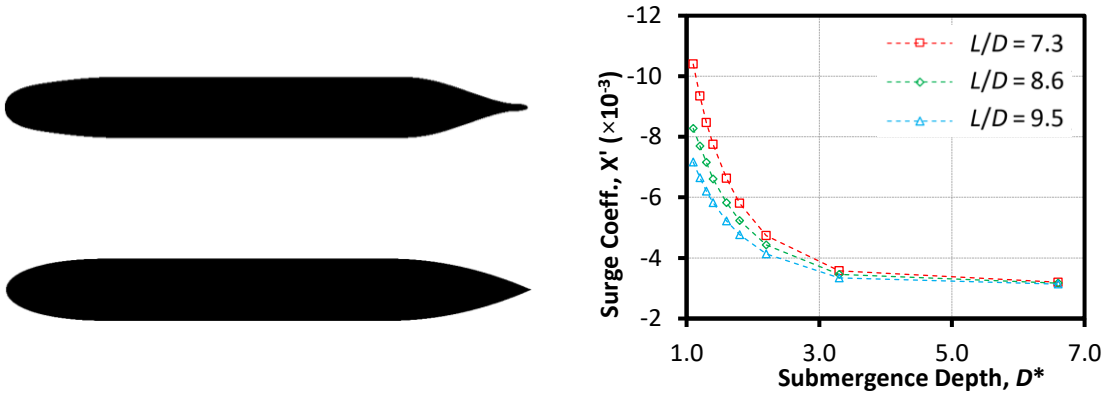


Figure 4: Bare hull SUBOFF with *L*/*D* = 8.6 (Top Left); Bare hull Joubert with *L*/*D* = 8.5 (Bottom Left). Surge coefficient, *X*' vs submergence depth, *D** for all three SUBOFF *L*/*D* configurations (Right).

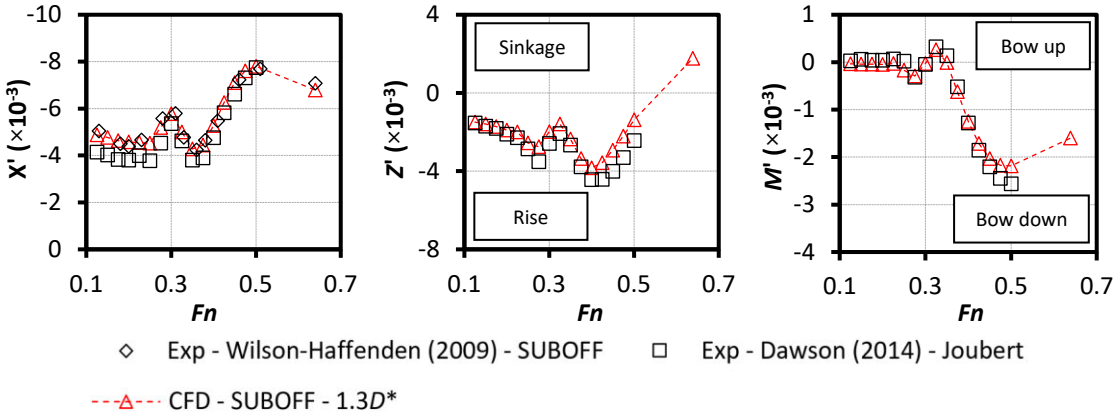


Figure 5: Surge coefficient, *X*' (Left); Heave coefficient, *Z*' (Middle); and Pitch coefficient, *M*' (Right) vs Froude number, *Fn* comparisons for the SUBOFF with *L*/*D* = 8.6 and Joubert with *L*/*D* = 8.5 at a submergence depth of 1.3D^*.

Overall, the CFD predictions for surge, heave, and pitch coefficient all followed experimental trends closely. Even though the comparisons for surge show a notable difference, this observation is expected, due to the sensitivity of the free surface, and the

complex flow structures that arise due to the proximity of the hull to the free surface is one of the main challenges in validating the numerical model. The presence of the sting (or support struts) which are used to mount to experimental model to the towing tank carriage can also affect the flow around the hull. Nevertheless, the confidence in the CFD model predictions is established for the purpose of this study as the predictions were within reasonable agreement with the experimental data and trends. As such, surge, heave, and pitch coefficient can be said to be validated.

4. RESULTS AND DISCUSSION

4.1 Effects of Froude Number, *Fn*

For the range of Froude number investigated all hydrodynamic coefficients show distinct peaks and troughs with respect to Froude number (see Figure 6). The peaks for surge are at Froude numbers of approximately 0.30 and 0.50. The peaks and troughs in the hydrodynamic coefficients are attributed to the change of wavelength of the free surface waves with respect to Froude number and its influence on the pressure field surrounding the shallowly submerged hull. For the pitch coefficient in Figure 6 (Bottom), the net pressure acting on the hull is shifted about the local origin of the hull resulting in a change of direction and magnitude of pitch moment.

All coefficients show high degrees of sensitivity with respect to Froude number whereby a small change in speed induces large effects on all three hydrodynamic coefficients. For the surge coefficient, an increase in operating Froude number from 0.2 to 0.3 caused an almost two-fold increase in surge force. Pitch showed large changes in behaviour with a small increase in Froude number, varying between a bow down and a bow up moment even within a small Froude number range of 0.23 to 0.35. When travelling near the free surface, an underwater vehicle generally has quite limited control due to its low operating speed, as shown previously in Figure 1 where the average Froude number for a surfaced submarine is approximately 0.22. As Froude number increases, a small change in speed can cause large and steep changes in the manoeuvring characteristics of the submarine, especially with regards to heave in Figure 6 (Middle) where an increase in Froude number from 0.26 to 0.33 causes an almost two times change in heave coefficient from being strongly attracted to weakly attracted towards the free surface.

Operationally, the large changes in heave and pitch can cause several issues: for one, the control surfaces might over-compensate for trim and instead of correcting for a bow down moment, are suddenly causing an increase in a bow up moment. Additionally, in correcting for the large suction towards the free surface, at the sudden trough at a Froude number of 0.33, the submarine might submerge abruptly, causing large motions that can jeopardise crew safety. These effects combined can be especially dangerous during evasive manoeuvres or during high-speed operations near the free surface and generally can be said to adversely affect vertical plane stability.

4.2 Effects of Submergence Depth, *D**

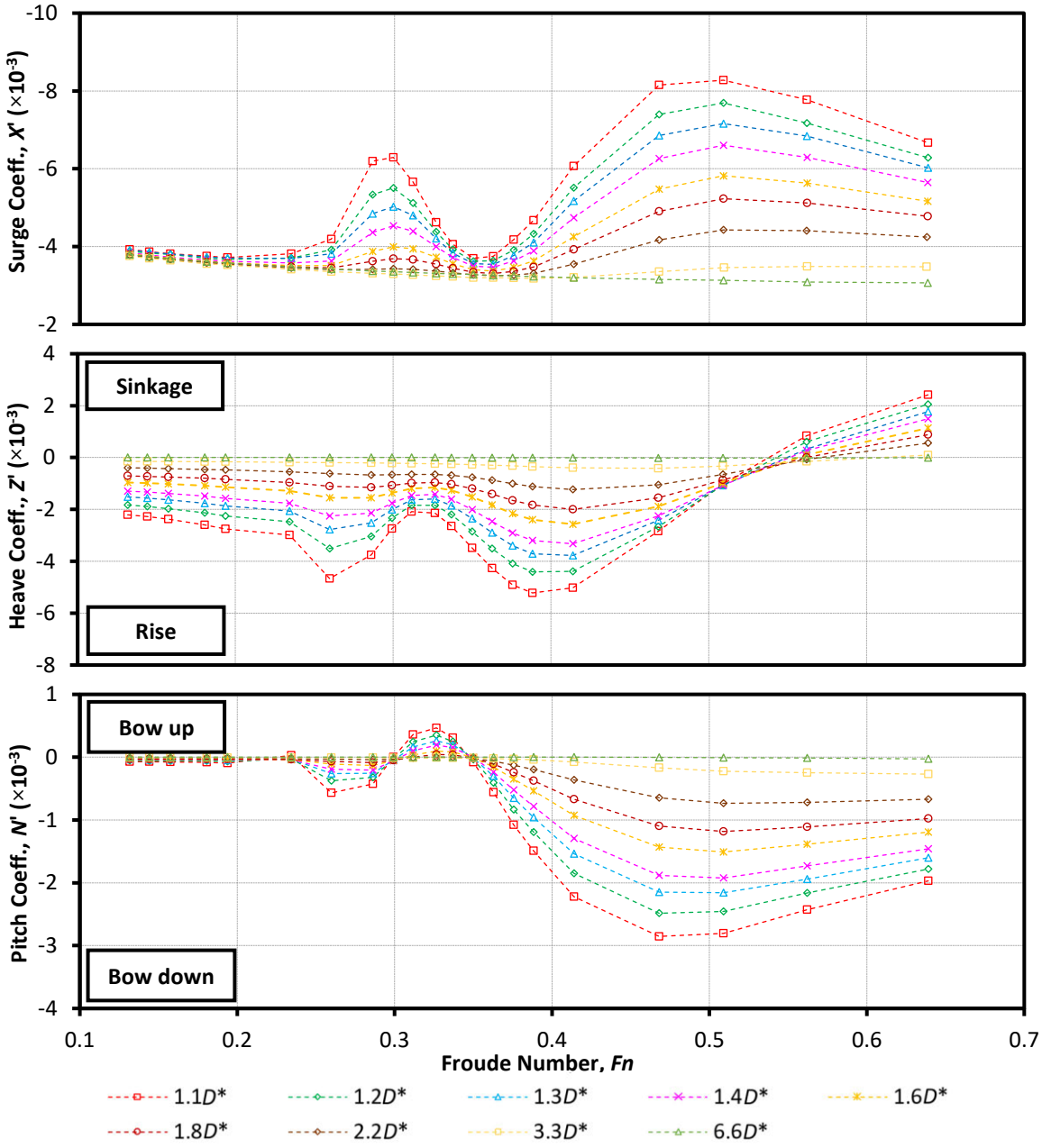


Figure 6: (Top) Surge coefficient, *X*'; (Middle) Heave coefficient, *Z*'; (Bottom) Pitch coefficient, *N*' vs Froude number, *Fn* of the *L*/*D* = 8.6 SUBOFF at various submergence depths, *D**.

From Figure 6, it is seen that the induced free surface effects for surge decreases exponentially with an increase in submergence depth shown in Figure 4 (Right). From an operational perspective, at Froude numbers of 0.2 to 0.3 for example (which is a typical surfaced operating speed range for submarines as shown in Figure 1), an increase in submergence depth from 1.1*D** to 6.6*D**, causes an almost two-times decrease in surge, see Figure 6 (Top). In the vertical plane, a shallowly submerged SUBOFF experiences large suction towards the free surface combined with a bow down moment, which it would not otherwise experience at larger submergence depths. At a submergence depth of 6.6*D**, the SUBOFF experiences zero heave and pitch and free surface effects can be said to be

negligible as shown in Figure 6 (Middle) and (Bottom). The hydrodynamic coefficients can be said to be largely depth dependent where a small change in submergence depth can greatly affect its magnitude. This is especially important at periscope depth, which is commonly defined as a submergence depth smaller than three diameters from the free surface (i.e., 3*D**). It is important to note that this threshold of 3*D** for negligible free surface effects is only applicable for calm water (sea state of zero) with no additionally generated free surface waves.

4.3 Effects of Length-to-Diameter Ratio, *L*/*D*

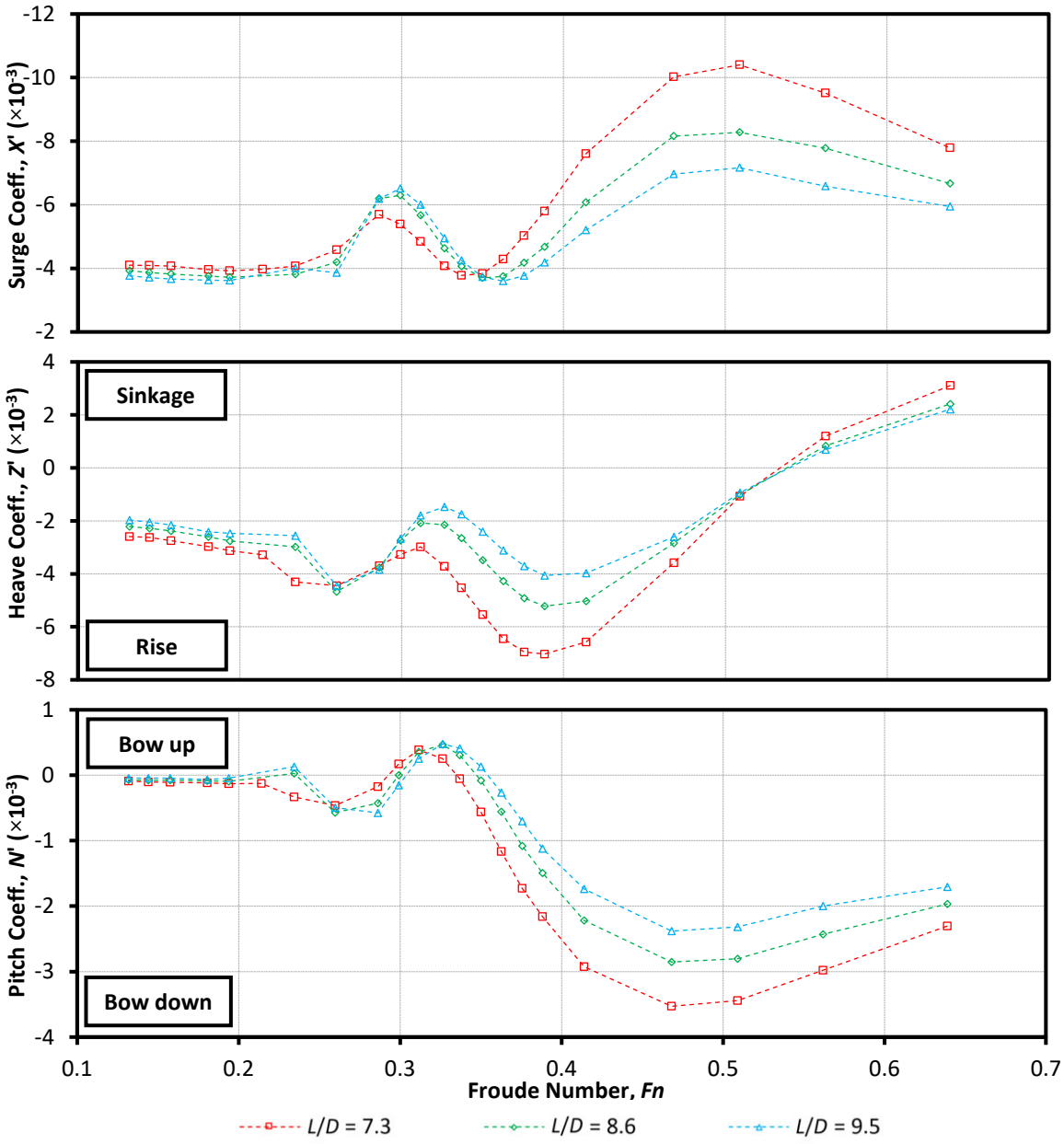


Figure 7: (Top) Surge coefficient, *X*'; (Middle) Heave coefficient, *Z*'; (Bottom) Pitch coefficient, *N*' vs Froude number, *Fn* at a submergence depth of 1.1*D** for *L*/*D* = 7.3, 8.6, and 9.5.

In this study, the parallel mid-section of the SUBOFF was varied in length to achieve the desired L/D. Investigating the surge coefficient at the shallowest submergence depth of $1.1D^*$ for all three hulls shown in Figure 7 (Top) that as L/D increases, the first surge peak does not exhibit as much sensitivity to L/D whereas the second peak at higher Froude numbers shows a substantial decrease in magnitude. A shift in the relative Froude numbers of peaks and troughs can also be observed with varying L/D. This is due to the geometry set-up whereby the diameter is kept constant with increasing length to obtain the three specified L/D ratios.

Comparing the heave coefficient for these models at the shallowest submergence depth of $1.1D^*$ in Figure 7 (Middle) shows that the shortest model with an L/D = 7.3 experiences the largest heave forces with a significant shift in the maxima and minima compared to the L/D = 8.6 and 9.5 models. The free surface induced heave force can be said to diminish with increasing L/D. Intuitively, the smallest model with its smallest surface area experiences greater heave force per unit area hence causing a greater force response in the vertical plane. This is true for pitch coefficient as well in Figure 7 (Bottom) where the shortest model experiences the largest pitch moment. With a lengthening of the body, a shift in the first peak of surge can be seen from a Froude number of Fn = 0.286 for L/D = 7.3 to Fn = 0.299 for L/D = 8.6 and 9.5. Comparatively, the first surge peak for the smallest L/D = 7.3 shows a much smaller amplitude compared to L/D = 8.6 and 9.5 which both show similar peak amplitudes. However, the second peak for surge occurs at a similar Froude number of 0.509 for all three geometries. As for the trough, a much clearer shift can be seen from Froude numbers of 0.337, 0.350, and 0.363 respectively for increasing L/D. Comparatively, heave and pitch do not show large Froude number shifts with lengthening of the parallel mid-section.

5. CONCLUSION

Throughout this study, Computational Fluid Dynamics (CFD) was used to investigate the near free surface effects of an underwater vehicle geometry, the SUBOFF. Numerical verification was first conducted and showed that the simulations were mesh independent and free from blockage effects. Experimental validation was then conducted to compare numerical results to experimental results which showed good agreement, with surge, heave and pitch matching experimental values and trends closely. Following this, simulations were then conducted by varying Froude number, submergence depth, as well as body L/D.

All three coefficients investigated, i.e., surge, heave, and pitch, showed distinct peaks and troughs when plotted as a function of Froude number. This is caused by the surface waves generated by the vessel as it travels near the free surface and can be explained via wave superposition, i.e., the bow wave adding together with the stern wave. The surge coefficient shows a similar two peak behaviour to surface vessels with clearly defined peaks. Heave and pitch on the other hand show a more complex behaviour with changes in both magnitude and direction as the Froude number increases. The combination of suddenly increasing resistance together with instability in the vertical plane due to change in heave force and pitch moment can cause endurance issues for underwater vehicles as additional power has to be expended to not only overcome the additional wave resistance

but also to maintain proper trim and depth when travelling near the free surface. The results indicate that submergence depths of approximately 3*D** or more the influence of the free surface will be negligible. However, it is important to note that this threshold is only for calm water (sea state of zero) and further studies are currently ongoing on the interaction under wave conditions.

With regards to the effects of *L/D* on the interaction characteristics, this study achieved the desired *L/D* by adjusting the length of the SUBOFF parallel mid-section. For surge, the *lowest L/D* model (*L*/*D* = 7.3) was shown to experience the largest surge coefficient which became especially evident at larger Froude numbers (*Fn* > 0.35). In the vertical plane, the lowest *L/D* model also experienced the highest heave force and pitch moment per unit area (due to its smaller surface area) compared to the other two models with larger *L/D* (*L*/*D* = 8.6 and 9.5). The differences between the lowest and highest *L*/*D* models at their respective maxima at a Froude number of approximately 0.51 are as such: 1.45 times for surge coefficient, 1.73 times for heave coefficient, and 1.48 for pitch coefficient. It has been shown in this work that increasing *L*/*D* has a beneficial effect when travelling in proximity to the free surface. However, the design consideration for *L/D* in underwater vehicles then evolves to whether the advantages of maintaining an optimal *L*/*D* for deep water travel (stated to be an *L*/*D* = 8 for a parallel mid-section [13] underwater vehicle) outweigh the large advantage of reducing adverse free surface interaction effects. In this study, the design choice of increasing length instead of diameter to reduce adverse free surface interaction effects is well-established for straight line manoeuvres in calm water. The work suggests that further investigation of the free surface effects be extended to include wave conditions and non-straight-line manoeuvres, e.g., horizontal drift and turning.

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Promoting Submarine Stealth by Reducing Submarine Mast Hydrodynamics

Ahmed M. Shama[1,2], Ahmed Swidan[1,2], John Young[1], Dev Ranmuthugala[3]

[1]SEIT, UNSW Canberra at ADFA, ACT, Australia a.shama@unsw.edu.au

[2]Arab Academy for Science Technology & Maritime Transport (AASTMT), Alexandria, Egypt

[3]Defence Science Technology DST Group, Victoria, Australia

ABSTRACT

Submarine mast movement while piercing the water surface causes a noticeable plume. Submarine stealth is thereby endangered by advanced radar technologies that can detect the submarine plume in snorkeling operations. In addition, the flow over the mast produces vibrations that generate a detectable noise. This study investigates plume impact reduction using the passive method of an amended mast geometry. The hydrodynamics of the resulting plume was numerically examined using commercial software that employs; the Reynolds-Averaged Navier–Stokes (RANS) equations, the Adaptive Mesh Refinement (AMR) technique, and the Volume of Fluid (VOF) method. The submarine mast was partially submerged while encountering calm waves at a range of Froude numbers (Fr) ranging from a magnitude of one to four in one increment. The plume parameters such as length and bow wave height were analysed at different flow velocities ranging from 0.8 to 4 m/s. Results indicate that enhanced submarine stealth would be attained by utilising the new amended mast geometry, which showed better performance with regard to the aforementioned parameters on the generated flow hydrodynamics.

Keywords

Hydrodynamics; Submarine Mast; Computational Fluid Dynamics (CFD); Adaptive Mesh Refinement (AMR); Volume of Fluid (VOF); Submarine Stealth.

INTRODUCTION AND BACKGROUND

Australian Submarine fleet is continually developing to enhance the protection of the borders. The advanced technologies of submarine mast design are currently utilised to keep pace with the detection techniques development. Submarine masts are used in periscope, communication, radar, and attack operations, and the submarine raises its mast according to the required mission. Accordingly, the submarine mast technology is improving to be a part of this fully integrated arsenal. The new submarine mast technologies aim to enhance the masts' capabilities and include a larger covering environment (Cocking et al., 2016).

While the number and technology of submarines grow, the submarine detection techniques are improved and developed. The submarine mast generates a detectable plume while

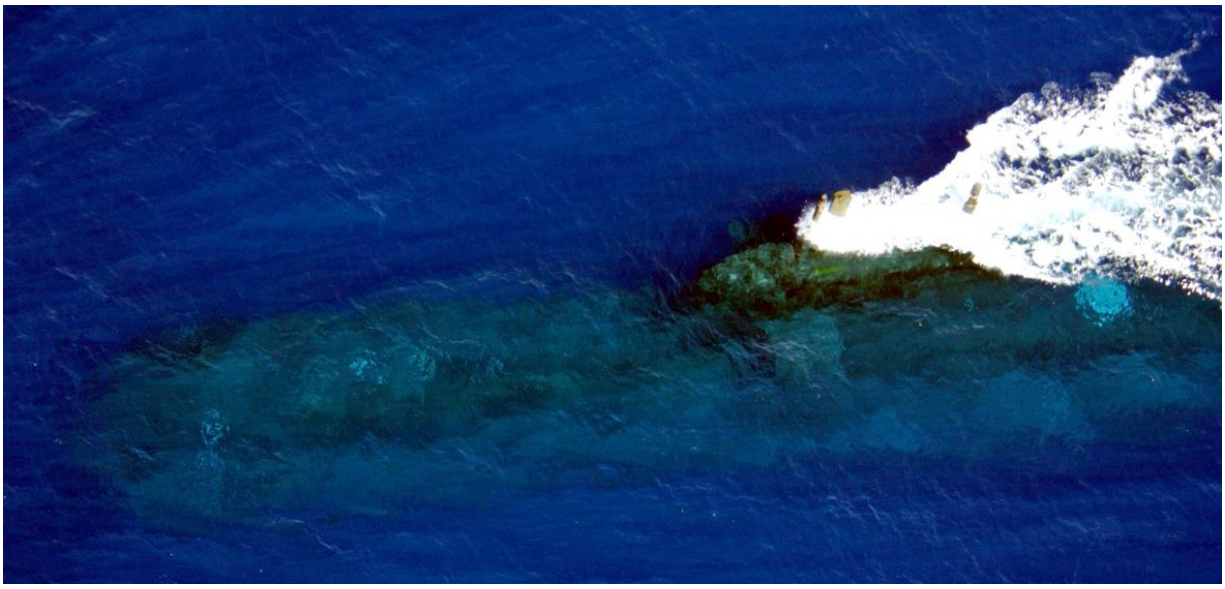


Figure (1). The plume generated over the submarine mast at the snorkeling operation

piercing the water surface, as shown in Figure (1). Submarine detecting is like searching for a ghost as the mast and the plume it produces is very small; however, the submarine's stealth during the snorkeling process is sensitive to detection by advanced radars (Anderson, 2022). Several studies have examined the generated plume at different velocities and water depths during snorkeling operations, providing parameters for this study.

Newly experimental data for an attached free-end cylinder in the towing tank were published by Potts et al. (2020). It was mentioned that the critical difference between the fully and partially submerged cylinder is the developed air ventilation pocket behind the cylinder. The free end cylinder caused vortex shedding dominated by the von Karman Street characteristics. The two modes of air-entrainment were explored at the regions along the cylinder wall and the wake behind the cylinder (Ageorges et al., 2019).

The aspect ratio between length and diameter of cylinder piercing surface L/D was studied with values ranging from 0.1 to 2 by Gonçalves et al. (2015). The created vortices by the free end cylinder were reduced when the aspect ratio was increased. In the current study, the submarine mast was submerged at a fixed depth with shallow submersion to examine the free end impact deeply. In addition, the velocity vectors over the top and bottom ends of the masts were explored in detail for various mast geometries and flow Fr.

Kawamura et al. (2001) employed Large Eddy Simulations (LES) for flow over a circular free surface cylinder at low Froude numbers Fr. They found that the low wave amplitude for flow Fr below 0.8 has no influence. The current work includes various flow Fr range from low Fr 1 to high Fr 4 with increment 1. This numerical model utilised the k-ω SST turbulence model in calculations because the experimental results were accurately reproduced for the same physical problem by Ducrocq et al. (2017).

The influence of the air-water interface on the vortices behind the circular cylinder was explored by Suh et al. (2011). As a result, the main vortex shedding was diminished, revealing small-scale vortices. Moreover, experimental flow measurements behind a finite height cylinder demonstrated that the vortex shedding was suppressed below the water surface (Ageorges et al., 2021). A more in-depth investigation of the generated vortices at the wake

region and near water surface will be discussed in this paper for the transverse and vertical layers.

RESEARCH OBJECTIVES

The challenges of the traditional circular mast are different based on the mast function that accordingly changes the size of the mast: the bigger submarine mast diameter, the larger plume generated, and the higher risk of detection.

There has been little research into submarine mast design and the generated plume reduction. The studied geometries were limited to foil shape, and an in-depth analysis of their impact is still required. Consequently, the foil shape with blunt and sharp edges and the shape of the combined foils were studied and compared with the results of the circular cylinder shape.

The previously covered flow speed range was for low Froude number; thus, the high Fr number range is studied. A comprehensive investigation of the flow near the free surface is performed using the computational fluid dynamics tools. Furthermore, the top and bottom mast ends at submerged depth are examined and analysed to demonstrate the generated vortices.

NUMERICAL MODEL TESTING CONDITIONS

The submarine mast pierces the water surface while partially submerged with a ratio of 0.2. Various testing conditions were investigated for different mast geometries. The submarine mast moving velocity range was 1 to 4 m/s, corresponding to the Fr range from low Fr 1 to high Fr 4. The mast investigated cross-sections shapes are the traditional circular, the foil with a blunt edge, the foil with a sharp edge, and combined two foils (merged). The utilised cylinder cross-section shape was the NACA 0036 symmetrical streamlined foil, with a maximum thickness of 36% of the chord length, as presented in Figure (2).

This thick foil NACA 0036 section was utilized due to the tower length limitations for multiple masts and to include a larger circular diameter inside the foil to avoid the mast thickness constraints. The zero-camper foil is recommended because the lift forces on the foil sides are equal, and the separated bubble isn't formed before the trailing edge. The flow over thick foil shape separates earlier than the flow over the thin foil shape with larger boundary layer thickness. This foil shape was used to control the flow and reduce the drag forces in aerospace applications (Martin et al., 2003).

The physical domain, as shown in Figure (3), was simplified to a circular cylinder with a diameter (D) and a length (L) partially submerged in water at a depth of 0.2 L. The mast end bottom was free since the end body of the submarine and the tower with dashed lines were ignored. There were gaps between the cylinder ends and the top and bottom of the numerical domain to allow flow movement above and below the cylinder. The flow velocity at the inlet simulated the mast velocity (U).

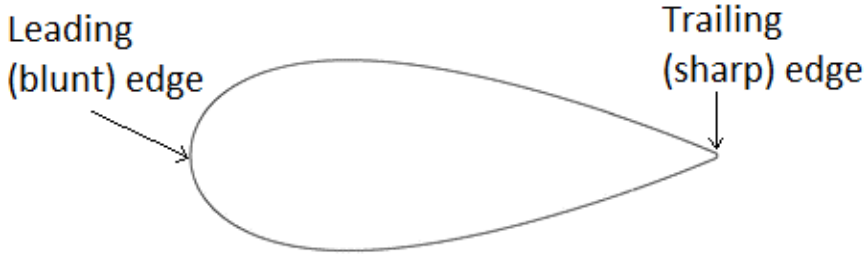


Figure (2). Streamlined mast cross-section of NACA 0036 foil shape.

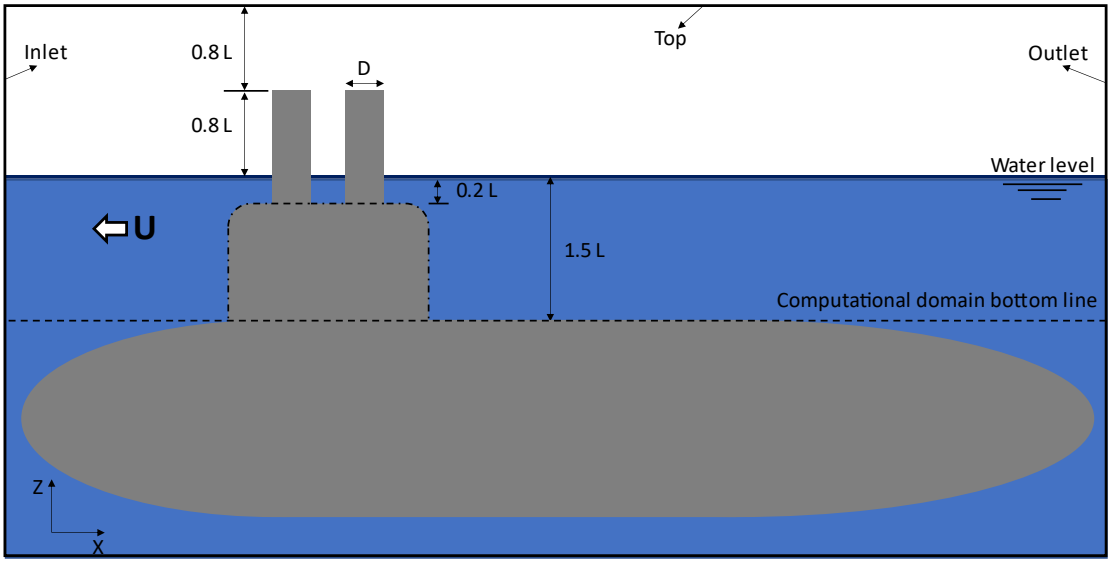


Figure (3). Computational domain boundaries.

The numerical calculations were performed using computational fluid dynamics (CFD) software called STAR-CCM+ (CD-Adapco, 2022). The Adaptive Mesh Refinement (AMR) was applied for grid dynamic regarding the free surface cells calculations. The Volume of Fluid (VOF) method simulated the interface line between the fluid phases. The VOF utilised the high-resolution interface capturing scheme (HRIC) for the sharp air-water interface.

RESULTS AND DISCUSSION

Results Validation

The current numerical model was validated by comparing the simulation results to earlier numerical and experimental data and utilised for both circular cylinder mast (Ahmed M. Shama, 2020) and streamlined mast (Ahmed M. Shama, 2021). The compared validated parameters of the results were the drag coefficient (global) and the bow wave height (local). In addition, the numerical model was utilised to investigate the various generated plume parameters. The flow over the cylinder created considerable drag at the laminar zone, followed by a drag crisis at the transition zone. The induced drag then reached a consistent range of values in the turbulent region.

Flow Over A Circular Cylinder

This study was performed in the laminar, transition, and turbulent zones that correspond to the studied flow Froude number Fr (1 to 4). Figure (4) demonstrates the vortices generated of the wake vicinity behind the mast at the free surface Level. The generated vortices differ by changing the flow velocity and mast diameter size. At the cylinder surface, the flow contours separated on the sides, and two large magnitude vortices were produced. At the downstream side, the flow stream behind the cylinder diverged as Kelvin Wake and the vortices shedding were observed. The captured vortices at Fr 0.8 show good agreement with the previous numerical and experimental work (Kawamura et al., 2001); however, there was vortices suppression due to the differences in the used circular cylinder size. The agreement with previous studies was on the separation point at the side, the vortices location, and the Kelvin wake angle.

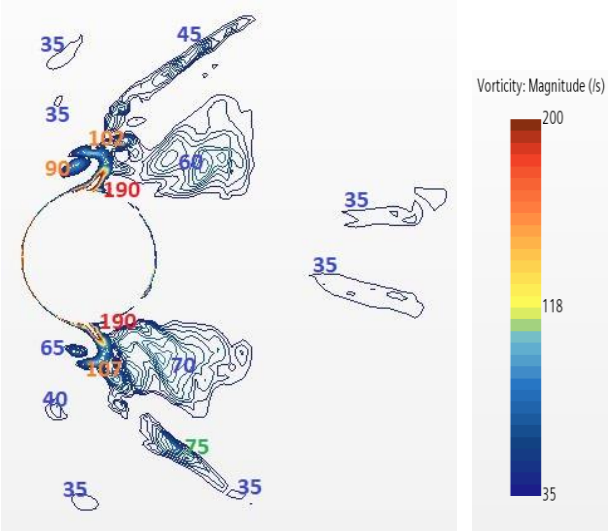
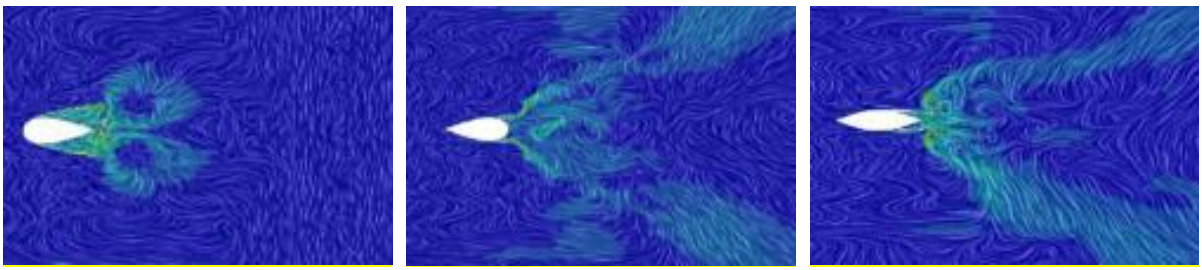


Figure (4) The generated vortices behind the Submarine circular cross-section mast at the water surface level at Fr 0.8.

Wake Behind Modified Submarine Mast Geometry

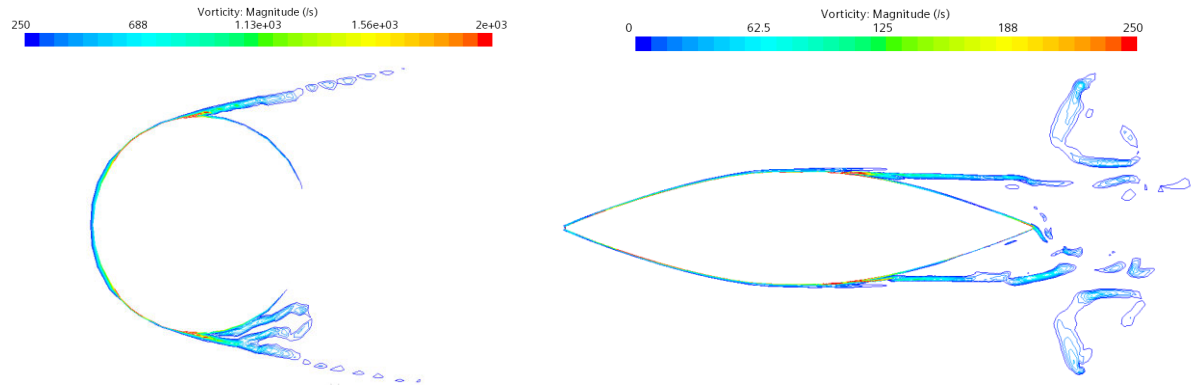
Among submarine masts with the same cross-section area, the circular mast benefited from being shorter in length (x-direction) than other designs restricted to the submarine tower area. Figure (5) show the effects of the modified mast geometry on the velocity vectors. The flow over the three-mast shapes was simulated at the same flow Fr. When the circular mast was replaced with a streamlined foil mast form (Leading edge foil), the drag coefficient was reduced by more than half. Also, the same percentage of drag reduction at higher Fr was achieved as for low Fr. The altered foil mast shape to the opposite by facing the water with the trailing edge decreased the generated bow wave height to half. In contrast, the bow wave heights of the circular and leading-edge foil masts were almost equal. The reduction of the bow wave height of the sharp edge foils, trailing edge foil, and merged two foils; was due to the late separation.

At the same flow speed, the separation points for the various mast shape considerably influenced the generated vortices. Due to the early separation and inner curvature of the body, the leading edge mast created the strongest and shortest vortices along the wake at the flow downstream. On the other hand, low-energy vortices were created by the late separation of the trailing edge and merged masts. Compared to the various mast geometries, the combined mast shape generated the least drag coefficient and vortices extremely. Thus, the merged mast shape is considered the optimal one.



(a) Leading edge foil (b) Trailing edge foil (c) Merged foils

Figure 5. Instantaneous velocity vectors over different mast geometry modifications.



(a) Circular cross-section (b) Combined two foils (merged) cross-section

Figure (6) The highest magnitude vortices pattern of the circular and merged mast cross-section shapes.

The produced plume and the generated vortices significantly impacted submarine detection regarding the combination of water flow and surface piercing cylinders. The produced bow wave height and vortices were found to be proportional to the mast movement velocity and mast cross-section shape. Figure (6) demonstrates the differences between the high magnitude vortices generated over the traditional circular cross-section and the new design of merged foils. The two figures 6 (a) and 6 (b) have different colour scales, where the maximum vortices magnitude in (a) is the lower in (b). The vital differences were revealed in the separation point and angle. The angle of separation was more significant for the circular mast cross-section. The later separation in merged foils shape generated less vortex shedding. Compared to the circular mast cross-section geometries and other forms, the merged cross-section mast provided the lowest bow wave height, drag coefficient, and vortices magnitude.

Air-Water Interface (Free Surface) and Mast End Effects

Figure (7) shows the maximum velocity in the produced wave splash zone. The produced bow wave created chaotic velocity spots on the air-water interface. The low velocity behind the cylinder surface made the air ventilation cause wave. The ventilation could reach the fully-ventilation mode at higher Fr.

The flow streamlines followed curvature routes at the bottom ends of the submerged mast; they were distinguished in high-velocity zones along the free surface and at the splash region of the plume. In addition, the lowest flow velocity streamlines were revealed between the mast end and the plume.

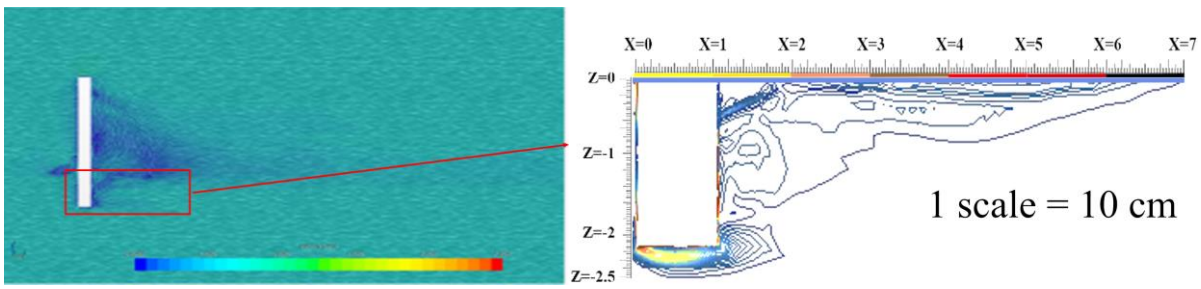


Figure 7. Flow velocity streamlines and the generated vortices and air-entrainment below the water surface at Fr 2.

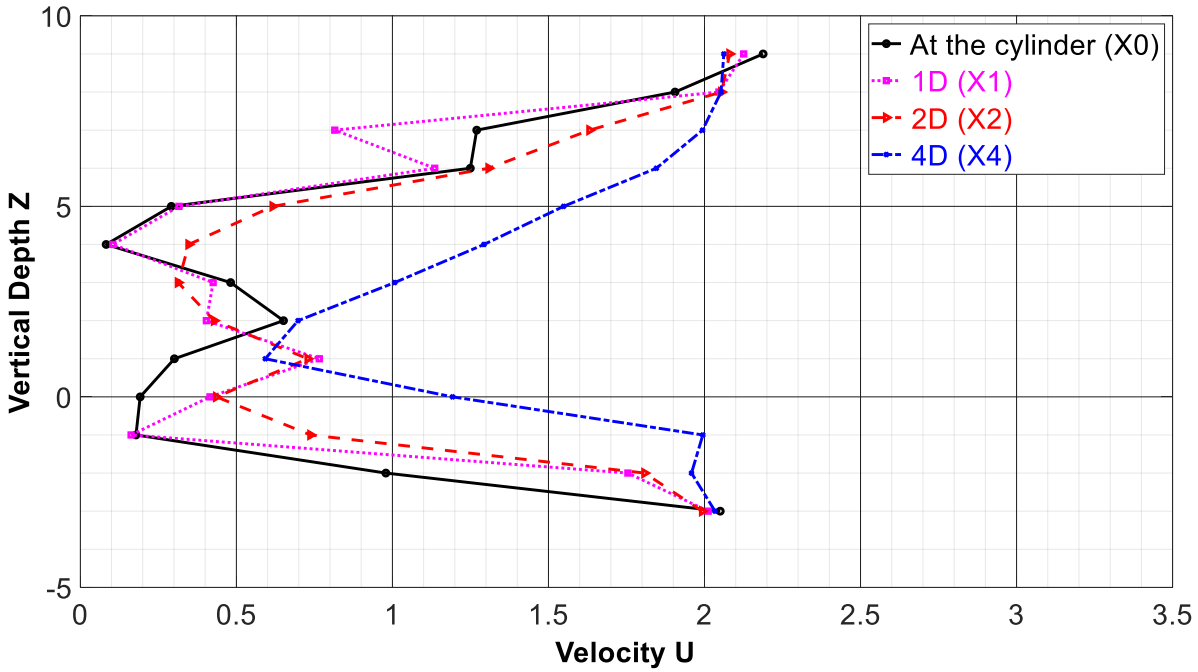


Figure (8). Flow velocity (U) over the vertical depth (Z) and longitudinal distance (X).

Figure (8) presents the local-averaged velocity over the vertical and longitudinal depth in the wake at Fr 2. The effects of the free-surface and cylinder free ends were demonstrated at X=1,2,3 D distance from the cylinder, and vertical depth range from Z -5 to 10 D. The vertical transition region for the far velocity upstream and the flow stream velocity impacted by the cylinder presence was from Z ± 2 D from the cylinder free end. The local velocity increased at the greater longitudinal distance from the cylinder. The plume characteristics at the air-water interface were changed in chaos pattern at the cylinder wake. At the air-water surface behind the cylinder in the Z = -1D – 4D, the bow wave height velocity suddenly increased to the max velocity and then reached the minimum velocity below and above the bow wave. The line points deflection from the repeated trend at some points occurred due to the water splash and water droplets disorder movement. At distance 4D from the cylinder, the flow velocity pattern showed a reverse appearance different than the previous line at a closer distance. The 4D velocity line could be interpreted as the wave breaking after reaching maximum height.

The lowest velocity values of the flow were shown below the top and above the bottom ends of the cylinder. The flow hydrodynamics were disrupted by the bottom end of the mast. This effect could be avoided at greater water depths or by varying the end shape when connecting another body to the end.

CONCLUSION AND FUTURE WORK

Surfacing of submarine masts causes a detectable plume while operating in snorkeling conditions, presenting a visual risk to submarine stealth. The simulated plume parameters generated by a range of amended mast geometries were validated and analysed with the focus on reducing the plume signature. The investigated mast cross-section geometries were the circular, blunt edge foil, sharp edge foil, and two merged foils shapes. The generated vortices' location and magnitude were dependent on both the mast cross-section shape and the relative flow velocity. The generated bow wave at the mast surface caused an interface cavity at the wake behind the mast. The flow streamlines at the vicinity of the air-water

interface significantly interfered with the plume, and the end bottom, which caused high vortices at the mast end and the water surface. The named merged mast geometry showed a better performance in comparison to the tested geometries, reducing both the plume bow wave height and the induced impact loads by 50 % and 80 %, respectively. In addition, the results showed that both the vertical and longitudinal localised velocities at the wake would accurately represent the generated plume.

The future work will concentrate on the mast-wave interaction to examine the validity of results in rough seas.

ACKNOWLEDGMENT

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Wakes of Surface-Piercing Cylinders

Douglas Potts, Australian Maritime College, douglas.potts@utas.edu.au
Jonathan Binns, Australian Maritime College, Jonathan.binns@utas.edu.au
Zhi Leong, Australian Maritime College, zhi.leong@utas.edu.au
Hayden Marcollo, AMOG Consulting, hayden.marcollo@amog.consulting
Alex Skvortsov, Defence Science and Technology Group, Alex.Skvortsov@dst.defence.gov.au

ABSTRACT

The wake characteristics of cylindrical structures such as those protruding through the free surface from a submerged platform do alter substantially depending on the structure, geometrical properties, and operating parameters. The wake characteristics can be described by two major regions: above water and below water. Where the above water wakes are derivatives of the bow wave run-up on the leading face of the cylinder, and the below water wakes are derivatives of the ventilation, which is the entrapment of air of the rear face of the cylinder.

This paper presents an experimental programme in a towing tank to characterise the wake of cylindrical structures of different diameters and forward speeds. Conventional experiments have the model attached from above the surface, however, this method is not representative of some real-world applications such as structures that are bottom mounted. [To the best of our knowledge] The authors developed the novel design of a submerged test platform, where the model is cantilevered from a single connection point up through the water column. The experiments collected a range of results including the forces, motions and wakes of the models where this paper will focus on presenting and defining the different wakes and initial insights into these phenomena.

INTRODUCTION

Vertical cylinders in a multi-phase environment (i.e., air and water) differ to single phase environment (i.e., water only) due to the fluid structure interaction of the free-surface interface between air and water which results in wake generation and pressure/force differentials. The wakes are of interest due to the visual and acoustic noises which are readily identifiable.

The purpose of this investigation was to experimentally determine if the long-standing test methodology of towing a cylinder mounted from above the free-surface and penetrating down into the water column is comparable to the more realistic scenario of the cylinder being mounted from below the free-surface and projecting up and out of the water column.

This paper presents some of the preliminary findings of the experiments with a focus on the cylinder wakes.

WAKE DEFINITION

There are two major wake regions: above and below the free-surface. Within these two regions are several wakes. The magnitude of the wakes is dependent on the geometric property of diameter and the operating parameter of velocity. The other primary geometric property is the overall length which dictates the magnitude of the wakes. The overall length may be broken down into the submerged length and the in-air length, where the former is described as the non-dimensional parameter of aspect ratio (*AR* or *L*/*D*)

Above Free-Surface Wakes

There are several above surface wakes, which were initially defined by Hay [1] as shown in Figure 1. The most prevalent and discussed wake phenomenon was the bow wave (D_1) which forms on the forward directional face of the cylinder. The secondary bow wave spray (D_2) develops proportionally to the magnitude of the bow wave up to a transitory point whereby the proportional correlation to the bow wave separates.

The magnitude of the bow wave spray with respect to height and downstream length increase with the velocity, where they transition from being small in magnitude and proximity to the model, to a greater magnitude and minimal proximity to the model. The difference in the bow wave spray is depicted in Figure 1.

The rooster tail (D_3) is an artifice of the top-down method due to the presence of the free end-tip, which requires the model to be 'fully-ventilated'. Hay described the phenomenon of full ventilation and therefore the existence of the rooster tail occurring at a length defined Froude number of 3.

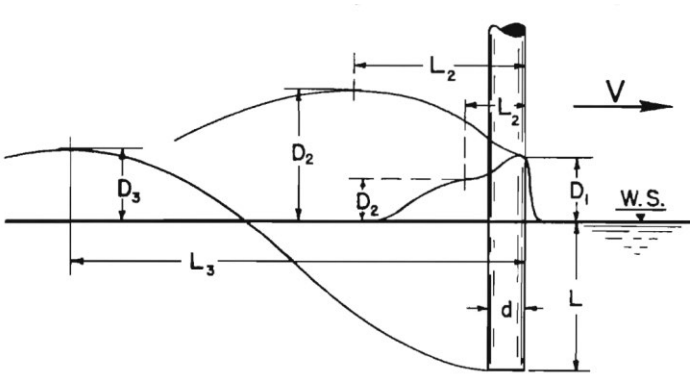


Figure 1: Above water wakes, after [1]

While the downstream heights and lengths of the wakes have previously been investigated and measured, there has been no work conducted on quantifying the width, as they are assumed to be derivatives of the separation angle and/or Kelvin wave theory.

Below Free-Surface Wake

The below free-surface wake, which is referred to as 'ventilation', 'ventilated wake/length/depth' or 'ventilated pocket'. Ventilation forms as a bluff body moves through a fluid whereby an air-pocket develops on the rear face of the body. As the velocity increases so too does the depth of the air-pocket. Figure 2 depicts ventilation, and Figure 3 describes the transition phases as noted by Hay [1] and defined by Thomsen [2]. As previously noted, the 'fully-ventilated' or 'base ventilation state' is the conditional requirement for the development of the rooster tail.

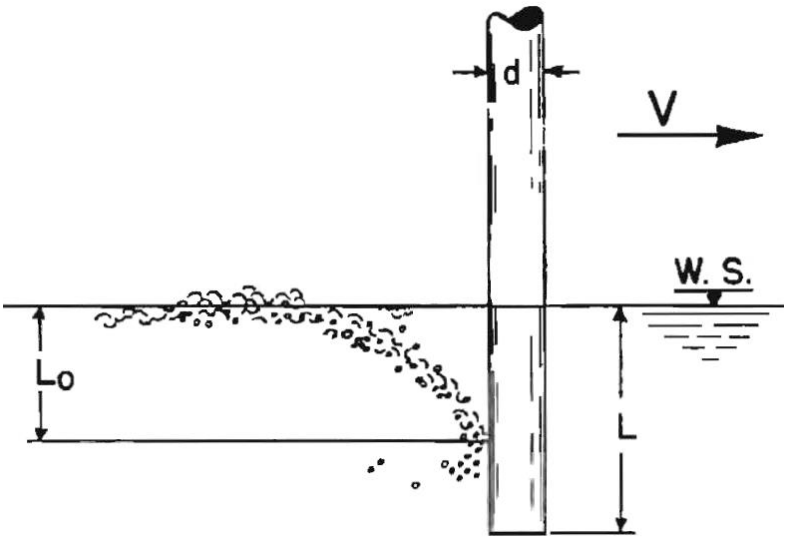


Figure 2: Below water wake – ventilation, after [1]

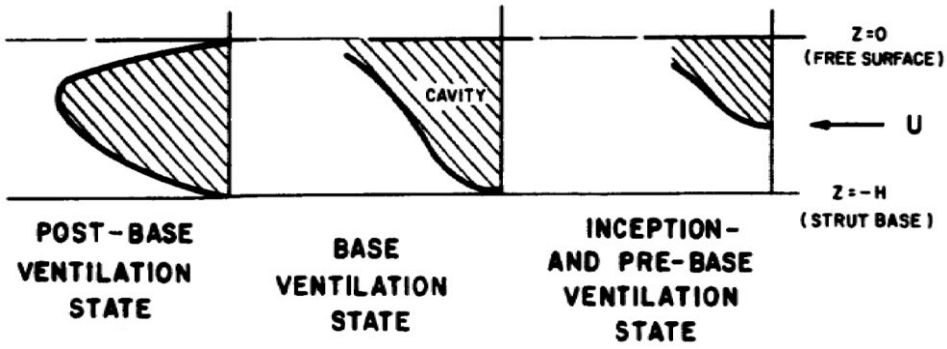


Figure 3: Transitory ventilation stages, after [2]

EXPERIMENTAL METHODS

The method in which experiments pertain to vertical cylinders exclusively consists of a finite length model being mounted above the free-surface and penetrating down into the water column with a submerged free end-tip. Experiments utilising the 'top-down' method have been conducted in flumes and towing tanks [1]–[9], where the scale and mounting method are the primary differing factors. Figure 4 presents the typical experimental arrangements for above-surface mounted cylinders from [1]–[9].

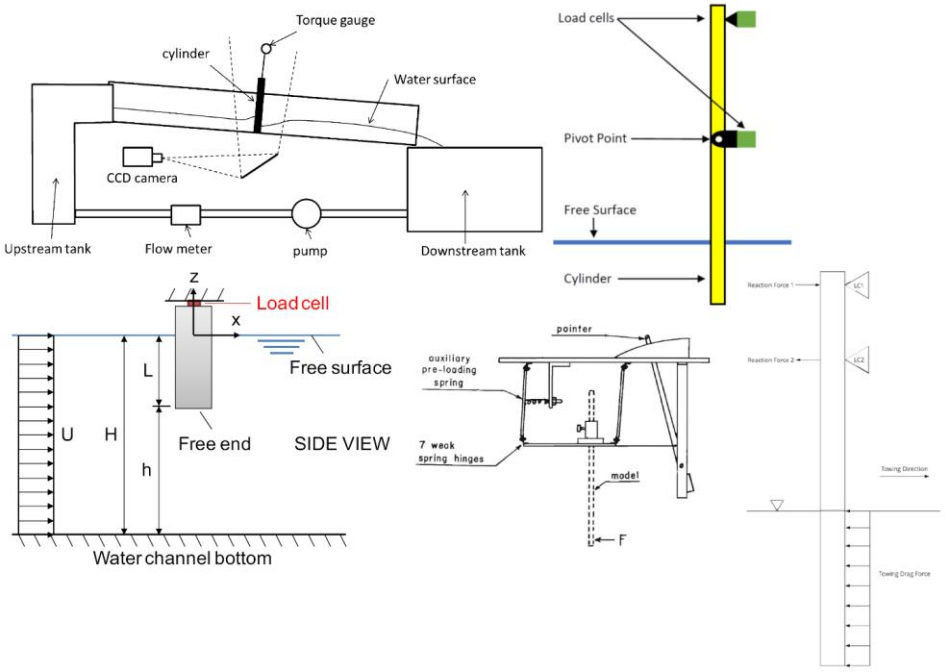


Figure 4:Above surface mounting for surface penetrating cylinder experiments

This investigation relates to a more representational scenario with the cylinder mounted below the free-surface and penetrating up through the water column. While this arrangement has been previously employed in flumes [10], [11], it has never been applied in a towing tank. Thus, the setup presented in this paper is the first of its kind. Similar to the top-down methodology, the 'bottom-up' method differs based on the facility in both scale and mounting setup.

TEST METHODOLOGY

The experimental investigation was undertaken at the Australian Maritime College Towing Tank. The testing arrangement consisted of a model cylinder being mounted on a submerged platform whereby the cylinder was cantilevered up through the free-surface as seen in Figure 5.

The design of the submerged platform was a large flat plat which traversed a rail system by way of wheel bearings. The platform was connected to the towing carriage by a 'strongback', which included a safety breakaway at the connection point. Each model was attached to a generic mounting plate, which in-turn was mounted to a 6DoF force transducer. Accelerations and therefore displacement motions were captured via an accelerometer mounted at the in-air free end-tip. The platform, rails, towing carriage connection point, and a test model may be seen in Figure 5.

The experimental programme consisted of several different diameter cylinders with a broad range of submerged aspect ratios and towing velocities. High speed cameras were used to capture both videos and stills of the wakes where the capture framerate varied from 20 to 160 FPS depending on the target wake and camera.



Figure 5: Submerged platform with model

RESULTS

A small sample of the data collected is shown herein. The specific testing arrangement for the shown images below is for a 76.1 mm OD cylinder with an aspect ratio of 10.

Figure 6 presents the geometric condition at a towing velocity of 2 m/s. At this point, the bow wave is becoming turbulent and breaking the surface tension, resulting in droplets being sprayed in all directions, and the bow wave spray height and length are still directly correlated to the bow wave height, as discussed previously.

The wakes depicted in Figure 7 are for the same condition noted above with a towing velocity of 4 m/s. The bow wave height is extremely turbulent with major fluctuations in magnitude due to the droplets interacting the with bow wave down the length of the cylinder resulting in the surface tension being altered. The bow wave spray is no longer derived from the bow wave due to the combined Froude number and surface tension effects, as noted by Figure 1.

The model for the described condition is seen to not be 'fully ventilated' as shown in Figure 8. At the maximum towing velocity, the cylinder remained in the "inception and pre-base ventilation state". From what is shown, it has been determined that ventilation has several characteristics:

1. Laminar flow stemming from the separation point
2. Cavitated ventilation
3. 3-Dimensional ventilation vortex sheets

Figure 9 presents a plan view of the model during a test run, where the width of the wakes may be determined, namely the bow wave spray and potentially the ventilation. As previously mentioned, the bow wave spray width has been assumed to be based on the separation point or Kelvin wave theory. The width of the above and below water wakes differ due to the alternate separation points.

Figure 10 presents the underwater side view of one of the test models where they are both deemed to be 'fully ventilated'. The ventilation effect differs vastly between the two methods with respect to the 'rooster tail' and the cavitated ventilation. As noted earlier the literature definition of the 'rooster tail' is solely an artifice of the mounting setup, where the free-end tip is.

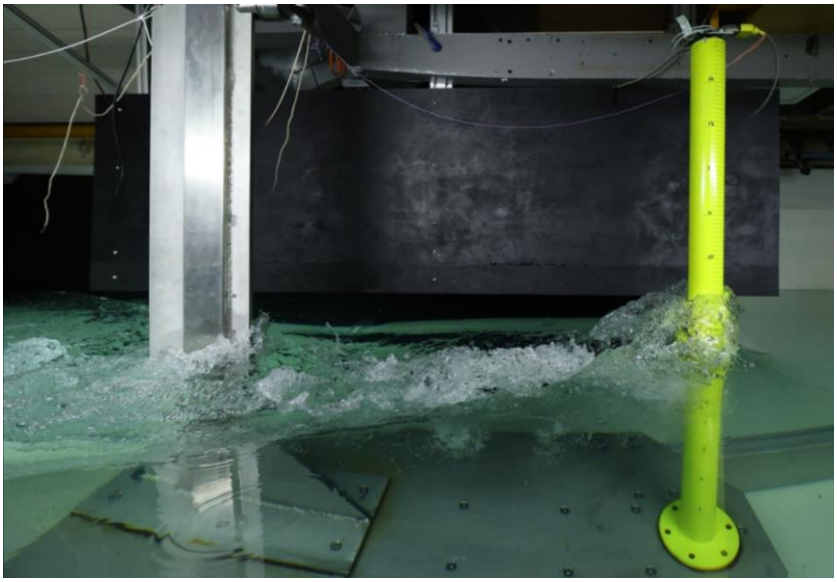


Figure 6: Above free surface side view of model cylinder, diameter = 76.1 mm, aspect ratio = 10, velocity = 2 m/s

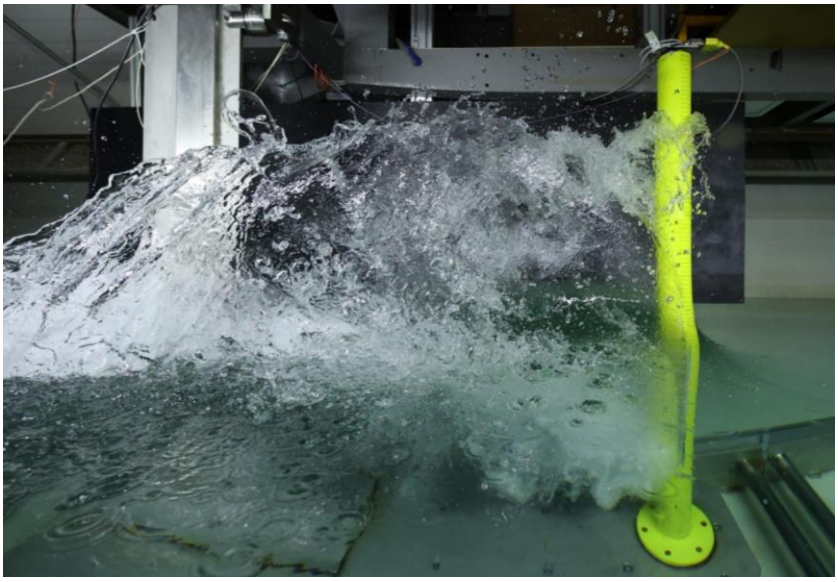


Figure 7: Above free surface side view of model cylinder, diameter = 76.1 mm, aspect ratio = 10, velocity = 4 m/s

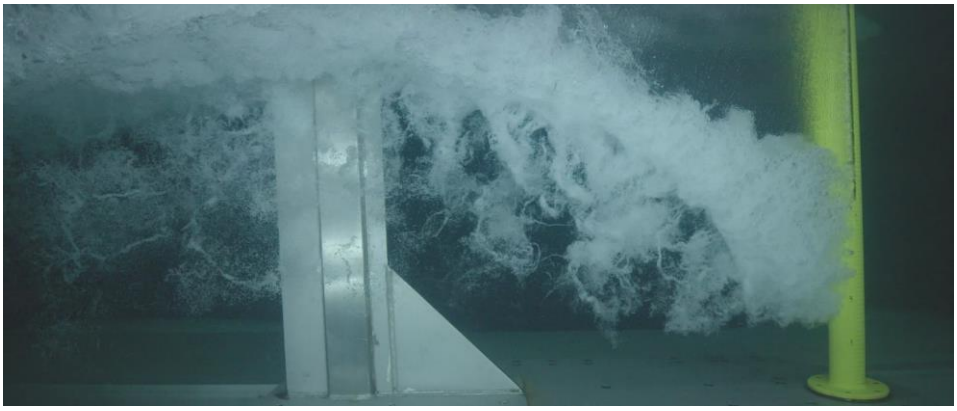


Figure 8: Below free surface side view of model cylinder, diameter = 76.1 mm, aspect ratio = 10, velocity = 4 m/s



Figure 9: Plan view of model cylinder, diameter = 76.1 mm, aspect ratio = 10, velocity = 4 m/s

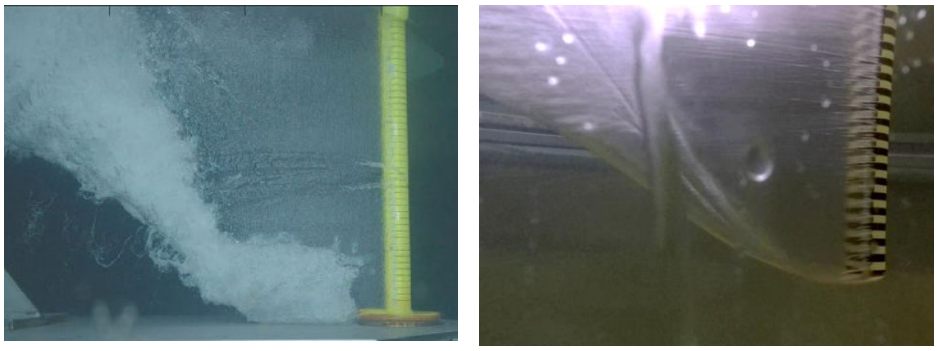


Figure 10: Side view of model cylinder, diameter = 48.3 mm, aspect ratio = 8, velocity = 4 m/s. Left: Current study, Right: Previous study [6]

CONCLUDING REMARKS

A novel submerged test platform that cantilevers a cylinder from a single connection point up through the water column for a towing tank is presented in this paper with preliminary results focusing on high-speed photography of the wake generated. The platform was successfully tested for speeds of up to 4 m/s, replicating the cylinder sizes and forward speeds of previous works that utilised a "top-down" rig that has the cylinder down through the free-surface instead, i.e. [1]–[9].

The results presented of a cylinder with a diameter of 76.1 mm is a subset of recent data measured using the submerged platform. The figures show high quality resolution of the different key characteristics of the wake structures including underwater photography of the ventilation phenomena which surpasses the resolution achieved in previous work, i.e., [1], [3], [6], [7], [12]. This demonstrates the capability of the submerged test platform with advanced high-speed photography and its potential to provide more detailed information of the wake structures of a free-surface piercing cylinder.

Further work is currently ongoing to compare the results of different cylinder sizes using the submerged platform against a previous experiment of the same cylinders which utilised a "top-down" rig across a range of speeds. The work includes comparisons in terms of forces and vibrations on the cylinders and the wake structures generated in order to identify the effects of the mounting approach and to provide further insight to the physics of free-surface piercing cylinders.

The forthcoming results coming from this large multi-stage project of work aims to develop appropriate baseline data that is essential for validation of numerical models that can be extended to real-world behaviour. These results will be presented in future published works.

ACKNOWLEDGEMENTS

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SESSION 15

Submarine Technology

Multi-phase brushless DC propulsion motors: dynamic modelling for platform integration studies

The sustainable submarine

Defence-industry collaboration for Australian collapse testing project

An end to submarine corrosion issues
Paper only - No presetation

Multi-phase Brushless DC Propulsion Motors: Dynamic Modelling for Platform Integration Studies

Kevin W. Sun and Hugh D. Torresan
Defence Science and Technology Group, Department of Defence, Australia
kevin.sun1@defence.gov.au, hugh.torresan@defence.gov.au

ABSTRACT

The uptake of electric propulsion systems for specialist maritime vessels has placed increased focus on optimised propulsion solutions, with high-performance electric motor design central to these efforts.

High-torque density, high-efficiency and significant fault redundancy characteristics provide ship builders with platform design flexibility, while improving safety and reducing operating costs.

The Multi-Phase Brushless DC propulsion motor combines the high fault-tolerant capability of multiple independent phase windings (+10) and distributed conversion, with the high efficiency, torque and power densities of a permanent magnet rotor. These advantages make them an ideal candidate for high performance propulsion applications in modern maritime platforms.

The adaption of any new technology onboard a maritime system comes with associated integration and technology risks. Multi-phase brushless DC machines are particularly challenging as techniques and methods to model and assess motors with +10 phases are, to date, not well established or widely used.

The Defence Science & Technology Group (DSTG) has developed novel modelling capabilities for multi-phase brushless DC machines and their distributed converters. The use of both dynamic modelling techniques, coupled with finite-element methods, allows the model to capture performance characteristics unique to high-phase number machines.

This paper presents the modelling capability in detail, and includes a case study demonstrating operation in a number of typical operational scenarios, including both phase-faulted and un-faulted states.

INTRODUCTION

The electric propulsion systems in maritime platform plays a critical role in the platform integration study in naval vessels. With the growing maturity of multi-phase brushless direct current (BLDC) motor technologies, their application in naval platforms offers a number of advantages over other motor types.

The multi-phase BLDC motor is a type of permanent magnet synchronous motor (PMSM) with high phase numbers and trapezoidal back-electromotive force (back-emf) voltage [1]. The multi-phase arrangement offers significant higher fault tolerant capability compared to conventional three-phase motors [2, 3, 4]. This improves the survivability and Safety of Life at Sea (SOLAS). The high phase number of the motor also reduces the torque ripple observed at the shaft and improves the efficiency of the naval platform.

The rotor of the multi-phase BLDC motor contains permanent magnets, which produces the magnetic excitation required [5]. This eliminates the need for rotor field induction, or separately excited field systems. The use of PMs afford several advantages over other machine types. By eliminating the need for supplying or inducing rotor currents, characteristics such as high power density, high efficiency, low maintenance and low torque ripple can be achieved [1].

Compared to traditional PMSM, which generally have sinusoidal back-emf. The BLDC motor has better utilization of the magnetic structure and allows higher power density to be achieved. This characteristic is advantageous in maritime applications.

The magnetic design of the BLDC motor stator and rotor dictates the operational capabilities of the electric machine. The magnetic design also produces machine parameters that are essential in the simulation modelling of the BLDC motor. In particular, the back-emf voltage, winding inductance and resistance are the critical electrical components that significantly determines the multi-phase BLDC motor performance capabilities [5].

MODELLING OF MULTI-PHASE BLDC MOTOR

The dynamic modelling of multi-phase BLDC motor is an important step in analysing the performance of the motor under different operating conditions. In order to obtain an accurate model representation of the multi-phase BLDC motor, a good understanding of the machine design is required. In the following sections, the key machine parameters are introduced. The electrical model of the multi-phase BLDC motor is then presented.

Figure 1 shows the cross-sectional diagram of a standard three-phase BLDC motor. As shown in the figures, the stator is the outer structure. The stator consists of slots which houses the windings. The rotor sits within the stator, with the PMs positioned on the surface of the rotor.

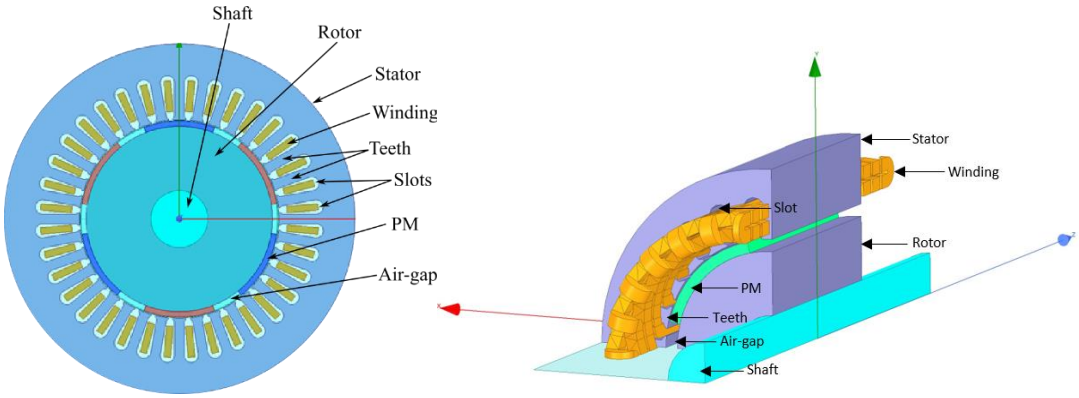


Figure 1 Cross-section of a BLDC

Figure 2 shows the electrical representation of a BLDC motor. The model has three main electrical components in series, a resistor, an inductor and a voltage source. The resistor R, represents the resistance in the stator windings and hence models the resistive losses introduced by the phase currents. The inductor L, represents the phase inductance that exists in the machine as a result of flux introduced by the stator coils. The voltage source E models the back-emf induced in the stator coil due to the rotor PM rotation. Out of the three components, the inductor and the back-emf voltage are most important parameters in the model, as they have significant influence on the torque performance and operating point of the motor. Furthermore, the values of the inductance and the back-emf voltage also require more computation due to the large number of design parameters.

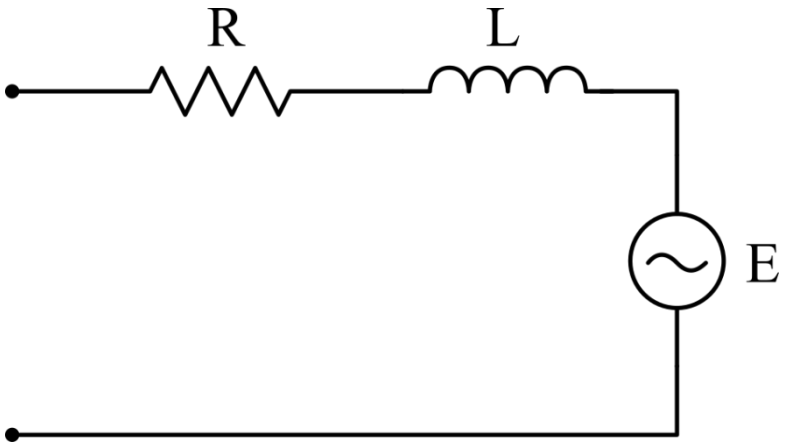


Figure 2 BLDC machine electrical model

The phase resistance in the BLDC motor is introduced by the stator coils. The resistance models the ohmic power loss in the winding, with I^2R, where I is the phase current. The phase coils are wound onto the stator to form the phase windings, introducing inductance to each phase of the motor. The modelling of inductance is fairly complex and computationally intensive, both analytically and numerically if finite element methods are used.

The phase inductance is made up of two main inductance components, which are self-inductance and mutual inductance. The self-inductance refers to the inductance generated purely from the current flowing in the individual coils. The mutual inductance refers to the

inductance generated from the coupling between phases as there are multiple phases wound around the stator slots each sharing the same ferromagnetic material.

The machine inductance helps to filter the harmonic rich outputs of the Pulse Width Modulated (PWM) converter. The current filtering capability is directly proportional to the leakage inductance. The inductor equation is given by:

$$\boldsymbol{V_L = L\frac{di}{dt}} \qquad (1)$$

where V_L is the inductor voltage and $\frac{di}{dt}$ can be interpreted as the current ripple. If no additional filter inductors are introduced, the leakage inductance of the machine determines the inductance in equation (1).

Equation (1) shows that the current ripple is inversely proportional to the inductance. That is, the larger the inductance, the smaller the current ripple. Both the fundamental current and the current ripple act to generate torque, while the current ripple produces torque ripple which generate noise and vibration.

The motor inductance is generally represented in the form of an inductance matrix [6]. The inductance matrix for a machine is always a square matrix, where the diagonal elements represents the self-inductance, L_s, and all other elements represent the mutual inductance, L_M. An example of an inductance matrix for a three-phase BLDC motor is shown in equation (2).

$$\mathbb{L}_{3\boldsymbol{\phi}} = \begin{bmatrix} \boldsymbol{L_s} & \boldsymbol{L_M} & \boldsymbol{L_M} \\ \boldsymbol{L_M} & \boldsymbol{L_s} & \boldsymbol{L_M} \\ \boldsymbol{L_M} & \boldsymbol{L_M} & \boldsymbol{L_s} \end{bmatrix} \qquad (2)$$

In order to accurately model higher phase number motors, the inductance matrix needs to be expanded to $n \times n$ to accommodate higher phase number BLDC motors and winding arrangements, where n is the number of phases of the motor.

The back-emf voltage in a multi-phase BLDC machine is induced when the rotating magnetic field from the rotor's PMs results in magnetic flux change in the motor's stator windings. The shape and magnitude of the back-emf is dependent on multiple factors including rotor-speed, permanent magnet arrangement, stator winding layout, and details of the rotor and stator magnetic circuit design amongst others. The back-emf voltage is commonly modelled as:

$$E = K_e \omega_r \qquad (3)$$

Where ω_r is the rotor speed and K_e is the back-emf constant. This shows that back-emf is linearly proportional to rotational speed.

Figure 3 shows a realistic back-emf voltage profile of a BLDC motor obtained from a finite element analysis (FEA). As shown, the voltage profile resembles a trapezoid, however the corners of the voltage waveform are rounded due to the continuous nature of magnetic fields. As the back-emf voltage and phase current directly influence the torque produced by the BLDC motor, the back-emf voltage needs to be modelled with high fidelity, which allows the optimum phase current required to be determined and injected.

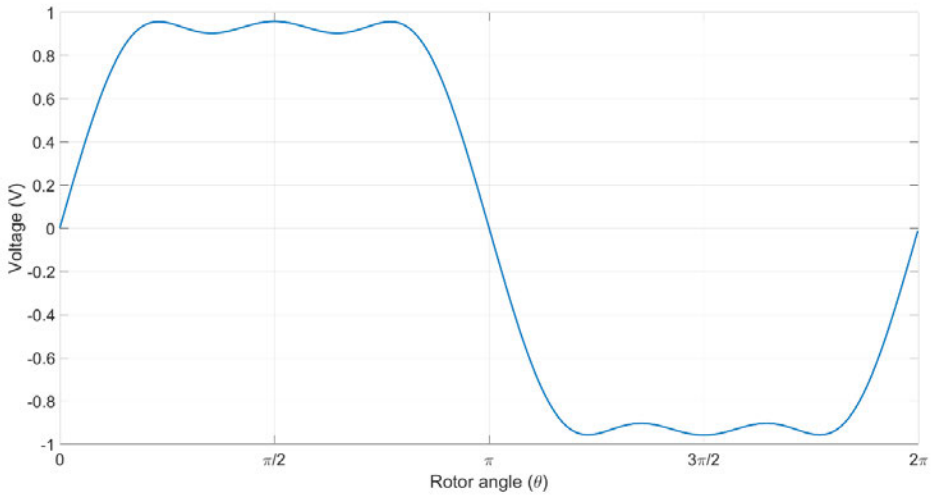


Figure 3 Realistic back-emf voltage of BLDC motor from FEA

TORQUE PRODUCTION

The torque produced from a BLDC motor can be determined from the electric model shown in Figure 2. The component that is used to represent the electromechanical conversion is the back-emf voltage. Therefore, the power absorbed by the voltage source in Figure 2 represents the output power of the machine. For example a three-phase BLDC motor, the torque can be calculated with the sum of the power from all three-phases, that's is:

$$\boldsymbol{\tau_e = \frac{1}{\omega_r}(e_a i_a + e_b i_b + e_c i_c)} \tag{4}$$

The electromagnetic torque can be convert to rotor speed with:

$$\boldsymbol{\frac{d}{dt}\omega_r = \frac{1}{J}(\tau_e - \tau_l - B_{damp}\omega_r)} \tag{5}$$

where J is the moment of inertia of the rotor, τ_l is the load torque and B_{damp} is the damping coefficient. Lastly, the rotor speed can be determined from:

$$\boldsymbol{\omega_r = \int \frac{1}{J}(\tau_e - \tau_l - B_{damp}\omega_r)} \tag{6}$$

MULTI-PHASE BLDC ELECTRICAL MODEL

Figure 4 shows a block diagram of the electrical model used for the multi-phase BLDC motor. The multi-phase BLDC motor electrical model block which can be scaled to any number of phases, is derived from the single phase electrical model shown in Figure 2. The differences are that the inductors are mutually coupled. Moreover, the back-emf voltage is also dependent on the rotor angle and the rotor speed. Therefore, the multi-phase model requires inputs of rotor angle, rotor speed and the terminal voltages that is driving the BLDC motor.

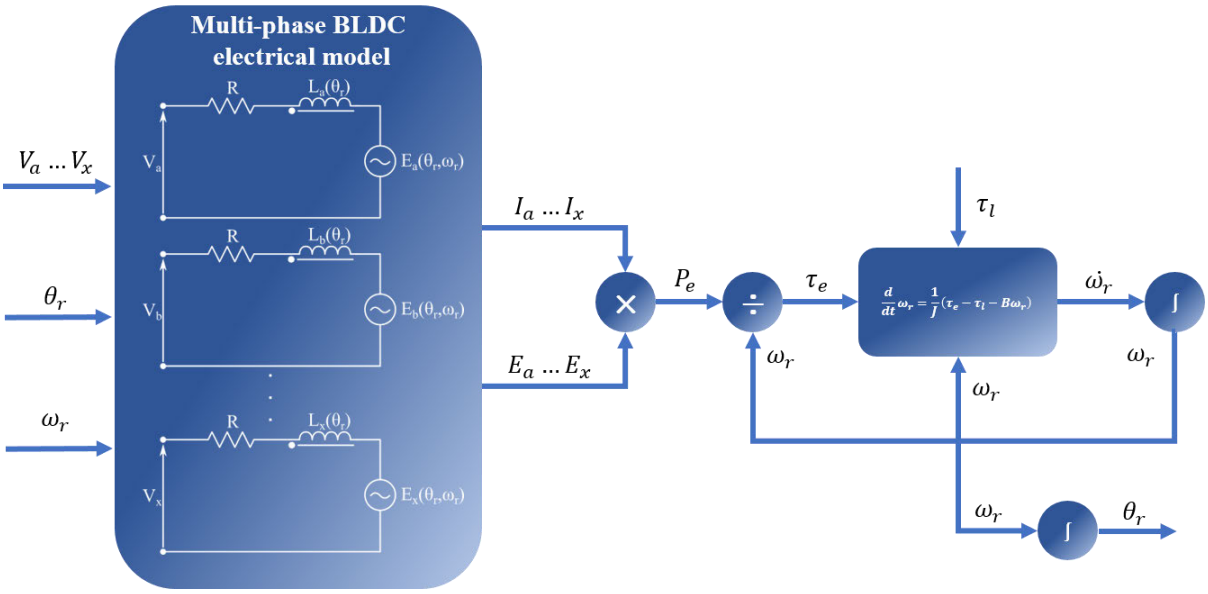


Figure 4 Multi-phase electrical model block diagram

POWER CONVERTER MODELLING

The power converter is responsible for synthesising the AC voltage required from DC voltage to control the multi-phase BLDC motor.

Modern power converters are semiconductor based devices that utilises switching to obtain required output voltages and currents. They have advantages such as high efficiency and high power density compared to traditional linear power converters [7].

One of the inherent issues with switching power converter is the generation of switching harmonics and ripple in output current. In motor drive applications, this creates problems such as torque ripple and Electromagnetic Interference (EMI). The modulation and topology of the power converter mainly controls the quality of the output content. The most common topology used in the single-phase applications is the two-level H-bridge converter.

Figure 5 shows a single-phase two-level H-bridge converter. The topology consists of 4 switching devices and a dc-link capacitor. Depending on the state of the switching devices in the H-bridge converter, the output voltage of the H-bridge converter can be either $+V_{dc}$, $-V_{dc}$ or 0.

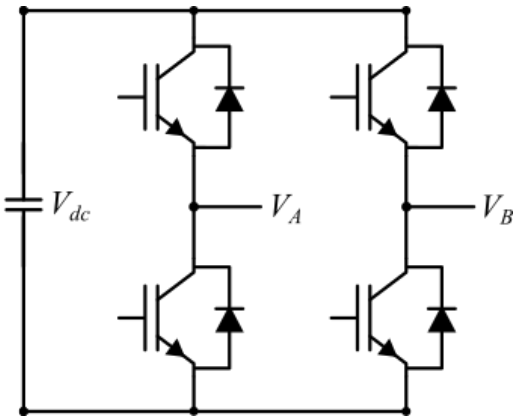


Figure 5 Single-phase H-bridge converter

Figure 6 shows a single-phase 3-level NPC converter. Unlike the H-bridge, the NPC converter consists of four switching devices per phase leg. There are also two series connected capacitors on the dc-link which share the total dc-link voltage approximately equally. This topology allows for five voltage levels to be synthesised at the terminals [3], i.e. $+V_{dc}$ $+\frac{V_{dc}}{2}$, 0, $-\frac{V_{dc}}{2}$ and $-V_{dc}$, as opposed to the three levels from the H-bridge. These additional levels enable the NPC topology to better approximate reference waveforms than the H-bridge, resulting in superior harmonic performance when tracking reference waveforms.

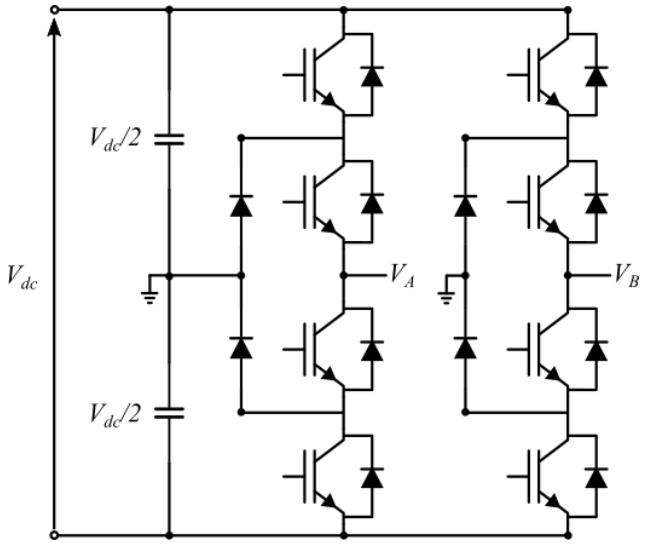


Figure 6 Single phase NPC converter

CONTROL OF MULTI-PHASE BLDC MOTOR

The speed control of BLDC motor can be achieved with a nested control loop structure, where the outer control loop calculates the phase currents that are required to achieve the desired speed and the inner calculates the converter voltage required to achieve the phase currents demanded by the outer loop. Figure 7 shows an example of the control structure. The speed Proportional-Integral (PI) controller calculates required phase currents, $i_{ref}[n]$ from the measured speed ω_{mea} and the desired speed ω_{ref}, where n denotes the phase index. The desired phase current $i_{ref}[n]$ is square-wave in nature and in phase with the back-emf

voltage as discussed in previous section. The desired phase current $i_{ref}[n]$ is then used to determine the reference voltage $v_{ref}[n]$ to obtain the desired current. The reference voltage is then converted to PWM signals through the PWM modulator and used to control the power converter.

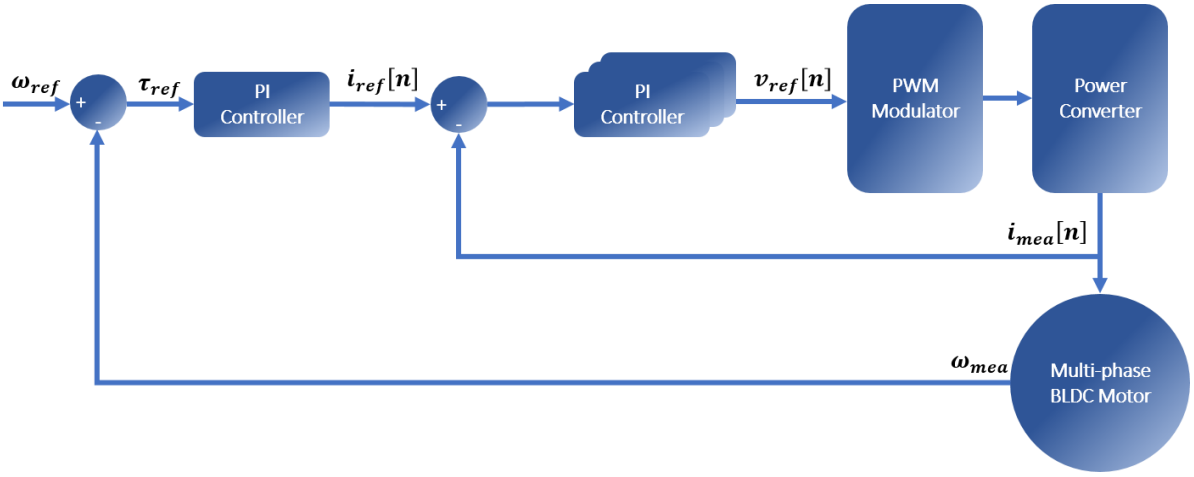


Figure 7 Multi-phase BLDC motor control block diagram

SIMULATION STUDY OF THE MULTI-PHASE BLDC MOTOR

A fictitious 11-phase BLDC motor was designed and developed in simulation to demonstrate the modelling technique presented. The appropriate control technique and power converters (both H-bridge and NPC) were implemented. The motor and power converter parameters were based on information obtained from existing open source literature.

Figure 8 shows the rotor speed performance of the 11-phase BLDC motor with a speed reference of 200RPM. The result show that the rotor speed can be effective accelerated to the desired speed reference over a time duration of 10 seconds.

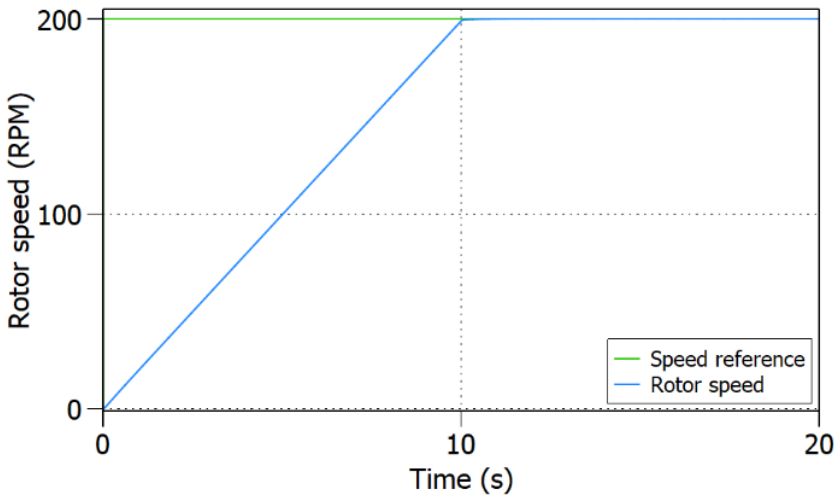


Figure 8 Rotor speed vs. speed reference (2-level H-bridge)

Figure 9 shows the phase A current versus phase A back-emf voltage. As discussed in previous sections, the back-emf voltage of a BLDC motor is trapezoidal. To achieve the most optimal torque performance, the phase current needs to be in phase and have the same shape profile as the back-emf voltage. This can be observed in the result.

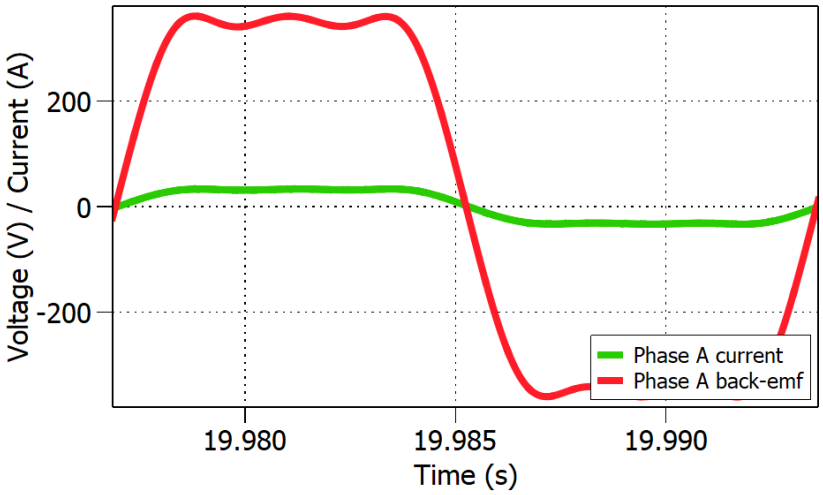


Figure 9 Phase current vs. back-emf voltage (2-level H-bridge)

Figure 10 shows the electromagnetic torque output of the motor. The torque ramps up as the rotor speed increases and maintains when the reference speed was reached. Some torque ripple can be observed due to the power converter switching action.

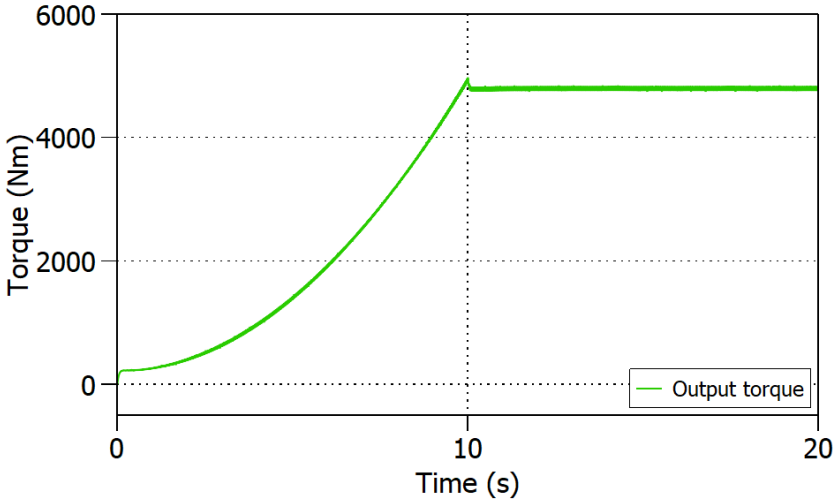


Figure 10 Electromagnetic torque (2-level H-bridge)

Figure 11 shows the comparison between the torque ripple performance obtained from a 2-level H-bridge converter and a 3-level NPC converter. As expected, the NPC converter produces less torque ripple due to the additional voltage level the converter can synthesis.

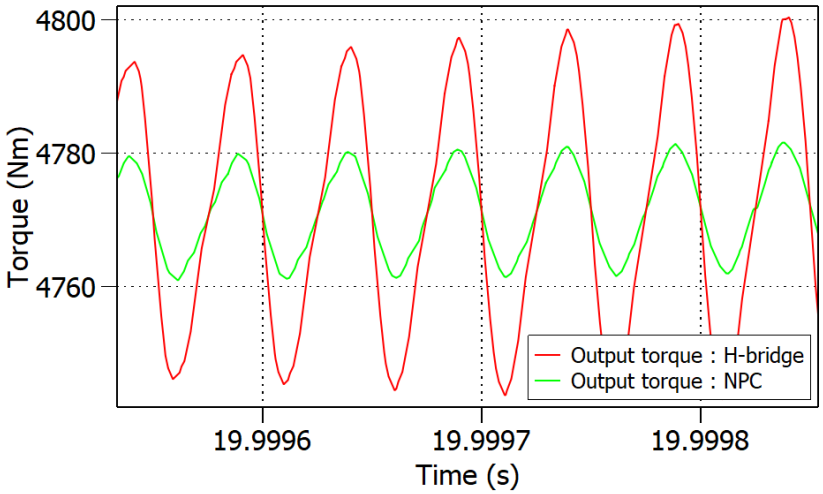


Figure 11 Torque ripple comparison between H-bridge and NPC

CONCLUSION

A multi-phase BLDC motor electrical model was developed to analyse the dynamic performance capabilities of the motor for the integration study in naval platforms. An appropriate motor drive consisting of the power converters and controllers was also developed to operate the exemplar 11-phase BLDC motor model. The model motor and drive system allows the analyses of dynamic mechanical performance such as speed and torque/torque ripple. The model also provides the ability to study different motor control techniques and operation modes. Lastly, the model allows the study of power converter operations.

The multi-phase BLDC motor model requires motor parameters that are derived from either analytical estimation, finite element analysis or experimental data. However, the latter two methods produces parameters of higher accuracies.

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Unlocking the Potential of Sustainable Submarine Design

A Harris, BMT, Australia and L Hammock, BMT, UK

SUMMARY

Submarines are designed for a service life of more than 25 years and therefore they need to be designed to meet the needs of tomorrow as well as today. This not only means a flexible operational capability but also implies increased importance should be placed on areas such as sustainability and climate resilience in design. Although submarines, through low signature requirements, often present a lower environmental footprint than their larger ship counterparts there is still a considerable concerted effort required to ensure the platform is environmentally sustainable, throughout its entire life: from concept to end of life disposal. This paper will explore the key drivers and factors behind environmental sustainability in submarine design, with examples demonstrating how sustainable principles may be used to improve the environmental impact of the platform, without compromising the mission and whilst improving performance. The paper will also discuss the role of teamwork in achieving this goal, including how designers, customers, shipyards and suppliers can all work together to maximise the benefits of a sustainable submarine design.

1. INTRODUCTION

Authors' note: This paper was originally presented at RINA WARSHIP 2021: Future Technologies in Naval Submarines. It has been revised to consider aspects of submarine sustainability pertinent to the life cycles of Australian submarines.

The term 'sustainability' is increasingly used but can have differing interpretations. The United Nations (UN) Bruntland Commission Report, (UN, 1987), defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs.".

Focusing in on Environmental Sustainability; it is more than simply Environmental Protection. There are various technologies available to reduce a platform's immediate impact upon the environment, however, to be Environmentally Sustainable the designer must assess the environmental impact over the whole lifecycle.

2. SUSTAINABILITY IN DEFENCE

An important consideration for Defence activities and assets is the ability to remain operationally effective. But this can be achieved in synergy with environmental sustainability. In fact, following a sustainable approach to asset design, procurement, operation, and disposal, can also provide opportunities for improvements and more efficient operation throughout the platform lifecycle.

Environmental sustainability policy for the Royal Australian Navy (RAN) is overseen by the Office of the Defence Seaworthiness Regulator (ODSwR). In the Defence Seaworthiness Management System Manual (Australian Government DoD, 2018), the Capability Manager is identified as responsible for ensuring that the Operational and Support Intent (OSI) covers all "hazards the maritime mission system might create for the environment (through areas of operation, operating doctrine, etc)".

Climate change is one domain which has, and will continue to have, an impact on the way that Defence, as a whole, protects, operates and fights. All sectors of Defence have a part to play in reducing the contribution to climate change and biodiversity loss.

3. APPLYING STATUTORY LEGISLATION TO SUBMARINES

National and international legislation applied to civilian shipping has been developed based upon civil operational assumption and ship arrangement. The International Convention on the Prevention of Pollution from Ships (MARPOL, IMO, 1983) and the International Convention on the Safety of Life At Sea (SOLAS, IMO, 1974) are largely prescriptive. Designing to prescriptive criteria can degrade military capability if no account is taken for instance of different operating philosophies. This is recognised by the IMO in the applicability text at the introduction to each convention, noting that they do not apply to warships. Instead, a goal-based approach can be adopted, allowing compliance arguments to be constructed rather than testing a design against prescriptive "checklist" items. The potential benefits of a goal-based approach were discussed by Polglaze (INEC, 2018). The different risk profile of a naval vessel should be considered, for instance when considering Escape and Evacuation, and the influence of Damage Control and Fire Fighting on potential abandonment.

Recognising this issue the International Naval Safety Association (INSA) produced ANEP-77, the Naval Ship Code (NATO, 2019), developed as a method of demonstrating equivalence with SOLAS for naval vessels. It is now accompanied by ANEP-102, the Naval Submarine Code. The codes are goal-based, and where prescriptive elements are unavoidable or desirable, these have been developed specifically for naval vessels. INSA is currently working with its membership to expand the scope of the codes to cover aspects of MARPOL compliance.

The Naval Ship and Naval Submarine Codes may have the potential to be adopted by national naval Flag Administrations in future as a method of demonstrating equivalence with MARPOL for submarines.

4. ASSET LIFECYCLE

The asset lifecycle is considered to follow the path of Strategy and Concepts, Risk Mitigation and Requirements Setting, Acquisition and In-service and Disposal, known as the Capability Life Cycle (CLC). Using this lifecycle framework allows the designer to assess and minimise the overall impact upon the environment. It applies equally to equipment, systems, and platforms.

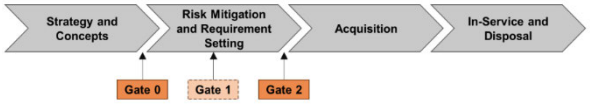


Figure 1 – The Defence Capability Life Cycle, reproduced from the Australian Defence Force Capability Life Cycle Manual v2.1, 2020

By undertaking an impact assessment early in the lifecycle, the full environmental impact of the platform can be understood and mitigated. The impacts of the production, transportation and disposal aspects of a programme are often overlooked yet may be designed-out during the early phases and by reassessing throughout the lifecycle, rather than attempting to remedy the impacts of equipment or platforms once in service. By starting with the end in mind, the design of the platform may be optimised throughout its life.

An impact assessment can be conducted at key milestones throughout the design process (for example, at design reviews and when a key design change is made), to assess the impact of the platform at each phase of its lifecycle. The cost of designing in mitigations at the front-end is almost always lower, and simpler, than attempting to rectify later. Refrigerant systems are a good example of this. The 2014 EU F-Gas Regulation (517/2014) controls the use and emissions of F-Gases. Hydrofluorocarbons (HFCs) will be phased down in the UK, to achieve a reduction of 79% by 2030, compared with average use between 2009 – 2012, with similar reductions to apply in Australia. Systems and equipment suitable for lower Global Warming Potential (GWP) refrigerants can be significantly different from those used in previous designs and can be complex and expensive to retrofit. Given the length of the life cycle of a platform, consideration should be given to the likely availability of preferred refrigerants during the platform's life, in order to design out issues of obsolescence, or increased cost, at a later stage. It may be reasonably assumed that some of the common refrigerants being used today with higher GWP will be phased out during the lifecycle of a platform. This can lead to increased operating costs during the phase out period, before the refrigerant becomes unavailable. The financial and environmental costs of retrofitting a different system during the platform's life must be considered at the front-end of the Capability Life Cycle, to allow the designer to investigate alternative refrigerants and systems, to future-proof the design.

Many designers are now considering ammonia and CO2 as viable alternatives to higher GWP refrigerants. Ammonia and CO2 have inherent safety hazards, however these hazards may be mitigated early in the platform design phase, making these options feasible. When selecting these options, it is important to investigate the supply chain of the ammonia or CO2: historically, the production of ammonia involved high temperatures and pressures, and was a very energy intensive process. The traditional Haber-Bosch method of producing ammonia is estimated to contribute around 1% of global Greenhouse Gas (GHG) emissions (Brown, 2016). However, greener methods of ammonia production are in development, which could improve its overall carbon footprint and make it a more sustainable product, as well as having a lower direct environmental impact.

Similar supply chain analysis should be undertaken when considering any system design or design change: including future fuel selections. Working closely with suppliers and shipyards to reduce the environmental impact throughout the supply and production chains, the further reaching environmental impact of the platform may be reduced.

5. WATER TREATMENT STREAMS

There are elements that the designer might consider when designing systems, to enable the end user to operate the platform in a more environmentally sustainable manner, during the in-service part of the platform lifecycle. Bilge management is one area where good operating practices may be encouraged through the design of the system. There are two types of bilge water that accumulates on ships and submarines: clean and oily.

Discharge of oily water is regulated under MARPOL Annex I (IMO, 1983). Bilge water with an oil content greater than 15 parts per million (ppm) shall not be discharged overboard. From a mission perspective, a submarine could also be compromised by oil sheen on the water surface, by discharge overboard of bilge water with oil content. Therefore, effective bilge management is important on a submarine from the perspectives of both environmental sustainability and operational sustainability.

Designing for a dry bilge concept, for example, involves the piping designer routeing clean drainages directly into small collecting tanks in the bilge. Designing this in from the start means that the contents of these small tanks are guaranteed to be oil free and so there is no risk of compromise to the environment or the mission when discharged.

The designer will have increased options available for treatment or storage solutions because a lesser volume of bilge water with potential oil content will remain.

6. WASTE NOT WANT NOT

Another example of using the design process to instil sustainable practises during the in-service phase, is reducing wasted energy.

When designing exothermic processes, designers should consider the possibilities of harnessing waste heat. Waste heat recovery systems do not have to be large and, when designed in from an early stage, may be easily integrated into a compact system design. Waste heat may be used for various applications such as heating of water or spaces. This careful use of energy is particularly applicable to diesel powered submarines. In addition to energy recovery, a mindset to reduce energy consumption on board is also important. The responsibility for sustainable submarine operations belongs to everyone on board, as well as the design and procurement teams. Switching off lights and non-essential equipment will help in the overall energy savings. Energy consumption reduction strategies in operation are also beneficial for the mission, as well as the environment: operational sustainability and environmental sustainability often work together.

For the designer: low energy equipment may be designed in. Low energy lighting, reduced flow shower heads, low flush toilets and treated grey water reuse on board for non-potable purposes are all ways to design in a manner that encourages environmentally sustainable operations in-service. By designing sustainably from the front-end, improvements to the maintainability of equipment and therefore operations are often also improved.

The incorporation of equipment with low energy consumption need not be limited to newly designed submarines. There is potential to reduce energy usage throughout the in-service phase of the CLC, especially when dealing with equipment obsolescence in an aging class of submarines. The planned Life-of-Type Extension (LoTE) for the Collins Class Submarines will provide the RAN with such an opportunity.

7. STARTING WITH THE END IN MIND

An important, yet often overlooked, part of the lifecycle is disposal. Disposal impacts are evident throughout the life of the platform. There are operational wastes generated from product or equipment packaging and waste generated by personnel. Waste is produced during design changes, when older equipment is removed, and in the packaging of new equipment to replace it. Finally, waste is generated at the end of the platform lifecycle, when the platform and its assets are removed from service.

Operational waste can be significantly reduced through careful analysis of the supply chain and working closely with suppliers. Increasing numbers of production companies are now looking at their impacts on the environment and to sustainable production. Many are finding ways to reduce the volumes of packaging used and to use recyclable packaging. Selecting suppliers with sustainability credentials, and working together with suppliers and manufacturers to maintain and improve these credentials, will reduce the waste associated with the platform.

Operational waste should always be separated to allow recycling when disposed of ashore. But the responsibility does not end there: the waste contractor should also be carefully selected for their ‘green’ credentials, to ensure that the waste generated by the platform will be handled in a sustainable manner.

There are some inherently difficult wastes generated on board a platform, which are difficult to store safely during a mission. Food waste and, where women are present on board, sanitary waste present a health hazard if stored incorrectly.

Storage of solid waste is one area where the reduction of environmental impact may have an impact on platform size and cost. Collins Class Submarines were introduced into service with a Garbage Ejector system, in which waste was compressed, canned and air-ejected from the submarine. The ejection process was a transient noise source, increasing detectability, as well as no longer being compliant with MARPOL, so there is an operational benefit in this change. Conversely, now that the Garbage Ejectors are no longer used, the volume required to store waste has had to be found from within the existing envelope of the submarine's pressure hull. In a new design submarine, by assessing the volumes and types of waste anticipated, at an early design phase, and through the careful selection of the most appropriate equipment for the type and volume of waste, sufficient space may be allocated from the outset to provide an appropriate solution. The penalty of storing waste is increased non-operational space use resulting in a fractionally larger submarine overall. It is useful for designers to understand these differences when comparing older, smaller classes of submarine with their larger modern equivalents.

When considered from the initial design phase, there are several solutions to a reduced waste production which help to mitigate the size increase which produce an inert, compact by-product for standard storage and landing ashore. More recent waste handling technologies are compact and quiet: making them potential candidates for use on submarines.

Submarine endurance is a key driver of operational effectiveness, and waste storage may be a limiting factor. By considering the whole life-cycle of waste on the platform: i.e. reducing the packaging of consumables to allow more stores, processing the waste in a way to safely minimise its stored volume onboard; it may be possible to extend patrol length.

Ultimate disposal of the platform and onboard equipment should be considered throughout the entire CLC of the platform. Whether equipment is being procured in the design phase or as a design change part way through the life of the platform, consideration should be given to how the materials will be handled at the platform or equipment end of life.

As well as designing for reduced waste and reusable or recyclable materials, the impact of waste should also be considered. Whilst toxic materials are inherently restricted onboard a submarine, some materials are hazardous to the environment, or require energy intensive processes to recycle or dispose of them. By avoiding the use of such materials, the overall environmental footprint of the platform is improved. Where the use of these materials cannot be avoided, they must be documented, along with volumes and locations, and a plan put in place for handling their disposal.

The security aspects of components and equipment should also be considered at the design phase to ensure that any security restrictions upon recycling / reuse are included in the disposal plan. Creating a disposal plan at an early point in the design phase, and maintaining the plan throughout the lifecycle, will ensure a clear picture of waste management and reduce the amount of waste consigned to disposal processes.

8. CONSIDERATIONS FOR NUCLEAR-POWERED SUBMARINES

In September 2021 Australia announced that it would, in collaboration with the UK and the US, commence studies to acquire at least eight nuclear-powered submarines (under the AUKUS security partnership). A Nuclear-Powered Submarine Task Force (NPSTF) has been established to determine how to achieve this. The NPSTF runs for 18 months from September 2021.

Considering the whole lifecycle provides a wider understanding of the ‘hidden’ environmental impact of nuclear power: the mining and processing of uranium and the radioactive waste handling should be considered when assessing the overall environmental impact of the platform.

Energy management is also still a relevant consideration for nuclear-powered submarines. Whilst nuclear energy is often considered to be ‘clean’ and ‘free’ in environmental terms, it should still be used mindfully. When using energy on board a submarine, the overall environmental ‘cost’ per unit of energy should be kept in mind. The energy built into a fuelled reactor is finite and Australian nuclear-powered submarines will not be refuelled (Department of Defence factsheet "Nuclear Stewardship", 2022). Excessive consumption of the reactor's Effective Full-Power Hours (EFPH) could therefore have a detrimental effect on the overall service life of the platform.

Disposal of nuclear submarines is an issue which requires consideration from the outset of the program. The UK and US have separate waste streams for spent nuclear fuel, reactors, and submarine hulls. The UK Ministry of Defence's Submarine Dismantling Project (SDP) illustrates the protracted timescales and high project workload associated with safe disposal and regulatory approvals. HMS *Dreadnought*, the UK's first SSN, was launched in 1960 and remains maintained afloat with her reactor in situ in 2022, in common with all ex-RN nuclear submarines. The first dismantling of an ex-RN nuclear-powered submarine (HMS *Valiant*) is planned to commence in 2023 (Naval Technology, 2022). The US Navy has dismantled, or is in the process of dismantling, about 147 of its decommissioned nuclear-powered surface ships and submarines in its Ship/Submarine Recycling Program (SRP). All ex-US Navy reactors are dry stored at the Hanford Nuclear Reservation, Richland, Washington, awaiting eventual burial.

The NPSTF includes a Nuclear Stewardship work stream. Nuclear Stewardship is defined as "the responsible planning, operation, application and management of nuclear material, technology and facilities" (Department of Defence, 2022). In its work to establish a regulatory and licensing framework for the naval nuclear enterprise, the NPSTF can consider disposal of nuclear-powered submarines now; to start with the end in mind.

9. CONCLUSIONS

Environmental Sustainability involves a holistic view of the platform across its lifecycle. It is about a mindset shift in the design, operation and disposal of a submarine. There are many systems and equipment available to reduce the environmental impact of a platform. However, often these options are not practicable for installation on board a submarine, due to space constraints, noise restrictions, weight considerations, power requirements and atmospheric conditions. By using sustainability principles from an early stage in the design process, elements of the platform requiring environmental impact mitigation can be reduced by design, resulting in a greater selection of environmental protection equipment, more suitable to the submarine environment.

Nuclear-powered submarines present special challenges to environmental sustainability. Evolving regulation and experience internationally, within the UK and the US affords opportunity to Australia to address disposal and dismantling in a sustainable manner.

Applying sustainability principles further, across the entire lifecycle of the platform, it is possible to reduce the environmental impact of a submarine, without compromising its mission capability. Indeed, in many of the examples cited in this paper, implementing sustainability practices at the front-end of the design process is also beneficial to operational effectiveness.

8. ACKNOWLEDGEMENTS

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Defence-Industry collaboration for Australian collapse testing project

Authors: Bernard Phelps (DST Group, Bernard.phelps@dst.defence.gov.au),
Hamidreza Yeganeh (JFD Global, H.Yeganeh@jfdglobal.com),
Steve McFall (SteelStruct Engineering, Steve.McFall@steelstruct.com.au),
Luke Howell (RM Surveys, Luke.Howell@rmsurveys.com.au),
David Scholtz (Wood Plc, david.scholtz@woodplc.com),
Adam Smith, (DST Ggroup, Adam.smith@dst.defence.gov.au)

INTRODUCTION

The Department of Defence through the Defence Science and Technology Group (DSTG) is undertaking a large-scale experimental program known as the DSTG Pressure-hull Collapse Testing Project (CTP). Since the release of the 2009 Defence White Paper [1], successive governments have been committed to the replacement of the RAN's Collins Class Submarine fleet and to the principle of Defence self-reliance. The development and conduct of the CTP is to address the risks and issues in acquiring, operating and maintaining the RAN's submarine fleet into the future.

The ability of the pressure-hull to withstand external pressure is critical for the safe operation of submarines, and so access to reliable and accurate assessment methods is essential. These assessment methods also need to be independent of the origins of the pressure hull design to enable independent design assurance. Available methods range from relatively simple analytical formulae to detailed numerical finite element analysis (FEA) and so vary in their theoretical approach, complexity, accuracy and the level of user expertise required. They are also strongly dependent on the level of information available on the design and condition of the pressure-hull at the time.

The purpose of the CTP is to obtain experimental data for the verification and validation (V&V) of DSTG software tools and analysis procedures for prediction of pressure-hull collapse. The CTP is being procured by DSTG through a four-year commercial contract with JFD Australia (JFD) and involves a significant number of subcontractors across Australia and in the UK. This paper provides an overview of the development of the CTP, details of the key activities undertaken to date, and a summary of key expected outcomes.

PROJECT BACKGROUND

The CTP involves the design, construction, measurement, monitoring, and testing to collapse of three ring-stiffened cylinders, of approximately 1.8 metres diameter and between five and seven metres in length. The conduct of large-scale collapse tests is an uncommon event generally, and tests of this size have not previously been attempted by Defence. A request for tender (RFT) for the supply of the CTP [2] was released in September 2018 and was structured to enable collective or separate provision of a number of identified "Key Services" that were

needed to be procured to complete and achieve the goals of the CTP. The scope of the CTP contract deliverables includes: project management, design review, detail design and fabrication of cylinders, end-closures, transport cradles and pallets, cylinder design review, surface finishing, dimensional measurements, materials testing, collapse test monitoring, hydrostatic pressure testing, post-test storage and final disposal of test items.

A total of 16 tenders were received, from within Australia and overseas, and these were reviewed and assessed by three separate working groups across DSTG and Defence Capability and Sustainment Group (CASG). The contract for supply of the CTP was subsequently awarded to JFD, with responsibility for overall project management coordination and delivery, with the supply of other "Key Services" being procured through subcontracts.

As there is no test facility within Australia that is able to undertake collapse testing of cylinders of the size and arrangement of the CTP test cylinders, they are being tested in the United Kingdom. Installation of the strain gauges is to be completed in Bristol, before transporting by road to Aberdeen, Scotland for connection of the test monitoring system and conduct of collapse tests.

PROJECT MANAGEMENT

JFD was awarded the contract for the delivery of the CTP in August 2019, and the project team was on-boarded in October to manage the project from Bibra Lake office in Perth. A project manager, a project coordinator and a lead engineer are dedicated to the CTP project to plan, organize and direct the project across three fabrication sites in Australia including Newcastle (JFD Cowan), Melbourne (APVH), and Perth (Steelstruct Engineering). On completion of the fabrication, the items are being shipped in inter-modal containers to the UK for collapse testing.

Overall, 30 different and predominately Australian, subcontractors are involved in CTP to provide design, procurement, manufacturing, transportation and testing works. The project execution started once the conceptual design (scantling drawings) was issued by DSTG and the project team were on-boarded. In the design phase, the detail drawings were developed, and the suitability of the design independently investigated through standard calculations and FEA. In addition, to minimise the risk of rework, all design information was assessed through engineering gate-reviews and formal design review sessions. A major factor during this phase, was to review previous relevant projects and utilising their lessons learned to ensure the CTP benefited from these projects and the knowledge was transferred to project team. As a result, the integrity of drawings, fabrication methodology and the collapse testing process were improved significantly.

One of the major project goals was to utilise the maximum capacity of Australian resources. The project team made significant effort to understand what Australian companies could contribute to the project. For example, procurement of the 80mm plate and forming to make

the semi-elliptical end-closures was one of the challenges that the project team encountered to keep this part of the work in Australia. Initially, it seemed that the steel should be supplied and cold pressed from outside of Australia as there is no locally produced plate of the required specifications, and no place to cold-form such thick plate in Australia. Fortunately, the project team managed to keep this part of work in Australia through negotiation with steel manufacturer Blue Scope to produce suitable 80mm plates. Also, instead of cold forming, the project team then located a suitable mould in APVH that could be used manufacture the end-closures through hot forming process.

The CTP cylinders are built with deliberate shape imperfections and are intended to be effectively destroyed during testing, which presented a significant project challenge. The design requirements and specified tolerances are not consistent with normal industry standard approach for pressure vessel fabrication. There is little-to-no industry records or practices that can be used for reference, so manufacturing processes need to be adapted and special processes implemented to achieve the desired shape and tolerances. These requirements must be passed onto all subcontractors to ensure consistency. Close oversight was needed to ensure that design and production errors were avoided and that out-of-tolerance issues were corrected in a timely manner and did not the impact the overall project.

CYLINDER DESIGN

The three test cylinders are designed by DSTG with the intention that failure should occur in an overall-collapse mode, at a gauge pressure of less than 7 MPa. The design of the three cylinders, shown schematically in Figure 1, is nominally identical, apart from variation in the length-to-diameter (L:D) ratio. This is achieved through increasing the number of frames in the second and third cylinders, while holding the other dimensions constant. The three cylinders are designated, in increasing length, as AUS1, AUS2 and AUS3 respectively. The ends of each cylinder are designated as End A or AFT, and End B or FWD, with the reference origin on the centerline at End A and positive towards End B.

The cylinders are fabricated from steel plates with a nominal yield stress 500 MPa. Each cylinder is fitted with a heavy end-flanges to provide rigid end restraint and for the attachment of end-closures that are used to seal the cylinders during testing. End-closures are semi-elliptical, are designed to be reusable and have numerous fittings provided for plumbing, sensor cables and access to inside the cylinders. Extensive material testing and dimensional measurements are conducted throughout the fabrication, to ensure the cylinders remain within acceptable tolerances and to provide high fidelity information for finite element analysis of the “as-built” cylinders.

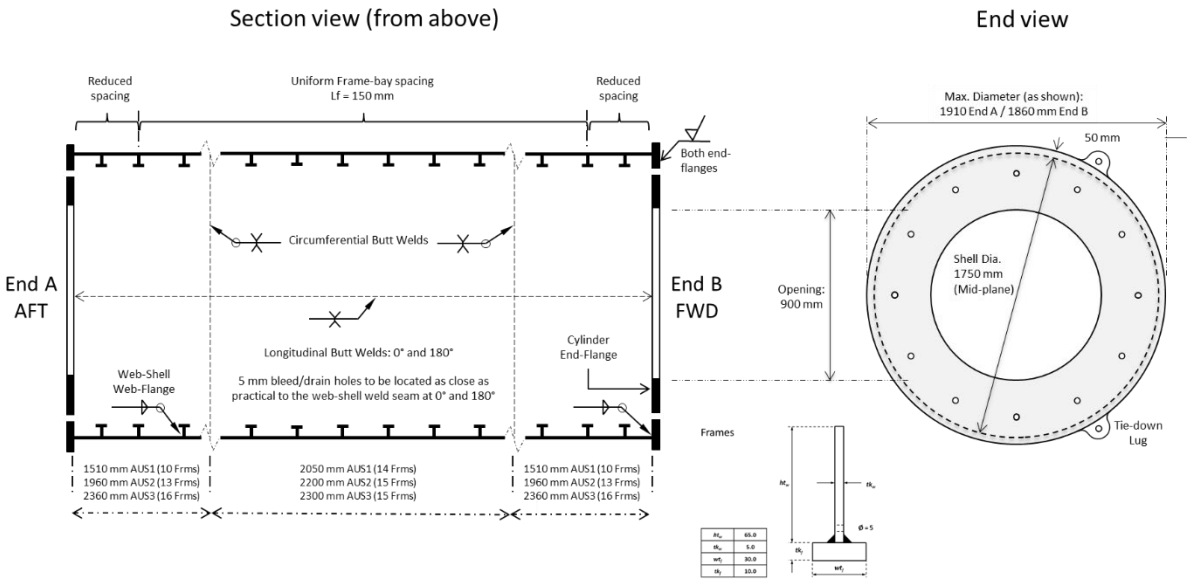


Figure 1. Schematic of the cylinder arrangement and scantling dimensions of the three CTP test cylinders

Although the cylinders are subject to tight build tolerances, in contrast to normal industrial practice, the cylinders are being built with a deliberate out-of-circularity (OOC) shape imposed. This is being done to test the worst-case scenario allowed by typical pressure-hull design rules (e.g. [3]). The OOC deviation has an n=2 mode shape with an amplitude of 0.5% of the mean, as-built radius and is mathematically defined by Equation 1.

$$\delta = a_0 . r_m . \sin(n\phi - \mu) \qquad \text{Equation 1}$$

where:

δ = deviation from the mean circle

a_0 = deviation amplitude = 0.5% of nominal radius (4.375 mm)

r_m = mean, mid-plane radius = 875 mm

n = OOC deviation mode shape = 2

ϕ = angle around the circumference from 0° (in radians)

μ = phase offset angle = $\pi/2$

In pressure vessels subjected to external pressure, shape imperfections have an adverse effect on the collapse strength of the hull compared to the ideal, geometrically perfect vessel. Imperfections such as OOC and frame-tilt are unavoidably introduced during fabrication and the effects must be considered in the design. The OOC imperfections are considered as the most critical of the shape imperfections as bending stress arising from the OOC is additive to direct axisymmetric (hoop) stress in the extreme fibres of the frame flange and attached shell plating [4]. This is particularly important for overall collapse where failure occurs through the onset of material yield in the frame.

The design and analysis of the three test cylinders has been undertaken using a number of methods, including semi-empirical analytical, elasto-plastic finite difference and nonlinear (NL) FEA. Collapse pressure predictions vary depending on analysis method, analysis stage and the specific cylinder. Generally, the elasto-plastic method provides the most conservative estimates, whilst the NL-FEA results generally indicate the highest pressures, so are considered as the upper-bound limits. Predictions for AUS1 across all three approaches are that collapse will occur in the range of 5.5 MPa to 7.0 MPa. The final as-built NL-FEA calculations are to be completed prior to the collapse test and are expected to provide the most accurate prediction of the collapse pressure.

CYLINDER FABRICATION

Welded fabrication of the CTP cylinders to within the required tolerances is considered to be one of the most difficult technical challenges of the CTP. The cylinder fabrication work was subcontracted to Steelstruct Engineering for all three cylinders, as well as the fabrication of end-flanges and completion of end-closures after the heads had been hot-formed. Steelstruct Engineering is a privately owned Western Australian company providing steel fabrication, hard-facing and precision machining services to Australia's mining and resource markets.

As shown in Figure 1, the cylinders are made up of three separate *cans* that are themselves fabricated from a number of ring-frames and two half-shells. Each frame is made up of three, 120°-arc web pieces and a flange that is rolled from a single strip of plating. The number of frames and dimensional tolerances for the CTP cylinders are unusual compared to typical pressure vessel manufacture, and the imposition of a deliberate OOC shape posed special considerations. Additionally, specific plates were allocated by DSTG to specific regions of each test cylinder, based on their strength and average thickness.

To test the production techniques that were best suited to achieving the required OOC shape, Steelstruct Engineering constructed two, full-diameter, but reduced length, trial *cans*. These were laser scanned by RM Surveys at various stages to establish the level to which the shape changed, particularly the OOC, during the fabrication. In seeking to achieve a final OOC shape as close as possible to the required mode and 0.5% OOC amplitude, the cut shape of the webs has an n = 2 mode shape, but with reduced amplitude to allow for the further distortion that is introduced during the longitudinal seam welding. The shell halves and frame flanges were rolled to suit the cut profile of the webs.



Figure 2 Frame welding jig in operation

A good deal of effort and innovation was required to achieve the tight fabrication tolerances. CNC-machined-profile collapsible jigs, were constructed to assist during both assembly and welding processes of the internal frames to achieve the OOC required. The frame welding jig held the frame web and flange pieces in position for initial tack-welding, and was mounted in a large rotator and turned at constant speed to complete the web to flange welds. This enables very precise control of welding speed and heat input, and results in very uniform weld profiles and tight control of weld distortion. A photograph of the frame welding jig being used for welding of the frame flange to web is shown in Figure 2.

Due to the long length and narrowness of the strips of plate to be used for the frame flanges, control of distortion during the cutting process was needed to ensure the frame tolerances were able to be achieved. The initial cutting of the flanges, left intermittent stitches between strips to restrict distortion during the cutting process. The strips were also cut to be slightly over-width, and when separated they were clamped together in groups and machined to the correct width. This resulted in very precise control of the shape of the flanges along their 5 m length.

The longitudinal seam welds between the two half-shells for each *can* is a significant source of local shape distortion that acts to pull in the shell along the seam. Welding of the internal frames to the shell also influences the shape outcome. An internal jig, shown in Figure 3 was fabricated to apply individually, adjustable loading to the frames during welding to the shell and of the shell longitudinal seams to minimise the distortion. Weld direction and order was also strictly controlled to counteract the pull in from the longitudinal seams.



Figure 3. Adjustable loading jig used to minimise inwards distortion from welding

Joining of the *cans* required that the shell plate be accurately aligned all the way around the circumference. This would typically be achieved using plate dogs and wedges, but the removal of temporary welds and parent metal associated with this technique could potentially affect

test outcomes. To avoid the use of welded attachments, hydraulic rams were staged off the internal frame structure was used to align the *cans* for welding.

END-CLOSURE DESIGN AND FABRICATION

The design of the end-closures and cylinder end-flanges was subcontracted to Wood Plc and the fabrication was, in the main, by Steelstruct Engineering. The end-closures are to be reused for each of the three tests, whilst there are separate end-flanges for each cylinder. To ensure there was no risk of end-closure failure, it was designed according to industry standards ASME VIII Division 2, Part 5 [5], with reference to AS 1210 [6] where applicable. Additionally, the specified design loads were marginally in excess of that which could be experienced during testing. The key design loads are pressure (12 MPa external and 0.3 MPa internal) and lifting and hoisting loads. A combination of analytical and FEA calculations were undertaken for the design assessments, which included specific evaluation for end-closures, end-flanges, hatches and other penetrations, pad-eyes, O-ring seals, bolts and nuts. Special attention was given to limiting stresses and distortion of the end flange and adjacent shell end-bays and stiffeners to avoid premature end bay failure.

The two end-closures differ only in that one (End A) has a number for penetrations (nozzles) incorporated to allow piping and sensor cables to cross the test assembly boundary. Both end-closures have a plug-type hatch to provide access to the inside of the cylinders. An exploded view of the End A closure arrangement and end-flanges is shown in Figure 4. A total of 15 cable nozzles are provide; 12 are required for AUS1 and three additional are to permit additional sensors to be used for AUS2 and AUS3 cylinder tests if needed.

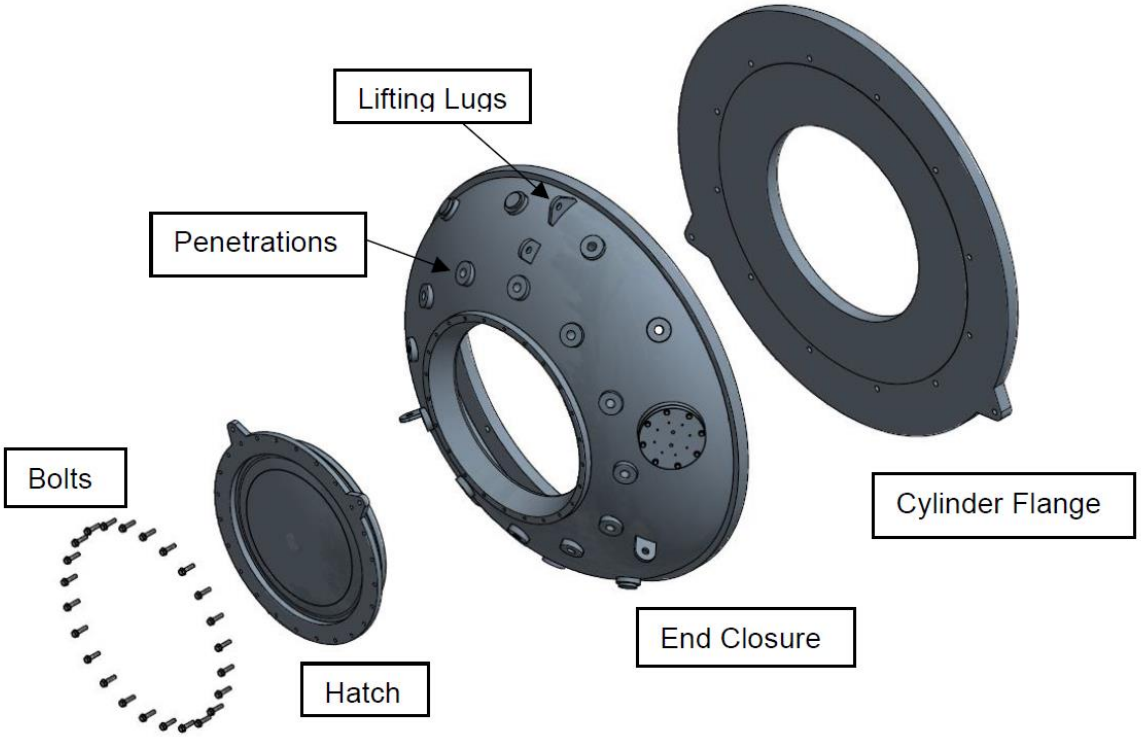


Figure 4. Exploded View of End-A Closure and Cylinder Flange

The fabrication of the end-closures commenced with hot-forming of two, 80 mm thick, steel blanks into semi-ellipsoid dome heads by APVH. The steel blanks were heated in a furnace at 900°C to 1000°C for around four hours, before being placed over the mould and pressed to the required shape (Figure 5), a process that took approximately two minutes to complete. Hot-forming of the heads resulted in some thinning of the material to approximately 68 mm, which was within the design limits of the end-closures. Although the forming press was around 100 years old, the forming was of sufficient accuracy that no further work, such as machining, was required to achieve the shape tolerances for the heads. The formed heads were trucked to Steelstruct Engineering for completion of the end-closures, such as trimming, boring and welding of nozzles, flanges and hatch seating.



Figure 5. End-closure head forming at APVH

DIMENSIONAL MEASUREMENT

The dimensional measurements for the CTP are subcontracted to Western Australian company RM Surveys Pty Ltd., Australia's first NATA accredited dimensional control provider. RM Surveys provide a wide range of survey and inspection services, including precise laser measurement.

The CTP measurements are all undertaken using laser tracker, laser scanning and touch probe measurements, and are processed with SpatialAnalyzer software [7]. The core element of the measuring system is the Hexagon Absolute 8525-7 Articulated Arm Coordinate Measuring Machine (AACMM) with an integrated RS5 red-light laser line scanner (shown in Figure 6).



Figure 6. Hexagon Absolute Arm with RS5 laser scanner and touch probe set up to confirm frame position being fitted-up to a shell-half

The AACMM has a working volume diameter of approximately 2.5m, so to scan an entire can or cylinder the scanner must be moved to different locations, using a network of control points to coordinate measurements. The control points consist of three-point nests, affixed to the structure to locate either a 38.1mm diameter probe on the AACMM or a 38.1mm spherically mounted retroreflector (SMR), as shown in Figure 7.



Figure 7. Three-point control nests; empty (centre), with seated SMR (left), and with touch-probe (right).

The control point's coordinate is recorded at the center of the sphere, meaning an equivalent point can be measured with the laser tracker (SMR) or AACMM (probe). For smaller cans, a network of these control points can be coordinated on the cylinder using the AACMM and probe, but for large cans and completed cylinders the points are coordinated using an API Radian Plus or Leica AT401 Laser Tracker and SMR, with resulting coordinate uncertainties (1σ) typically <0.05mm.

The laser scanner measurements result in the collection of a large number of 3D data point coordinates (i.e. X,Y,Z) that is referred to as a "point cloud", typically with an accuracy of 0.028mm. Expected absolute accuracy of scanned points is <0.1mm. The scan data is used to generate discrete points at nodes required for generation of FEA models by DSTG. This is achieved by extracting and averaging all scan points within a specified distance of a vector defining the desired node. The procedure to process cloud data and resolve measurement

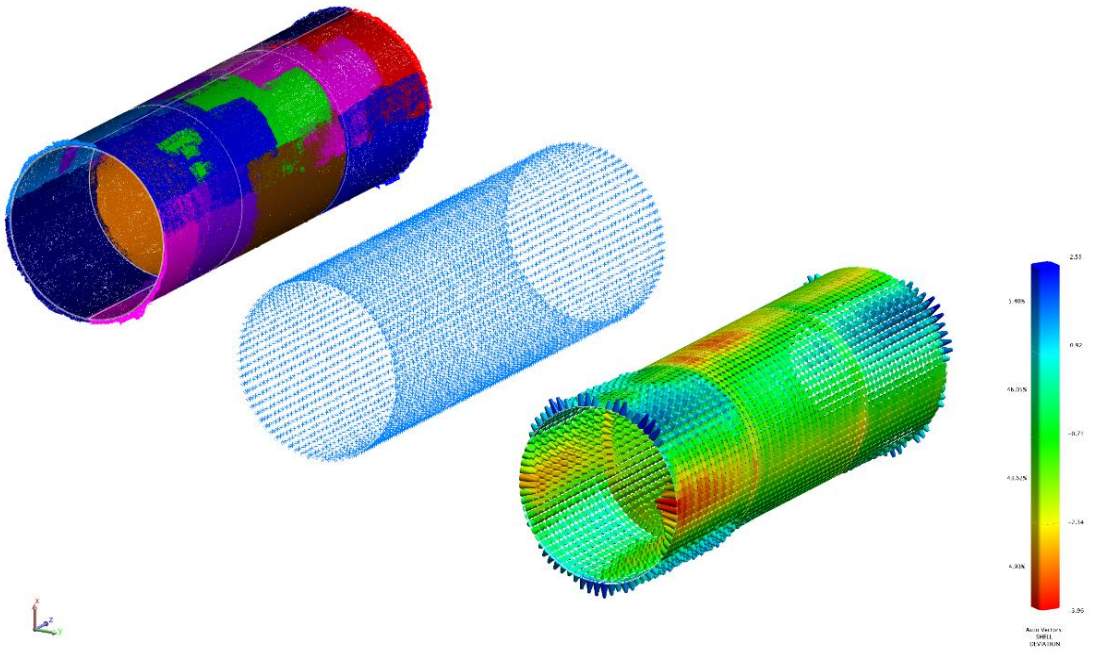


Figure 8. Raw laser scan data of AUS1 outside surface (left), resolved OOC measurement nodes (center) and vectors showing deviation from design model (right)

nodes was partially automated in SpatialAnalyzer using the program's measurement plan scripting environment, and different stages are depicted in Figure 8.

In addition to providing data for DSTG's FEA models, the as-built data was fed back to Steelstruct Engineering to;

- Inform refinements to the fabrication process
- Monitor dimensional changes during fabrication
- Compute accurate masses and centres of gravity
- Verify compliance of critical items, such as the end closure sealing faces as shown in Figure 9.

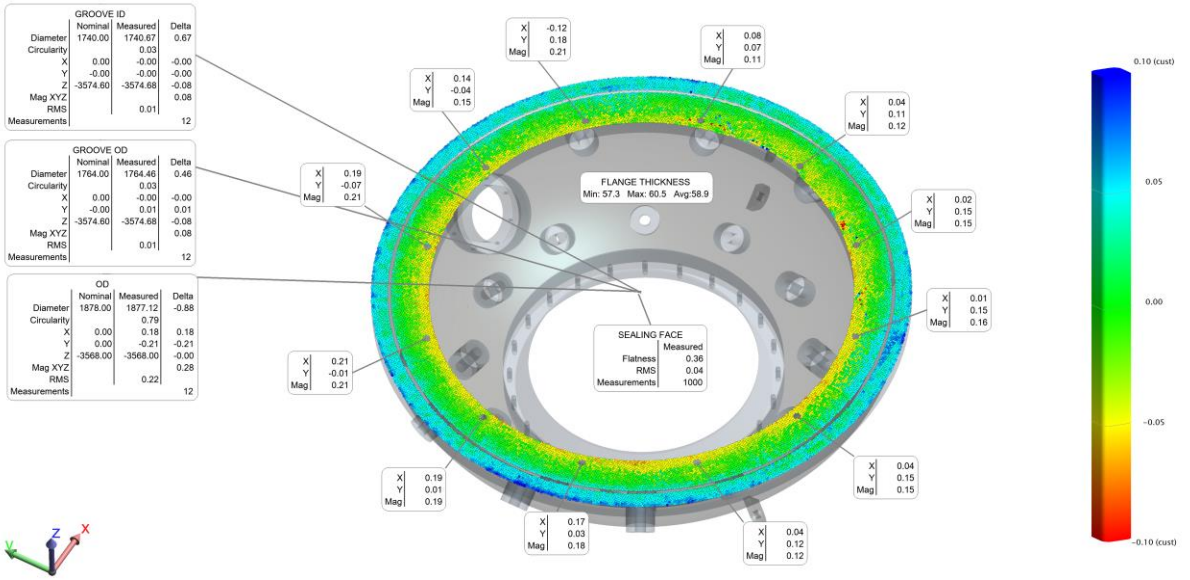


Figure 9. Laser scan survey heat map of machined surface on end-closure

One of the most significant sources of error in dimensional measurement is thermal expansion and contraction [8]. For a metallic object the size of the CTP cylinders this could significant, so is compensated by the SpatialAnalyzer software through use of a calibrated scale bar of the same material as the cylinder. A reference temperature of 20°C is used for all measurements.

TRANSPORT SYSTEMS

Safe transport of the precisely constructed cylinders from the fabrication site (Perth, Australia) to the collapse pressure testing facility site (Aberdeen, UK) is a significant project undertaking. To ensure that the cylinder dimensions and geometry is unchanged during transit, a robust cradle is required for each cylinder. A bespoke cradle design, based on JFD's road and sea transportations series, is used to protect the cylinder from any potential damage, including corrosion and damage to highly machined surfaces. Similarly, two steel pallets are designed and manufactured for the cylinder end-closures to protect them from any damage during transportations. Both transport cradle and pallets are shown in Figure 10.

Standard ISO shipping containers will be used to transport each fabricated cylinder through road and sea from fabrication site in Perth to collapse testing facility in Aberdeen.



Figure 10. Cylinder AUS1 transport cradle (LHS) and end-closure pallets (RHS) being prepared for shipping

Several key design features of the transport cradles and pallets are highlighted.

- Cradles are designed to accommodate the total length of cylinder without contacting the cylinder shell. This means the cylinder end-flanges are the only contact points when the cylinder loaded to the cradle.
- Longitudinal movement during transit is a key transport risk. Therefore, both a stopper mechanism and tie-down slings are included to restrain the cylinder from sliding.
- Vertical and lateral movements during transit are other identified risks. Tie down lugs are fitted to the cradles to the cylinder end-flanges to restrain movements in both directions.
- The suitability of the design of the cylinder transport cradle and end-closure pallets () are determined through classical beam theory and FEA.
- Stresses and deflections were assessed for two scenarios with the cradle and pallets lifted by 4-point lift or forklift and included relevant duty and hoisting factors. All maximum individual member equivalent stress and deflections were found acceptable and within the limits.
- Cradles are designed to accommodate changes in shape of the cylinders as a result of the collapse tests, as the cylinders are being shipped back to Australia after testing.

TEST MONITORING

Reliable strain and pressure monitoring is essential for the success of the CTP. If sensors or other elements of the monitoring system fail during the tests, then the value of the test is reduced or potentially lost altogether. The responsibility for development, installation and operation of the monitoring system was subcontracted to James Fisher Strainstall. The company has vast experience in strain monitoring across a wide range of applications and environments, as well as having conducted a number of similar tests in the preceding decade.

The CTP specification calls for up to 200 individual strain gauges with a total of 320 strain sensor channels and six pressure transducers; options are provided if this needs to be increased for AUS2 and AUS3 tests. The strain gauges are only installed on the inside of the cylinder as this is the area of most interest with overall collapse being initiated through frame failure, and it also reduces the risk of accidental damage. The pressure transducers are provided to measure pressure within the test cylinder and the hydrostatic pressure chamber and are situated on pipe tapings. Strain gauges are not fitted to all frames, rather gauges are concentrated to areas of most interest such as: frames closest to amidships, near transverse weld seams where slight alignment adjustments may have pre-stress the shell plating, and at the end-bays adjacent to the end-flanges where high stresses are known to occur under external hydrostatic pressure [4]. The gauges are distributed around frames and frame-bays near peak OOC deviations where maximum strains are expected to occur.

Strain gauges are all Vishay 350 ohm general purpose strain gauges with either axial or biaxial configuration. Gauges are wired in a common, three-wire quarter bridge configuration and are connected to junction boxes that are located on the End A cylinder flange. A total of 12 off multicore subsea cables, accommodating 27 strain gauge channels per cable are used. The cables are 36m in length and are manufactured by CRE in Aberdeen specifically for CTP project. As depicted in Figure 11, cables are routed from the junction boxes, through the End A end-closure back into the pressure chamber and then out again through penetration plates to the data acquisition system. The HBM MGCplus [9] data acquisition system and Catman DAQ [10] software is used to acquire strain gauge and pressure data during the collapse tests.

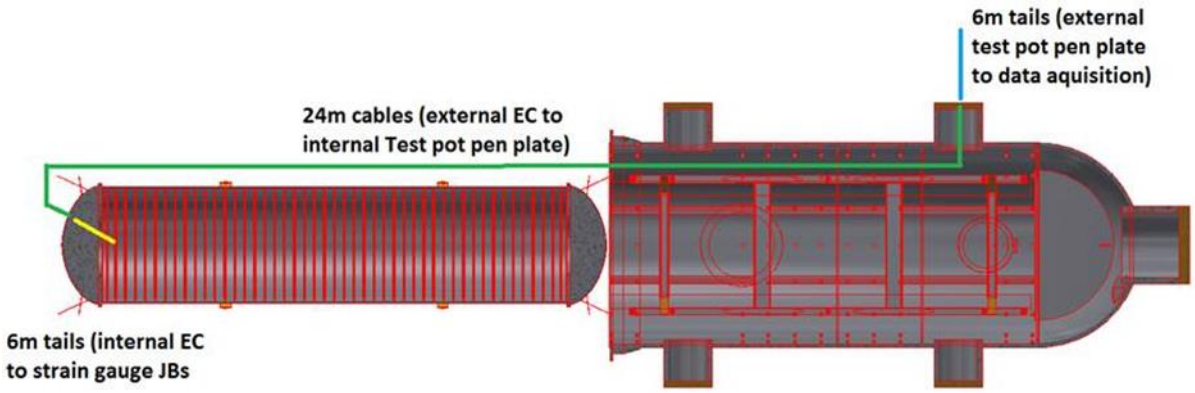


Figure 11. Schematic of NHC hydrostatic pressure chamber showing cable route from AUS3 cylinder (from above)

COLLAPSE TESTING

The National Hyperbaric Centre (NHC) a JFD company in Aberdeen will be the host to conduct the collapse pressure test. NHC has one of the largest pressure chambers (test pod) in the world, which can apply 100 bar external hydrostatic pressure and is well utilised to support North Sea subsea and diving industries. The NHC facility has been used to *hydrotest* JFD manufactured Submarine Rescue Vehicles (SRV) and other diving products before commissioning. The overall dimensions of the CTP cylinders with the end-closures fitted, are

designed as large as possible and still be accommodated in NHC chamber. Thus, the AUS3 cylinder will be the largest test article ever fitted into the NHC chamber for hydro-testing.

The collapse test process consists of three distinct stages: assembly, testing and disassembly and inspection.

Assembly process: Once the strain gauges are installed in Bristol, the cylinder is transported to the NHC facility, and the end-closures are attached to the cylinder. As shown Figure 11, cables are routed from inside of the cylinder, through the end-closure via special penetrators, into the inside of the NHC hydrostatic pressure chamber and then outside to the data acquisition system through a penetrator plate. Outside of chamber, the cables are connected to a data acquisition system. At the end of this stage, the assembled cylinder is transferred to inside the NHC chamber and prepared for pressurisation.

Test process: Once the cylinder assembled, it is moved into the NHC chamber on a purpose-built trolley (such as in Figure 12), and is then filled with transformer oil to ensure that no air remains inside the cylinder. The NHC test pod is then filled with water and both the test pod and the test cylinder are gradually pressurised until well above the expected collapse pressure. The cylinder is then isolated and the transformer oil is slowly drained to cause a differential pressure on the test cylinder, which is increased until the collapse occurs. The sudden collapse will cause a deformation of the cylinder and a drop in the water pressure in the test pod. The pressure drop and fluid inside the cylinder assembly, prevent the deformation proceeding beyond the initial collapse.

Throughout the pressurisation and de-pressurisation cycle, the installed strain gauges will monitor the strains in cylinder shell and frames, and the pressure sensors monitor pressure changes in test chamber and the cylinder. The change in strain and pressure at a number of pre-determined locations is displayed graphically on a remote monitor and all data is recorded automatically by the data acquisition system. Detailed comparison of strain and pressure data against results predicted through NL FEA and other analyses will be used for V&V of the different analysis approaches.

Disassembly and inspection: On completion of the collapse test process, the chamber is drained of water, the oil is discharged from the cylinder, and the assembly is removed from the NHC chamber. The cables are then disconnected from the monitoring system, the end-closures removed and the cylinder is relocated back onto the transport cradle for cleaning, inspection and photographing. To assist the visual inspection, a series of grid lines has been arranged and painted during the fabrication process. The cylinder is then repacked into a container for return shipment to Australia and laser scanning of the deformed shape.



Figure 12. Insertion of a SRV into the NHC hydrostatic pressure chamber for testing

Although the data collected through the data acquisition system is to be extracted for further analysis and interpretation, the initial results and visual inspection will show how close the actual collapse pressure and the mode of collapse are to the predicted results.

At the time of writing, the collapse test of cylinder AUS1 is due to be carried out at JFTS (NHC), Aberdeen in mid-March 2022. As a result of the effects of the Covid-19 pandemic however, there have been significant delays caused to shipping to and from Australia. The AUS1 cylinder only departed Australia on 12 December 2021 and testing may be delayed as a result.

CONCLUSIONS

The DSTG pressure-hull collapse testing project is a significant task that is being undertaken to conduct three, large-scale collapse test experiments. The project involves the delivery of precision made cylinders and peripheral items as well as extensive monitoring and specialised hydrostatic pressure testing. It is a one-of-a-kind project that has not previously been attempted before by Australia.

The project has brought together a team involving over 30 different organisations in both Australia and the United Kingdom. A diverse range of skills and capabilities has been assembled that ranges from the pressing of thick end-closure heads in a 100 year old machine to accurate scanning of cylinders using the latest laser scanner technology. Each contribution is essential and must be managed as a cohesive unit to deliver the successful outcomes for the project. This has been achieved through open and clear communications between all parties, understanding the importance of individual contributions, and the recognition that the project is an experiment and so subject to change as it progresses.

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Wrought Copper Nickel Chromium

A New Concept for Corrosion Resistant Metals

By

Mr Ivan Richardson BSc Hons Metallurgy, C Eng, DMS
Copper Alloys Ltd, Stoke on Trent, ST6 2EP, UK
science@britishcorrosioninstitute.com

CONTENTS

ABSTRACT 4

INTRODUCTION 5

HISTORICAL DEVELOPMENT 6

METALLURGY OF WROUGHT CNC 7

TABLE 1. COMPOSITION OF DEF STAN 02-886 PART 1 AND DEF STAN 02-824 PART 1 7

CORROSION RESEARCH 9

TABLE 2 - NICKEL BASED ALLOYS 9
TABLE 3 - COPPER BASED ALLOYS 9
TABLE 4 - TITANIUM ALLOYS 10
TABLE 5 - SUPER AUSTENITIC/SUPER DUPLEX/MARTENSITIC ALLOYS 10
TABLE 6 - STAINLESS STEELS 10

CREVICE CORROSION 11

TABLE 7 - CORROSION WEIGHT LOSS AFTER 4 YEARS (LEAST RESISTANT FIRST) 14
CREVICE CORROSION SAMPLES 4 YEARS 15

IN-SERVICE PERFORMANCE OF CUNI30CR2 DEF STAN 02- 824 17

METALLURGICAL DIFFERENCE BETWEEN WROUGHT PRODUCTS AND SAND CASTINGS 17

GALVANIC INTERACTION OF WROUGHT CNC 18

TABLE 8 - GALVANIC WEIGHT LOSS RESULTS 18

BIOFOULING PROPERTIES 19

EROSION CORROSION 21

MECHANICAL PROPERTIES 22

MECHANICAL STRENGTH OF CUNI30CR2 AT ELEVATED TEMPERATURES 22
FRACTURE TOUGHNESS 23
WELDING 23
FATIGUE PROPERTIES 23
ROOM TEMPERATURE MECHANICAL PROPERTIES 24
TABLE 9 - MECHANICAL PROPERTIES OF TOP 10 HIGH STRENGTH ALLOYS AT ROOM TEMPERATURE 24

CONCLUSION..... 25

REFERENCES..... 27

Wrought Copper Nickel Chromium

A New Concept for a Corrosion Resistant Copper Alloy

Mr Ivan Richardson BSc Hons Metallurgy, C Eng, DMS
Copper Alloys Ltd, Stoke on Trent, ST6 2EP, UK

ABSTRACT

For decades corrosion resistant copper alloys have been utilized in seawater applications for their unique combination of properties, which include anti-biofouling, non-sparking, resistance to cavitation corrosion, excellent wear properties and low magnetic permeability.

However, one disadvantage of copper alloys has been a lack of mechanical strength and in the case of nickel-aluminium bronze (NAB), complex corrosion mechanisms that have limited their suitability for marine engineering. Wrought copper nickel chromium (CuNi30Cr2) is an alloy that has been developed to overcome this and present engineers with a galvanically compatible, high strength, anti-biofouling, corrosion resistant alloy.

The key to enhancing mechanical properties does not rely on a precipitation hardening mechanism but spinodal decomposition, which is a chemical strengthening mechanism and enhances the stability of the metal structure. Additionally, wrought copper nickel chromium is a single phase alloy and therefore does not suffer from selective phase corrosion which has been problematic with some copper based alloys such as NAB in marine salt water environments.

This paper evaluates the wrought version of CuNi30Cr2, which can now be manufactured to UK Defence Standard 02-886 or to CNC-1™[1], which guarantees higher integrity. Wrought copper nickel chromium (wrought CNC) also presents significant scope for improving design options as it combines relatively high mechanical properties, extreme toughness, increased internal integrity and very good corrosion resistance.

This paper provides the findings of a four-year corrosion programme with comparisons against 26 other alloys involving a range of copper alloys, nickel copper, nickel alloys, titanium, super duplex and other stainless steels. General corrosion, galvanic and crevice corrosion in a seawater environment were all examined as well as mechanical properties.

[1] CNC-1 is a trademark of Copper Alloys Ltd.

Keywords: Cu-Ni-Cr, Copper-Nickel-Chromium, CuNi30Cr2, CNC-1™, C71950, Def Stan 02-886, Corrosion, Impact Strength, Shock Resistance, Crevice Corrosion.

INTRODUCTION

Corrosion resistant copper alloys have been utilized in seawater applications for many years due to their unique combination of properties, such as resistance to biofouling, non-sparking, resistance to cavitation corrosion, excellent wear properties and low magnetic permeability. However one of the main disadvantages of the more common engineering alloys is that they only have moderate mechanical strength.

Wrought CNC has been developed which is a forged alloy and does not rely on a precipitation hardening mechanism for increasing the mechanical properties but has a chemical strengthening mechanism known as *spinodal* decomposition. This is beneficial because it makes the alloy more resistant to stress corrosion cracking and also removes the problem of secondary phase corrosion. Wrought CNC has a single α (alpha)-phase face-centered cubic (FCC) structure, which is a simple microstructure and is not susceptible to the vulnerable phases during heat treatment and welding.

Subsequently, this single-phase structure does not suffer from selective phase corrosion (SPC), which has been problematic with some copper based alloys such as NAB in marine salt water environments.

For over 25 years, the alloy in the cast form (which has the same chemical composition as wrought CNC) has been used for 200 components on submarine platforms with no reports of component failure. Sand cast parts examined in early 2000, after 10 years in service, only indicated superficial oxidation and after cleaning were returned to the platform for continued use. As a result the UK Ministry of Defence has stated that CNC is “exceedingly good in seawater with various exposure trials reporting rates of less than 0.1mm/year”.[2]

Wrought CNC has been allocated the UK Defence Standard 02-886, the UNS standard C71950, and a commercial standard CNC-1™; the latter offers an enhanced level of testing. The combination of much higher mechanical properties, increased toughness and internal integrity compared to cast material and other wrought alloys makes wrought CNC an attractive alternative material for design engineers in a range of marine industries. In fact the UK Ministry of Defence has stated that CNC is designed to enhance survivability of components as the

[2] Def Stan 02-824 Part 1 Issue 2, Page 40

fracture toughness, resistance to crack propagation and shock resistance are “much greater” than NAB.[3]

Wrought CNC also presents considerable advantages over some of the more conventional alloys such as 90/10, 70/30 cupro-nickel and nickel-aluminium bronze (CuAl10Ni5Fe5). Wrought CNC has five-times the toughness of wrought NAB and 40% greater 0.2% proof stress. Wrought CNC has four-times the proof strength of 70/30 cupro-nickel and five-times the erosion corrosion resistance.

Typically, in forged bar form up to 150mm diameter (5.9 inches), wrought CNC can be manufactured to over 700MPa 0.2% proof stress whilst still maintaining excellent toughness which exceeds 100 Joules Izod impact strength at room temperature.

This paper describes some of the findings of a four-year corrosion programme evaluating the material with comparisons against a range of copper alloys, nickel-coppers, ‘super alloys’, titanium, super duplex and other stainless steels, covering 26 alloys, examining general corrosion, galvanic and crevice corrosion in a seawater environment. Comparisons are also made regarding mechanical strengths.

HISTORICAL DEVELOPMENT

70/30 cupro-nickel was developed by the British Royal Navy in the 1930s for condenser tubes. This was to replace 70/30 copper zinc brass tubes, which suffered corrosion problems and was limited by their inability to resist erosion corrosion at modest flow rates of seawater particularly if sand particles were present.[4] To increase the strength and corrosion resistance of 70/30 cupro-nickel for marine applications, it was found beneficial to add up to 1% manganese and 0.6-1.0% iron.

During the mid-1970s, the US Naval Research Laboratories embarked on a programme to examine corrosion erosion resistance of 70/30 cupro-nickel (C71500) compared with Wrought CNC (CuNi30Cr2.5 to C71900) in seawater piping systems under various flow conditions to establish if the new alloy could withstand higher flow rates than standard 70/30 cupro-nickel. It was concluded that Wrought CNC could tolerate five-times the flow rates of conventional 70/30 cupro-nickel.[5]

In the UK during the same period, the Ministry of Defence (MOD) commissioned research into an alloy originating in BS1400 CN1 CuNi30Cr. This was to provide an alternative to cast NAB which had suffered aggressive selective phase corrosion (SPC) in submarine seawater

[3] Def Stan 02-824 Part 1 Issue 2, Page 42
[4] 90/10 and 70/30 Alloys Technical Data Publication TH31 CDA UK Sep, 1982
[5] R Ferrara, Naval Ship Research and Development Centre Annapolis USA, 1978

applications.[6] As a result of the research, in 1986 Defence Standard (Def Stan) NES 824 Part 1[7] was issued for sand cast products, and was updated to the latest revision Def Stan 02-824 Part 1 in 2014.[8]

In the year 2000 Sir Robert Walmsley, UK Chief of Defence Procurement, announced that over £6 million had been spent by the MOD in CNC castings research. Despite this, the process technology required to reliably and consistently produce CNC in wrought form was not adequately developed and the project was abandoned.[9]

However, in 2012 the project was picked up by Copper Alloys Ltd who, in liaison with the UK MOD embarked on wrought production trials following the successful development of improved process technology in casting control and forging on other complex marine alloys.

The result of the work carried out by Copper Alloys Ltd proved that it was possible to overcome the problems that had blighted the earlier trials (including catastrophic forging failure, linear oxide inclusions and production unpredictability) and successfully produced several forgings on which the following corrosion and mechanical results are based. In 2014 a draft wrought specification was issued: Def Stan 02-886 Part 1.

METALLURGY OF WROUGHT CNC

Table 1. Composition of Def Stan 02-886 Part 1 and Def Stan 02-824 Part 1

Element	% by weight	
	Not less than	Not more than
Nickel	29.0	32.0
Chromium	1.6	2.0
Iron	0.5	1.0
Manganese	0.5	1.0
Silicon	0.20	0.40
Zirconium	0.05	0.15
Titanium	0.03	0.15
Copper	Remainder	
Impurities		
Lead		0.005
Phosporous		0.005
Bismuth		0.001
Sulphur		0.005

[6] R.C. Barik, J.A.Wharton, R.J.K Wood, K.R.Stokes, "Nickel–Aluminium Bronze Pitting Corrosion in Seawater". University of Southampton, 2009

[7] Defence Standard NES 824 Part 1 Issue 1 1986: Copper Nickel Chromium Sand Castings & Ingots, 1986

[8] Defence Standard 02-824 Part 1 Issue 3 2014: Copper Nickel Chromium Sand Castings & Ingots, 2014

[9] Sir Robert Walmsley,"Stop That Leak" Paper at the Royal Academy of Engineering, Nov 2000.

Carbon		0.020
Cobalt		0.050
Boron		0.001

Wrought CNC belongs to one of the unique alloy systems that exhibits *spinodal* decomposition. This phenomenon occurs in a narrow composition range where two identical phases exist together at the same temperature, which is known as the miscibility gap. Figure 1 below is a section through a ternary phase diagram of Cu/Ni/Cr at 930^{o}C where two Gamma phases 1 and 2 exist simultaneously. They differ in chemical composition but have the same lattice structure. During cooling they exist in a higher thermodynamic condition and when re-heated seek to achieve a lower energy state. In doing so they exert a strain on the lattice, which increases the hardness and mechanical strength.

Unlike a precipitation hardening mechanism, there are no discreet particles formed and hence there is no galvanic interaction between phases in corrosive environments. This phenomenon occurs throughout the FCC structure and is not confined to grain boundaries so that over-ageing is difficult to achieve unless heated for extended periods.

The spinodal formation cannot be observed under normal microscopic observations as it is occurring at the atomic level and can only be seen in an over-aged form resulting from a long heat treatment shown in Figure 2 below. This photograph illustrates the formation that appears after the coherent spinodal structure has been destroyed by over ageing for three weeks at 700^{o}C.

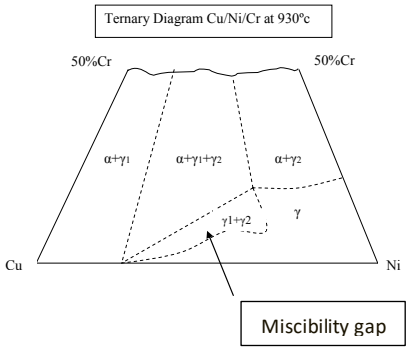


Figure 1. Meijering 1955. [8]

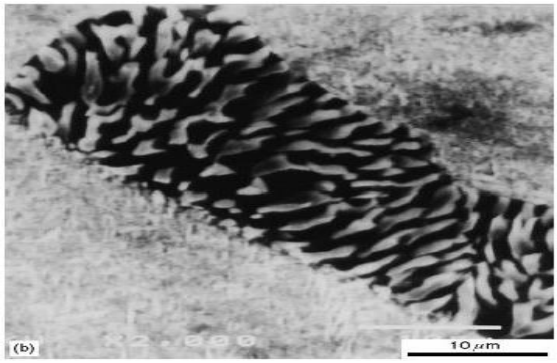


Figure 2. Three weeks ageing at 700°C and deep etching in Rosenthal's etchant for 2 hours.[9]

The microstructure in the forged and heat treated condition exists as an all α fine equiaxed structure as shown if Figures 3 and 4.

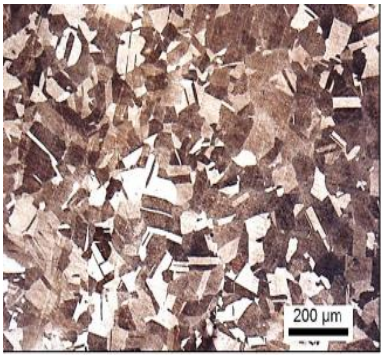


Figure 3: Equi-axed single phase α grains 100x magnification



Figure 4: Forged billet 238mm dia macro cross-section with fine grain structure

CORROSION RESEARCH

The corrosion project, known as the British Corrosion Project involved 26 alloys which are commonly used in seawater application and were immersed in three locations. Two were immersed in seawater at Shotley and Levington marina, and the third in a sewerage works. The ongoing trials will be for a period of up to 10 years. The alloys are:

Table 2 - Nickel Based Alloys

ID	Alloy	Fe %	Ni %	Cr %	Mo %	Nb %	Ti %	Al %	Cu %
9	Ni-Cu 400	2.5 max	63 min						31
10	Ni-Cu K 500	2.0 max	63 min				0.6	3	30
11	Ni-Cr-Mo625	5.0 max	58 min	21.5	9	4			
12	Ni-Fe-Cr 718	Bal	52.5	19	3	5	1.0	0.5	
13	Ni-Fe-Cr 825	22 min	42	21.5	3		1.0		2

Table 3 - Copper Based Alloys

ID	Alloy	Cu %	Al %	Ni %	Fe %	Mn %	Cr %	Si %	Ti %	Zr %	Sn %
1	Def Stan 02-833.[10]	Bal	9.25	5	4.5	0.5 max					
2 & 24	Def Stan 02-835.[11]	Bal	1.5	15	0.95	4.5	0.5 max				
3	Wrought CNC	Bal		30.5	0.75	0.75	1.8	0.3	0.55	0.55	
5	BS 3B 25[12]	Bal		2.25		0.1		0.65			

6	Def Stan 02-780[13]	Bal		31	0.8	1.0					
7	UNS C72900	Bal		15							8
4 & 8	DIN 2.1504[14]	Bal	2.75	14.2	1.0	0.75					
25	ASTM B 150 C63200	Bal	9.1	4.4	3.9	1.6					
26	CW307G[15]	Bal	9.75	5.0	4.0	1.0max					

Table 4 - Titanium Alloys

ID	Alloy	Ti%	Al%	V%	N%	C%	H_2%	O_2%	Fe%
22	Ti Grade 2	Bal			0.03max	0.08max	0.015max	0.25max	0.3max
23	Ti Grade 5	Bal	6	4	0.05max	0.08max	0.012max	0.13max	0.25max

Table 5 - Super Austenitic/Super Duplex/Martensitic Alloys

ID	Alloy	Fe%	Ni%	Cr%	Mo%	Mn%	W%	Cu%	Nb%	N %	Si %	C%
14	S31254	Bal	18	20	6.25			0.75		0.2		0.02max
15	S32550	Bal	6	25.5	3.5	1.0		1.75		0.22		0.025max
16	S32750	Bal	7	25	4	1.0		0.5		0.30	0.45	0.03max
17	S32760	Bal	7	25	3.5		0.75	0.75		0.25		0.03max
18	S31803	Bal	5.5	22	3					0.1		0.03max
21	S17400 17/4PH	Bal	4	16				4	0.3			0.07max

Table 6 - Stainless Steels

ID	Alloy	Fe%	Ni%	Cr%	Mo%	Si%	C%
19/27	316L	Bal	11.5	17	2.25		0.07max
20	304L	Bal	9.25	18.5			0.07max
28	321	Bal	10.5	18		0.5	0.08max

The two marinas were chosen as they represented two different salt water environments, Figures 5 and 6. The sewerage works was used to study the impact of hydrogen sulfide and high bacterial content. Shotley Marina is operated on a lock gate system that results in a fairly static condition with little water movement. This was to simulate water in a dock location. The

second, Levington Marina is open and subject to tidal changes with flowing water. One rack was removed from Shotley Marina after 4 years and the results are presented below. There are two further racks remaining for up to 10 years.



Figure 5 and 6: Location Maps of 2 test sites

CREVICE CORROSION

Crevice corrosion is one of the most complex and challenging corrosion problems as it can be initiated by many factors some of which are outside the direct control of the design engineer. The phenomenon can be described as the localized attack of a metal surface either adjacent to a gap, in a gap between two metals or between a metal and another substance organic or inorganic.

A cell is then formed in a gap in an electrolyte such as salt water, which allows a current to flow between a cathode and anode formed between areas of high and low oxygen known as differential aeration. The pH of the cell can also change during the corrosion process leading to accelerated attack.

The Design Engineer can minimise this type of attack by careful selection of material, ensuring there are no gaps in the design and by carefully controlled installation. It is also important to ensure there are no external factors that can create a cell, such as poor coatings, marine growths and weld spatter during any joining or repair operation. Therefore the most robust engineering solution is to specify metals that can resist crevice corrosion and offer sufficient mechanical strength to be useful in a range of applications.

The standard for crevice corrosion testing of iron-base and nickel-base stainless alloys in seawater ASTM G78-15[10], which has been used for the purposes of this project.

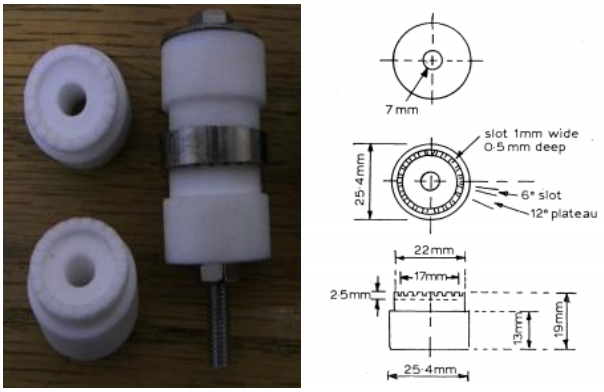


Figure 7: Test formers used for crevice corrosion tests

Specimen sizes were approximately 25.4mm diameter x 10mm thick (1 x 0.393 inch) thick and abraded to 120-grit on mating surfaces, see Figure 7. Each specimen was pre-weighed to two decimal places and then re-weighed after the four-year period having been cleaned with dilute hydrochloric acid to remove oxides and crustacean deposits.

Where obvious corrosion had taken place, the discs were sectioned and mounted in clear plastic for observation under an optical microscope with a graduated measuring eyepiece to record the depth of any corroded areas.

Corrosion Test ring after 22 months

[10] ASTM G78-15, Standard Guide for Crevice Corrosion Testing of Iron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments, ASTM International, West Conshohocken, PA, 2015



① CuAl9Ni5Fe5 ② CuNi15Mn5AlFe ③ CuNi30Cr2 ④ CuNi14Al3Fe ⑤ CuNi3Si ⑥ CuNi30 ⑦ CuNi15Sn8 ⑧ CuNi14Al3Fe ⑨ Ni-Cu 400
⑩ Ni-Cu K500 ⑪ Alloy 625 ⑫ Alloy 718 ⑬ Alloy 825 ⑭ 6%Mo St.St. ⑮ Superduplex ⑯ Superduplex ⑰ Superduplex ⑱ Duplex ⑲ 316L
⑳ 304L ㉑ 17-4 PH ㉒ Ti Gr. 2 ㉓ Ti Gr. 5 ㉔ CuNi15Mn5AlFe ㉕ CuAl9Ni5Fe4Mn ㉖ CuAl10Ni5Fe4 ㉗ 316 ㉘ 321

The stainless steels corroded in a completely different mode compared to the copper based alloys. For example 17/4 PH Martensitic, 304L and 306L stainless steel had deep cavities under specific castellations whereas the castellations on the copper based samples remained slightly raised with loss of metal between the castellations or on the edge of the specimen.

Pitting corrosion was also observed on the outer circumference of all of the copper based samples except the wrought CNC (CNC-1/Def Stan 02-886) samples. Pitting was also seen on the two nickel copper alloys, 304L, 306L and martensitic 17/4 PH stainless steels.

The super duplex, titanium samples and wrought CNC remained free of pitting and crevice corrosion. The remaining copper based alloys and nickel copper alloys remained free from crevice corrosion but did suffer various degrees of pitting corrosion and corrosion at the sample edges.

Table 7 - Corrosion Weight Loss after 4 years (least resistant first)

ID	Specification	Original Wt (grams)	Final Wt (grams)	Wt loss	%
21	Martensitic 17/4 PH	34.53	33.38	1.15	3.33
20	Stainless 304L	32.78	31.87	0.91	2.78
9	Ni-Cu 400	41.34	40.23	1.11	2.69
10	Ni-Cu K500	40.57	39.55	1.02	2.51
4	Din 2.1504	45.12	44.1	1.02	2.26
2	Def Stan 02-835	54.35	53.35	1	1.84
1	Def Stan 02-833	31.39	30.82	0.57	1.82
26	CEN CW 307G	34.91	34.44	0.47	1.35
8	Din 2.1504 N	59.48	58.69	0.79	1.33
19	Stainless 316L	33.08	32.7	0.38	1.15
7	C72900	42.02	41.6	0.42	1.00
5	BS 3B 25	37.56	37.21	0.35	0.93
25	ASTM B 150 C632000	74.07	73.39	0.68	0.92
6	Def Stan 02-780 70/30 CuNi	37	36.69	0.31	0.84
22	Titanium Grade 2	16.94	16.91	0.03	0.18
3	Wrought CNC	39.62	39.56	0.06	0.15
14	Super Austenitic S31254	36.67	36.64	0.03	0.08
18	Duplex S31803	30.27	30.25	0.02	0.07
15	Super Duplex S32550	35.5	35.49	0.01	0.03
13	Ni-Fe-Cr 825	53.74	53.73	0.01	0.02
11	Ni-Cr-Mo 625	40.31	40.31	0	0.00
12	Ni-Fe-Cr 718	41.09	41.09	0	0.00
16	Super Duplex S32750	34.42	34.42	0	0.00
17	Super Duplex S32760	38.39	38.39	0	0.00
23	Titanium Grade 5	18.28	18.28	0	0.00

Table 7 above represents the weight loss, in decreasing order, of all specimens under crevice conditions. The weight loss is a measurement of both crevice corrosion loss and any pitting corrosion that occurred outside the crevice area.

The wrought CNC had the least overall loss of all the copper alloys and did not suffer any crevice attack. There was a minimum general loss of 0.15% over the four-year period, which was represented by a slight coarsening of the surface on all exposed faces.

This research has identified a range of types of corrosion attacked that has occurred on the various samples. These are identified and shown in Figures 8-20 below.

The 17/4 PH martensitic stainless steel gave the least favourable result with 3.33% loss and crevice corrosion which penetrated the complete thickness of the 10mm (0.397 inch) sample. The 304L sample was also penetrated for the whole thickness of the sample and the 316L had a cavity 6mm deep under one of the castellations, Figure 21 below.

Both the nickel-copper alloys 400 and K500 (UNS N04400 and N05500 respectively) had areas of pitting corrosion on the outer periphery of the samples Figure 14 & 16 to a depth of 0.8mm on the alloy K500 and metal loss on the castellated face was 0.3mm, see Figure16.

Crevice Corrosion Samples After 4 years

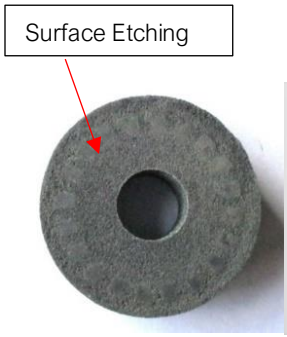


Figure 8
Wrought CNC
Total Metal Loss 0.15%



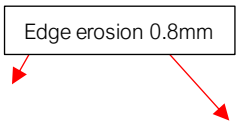
Figure 9

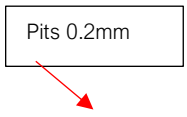


Figure 10
Def Stan 02-833
Total Metal Loss 1.82%



Figure11





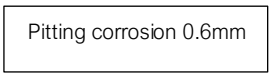




Figure 12

Def Stan 02-780 70/30 CuNi
Total Metal Loss 0.84%



Figure 13



Figure 14

Ni-Cu 400 (N04400)
Total Metal Loss 2.69%



Figure 15

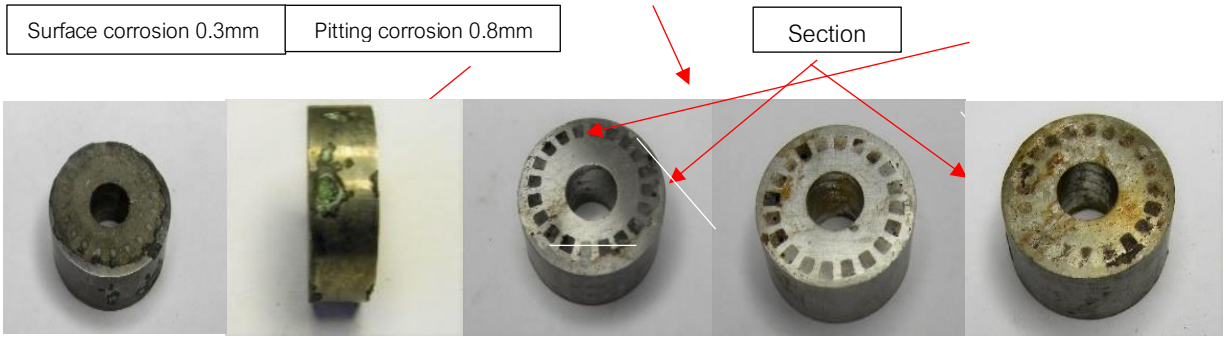


Figure 16 Figure 17 Figure 18 Figure19 Figure 20

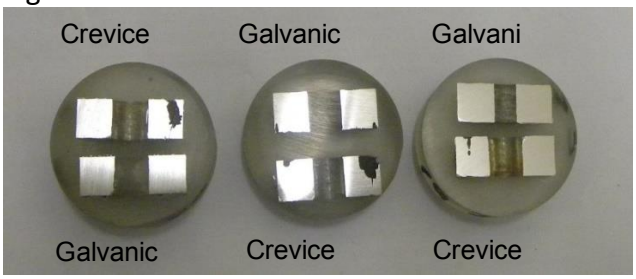
Figure 16&17
Ni-Cu K500 Total
Metal Loss 2.51%

Figure 18
Stainless 304L
2.78% Total Metal Loss

Figure 19
Martensitic Stainless 17/4 PH
3.33% Total Metal Loss

Figure 20
Stainless 316L
1.15% Total Metal Loss

Figure 21



Stainless 304L Martensitic Stainless 17/4 PH Stainless 316L

IN-SERVICE PERFORMANCE OF COPPER NICKEL CHROMIUM

During the initial development of cast copper nickel chromium, over 200 components were incorporated in Vanguard and Trafalgar class submarines during the early 1980s.[11]

Some of these were removed some ten years later, a sample of which is illustrated in Figures 22-24 below. The seawater inlet connector exhibited some marine barnacle growth (Figure 22), which was minor considering the length of service, and is an excellent illustration of resistance of CNC (the cast and wrought versions have the same chemistry) to marine fouling.

The components were given a mild glass bead blast and returned to service following the ships refit. After cleaning the component looked almost new, as shown in Figure 23, with a mild etching of the surface, as shown in Figure 24.

As no physical measurement could be made of metal loss it was estimated that corrosion was approximately 0.15mm over the ten-year period and it was free from crevice corrosion confirming recent findings from the trials.

These components have now been in service close to 30 years with no reported failures to date.



Figure 22



Figure 23



Figure 24

METALLURGICAL DIFFERENCE BETWEEN WROUGHT PRODUCTS AND SAND CASTINGS

Converting the cast product into wrought product involves a controlled pre-heat to elevated temperature, where the material can be shaped whilst hot using a variety of possesses. These include press, hammer & rotary forging, strip/bar rolling, extrusion, closed die forging and ring-rolling. The resulting products include bars (round, flat, square), stepped shafts, boss forgings, rings, blocks and complex shapes closed-die forged shapes.

Hot forming processes are carefully controlling to ensure the cast structure is fully broken down into a fine uniform wrought structure. Wrought products have greater soundness and integrity

[11] J Galsworthy, J Mawella, D Handley. Inter-Naval Corrosion Conference held at Devonport Naval Base, New Zealand, 16-18th April 2002.

compared with cast products and have a higher combination of mechanical strength and toughness.

With a fine uniform structure, wrought products have significant advantage over castings. Mechanical properties are more consistent across components. As castings do not have to undergo the stresses involved with forging, the impurity levels are normally higher in castings. This can become even more of a problem as a casting cools at different rates throughout the component, and the impurities gather at the last point of solidification.

Corrosion rates are increased by non-uniformity. When there are inconsistencies, either chemically or physically, in the metal, corrosion will be more prevalent. The absence of porosity in wrought products, and the uniformity of structure means that for a given chemistry equipment will last longer if made from wrought CNC.

Cost is also a consideration for engineers. With the reliability of the forging process and the ease with which this can be tested prior to machining with low cost ultrasonic examination wrought CNC is favourably comparable in cost to cast CNC.

GALVANIC INTERACTION OF WROUGHT CNC

A galvanic coupling with each of the alloys was made with wrought CNC on 1:1 ratio basis. Where possible a 25mm diameter sample was used by10mm thick and abraded flat with a 120-grit finish. The samples were bolted together using a stainless steel bolt, which was insulted from the samples with a rubber tube. These were then screwed into a polypropylene rack and an electrical check conducted to ensure circuit contact, and immersed at Shotley Marina for four years.

Each sample was pre-weighed before immersion and again after the four periods having been cleaned in mild hydrochloric acid. Table 9 represents the weight loss from copper nickel chromium in the first column and in second column the corresponding weight loss from the coupled alloy.

The greatest loss was with the super duplex alloys samples with 2.61% and 2.40% loss over the four-year period but still performed well against titanium grade 5 and Ni-Cr-Mo Alloy 625. It also it appeared significantly nobler than any of the other copper based alloys.

Table 8 - Galvanic Weight Loss Results

Identification	Specification	% CNC loss	%Alloy Loss
17	Super Duplex S32760	2.61	nil
14	Super Austenitic S31254	2.40	nil
23	Titanium Grade 5	2.36	nil
10	Ni-Cu K500	2.14	0.87

18	Duplex S31803	2.07	nil
19	Stainless 316L	2.06	0.92
11	Ni-Cr-Mo 625	2.00	nil
16	Super Duplex S32750	1.94	nil
13	Ni-Fe-Cr 825	1.77	0.04
9	Ni-Cu 400	1.54	0.42
12	Nickel 718	1.35	nil
20	Stainless 304L	1.24	1.74
6	Def Stan 02-780 70/30 CuNi	1.09	1.35
5	BS 3B 25	0.92	6.17
7	C72900	0.37	3.90
2	Def Stan 02-835	0.34	2.26
8	Din 2.1504 N	0.30	1.29
25	ASTM B 150 C63200	0.27	0.93
4	Din 2.1504	0.20	1.22
1	Def Stan 02-833	0.17	0.69
26	CW 307G	0.05	0.96
21	Martensitic 17/4 PH StSt	0.05	5.84

BIOFOULING PROPERTIES

Figure 26 below illustrates the marine growths, which were seen after 22 months' immersion. The bottom of the rack contains tensile specimens. The first eight samples on the left side of the rack are all copper based and the attachment of marine organisms starts to appear on nickel copper alloys 400 and K 500 specimens. Although both of these alloys contain approximately 30% copper this was not high enough to discourage growths.

Figure 26: Corrosion rack after 22 months



① CuAl9Ni5Fe5 ② CuNi15Mn5AlFe ③ CuNi30Cr2 ④ CuNi14Al3Fe ⑤ CuNi3Si ⑥ CuNi30 ⑦ CuNi15Sn8 ⑧ CuNi14Al3Fe ⑨ Ni-Cu 400
⑩ Ni-Cu K500 ⑪ Alloy 625 ⑫ Alloy 718 ⑬ Alloy 825 ⑭ 6%Mo St.St. ⑮ Superduplex ⑯ Superduplex ⑰ Superduplex ⑱ Duplex ⑲ 316L
⑳ 304L ㉑ 17-4 PH ㉒ Ti Gr. 2 ㉓ Ti Gr. 5 ㉔ CuNi15Mn5AlFe ㉕ CuAl9Ni5Fe4Mn ㉖ CuAl10Ni5Fe4 ㉗ 316 ㉘ 321

Figure 27: Corrosion rack after four years

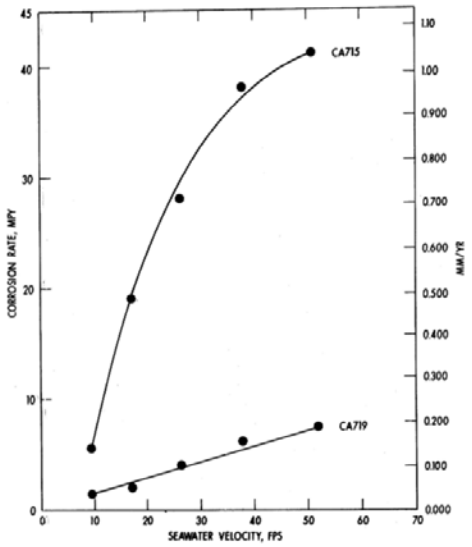


Even after four years, as Figure 27 above shows, the copper based alloys still remained free from marine organisms.

EROSION CORROSION

During Naval Ship Research in the 1970s work conducted by Robert Farrara to investigate flow rates in seawater piping systems for two alloy systems: 70/30 cupro-nickel to CA715 and CuNi30Cr2.5 to CA 719 (wrought CNC).[12] The results are presented in Figure 28 below indicated that wrought CNC could withstand five-times greater flow rates under erosion corrosion conditions than conventional 70/30 cupro-nickel.

Figure 28: Erosion Corrosion Rates in Flowing Seawater of Wrought 70/30 Cupro Nickel and Wrought CNC



Even at flow rates of 15m/sec (50ft/sec), the average corrosion rate of wrought CNC was 0.2mm/year compared with 1.0mm/year for 70/30 cupro-nickel.

While wrought CNC could withstand higher flow rates, it was found to be slightly worse on pitting corrosion in static water conditions but well within design constraints. Although erosion corrosion was not part of the current program it was considered relevant to include this historic study as it identifies the suitability of wrought CNC for seawater pipe systems.

[12] R Ferrara, Naval Ship Research and Development Centre Annapolis USA, 1978

MECHANICAL PROPERTIES

In-depth research was conducted by J Galsworthy and D Baxter on behalf of the UK MOD at the Defence Evaluation Research Agency to investigate both mechanical and physical properties of cast and wrought CNC in the mid-1990s.[13]

The graph below illustrates the mechanical properties of both cast and wrought CNC at elevated temperatures up to 850°C.

Mechanical Strength of Copper Nickel Chromium at Elevated Temperatures

Table 10 - Mechanical Properties Aged at 475°C

Condition	0.2% Proof Stress	UTS	Elong	Izod
	N/mm²	N/mm	%	Joules
As forged 240mm sq	405	569	27	134,135,133
Forged & aged 10 hours @ 475C	408	596	27	130.136,138
Forged & aged 7 days @ 475C	421	618	27	132,118,126

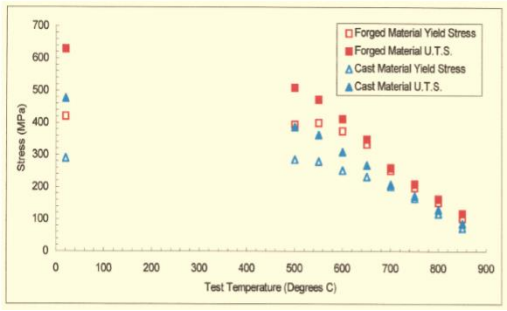


Figure 29: UTS and Yield Stress versus Temperature

Measurements indicated that CNC could maintain a reasonable strength level to 600°C with a marginal fall in proof stress for the wrought product. There was however a greater decline in UTS over this temperature range, although a higher level was maintained to 500°C.

Further work conducted by Copper Alloys Ltd illustrated the stability of the alloy after long ageing times. Table 10 above illustrates the unique properties of this spinodal alloy, that unlike other copper based precipitation hardening alloys Wrought CNC did not show a rapid decline in mechanical properties over the same period.

[13] J Galsworthy, D Baxter, Forged copper-nickel-chromium alloy for seawater systems components. Materials Technology Conference 22-24 April 1997 Halifax, Canada

Fracture Toughness

Fracture toughness is an extremely important property for components employed in submarine applications for sub-sea platforms. The ability to withstand high pressures, high loads and their resistance to crack propagation under explosive condition is a vital property in design and alloy selection. Work conducted by J Galsworthy and D Baxter [14] illustrates the advantages of wrought CNC against the cast product, see Figure 30 below.

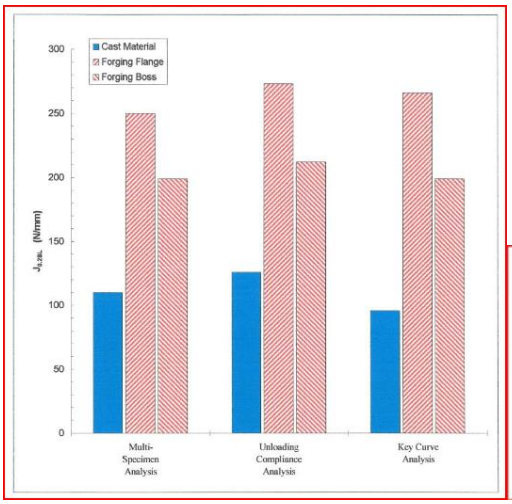


Figure 30 - The Fracture Toughness of Cast (blue) and Wrought CNC (red)

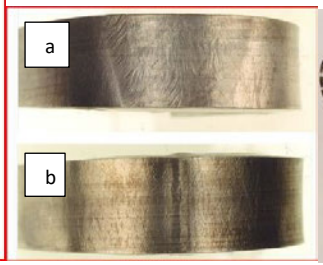


Figure 31
Weld bend tests (a) MIG weld (b) EB weld



Figure 32
Tensile and impact specimen

Welding

Wrought CNC can be successfully welded by MIG, TIG and electro-beam techniques using matching welding wire. Figure 31 above illustrates the ductility and toughness after welding, shown here is a full bend test without cracking. Another feature of wrought CNC is that it does not require complex heat treatment or suffer problems with the heat affected zone from welding.

During current mechanical testing the tensile specimens exhibited the classical cup and cone fracture typical of ductile material Figure 32, and after impact testing many of the specimens do not completely fracture.

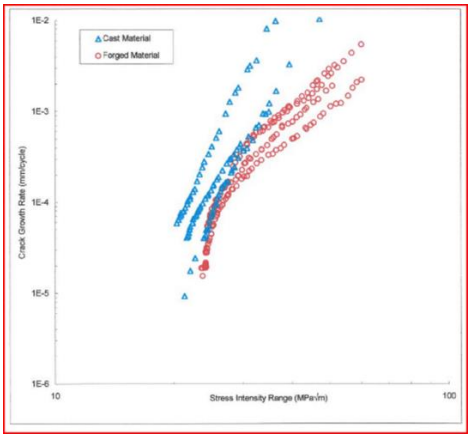
Fatigue Properties

Other studies have indicated that the fatigue strength of wrought CNC is in the region of 275MPa after 10^8 cycles. For design purposes, low frequency fatigue properties in seawater are

[14] J Galsworthy, J Mawella, D Handley. Inter-Naval Corrosion Conference held at Devonport Naval Base, New Zealand, 16-18th April 2002.

vital and are presented in Figure 33 below by work conducted by J Galsworthy and D Baxter.[15] The results indicate that wrought CNC has higher resistance to crack propagation than cast CNC at comparable stress levels. This again highlights the engineering advantages of having a more uniform and finer grain size, namely higher mechanical properties and greater toughness. Work in 2018 on Wrought CNC by the Defence Science and Technology Group (part of the Australian MOD) has confirmed these findings.

Figure 33 - Low frequency corrosion fatigue (0.0083 Hz) of cast (blue) and wrought (red) CNC in seawater at R=0



Room Temperature Mechanical Properties

The top ten alloys used in the corrosion programme and graded by 0.2% proof stress are listed in Table 9 below. The bulk of the bar stock of 25.4mm (1 inch) diameter was purchased from metal distributors with the exception of the Wrought CNC sample which represents properties obtained from a 130mm (5.11 inch) forging.

Table 9 - Mechanical Properties of top 10 High Strength alloys at Room Temperature

ID	Specification	0.2% N/mm²	UTS N/mm²	Elongation %	R of %	Impact Joules	YM KN/mm²
23	Ti Grade 5	952	1023	15	36	23,23,23	116
12	Ni-Fe-Cr 718	903	1240	29	52	99,102,98	193
21	Martensitic stainless	844	964	22	63	149,136,145	184
4	Din	801	945	16	26	20,22,22	133.7
3	Def Stan 02-886	717	811	21	36	110,111,111	139
7	C72900 CuNi15Sn8	713	905	20	21	8,8,8	140
10	Ni-Cu K500	676	1085	25	48	70,69,72	173.5
5	BS 3B 25 CuNi3Si	640	719	15	52	90,85,62	142.1
15	Super Duplex	633	825	37	77	299,299,299	179
11	Ni-Cr-Mo 625	501	906	50	51	130,128,121	191.8

[15] J Galsworthy, D Baxter, Forged copper-nickel-chromium alloy for seawater systems components. Materials Technology Conference 22-24 April 1997 Halifax, Canada

The strength properties of Wrought CNC are less than Grade 5 Titanium and Ni-Fe-Cr 718, although the impact strength is comparable. Wrought CNC has over four-times greater impact strength than Grade 5 Titanium at room temperature.

In summary, the important properties of wrought CNC are as follows:

- High mechanical strength
- Excellent toughness and ductility
- Non sparking
- Low magnetic permeability
- Single phase and does not suffer from SPC
- Can be non-destructively tested by ultrasonic inspection
- Mechanical tests relate directly to individual forgings
- Free from defect weld repair
- Can be joined if required by welding without complex heat treatment
- Stable mechanical properties at elevated temperatures
- Freedom from hydrogen embrittlement

CONCLUSION

The four-year trial has confirmed the excellent corrosion resistance of wrought CNC and supports the findings reported by Galsworthy and Baxter[16] both from a crevice and pitting corrosion perspective.

Important properties include: general corrosion 0.02mm/year, crevice corrosion <0.02mm/year, nil selective phase corrosion rate and impingement resistance 6-8 m/sec.

From current findings and previous research, the alloy has added advantages over many other marine alloys and offers an opportunity to reduce through-life costs with the potential of 30 years service for sub-sea platforms without any inherent corrosion issues.

[16] J Galsworthy, D Baxter, Forged copper-nickel-chromium alloy for seawater systems components. Materials Technology Conference 22-24 April 1997 Halifax, Canada

The combination of corrosion resistance that is superior to all other copper alloys and mechanical properties similar to stainless steel, wrought CNC presents a compelling material for marine engineering.

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11 Defence Standard 02-835 Issue 2, 2011: Requirements for High Strength Copper Nickel Manganese Alloy,Forgings,Forging Stock,Rods & Sections

12 British Standard Aerospace Series BS 3B 25 2009:Copper-Nickel-Silicon Alloy Rods.

13 Defence Standard 02-780 Part 2 Issue 2 2009: Requirements for Copper Nickel Alloy Material,Forgins,Forging Stock,Rods and Sections

14 DIN –WL 2.1504 Oct 2012:Wrought alloy-Nickel Bronze (for bars)

15 British Standard BS EN 12163 CW 307G:2011: Copper & Copper alloy rod for general purposes

16 ASTM G 78-15 Standard guide for crevice corrosion testing iron based and nickel base stainless steels in seawater and other chloride-containing aqueous environments.

17 J Galsworthy,J Mawella, D Handley. Inter-Naval Corrosion Conference held at Devonport Naval Base, New Zealand, 16-18th April 2002.

18 J Galsworthy, D Baxter, Forged copper-nickel-chromium alloy for seawater systems components. Materials Technology Conference 22-24 April 1997 Halifax, Canada

SESSION 16

Autonomous Vessels

Comparison of acceleration prediction methods for an underwater vehicle
Refereed

Underwater networks connecting Robotic Autonomous Systems (RAS)

Persistent autonomous data gathering and monitoring - a future vision for autonomous ocean observations
No paper provided

Comparison of Acceleration Prediction Methods for an Underwater Vehicle

Lachlan Bennett[1,2], lachlan.bennett@dst.defence.gov.au
Anthony Fowler[2]
David B. Clarke[2]
David A. Pook[2]

[1] Advanced VTOL Technologies Pty Ltd
[2] Maritime Division, Defence Science and Technology Group

ABSTRACT

Characterising the acceleration performance of an underwater vehicle for tactical manoeuvres during missions and emergency situations is paramount. Accurately predicting the acceleration of an underwater vehicle can be challenging. The transient nature of rapid acceleration from a stationary state, bollard pull, or low speed condition, to a high speed self-propulsion flow regime significantly changes the wake-flow seen by an aft positioned propulsor typical of underwater vehicle designs. The altered wake-flow possibly invalidates the underlying propeller modelling assumptions in the standard Gertler-Hagen coefficient based hydrodynamic model. Simulation of the acceleration with 1-Degree-Of-Freedom (1-DoF) Computational Fluid Dynamics (CFD) offers the opportunity to capture the transient behaviour accurately but it is expensive in terms of time and modelling complexity.

To investigate possible differences in acceleration prediction between a Gertler-Hagen coefficient based model and 1-DoF CFD, a numerical investigation of a deep underwater vehicle (free of surface effects) undergoing 1-DoF horizontal acceleration manoeuvring test cases was conducted for a generic underwater vehicle design. By applying a prescribed propeller rotation rate in order to accelerate the underwater vehicle, the differences in the resulting predicted motion of the coefficient based model, a method based on the ITTC-78 performance prediction method, and two CFD propulsor simulation techniques were explored. One CFD simulation technique included the full flow details and geometry of the propeller as a rotating mesh. The second CFD method simulated the propeller as an actuator-disk, applying a pressure jump coupled to open-water propeller data using thrust identity and advance coefficient. Comparisons are presented for 1-DoF acceleration manoeuvres, which test underlying assumptions for each method. The results provide confidence in using the more efficient Gertler-Hagan and quasi-static method based on the ITTC-78 performance prediction method, for predictions of acceleration for deep underwater vehicles and a relatively well developed wake flow. Differences in predictions were observed between the methods for situations where the flow was not developed.

INTRODUCTION

During their operational lifetime, underwater vehicles will be exposed to extreme operational conditions and mission critical situations that require a known acceleration

capability. Accelerations from rest, or any specified ahead speed, to a higher speed is an important maneuverer for underwater vehicles which can be required to change position rapidly in a task force, or to accelerate suddenly for tactical reasons (Mandel, 1967). Acceleration performance is also one of the major platform requirements that is assessed during sea trials (Australian Government DoD, 2007). Hence, accurate prediction of acceleration performance is important.

Coefficient-based hydrodynamic models, such as the Gertler-Hagen model (Gertler & Hagen, 1967), provide a computationally efficient means of determining the acceleration of an underwater vehicle. However, there may be manoeuvres that violate the underlying assumptions in the hydrodynamic model, significantly impacting the accuracy of its predictions. Simulating rapid acceleration manoeuvres, it is critical that the propulsor's performance is accurately considered. An aft-mounted propulsor's performance is strongly dependent on the wake flow entering, and the wake flow entering is dependent on the propulsor's interaction with the hull. Coefficient based methods that use propeller performance curves determined from open-water testing can be corrected for hull interaction effects. However, for manoeuvres like rapid acceleration from low speeds, the assumed hull interaction corrections might be inaccurate.

With high performance computing capability becoming standard, predictive methods using Computational Fluid Dynamics (CFD) can now simulate entire manoeuvres and provide detailed insights into the non-steady hydrodynamics without assumptions or corrections for the propulsor and hull interaction. For example, the transient changes in the wake flow during acceleration that are not captured by standard coefficient-based methods, can be included in the simulation.

This paper compares the acceleration predictions of the Gertler-Hagen coefficient-based model (CBM) against 1-Degree-of-Freedom (1-DoF) CFD simulations. Two CFD simulation techniques are used, one that includes the propeller geometry rotating behind the underwater vehicle, the other using an actuator disk coupled to open-water propeller performance curves. Acceleration predictions are also calculated with a quasi-static method based on the ITTC 1978 performance prediction method (International Towing Tank Committee, 2017).

BB2 GEOMETRY DESCRIPTION

The BB2 generic underwater vehicle geometry (Overpelt, Nienhuis, & Anderson, 2015) seen in Figure 1 was chosen as a representative underwater vehicle for this study. The BB2 in this study is coupled to the MARIN 7371R propeller, also shown in Figure 1. All analysis was performed at full scale. Particulars of the BB2 are summarised in Table 1.

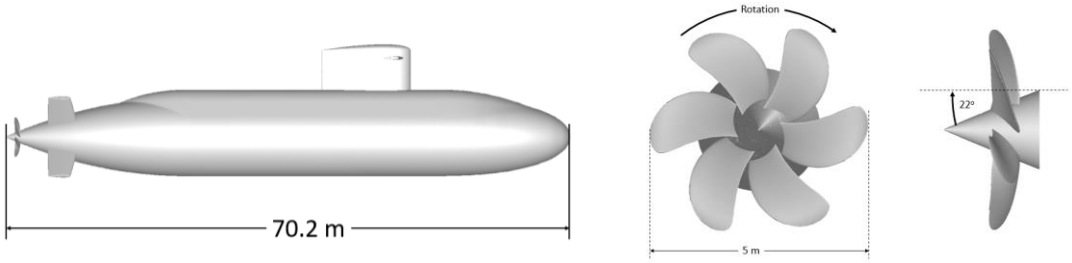


Figure 1 – Left: the generic underwater vehicle geometry, BB2. Middle and right: the MARIN 7371R 6 Blade propeller with a 22 degree tapered cone hub.

Table 1 - Particulars of the full-scale, generic underwater vehicle, BB2.

Particular	Value
Length, *L* (m)	70.2
Propeller Diameter, *D* (m)	5
Actuator Disk Location (from bow) (m)	68.87
Submerged Displacement (t)	4551
Surface Area (m^2)	2143.5

ACCELERATION CASES

Two acceleration maneuverers were performed using the selected prediction methods. For the first case, Case 1, the BB2 was accelerated from a self-propulsion condition at 2.57 m/s (5 kts), to a self-propulsion condition at 5.14 m/s (10 kts). For the second, Case 2, it was accelerated from a stationary condition of 0 m/s with no propeller rotation, to a self-propulsion condition at 2.57 m/s.

For each case, the acceleration was controlled by the propeller rotation rate. To rapidly accelerate the underwater vehicle, the propeller rotation rate was increased from its initial specified speed for self-propulsion, by an arbitrary rate of 10 rpm per second until it reached the required rotation rate for self-propulsion at the final speed. The propeller rotation rate was then held constant for the remainder of the acceleration.

All acceleration simulations and calculations used water with a density (ρ) of 1025 $\mathrm{kg/m^3}$ and dynamic viscosity (μ) of 1.003 × 10^{-3} $\mathrm{Pa.s}$. It was assumed that all acceleration maneuverers were occurring at depth, free of surface effects. Hull fouling was not included.

ACCELERATION PREDICTION METHODS

The four methods for predicting acceleration assessed were:

- Gertler-Hagen coefficient-based model;
- 1-DoF CFD including a rotating propeller;
- 1-DoF CFD with an actuator disk coupled to open-water propeller curves; and
- quasi-steady method based on the ITTC-1978 performance prediction method.

Except where stated, details of the CFD method below apply to both CFD-based methods.

Gertler-Hagen Coefficient-Based Model Method

An in-house 6-DoF time-domain manoeuvring code developed at Defence Science & Technology Group (DSTG) based on the Gertler-Hagen coefficient-based model (CBM) was used. This code features an in-built autopilot to maintain constant depth, pitch angle and horizontal heading. The simulated control surface deflections were less than 1° during the acceleration simulations, with a negligible influence on resistance and hence the acceleration performance. Hydrodynamic coefficients for the BB2 were determined using CFD in past studies. A CBM simulation of a manoeuvre can be computed in a few minutes using a desktop computer.

For Case 1, the BB2 accelerating from 2.57 m/s, the CBM simulation were first simulated for 300 seconds to ensure self-propulsion stability before accelerating to 5.14 m/s. For Case 2, acceleration from an at rest condition, a low underwater vehicle speed of 0.005 m/s had to be set to maintain code stability. This was simulated for 200 seconds to achieve a near stationary, self-propulsion state before accelerating to 2.57 m/s.

CFD Methods Computational Domain and Boundary Conditions

The BB2 geometry was placed in a rectangular domain with the extents shown in Figure 2(a). The blockage ratio was approximately 0.2%. No sensitivity to blockage ratio was performed. As the acceleration was constrained to 1-DoF in the horizontal x-direction only, no control surfaces deflections were considered. The computational domain was divided into three zones, the Inner Zone, Outer Zone, and Propeller Zone, as seen in Figure 2(a).

As shown in Figure 2(a), the inlet and outlet boundaries were a pressure inlet and pressure outlet respectively. At these boundaries, the turbulent intensity was set to 2%, and the turbulent viscosity ratio was 4. The turbulence specified at the boundary condition will have negligible effect on the solution. The related simulations of a streamline body accelerating due to buoyancy (Yen et al. (2019), used to develop CFD techniques in this paper, set the same turbulent quantities at the boundary conditions.

The BB2 and propeller surfaces were no-slip walls. The mesh in the Propeller Zone was substituted with either the mesh representing the full propeller geometry, Figure 2(b) for the rotating propeller mesh simulations, or a mesh representing the propeller as an actuator disk, Figure 2(c). All zones were joined by non-conformal mesh interfaces.

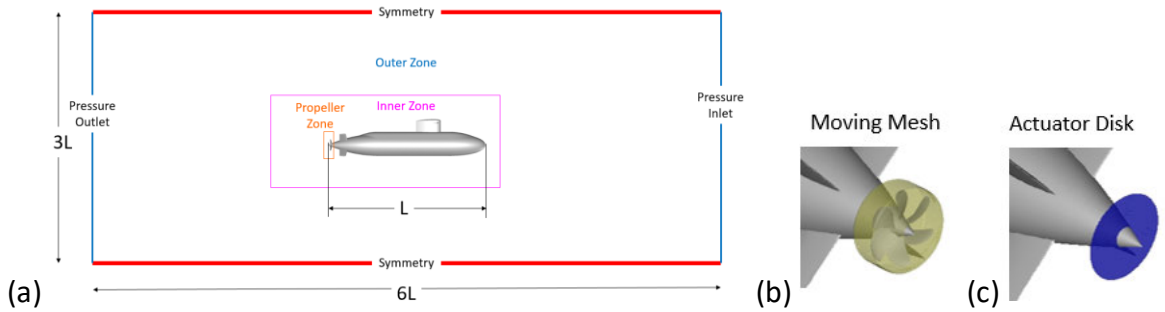


Figure 2 – (a) The CFD computation domain with three mesh zones and boundary conditions. (b) Propeller Zone (yellow), including propeller geometry that rotated about the propeller's axis. (c) Actuator Disk (blue) in the Propeller Zone.

The Inner Zone and Outer Zone used structured meshes. The Inner Zone, Figure 3(b) contained 500 cells along the BB2 hull in the lengthwise direction, and 380 cells around the hull circumference. The first cell wall height was 0.3 mm, which gave an average *y+* value in the order of 35 for 5.14 m/s, placing the first cell in the turbulent boundary layer log law region. The Inner and Outer zones contained 40 & 13 million cells respectively.

As mentioned, the Propeller Zone had two separate volume meshes created. In both instances, they employed the same first wall cell height and boundary growth rates used for the Inner Zone. At the mesh interface between the Propeller and Inner Zones, the mesh cell count on each side of the interface differed by less than a factor of two. For the actuator disk in the Propeller Zone, structured meshing was used. This mesh had a total cell count of 4 million cells. Unstructured meshing was used for the propeller geometry in the Propeller Zone, Figure 3(a). To capture the boundary layer on the propeller blades, 30 prism layers were grown from the blade and hub surfaces. At the sliding mesh interface, 5 prism layers were grown at a uniform spacing of 28 mm. The remaining volume was filled with tetrahedral cells. The mesh contained a total of 10 million cells.

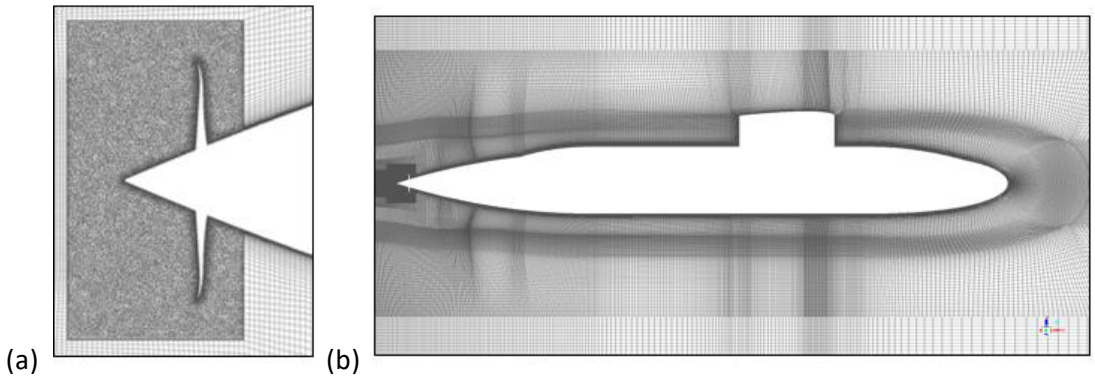


Figure 3 – (a) Centre line section through un-structured mesh of moving mesh propeller zone & (b) centre line section through inner domain containing main hull

CFD Methods Numerical Details

The commercial CFD code ANSYS Fluent was used for this study to solve the Unsteady Reynolds–Averaged Navier–Stokes (URANS) equations with the $k\omega$ Shear Stress Transport (SST) turbulence model. All simulations were performed in double-precision, with second-order differencing schemes for all flow variables, the SIMPLE algorithm for pressure-velocity coupling, and the Green–Gauss cell-based method to calculate gradients. Time was advanced with the second-order implicit scheme, with a time step of 0.01 seconds. A CFD simulation of an acceleration manoeuvre can take days to compute using hundreds of cores on a High-Performance-Computer (HPC).

For each time step, the resistance of the BB2 was monitored for convergence in order to determine the number of inner iterations required. Convergence was considered acceptable when the percentage change per iteration was less than 0.1%.

Determination of the mesh motion in the *x*-direction at each time-step, was calculated from the forces on the BB2 and propeller and a Runge-Kutta 1-DoF solver. This 1-DoF solver was

coupled with the solver using ANSYS Fluent user defined functions. Unpublished studies have verified this user code against theoretical test cases involving a sphere accelerating due to buoyancy forces (Guo, 2011). Validation studies of a buoyancy driven model detailed by Yen et al. (2019) were also repeated using this solver.

All CFD simulations begun from self-propulsion at 2.57 m/s, were simulated for 100 seconds (underwater vehicle travels $> 3L$) to achieve a steady-state condition before accelerating.

Propeller Zone with Moving Propeller Details

The Propeller Zone including the propeller geometry, see Figure 2(b), was rotated about the propeller's shaft axis, creating motion relative to the surrounding inner domain. This CFD method is potentially the most accurate but comes with added computational cost.

As input data for the Case 1 and Case 2 accelerations, the Propeller Zone rotation rate was varied until self-propulsion was achieved at 2.57 and 5.14 m/s. Table 2 shows the required propeller rotational speeds to achieve self-propulsion were very similar to the rotational speeds required in the CBM. Hence, for consistency, the rotational speeds predicted using the CBM were used for all CFD simulations.

Table 2 – Self-propulsion propeller rotational speeds

Underwater Vehicle Speed (m/s)	Propeller RPM		% Difference
	CBM	CFD	
2.57	28.8	29.1	1.0
5.14	57.6	57.7	0.2

Propeller Zone with an Actuator Disk Details

For this method, the geometry of the propeller was replaced by an actuator disk at $0.98\mathrm{L}$ from the bow. A fan boundary condition was applied at the actuator disk, which adds a pressure jump to the flow. The pressure jump was specified as constant over the actuator disk. At each time step, the expected pressure jump was calculated from open water propeller curves. The actuator disk method for each time-step can be summarised as:

- Determine the effective advance velocity of the actuator disk based on the underwater vehicle speed and an effective wake fraction relationship determined from open-water propeller thrust curves (i.e. thrust identity).
- Based on the effective advance ratio, and the rotational speed specified, determine the thrust from open-water propeller thrust curves.
- Correct the thrust to account for different hub thrust contributions between a propeller and an actuator disk.
- Convert the required thrust to an average pressure jump across the actuator disk.

The details of the process are presented below.

The thrust generated by the propeller is characterised by open water performance curves. The open water performance curves for the MARIN 7371R propeller were calculated at a

scale of 1:28 using CFD. These CFD simulations used a rotating propeller mesh (i.e. Propeller Zone with propeller geometry mesh) with a streamlined nose cap installed upstream to ensure the inflow to the propeller was parallel. The propeller's speed of advance, U_A, was equal to the free stream flow velocity, U_s. Thrust of the propeller blades versus advance curves were generated by varying the free stream velocity while the propeller's rotational speed (n) was held constant at 15 rps. The resulting thrust from the propeller blades, T, is shown in Table 3 for different advance speeds between 0.5 and 2 m/s. The calculated thrust coefficient,

$$K_t = \frac{T}{\rho D^4 n^2}, \tag{1}$$

and advance ratio,

$$J = \frac{U_A}{nD}, \tag{2}$$

are also shown.

Table 3 - Open water performance data for Marin 7371R Propeller at 1:28-scale calculated with CFD. Thrust is for the blades only.

n (rps)	D (m)	U_A (m/s)	J	T (N)	K_t
15	0.179	2.0	0.747	32.704	0.143
15	0.179	1.5	0.560	54.354	0.238
15	0.179	1.0	0.373	74.608	0.327
15	0.179	0.5	0.187	93.906	0.411

The open-water thrust coefficient of the propeller blades was fitted with the polynomial,

$$K_t = -0.0739\,J^2 - \,0.4092\,J + 0.4901. \tag{3}$$

The propeller advance ratio to generate the required thrust for the BB2 at the 2.57 and 5.14 m/s self-propulsion conditions was then determined. The required propeller blade thrust for self-propulsion was known from the CFD simulations of the BB2 including the propeller geometry. A thrust coefficient based on underwater vehicle speed was used with (3) to determine the effective advance ratio of the propeller (thrust identity), and hence the propeller's speed of advance relative to the flow, which differs from the vehicle speed. The effective wake fractions,

$$w_e = \frac{U_S - U_A}{U_S}, \tag{4}$$

for 2.57 and 5.14 m/s are shown in Table 4. The effective wake fraction varies with underwater vehicle speed. For acceleration Case 1, acceleration from 2.57 to 5.14 m/s, the average of these two effective wake fractions was used to relate underwater vehicle speed with propeller advance ratio. For Case 2, the effective wake fraction at 2.57 m/s was used to determine the advance velocity at the propeller.

Table 4 – Effective wake fraction at self-propulsion for the BB2 at different speeds.

Speed (m/s)	Effective Wake Fraction, w_e
2.57	0.308
5.14	0.284

With the effective wake fraction, the propeller thrust for a given rotational speed could be determined as the BB2 accelerated. However, open-water tests with an effective wake correction does not account for the differing interaction with the hub, for the propeller and actuator disks methods. A hub correction to the thrust must be applied as the actuator disk's effect is different to the propeller's effect.

Referring to Figure 4, considering a control volume encasing the propeller and hub, a comparison between the blade thrust and hub thrust, or actuator disk thrust and hub thrust, is made. The percentage contribution of the hub to the overall control volume thrust increased from 5% for the propeller, to 10% when the actuator disk was used. Note, outside this control volume, all forces on the hull and appendages were negligibly different for the propeller and actuator disk cases.

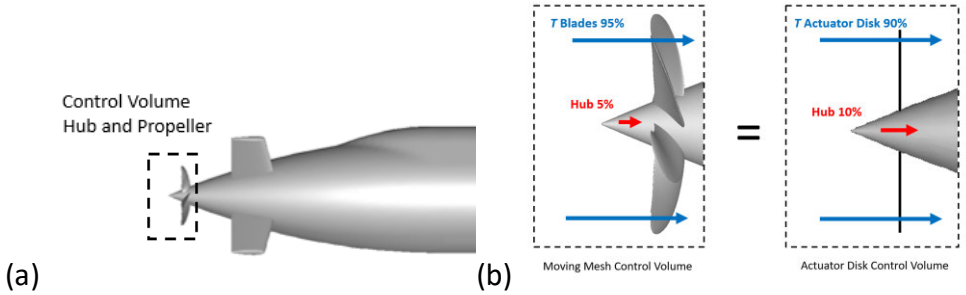


Figure 4 – (a) Control volume for the propeller/actuator-disk and hub. (b) Relative thrust for the propeller blades and hub, or actuator disk and hub.

In order to match the net thrust of the control volumes for the actuator disk and moving propeller mesh methods, the thrust applied across the actuator disk was reduced by 5% to account for the greater hub contribution. It is speculated the actuator disk hub contribution is greater because when the blades are removed, the hub area is increased. Also, the pressure jump across the actuator was set to be uniform, for the rotating mesh method this is not the case and this will result in different hub pressure distributions.

CFD Methods Time Step and Grid Independence

Unpublished investigations using this mesh at a model-scale checked solution dependency to grid refinement by doubling the mesh total cell count to 120 million cells, the wall adjacent cell heights were held constant. Acceleration simulations with the refined grid showed the displacement after the total acceleration period differed by less than 0.5%.

Time step dependence was checked by reducing the time step size from 0.01 to 0.005 seconds. The same convergence tolerance of the resistance monitor (0.1%) was used to control the number of inner iterations for each time step. Using Case 1, the difference in total displacement and velocity predicted after the acceleration period was less than 0.5%.

Method Based on the ITTC-78 Performance Prediction Method

The final method presented was based on the ITTC-78 performance prediction method (International Towing Tank Committee, 2017). The BB2 acceleration is assumed quasi-steady and the ITTC-78 performance prediction method applied at each instance. A time

step of $\Delta t = 0.05$ seconds was used. Based on the force imbalance between the open-water thrust (T) corrected for thrust deduction, towed resistance (R) and added mass forces (m_{Added}) (see Figure 5), the acceleration could be determined from (5) and velocity obtained numerically for the next time step using the forward Euler method (6) .

Acceleration:

$$a_x = \frac{T(1-t) - R}{m + m_{Added}} \tag{5}$$

and, forward Euler:

$$U_s^{n+1} = U_s^n + a_x^n \Delta t \tag{6}$$

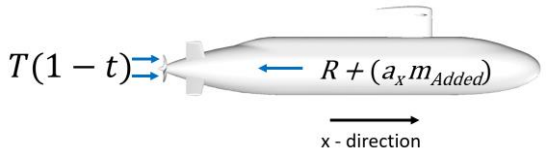


Figure 5 – Forces acting in the x-direction on the BB2 during acceleration.

The thrust force with respect to time was determined using the same process outlined for the CFD actuator disk method, i.e. thrust identity. However, rather than applying the final hub correction to propeller thrust to account for the actuator disk and moving mesh hull pressure differences, the thrust deduction (7) (Renilson, 2018) was applied to the propeller thrust (T) to correct for propeller interactions with the hull.

To calculate thrust deduction factors (t) for the BB2, full-scale towed resistance and moving mesh self-propulsion tests were conducted to determine the towed resistance (R) and equivalent self-propulsion thrust (T) in (7). These vary with speed and are shown in Table 5 for 2.57 and 5.14 m/s. For both cases the thrust deduction factor was assumed constant. For Case 1 an average value of 2.57 and 5.14 m/s was used, for Case 2 the value at 2.57 m/s was used.

$$t = 1 - \frac{R}{T}. \tag{7}$$

Table 5 – Thrust deduction factor for the BB2 for different underwater vehicle speeds.

Speed (m/s)	Thrust Deduction factor , t
2.57	0.208
5.14	0.192

During the quasi-steady acceleration, the towed resistance (R) was determined with:

$$C_T = C_F\,(1 + k_F), \tag{8}$$

$$C_T = \frac{R}{0.5\,\rho\,S U_S^2}, \tag{9}$$

where the frictional resistance coefficient is determined from the ITTC-57 correlation line,

$$C_F = \frac{0.075}{(\log_{10} \mathrm{Re} - 2)^2}, \tag{10}$$

and the form factor, k_F, was assumed constant, independent of Reynolds number. For a Reynolds number, $\mathrm{Re} = 1.8 \times 10^8$, the form factor was determined as 0.242 from BB2 full-scale CFD resistance simulations.

The added mass, m_{Added}, was determined using CFD for the direction of acceleration under investigation. Applying inviscid flow and accelerating the BB2 at a known rate, this was determined to be 214.710 t.

RESULTS

Figure 6(a) shows the velocity vs time traces for acceleration Case 1 as predicted by the four different methods. For ease of comparison, all methods were aligned to have their acceleration begin at 300 seconds. Also plotted for reference on the secondary axis, is the commanded propeller rotational speed. It is immediately evident that all methods show excellent agreement. The velocity time traces are almost the same for each method, with less than 2% difference seen at a given instance.

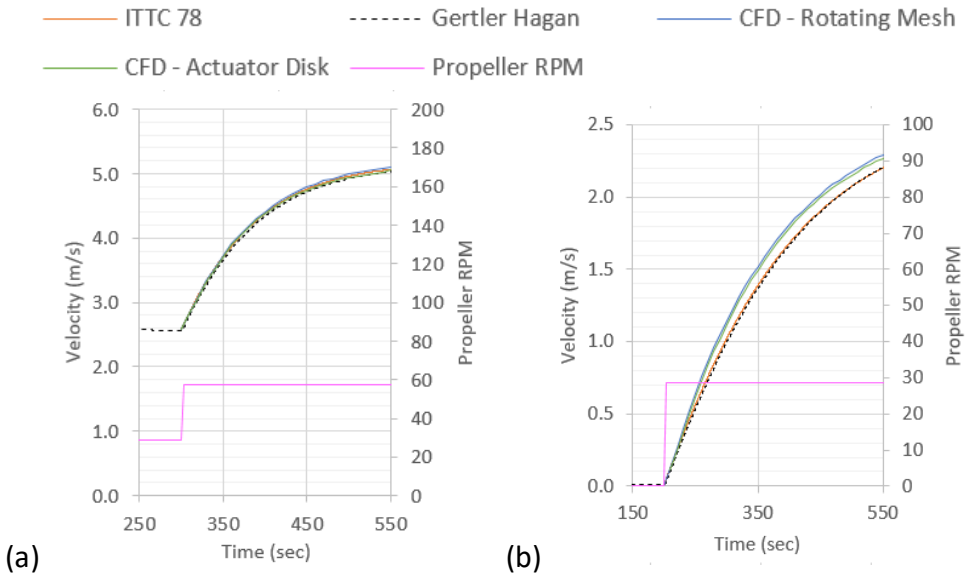


Figure 6 – BB2 speed vs time for: (a) acceleration Case 1; (b) acceleration Case 2.

Given the velocity traces were so close, the difference in total displacement predicted by all methods after 250 seconds of acceleration was less than 1.5%. The total distance travelled was approximately 1080 m.

Figure 6(b) shows the velocity trace for acceleration Case 2, from rest to 2.57 m/s. The CFD methods were initialised at a quiescent state. The CBM was run for 200 seconds to achieve a self-propulsion condition at a free stream velocity at 0.005 m/s. All plots have been aligned to this start time. There are two distinct velocity traces predicted by the methods. Both CFD simulations essentially predict the same steeper initial acceleration rate between 200 and 400 seconds when compared to ITTC-78 based method and the CBM. At 350 seconds, the difference in instantaneous velocity is at a maximum with the CFD methods predicting a velocity 10% greater. After 350 seconds of acceleration (550 seconds) the CFD methods had travelled 8% further with a total distance travelled of 525 m. The agreement between the between the ITTC-78 and CBM acceleration traces would indicate that the impact of the control surface movement of up to 1 degree in the CBM model is almost

negligible, Figure 6(b) . The difference between these and the CFD methods could possibly be due some of the assumptions made for the ITTC-78 and CBM methods, e.g. constant thrust deduction, as discussed

DISCUSSION

The results presented for acceleration Case 1, which accelerates from a self-propulsion state, show excellent agreement between all four acceleration prediction methods. In this case the BB2 is at speed and the wake flow around it is fully developed from the beginning of the acceleration manoeuvre. The varying level of assumptions for the methods that applied propeller performance curves, appear valid in these situations.

For Case 2, accelerating from a stationary state, there are significant differences in the predicted acceleration that leads to differences in the predicted total distance to accelerate to 2.57 m/s. Unlike Case 1, the flow field around the BB2 develops during the manoeuvre.

Interestingly, for Case 2, both the CFD methods with the moving propeller mesh, and the actuator disk, provided very similar predictions. CBM and the quasi-static method based on the ITTC-78 performance prediction method also provided similar predictions, with both these methods predicting reduced acceleration from the beginning of the manoeuvre when compared with the CFD methods. This suggests that the differences in model assumptions made for these and CFD methods are sensitive for this situation where there is a high acceleration relative to the flow speed.

The CFD actuator disk method used open water propeller curves and the thrust identity to determine its operating point during the simulation. A key input to this was the effective wake fraction, which was assumed constant and used the value obtained at 2.57 m/s self-propulsion. The same open-water propeller curves and effective wake fraction were used in the ITTC-78 based prediction method that predicted a reduced acceleration rate similar to the CBM, eliminating this as a cause of the difference. As the CBM and the ITTC-78 based method both predicted similar acceleration rates to the CFD methods for Case 1, it suggests all methods have similar predictions of resistance and added mass, eliminating this as a cause of the differences compared to CFD.

One assumption that does separate the CFD methods from the CBM and ITTC-78 based methods, is the thrust deduction. In both CFD methods the changes in thrust deduction, due to the presence of the propeller, is implicitly simulated by the resulting flow fields around the hull and hub of the BB2. In the CBM and ITTC-78 based methods, the thrust deduction coefficient is used to account for this and it is assumed constant for the simulation duration.

A constant thrust deduction implies that the flow field is fully developed. For Case 1, where agreement is good between all prediction methods, the assumption of constant thrust deduction appears valid. For Case 2 this is not the case, because when accelerating from a still condition, there will be some time required for the flow field to develop around the hull. To test this hypothesis, the ITTC-78 based prediction method was modified, for Case 2, to incorporate a thrust deduction coefficient that varied as the underwater vehicle

accelerated. Assuming the thrust deduction factor to be zero for the underwater vehicle at rest, it was linearly increased to its 2.57 m/s value (see Table 5) over the time taken for the BB2 to travel 1 length, and then held constant for the remainder of the acceleration. The corresponding velocity profile is shown in
Figure 7.

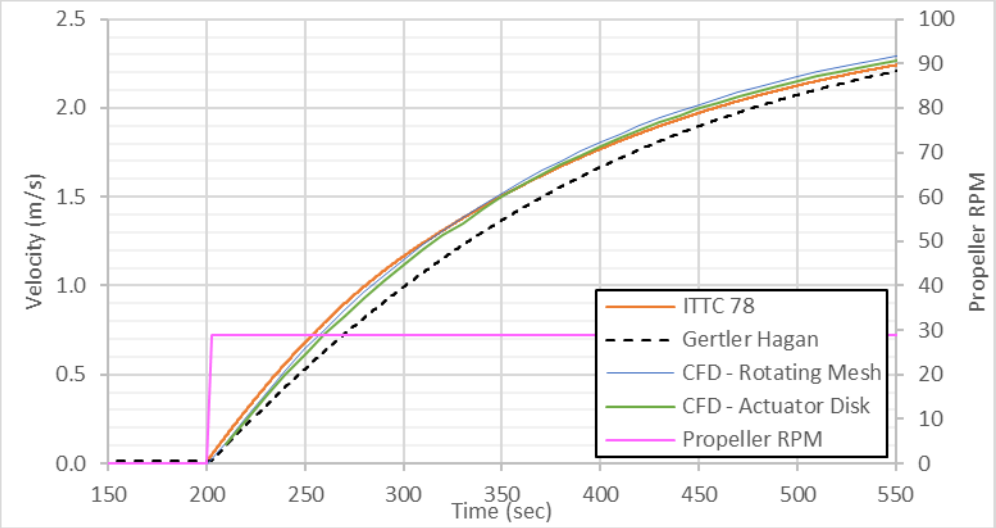


Figure 7 - BB2 speed vs time predictions for acceleration Case 2, with the ITTC- 78 based method modified to vary thrust deduction with time.

In
Figure 7, it can be clearly seen that assumed, non-constant thrust deduction factor improved the prediction of ITTC-78 based method when compared to the CFD methods, particularly during the initial stage of the acceleration. At 350 seconds, the instantaneous velocity is less than 1.5% different and the total displacement at the end of the simulations agree to within 1%.

Simulation of a platform with open water propeller curves and applying a constant thrust deduction should be used with caution in situations where there is a significant change in the flow field at the aft end during an acceleration. At every speed there is an acceleration limit, after which the use of the open water propeller curves with constant thrust deduction will start to become invalid. Typically, at cruising speeds, the acceleration performance envelope of a vessel will not hit this limit. However, when speeds are reduced, this acceleration limit will approach zero. Hence, there will be instances in service where this is regularly exceeded, especially as this is when rapid acceleration manoeuvres typically take place.

CONCLUSION

In this study, four different simulation methods have been used to predict motion traces of two generic acceleration manoeuvres. These results provide confidence in using the more efficient CBM or quasi-static method based on the ITTC-78 performance prediction method, for deep underwater vehicles accelerating from a speed with a relatively well

developed flow field. However, differences in the predicted acceleration were seen when accelerating from a stationary state and the flow field is not fully developed.

It was deduced that all methods investigated had similar resistance and added mass. Assuming a constant effective wake fraction also had minimal effect on the motion traces.

At speed, with a fully developed flow regime, the method used to simulate the thrust deduction did not significantly influence the motion traces, indicating that the use of the open water propeller performance curves is valid in this instance.

However, motion trace predictions for manoeuvres accelerating from a low speed/still condition were found to be significantly influenced by the methodology used to simulate the hull thrust deduction. Assuming a constant thrust deduction for the CBM and ITTC-78 methods over compensated for this phenomenon when compared to CFD methods. The CFD methods implicitly capture changes in the thrust deduction as the body accelerates but at a significantly increased compute cost. The ITTC-78 based method achieved a similar prediction of motion if the thrust-deduction-factor was assumed to ramp linearly with time. However, CFD methods provide a detailed flow-field that could be used for further analysis such as predicting cavitation during the manoeuvre.

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INDO PACIFIC 2022 - Presentation Paper

Underwater networks connecting Robotic Autonomous Systems (RAS)

Presented by Scott Elson/ Sandro Ghiotto

L3Harris Integrated Mission Systems Australia Pty Ltd

Email: Scott.Elson@L3Harris.com

Email: Alessandro.Ghiotto@L3Harris.com

L3Harris Integrated Mission Systems Australia Pty Ltd
108 Marine Terrace, Fremantle
WA 6160, Australia
www.L3Harris.com

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Table of Contents

1. Integrated undersea Surveillance Systems 3
1.1 Need for Underwater communIcation 3
1.2 History of L3Harris and Underwater commuincation 5
1.3 Acoustic protocols 6
1.3.1 HAIL 6
1.3.2 MASQ 6
1.3.3 STANAG 1481 7
1.3.4 JANUS - STANAG 4748 7
1.3.5 PHORCYS 7
1.4 Underwater Networks 7
1.4.1 Underwater Reliability 8
1.4.2 Adaptive Self Healing Network - MESH 8
1.4.3 CommunIcation signal Security 9
1.5 GPM300 – AcoUstic Modem 9
1.6 CUUUWI 10
1.7 MASQ.OEM – for RAS developers 12
1.7.1 MASQ.OEM INTEGRATION - IVER 13
1.7.2 MASQ.OEM INTEGRATION – deployable Autonomous Seabed Nodes 13
1.8 SEA5012 - Uderwater networking 14
2. Connecting Robotic Autonomous Systems 15

List of Figures

Figure 1 – L3Harris Integrated Undersea Surveillance System 3
Figure 2 – Range and Data rate specifications for representative communications systems 8
Figure 3 – Adaptive Network Routing 9
Figure 4 GPM300 fitted to Deapsea Challenger 10
Figure 5 CUUUWi Concept 11
Figure 6 – Ocius Bluebottle offshore Western Australia RV Whale Song 11
Figure 7 – MASQ.OEM Interface Board 12
Figure 8 – MODEM for The Iver4 – 900 13
Figure 9 – Node test launch 13
Figure 10 – Submarine deploys nodes 14

List of Tables

Table 1 – Capacity of modes with approximate data rates and effective ranges 4

1. INTEGRATED UNDERSEA SURVEILLANCE SYSTEMS

In the 2016 Defence White Paper, and more recently in the 2020 Defence Strategic Update and Force Structure Plan, the Commonwealth emphasised the need to meet the challenging threat and proliferation of submarines in the Indo/Pacific region. The development of a capable, agile, and potent Australian Defence Force (ADF), able to protect Australia and its national interests in a demanding future operating environment, requires the modernisation and the enhancement of the potency, range and capability of Australia's Maritime platforms, weapons, and surveillance systems. Through Project SEA5012 PH 1 the Commonwealth intends to invest in the Royal Australian Navy's (RAN) next generation of undersea surveillance to counter the current and future subsurface threats in the region and to Australia. To meet these strategic objectives, the SEA5012 PH 1 project team has issued a Request for Information (RFI) seeking industry input in support of the development of an Integrated Undersea Surveillance System (IUSS).

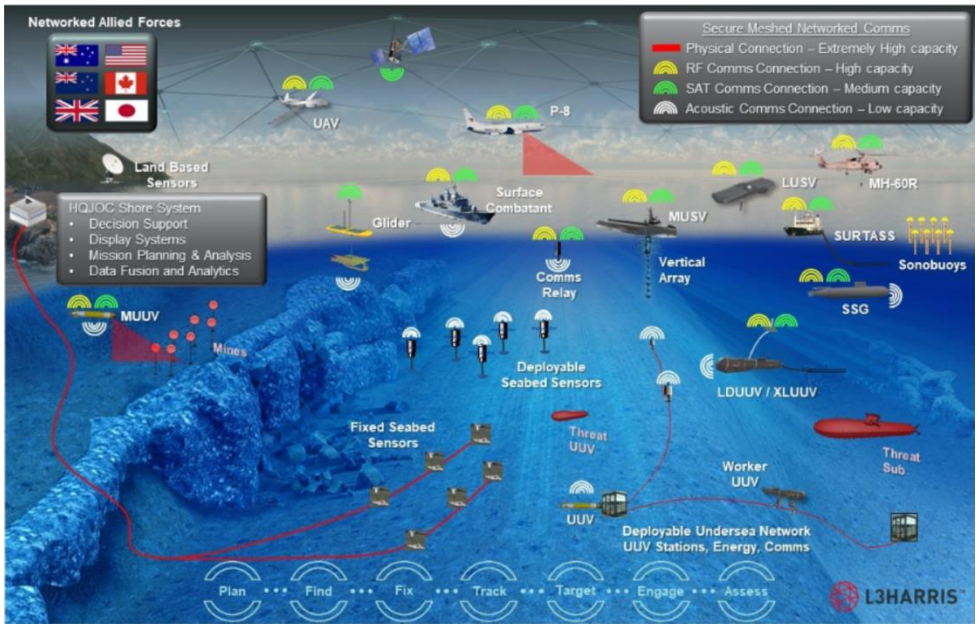


Figure 1 – L3Harris Integrated Undersea Surveillance System

1.1 NEED FOR UNDERWATER COMMUNICATION

An IUSS (Integrated Undersea Surveillance System) utilises multiple modes of communication from sensors to points of data aggregation. In general, increased automation and sensor analysis is required at points where the available communication capacity is lower. Conversely, where there is higher capacity, raw data can be transferred to and analysed in a central location. Figure 1 shows the variety of rates available to the various sensors in the undersea system.

Table 1 lists the corresponding approximate data rates and effective maximum ranges.

Table 1 – Capacity of modes with approximate data rates and effective ranges

Capacity	Modes	Data Rates	Ranges
Extremely High	Fibre-optic cable	~10 gigabit	> 1000 km
High	Line of Sight RF Comms	~100 megabit	< 500 km
Medium	Satellite Comms	~10 megabit	> 1000 km
Low	Acoustic Comms	~1 kilobit	< 100 km

Raw acoustic data is commonly down-sampled to the frequency band of interest to minimize required capacity. These rates can vary significantly based on the sensor and desired target characteristics that are being exploited. However, a reasonable sampling rate of 10 kHz can be used to compare the different modes of communication. Sampling resolution can also vary with sensors, but a reasonable modern analogue to digital converter (ADC) samples at 24-bit, commonly up-sampled to 32-bit complex sampling. With these assumptions, each sensor in the system produces approximately 640 kilobits of information per second. This example clearly demonstrates the need for local processing of sensor data into contacts because bandwidth of a single acoustic channel can far exceed the available bandwidth of acoustic comms.

Extremely high-capacity systems, such as a fibre-optic network of fixed hydrophones, can support essentially unlimited numbers of sensors with added fibres. Data collected on this network can be aggregated at a shore facility and analysed in real-time. Shore processing locations facilitate the use of advanced signal processing techniques that are computationally expensive because the limitations on space and power are not nearly as severe as on many mobile platforms. Such facilities are also logical locations for fusion of lower capacity sensor detections into the overall tactical picture.

High and medium capacity systems, (e.g., sonobuoys, gliders, surface craft, helicopters, and un-crewed surface vehicles) do not typically have the required bandwidth to continuously broadcast raw sonar data in real-time. Some have enough bandwidth that a limited amount of compressed detection data can be transmitted back to shore automation and operators. In acutely bandwidth limited cases on-board processing is required to first identify contacts of interest before relaying down-sampled information back to the data centre. This signal processing can vary in complexity based on the available computing power on the platform. For example, surface craft have relatively high computational power at their disposal that can utilise adaptive beamforming to increase the signal to noise ratio needed to identify distant or quiet targets. However, sonobuoys and gliders are much more power constrained and can send only tracks or limited snapshots of sonar data back to the data centre for further processing.

Low-capacity systems, depending on acoustic communications, do not have the available bandwidth to relay any meaningful amount of raw sonar data. Instead, these systems much first reduce the sonar data down to detection contacts that include target state and variance estimates. These low-data rate products can then be transferred and

relayed back to the data centre. As with surface and air units, the available power varies considerably in the undersea realm. Submarines have exceptional sensors and computational power available to process raw data and produce contact reports prior to relaying. However, un-crewed vehicles and temporary-fixed installations are greatly power constrained. This underscores the need for feature extraction and classification algorithms that are both high-performance and efficient so that they can be implemented in power-limited remote applications.

1.2 HISTORY OF L3HARRIS AND UNDERWATER COMMUINCATION

L3Harris has been developing underwater communication systems for many years, in which the technologies are currently deployed in RAN programs as below:

- SAARS - Fixed range developed to support acceptance and ongoing maintenance of the CCSM acoustic signature
- STS - L3Harris acoustic Submarine Tracking System (STS) unique to the Australian capability, upgraded under the SEA1439 Phase 6 SONAR baseline
- HAIL – Hydro Acoustic Information link – Providing low probability intercept long-range underwater water acoustic commutations at speed and depth. Fitted to CCSM, AWD and soon to be on the ANZAC vessels
- PASOR – Portable acoustic range allowing for tracking and ranging of submarines and other subsea assets at speed and depth
- AUSSNet - Underwater communications and ASW Sensors network system
- MASQ – Multichannel Acoustic Signalling QoS - An enhancement of HAIL allowing for higher bandwidth and latest generation DSP architectures, proven to operate from the bottom of the Marianas trench – near 11km subsea
- CUUUWi – Sea surface persistent and controllable gateway buoy systems allowing Shore to subsea communication using HAIL, MASQ or other subsea protocols
- Other Anti-Submarine, Surveillance, Detection, and Vulnerability systems for use by Submarines and Surface ships, currently being developed under a Defence Innovation Hub funding can be provided on request.

1.3 ACOUSTIC PROTOCOLS

Underwater acoustic communications are a global domain in which different manufacturers produce different devices and implement different (and usually incompatible) communication protocols. The myriad of vendor-specific protocols is not conducive to collaboration amongst different industry, academia and research partners. Below is a few of the common protocols in operation within the Australian Defence Forces.

1.3.1 HAIL

L3Harris developed HAIL in Australia in the late 1990's to enable RAN submarines with communications at speed (up to 30 knots) and depth, using spread spectrum acoustic signalling for low probability of intercept (LPI). HAIL has been on board RAN submarines and surface vessels continuously.

1.3.2 MASQ

L3Harris has continuously sustained development in acoustic communications and made a series of improvements over HAIL that are included in the current product, MASQ (Multichannel Acoustic Signalling QoS). MASQ was initially developed to overcome the increased data rate and underwater networking requirements that were introduced with L3Harris' Acoustic Undersea Surveillance Sensor Network (AUSSNet).

The MASQ signalling has been continuously refined over the last 10 years and has been extensively utilised in most of the world's oceans for Defence and Commercial applications. MASQ has been proven to be reliable in the most challenging acoustic environments; in high noise such as Singapore Harbour; strong reverberation such as the basalt bottom shallow waters near Kiel, Germany; and under high pressure, with long multipath during the many scientific expeditionary dives to the deepest ocean trenches for James Cameron and then for Triton Submarines.

MASQ improves over HAIL with:

- Network addressing for source-receiver mapping through a network of nodes
- Sleep mode for long-endurance battery powered operation. A low power wakeup signal precedes the main MASQ signal and starts the main processor in a few microseconds
- A Rake receiver for recovering and deconvolving multipath signals. The recovered multipath energy which normally presents as noise significantly improves receiver sensitivity, enabling longer range, better LPI (lower radiated signal level) and overall, more robust communication
- Support for time of flight for distance measurement to sub meter accuracy with appropriate high accuracy time reference

1.3.3 STANAG 1481

The NATO Classified STANAG 1481[1] was ratified with a customised version of MASQ (not compatible with standard MASQ). The standard is intended for use for Identification of Friendly Submarines (IFS).

1.3.4 JANUS - STANAG 4748

The JANUS standard was published as a NATO Standard (STANAG 4748) and has been implemented by an increasing number of vendors.

JANUS was developed to allow interoperability within the NATO Science and Technology Organization (STO) Centre for Maritime Research and Experimentation (CMRE) towards the establishment of a standard for digital underwater acoustic communications.

1.3.5 PHORCYS

The UK DSTL has begun development of a underwater digital communication waveform called Phorcys[2], The aim is to develop Phorcys as an open standard for secure acoustic communications that will enable navies to collaborate and interoperate, assuring secure transmissions and communications.

1.4 UNDERWATER NETWORKS

The transport and network layer software has been updated recently within the MASQ protocol. L3Harris underwater communications transport and network layers are combined and incorporate a number of bandwidth and energy preserving techniques whilst optimising quality of service.

The Network-Transport Layer functionality includes:

- Store and forward of Packets. This is required for networks that have intermittent connectivity
- Explicit and implicit acknowledgement of Packets. Implicit acknowledgements leverage forwarded messages as acknowledgement, thereby halving the number of required transmissions
- A Retransmission scheme. Efficient Methods for guaranteeing service in the event of partially or fully missed messages, including Packet concatenation and fragmentation
- Optimisation of transmit power. Encoding of the acoustic noise level in each transmitted signal. Responding messages are power optimised for noise level and link margin

1 https://standards.globalspec.com/std/14252733/STANAG%201481

2 https://navalpost.com/phorcys-a-new-solution-for-underwater-comms/

- Static routing with failover support, providing autonomous re-routing to alternate network paths and the leapfrogging of failed nodes

1.4.1 UNDERWATER RELIABILITY

The L3Harris MASQ Underwater Communications and the Network Layer function is designed primarily to provide the best-available reliability in wireless underwater communication.

The focus in reliability over maximum data rate, as compared with the data-rate focussed underwater communication methods and products by others is illustrated by Figure 2 which shows the raw data rate (claimed) and range (claimed) by various underwater communication system developers/vendors. L3Harris' focus on reliability is seen as a trade-off of data rate for range.

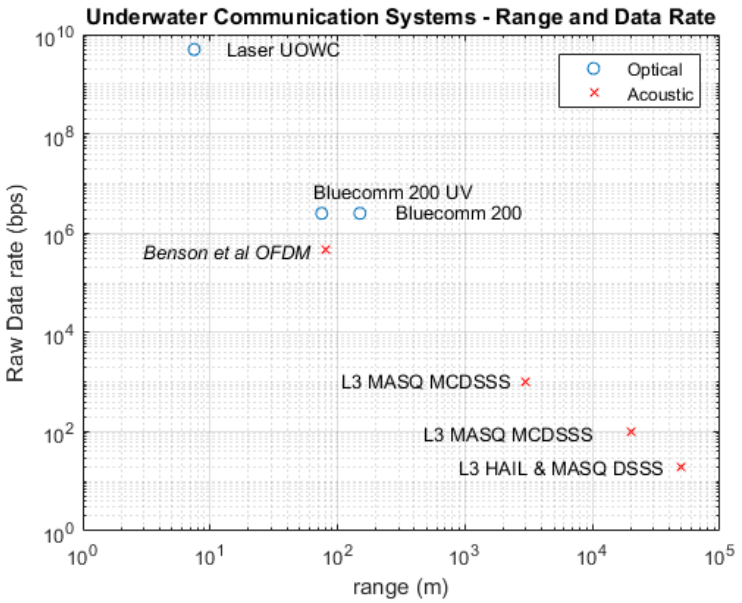


Figure 2 – Range and Data rate specifications for representative communications systems

1.4.2 ADAPTIVE SELF HEALING NETWORK - MESH

A mesh network improves communication reliability and offers routing redundancy. When one node can no longer operate, the rest of the nodes can still communicate with each other, directly or through one or more intermediate nodes. Wireless mesh networks can self-form and self-heal. Wireless mesh networks work with different wireless technologies including 802.11, 802.15, 802.16, cellular technologies and need not be restricted to any one technology or protocol.

In the terms of underwater communication, the topology tends to be more planned and static, so that routes computation can converge and delivery of data to their destinations. Networks can include gateways or other devices which bring data in and out of the mesh.

Adaptive signalling levelling can allow the underwater acoustic emissions to reduce, ie providing the quietest route that minimises power consumption and probability of intercept.

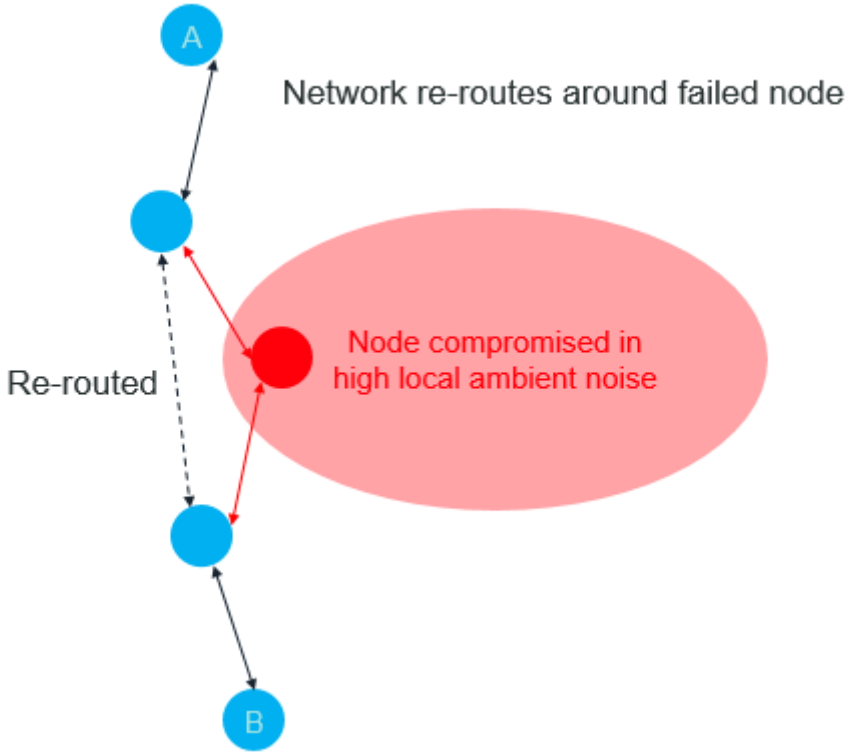


Figure 3 – Adaptive Network Routing

1.4.3 COMMUNICATION SIGNAL SECURITY

By utilising the pseudo-random spreading codes that are part of the Direct Sequence Spread Spectrum (DSSS) Modulation methods within the protocols, the signalling schemes used within MASQ allow for multi-layered Encryption.

Operational secure modes can be included with encrypted with AES-128 or AES-256 methods and within the spreading codes implemented.

It is aimed that differing encryption keys can will be included to allow for customer mission requirements.

1.5 GPM300 – ACOUSTIC MODEM

The GPM300 Acoustic Modem is L3Harris' long-range subsea communications system first used as part of James Cameron's Deepsea Challenge expedition in 20123. The modem uses third generation MASQ (Multichannel Acoustic Signalling QoS) multichannel Direct Sequence Spread Spectrum (DSSS) technology for high reliability communications, robust against multipath inter-symbol interference. This technology is fitted to existing Collins Class Submarines (CCSMs) as part of the Submarine Tracking Sub System (STSS). In addition, the modem is also capable of HAIL, which is already a

[3] P. Roberts, N Andronis & A Ghiotto, "Voices from the deep – Acoustic communication with a submarine at the bottom of the Mariana Trench", Australian Acoustics Society 2012

permanent fit on CCSMs and AWD. It can also be used as a STANAG 1074 compliant underwater telephone (UWT) and future will include JANUS[4].



Figure 4 GPM300 fitted to Deapsea Challenger

The GPM300 can be integrated on all subsea equipment allowing for long range reliable underwater communication between systems. The technology was developed and is maintained in Australia by IMSA and has been exported to Navies and commercial projects worldwide.

Whilst providing superior performance, the GPM300 is provided in a fixed form factor, and is tightly coupled processor, power amplifier, and transducer

1.6 CUUUWI

The CUUUWi SATCOM/Acoustic Gateway provides two-way voice and SMS connectivity between Subsea assets and CUUUWi-registered mobile phone users, auto engaging the Iridium SATCOM network when the Gateway is beyond the terrestrial network range.

CUUUWi uses an L3Harris GPM300 acoustic modem to achieve through-water communications with submarines at ranges up to 20 km using MASQ and HAIL, and up to 15 km using underwater telephone. The CUUUWi system provides underwater network routing and store and forward capabilities to overcome the mobile and adhoc characteristics of submarines in the network.

[4] https://www.researchgate.net/publication/265594031_The_JANUS_underwater_communications_standard

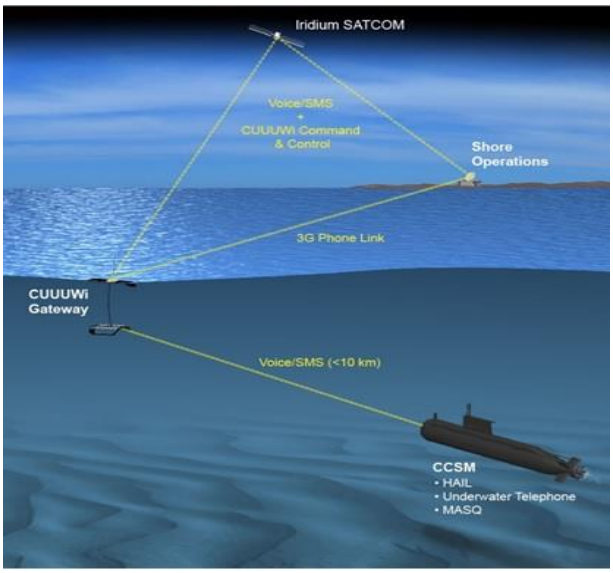


Figure 5 CUUUWi Concept

L3Harris is seeking to develop the CUUUWi gateway system into a Submarine or UUV launchable communication gateway that would provide a submarine commander or subsea swarm the option to initialise gateway communications at depth underway at their discretion. These options widen the CUUUWi gateway utility to include patrol, task group, and theatre operations.

CUUUWi has been integrated with four Defence MOS SPO owned Liquid Robotics Wave Gliders, and the OCIUS Bluebottle.



Figure 6 – Ocius Bluebottle offshore Western Australia RV Whale Song

1.7 MASQ.OEM – FOR RAS DEVELOPERS

L3Harris is investing to make the MASQ protocol available to a larger user community, including off board sensors installation kits, by conducting R&D in smaller, modular, software defined solutions under the MASQ.OEM framework. Latest protocol developments include rake receiver, network/mesh mode, LPI signalling, encryption and power adaption control.

The MASQ.OEM is being developed to provide

- Low cost, Low SWaP
- MASQ on Raspberry Pi 4
- Analog interface board (85mm x 77 mm)
- Transducer (power amp / preamp) interface boards
- Custom carrier boards
- Distributed processing option (software runs on host processor)
- Standard interfaces (Ethernet, USB)
- Wet-end flexibility

MASQ.OEM currently support MASQ, and in the future will include JANUS[5]. and the Phorcys waveform and others allowing for interoperability.

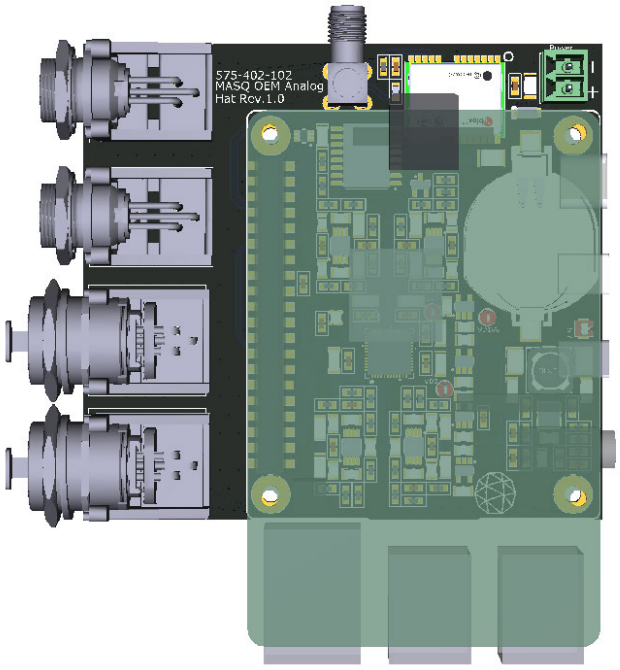




Figure 7 – MASQ.OEM Interface Board and IVER 3

[5] https://www.researchgate.net/publication/265594031_The_JANUS_underwater_communications_standard

1.7.1 MASQ.OEM INTEGRATION - IVER

Integration of MASQ.OEM allows for rapid insertion in existing RAS platform, with minimal customisation. Aim to integrate with existing spare sensor processing and customised transducer that can be moulded within the body of the system. Below is an indicative installation into an IVER4 900 front payload section.

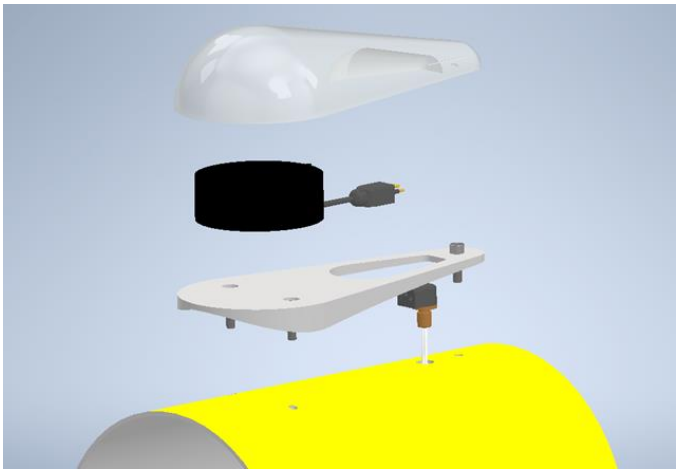


Figure 8 – MODEM for The Iver4 900

1.7.2 MASQ.OEM INTEGRATION – DEPLOYABLE AUTONOMOUS SEABED NODES

L3Harris have developed a smaller, lighter, low cost and rapidly deployable AUSSNet with longer endurance, and significantly upgraded networking capability.



Figure 9 – Node test launch

Two of the types of surveillance outcomes are deemed achievable by using the autonomous seabed nodes. These are:

1. Acoustic sampling and categorisation to build environmental and anthropogenic acoustic patterns over time.
2. Detection and alert of acoustically significant events.

The communication of an alert signal is relayed through the node network using MASQ acoustic communications.

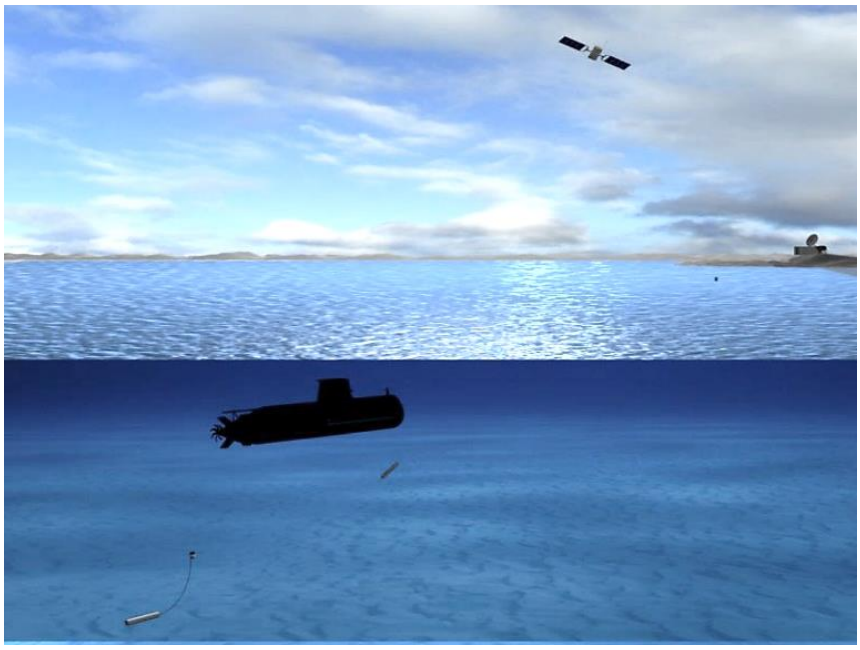


Figure 100 – Submarine deploys nodes

1.8 SEA5012 - UDERWATER NETWORKING

Australia's Maritime jurisdiction is enormous and diverse, covering 13.6 million square kilometres (or 4% of global ocean areas).[6] Australia's Maritime approaches are critical for trade, natural resources development and acts as a natural barrier for the defence of the nation. Situational awareness of these approaches particularly the undersea domain is essential to protecting these interests. The underwater environment is complex and becoming more so with increased density and variety of users, including threat vectors such as submarines, mines, and autonomous underwater vehicles. The rapidity of technological advancement in networking, autonomy, concealment, lethality, and longevity of deployment have further complicated this environment. To address this increasing complex environment and meet the challenging threat vectors, the Commonwealth has emphasised the need for improved undersea domain awareness through the provision of advanced persistent undersea surveillance capabilities across specific and wide area areas of interest.

[6] DSTG EDTAS insights paper – Remote Undersea Surveillance, Emerging Disruptive Technology Assessment Symposium, 2021, p.4

2. CONNECTING ROBOTIC AUTONOMOUS SYSTEMS

All underwater RAS systems working within a common environment will require interoperable underwater communications that are reliable, networkable, self-healing and secure.

L3Harris offers a sovereign underwater communications capability that is in service today can be easily adapted to all subsea systems, that includes todays and future protocols allowing for interoperability.

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Persistent Autonomous Data Gathering And Monitoring - A Future Vision For Autonomous Ocean Observations.

Robert Dane, Robert Dane

Ocius' Uncrewed Surface Vessels (USVs) called Bluebottles are named after the Australian marine animal, that lives at sea and uses its body as a sail. Bluebottles autonomous robots powered by sun, wind and waves that navigate for long periods over cover vast areas to conduct autonomous surveillance missions distant from the mainland. They are AMSA approved for autonomous operations in Australia's EEZ.

Ocius is working with the Australian Defence Department, Australia's leading naval architects and boat builders, University of NSW, AMC and Defence Primes to build a quiet platform that can carry a 300kg payload, tow a 'thin line' array and power that payload and array with 150W average and peak loads of kW continuously operating 24 hours per day, sustainably and indefinitely with just 8 hours sun/day. They have months endurance and unlimited range.

Ocius is completing a DIH contract with persistent monitoring and surveillance with 5 Bluebottles operating in the Indian Ocean from September - Dec 2021 and ASW activities with Thales Australia in Q1 2022. Ocius will present unclassified results and data of relevance to submariners, ADF and ABF personnel at the conference.

SESSION 17

Ship Sustainment

Hey Siri!' for the marine coalface
Paper only - No presentation

Lessons learnt from oil and gas: Practical opportunities to increase operability and capability through optimising inspection, engineering and repairs

Innovative concepts within LCM analytics

'Hey Siri!' for the Marine Coalface

Carl Byers (Contexere), Gabe Batstone (Contextere) & Kai Skvarla (Serco)
gabe@contextere.com

ABSTRACT

Each day, military and civilian maintenance, repair and overhaul (MRO) personnel spend over 30% of their day searching for information. Even when they are actively engaged in their work, they will do the job incorrectly up to 25% of the time. At the same time, there is a tremendous amount of data available from streaming sensors, enterprise data systems and reference materials designed to help organizations make better decisions. Unfortunately, engineers rarely benefit from last mile analytics and maintainers are left to rely on decades old work procedures, resulting in little opportunity for improvement in equipment efficiency or workplace productivity.

In this presentation, the authors will discuss efforts on the RSV Nuyina to develop and test a new insight engine for Maritime Analytics and an advanced virtual assistant for MRO technicians that empowers the platform to increase overall equipment efficiency (OEE) and crew productivity. This prototype solution uses machine learning (including transformer based neural networks) to extract IOT, enterprise data and previously inaccessible last mile information to generate new operational insights. In addition to leading to better planning decisions this knowledge can then be deployed to the last tactical mile though AI-enabled work instructions for maintainers on mobile devices. Finally, we will discuss how this technology will successfully educate workers, eliminate rework, and improve workplace safety.

THE CURRENT MARITIME AND INDUSTRIAL CHALLENGE

Each day, millions of men and women in thousands of organizations throughout the world spend over 30% of their day on non-productive time (NPT) activities. They are not idly wasting time, rather they are actively trying to find the right information, waiting for guidance, or attempting to coordinate with other work teams. While this condition exists throughout companies and across industries, it is particularly endemic within technical maintenance and operations activities.

Exacerbating the situation is the human error rate (HER). Once these workers have the information they need, they are still likely to do the job incorrectly 25% of the time. This high HER results in costly rework as well as the broader potential of catastrophic equipment failure and human injury. In addition, these issues lead to unplanned downtime, low employee engagement, and lost asset productivity.

INFORMATION TECHNOLOGY GAPS

The reasons for the current state of low productivity and high human error are as varied as the companies that experience the problem. In most organizations, data is trapped in silos and contextual relevance across functional domains and activities is often lost. In addition, the disconnect between headquarters IT systems and field operations OT results in

information not being available where and when it is often needed - on the last tactical mile. Despite massive corporate investment in data capture and analytics, the application and benefits of that information remains constrained to the core of headquarters operations – enterprise efficiency and production optimization (opex), and capital equipment investment planning (capex). Frontline workers rarely have access to information that may be relevant to their own decision-making and activities.

Conversely, there is often an incomplete understanding of equipment operation and maintenance issues because of ineffective data collection in the field. As a result, systemic equipment or human error is difficult to identify, analytics significantly lags major equipment issues, and prediction of potential failure modes is inaccurate and slow. In addition, manuals become out of date and operational advisories and service bulletins are not provided in a timely manner. Furthermore, peer knowledge sharing is hampered by non-existent or poorly integrated digital tools on the job.

With the emergence of the Industrial Internet of Things (IIoT) and machine learning (ML), there is an intense focus on making equipment smarter and self-optimizing using on-board sensors and remote or centralized analytics. The collected information is also being used to support maintenance planning and pre-positioning of personnel and spares to accelerate maintenance processes. While the IIoT generates massive amounts of new data to support enterprise decision-making and ML is used to identify trends and predictions, it represents yet another silo of information that is rarely available to frontline personnel. Knowledge of the condition of the equipment around them and ML in their hands to provide timely decision support and insights would enable frontline workers to make immediate decisions and take action that could improve operations and efficiency, increase safety, avoid equipment failures, and reduce unplanned downtime.

WORKFORCE SKILLS GAPS

While not trivial, many of the issues identified above can be addressed through integrated data management and effective digitization infrastructure. However, there remains a fundamental structural gap that will continue to impact companies – this issue is the workforce skills gap.

New technologies and demographic shifts have been radically transforming the way that organizations conduct business and the type of skills their talent need to help them thrive in this new age of work. The World Economic Forum (WEF) reported in 2020 that nearly 50% of companies expected that automation would lead to some reduction in their full-time workforce and that more than half of all employees will require significant reskilling and upskilling. The Covid-19 crisis has exacerbated these trends.

The combination of workforce retirement and slow time to proficiency is resulting in lost expert tacit knowledge and a lack of skilled personnel. Fewer, more inexperienced people are expected to do more with less on equipment that is increasingly complex. This challenge worsens the NPT and HER and is not solved simply through more data.

Upskilling and reskilling at scale can enhance the economic dynamism of their businesses, at the same time as it can create an ecosystem that ensures all workers are employable and

productive in the new world of work. This problem has historically been addressed with a patchwork of training solutions with a combination of classroom, on-line self-paced, and on-the-job learning coupled with knowledge refreshers to reduce skill fade. However, these solutions do not scale to the enormity and pace of change of the current challenge. New approaches that enable workers to perform and learn on the job are essential to adapt to this need.

The WEF has emphasized the urgency surrounding this issue. So much so that is has launched the Reskilling Revolution Platform with the mission to provide better jobs, education and skills to one billion people by 2030. This initiative brings together businesses, civil society, and education and training partners to collectively drive coordinated action and address workforce transformations through intra- and cross-industry collaboration.

A centrepiece of this WEF Platform is the Skills Link Alliance, an ecosystem of partnerships between learning providers, employers and governments designed to operationalize the Reskilling Revolution and shift toward a skills-based labour market by adopting a common language for skills, recognizing skills-based credentials, partnering for skills-based learning delivery, and adopting and championing skills-based workforce strategies. Contextere is a founding partner of the Skills Link Alliance.

EFFECTIVE DECISION SUPPORT FOR FRONTLINE WORKERS

Technical ("blue collar") maintenance and operations teams are the backbone of asset intensive industries. Frontline worker performance efficiency and situational awareness has a direct impact on enterprise productivity and economic performance as well as customer and employee satisfaction. As more data and information becomes available across the enterprise, the implication of that data needs to be in the hands of those on the frontline – where warms hands touch cold steel. Furthermore, insights and experiences from those working directly with the equipment are a critical input to opex and capex planning. As a result, it is critical to enable these technical personnel with the most advanced technologies and solutions for knowledge development, situational awareness, information delivery and capture, and decision support.

A variety of technological solutions have been implemented or tested to address these issues and improve the performance and safety of frontline workers. These include mobile access to enterprise data systems and electronic manuals, digital data entry, and reporting on tablets and smartphones. Augmented/virtual reality (AR/VR) and remote video assistance are the latest evolution of this digitization and mobility journey.

However, each of these existing strategies to deploy information to the frontline worker take the view that, if information is accessible and portable, it will have inherent value and will be useful. However, the reality is that it is not more information that they require. Instead, they need smarter systems – systems that understand the context of who they are, where they are, what is happening around them; systems that proactively determine what information they need and that make it easy to find the information that they require the moment that they need it.

Decades of research has been conducted on decision support in high workload environments. These techniques begin with an understanding of the user's local and physiological context and serve to either focus attention on critical items or remove the information noise within the operating environment. While much of that research has been focused on mission critical military applications, contextual cueing strategies are recognized to increase situational awareness, reduce user anxiety, and decrease cognitive workload.

Context aware computing driven by ML and data integration enable a new generation of frontline worker solutions that are smarter, more relevant to the end user and that are designed to determine and deliver the right information and insight to the right user at the right time, in a format appropriate to the user's device and work environment.

THE CONTEXTERE INSIGHT ENGINE - NEW BENEFITS FROM MACHINE LEARNING

Context aware computing is enabling a new category of mobile applications that provide user-centric in-situ guidance and recommendations. General purpose agents such as Apple's Siri, Google Assistant, and Amazon's Alexa have become commonplace in most people's lives. However, the industrial environment has not yet benefitted from this powerful class of solutions.

Within enterprise environments, Gartner has identified a new class of digital workplace solutions – Insight Engines – that combine ML and search to deliver powerful insights from enterprise data. Gartner differentiates insight engines by the complexity and range of the content that is indexed and correlated, the richness of the relevancy methods, and the complexity of the queries and subsequent insights that are delivered to people and machines.

The Contextere Insight Engine is the first solution to combine data extraction, machine learning, and natural language understanding to provide insights and decision support to frontline technical workers operating, maintaining, and manufacturing complex equipment. This capability enables industrial workers to get the job done right the first time, develop their knowledge and skills on the job, and improve their productivity and safety.

In recognizing Contextere in its 2020 Cool Vendors for the Digital Workplace report, Gartner noted that analytics and insights engines "typically focus on the needs of desk-based workers in large organizations", whereas the Contextere Insight Engine is unique in that it "uses context alone to proactively deliver all of the relevant information needed to complete a task" regardless of user location or domain.

Contextere applies ML together with conversational natural language processing to proactively and predictively deliver curated guidance to a technician or analyst in an industrial setting based on their evolving local real-time context and interests. The focus of Contextere algorithms is to determine and deliver just the right piece of information – a reductionist approach to curating the vast amount of available enterprise data.

By providing critical information proactively, when and where it is needed, the Contextere solution enables each worker to make better decisions and conduct operation, maintenance, and repair activities effectively and safely.

In contrast to ERP systems of record, Contextere integrates and semantically correlates structured data across enterprise systems and fuses that data with other unstructured 'small' or real-time equipment data. Unlike remote assistance and AR/VR applications, Contextere constantly determines user context and provides real-time, context-driven guidance and insights driven by ML and natural language processing. Contextually relevant insights are dynamically determined based on the evolving human-machine context and presented in real-time to the user on their mobile or wearable device (with or without AR).

As Gartner noted in their 2020 Digital Workplace report, Contextere is "focused on augmented knowledge which is deeper and more substantial than augmented reality". Contextere ML algorithms are uniquely optimized for small datasets containing highly technical domain-specific language and constantly determine and deliver curated guidance and insights for frontline workers.

A CASE STUDY – SERCO AND THE RSV NUYINA

Serco Canada Marine and Contextere formed a strategic partnership in 2019 to investigate how ML can be used to solve complex maritime challenges related to prediction, prevention, and prioritization of in-service support (ISS) activities.

Serco selected the RSV Nuyina to deploy a proof of concept (POC) implementation of the Contextere Insight Engine. RSV Nuyina is an icebreaking research and supply vessel supporting Australian scientific activities and research bases in Antarctica. Capable of deploying a wide range of vehicles, including helicopters, landing barges and amphibious trucks to support the resupply operation, the new ship provides a modern platform for marine science research in both sea ice and open water. Serco Australia project managed the overall ship design and building process and will operate and maintain the vessel for up to 30 years.

This new ship platform provided an opportunity to validate the ability of the Contextere Insight Engine to extract and curate domain specific technical maritime data and generate operational insights. By unlocking massive amounts of last mile data this initial implementation would demonstrate the ability to increase workforce productivity and maximize shore time for Serco customers around the world.

The POC implementation analyzed over 20,000 documents and files and was able to achieve over 95% data extraction accuracy on the POC dataset. The Contextere Insight Engine achieved over 90% accuracy in understanding user questions and identifying correct answers within the dataset. These correct answers were returned to users within the Contextere app on Microsoft Teams in under two seconds, enabling the POC to begin testing the target operational objectives to:

- reduce time spent looking for information by 75%;
- increase first time right execution to 95%;
- decrease non-productive time by 50%; and,
- decrease requirements for technical support by 50%.

CONCLUSION

The application and use of ML continues to rapidly evolve, becoming a virtually ubiquitous capability within the systems we use daily in our lives. With the advent of the Contextere Insight Engine, frontline technicians and operators can now benefit directly from this evolution, obtaining contextually relevant insights and guidance in seconds, wherever and whenever they need it.

With Contextere, technical frontline workers can continuously grow their knowledge and competency on the job, stay safe, and be their productive best. In turn, companies receive the benefit of effective workforce development, maximum equipment uptime, and optimal human-machine performance.

Lessons learnt from Oil and Gas: Practical opportunities to increase operability and capability through optimising inspection, engineering and repairs

Matthew Williamson MRINA C.Eng, Alex Mosnier MRINA C.Eng, Emma Tongue MRINA C.Eng, Colin Spence MRINA C.Eng

1. ABSTRACT

Traditional hull integrity management methods originally designed for trading vessels on a regular docking cycle are sub-optimal for assets that have different usage patterns (e.g. FPSOs moored offshore). Given the constraints around inspection and repair timing, novel and innovative methods have been developed to achieve a more targeted and flexible approach. These methods prioritise engineering investigation and structural risk evaluation over taking an asset out of service for survey and repair.

This paper presents results from several case-studies and details savings and increases in operability achieved. Areas where a tailored engineering strategy and risk-based approach prove advantageous compared to the simpler prescriptive approach of periodical inspections, drydockings and repairs are presented. Furthermore, the regulatory context within Australia from a Class and Statutory perspective is discussed.

The commercial techniques and case studies are then reviewed within a naval context, in particular given the latest “goal-based regulations”, exploring how similar approaches might increase capability and operability of front-line naval assets.

2. INTRODUCTION

Traditionally for marine assets, engineering optimisation of hull structures has been limited to the design stage. During operations hull structure is typically dealt with using a prescriptive rule-based approach [1], [2], [3], [4], [5]. These robust requirements are normally specific to generic vessel categories and loading conditions and based on decades of experience over numerous operational areas. They enable Surveyors with limited asset specific design knowledge to carry out inspections and specify standard repairs when generic acceptance criteria are not met. In the context of a cargo ship or oil tanker trading between ports on a regular docking cycle, or a bulker with long voyages in a ballast condition this approach makes sense. Inspections can easily be scheduled, and cost of repairs is low.

There are however other types of assets which can benefit from a more tailored and flexible approach. This is enabled using increased engineering expertise and alternative regulatory frameworks to optimise hull structural integrity management. This reduces risk and increases asset availability and capability whilst in operation.

This paper describes optimisation in the areas of inspection, engineering assessment and risk mitigation. It also presents case studies demonstrating savings and increase in operability achieved for Floating Offshore Units. Building on this experience this paper also suggests where these techniques may be transferable to the Naval sector.

3. INSPECTION AND MAINTENANCE

Historical approach and background

Inspection requirements for vessels in service have traditionally consisted of periodical survey, with most inspection carried out at regular intervals and most work performed during dry-dock at five-year intervals [1], [2]. Classification Societies have also introduced continuous hull survey [1], [2], whereby major inspections can be staggered across the five-year cycle providing operators with more flexibility. The scope of both these types of inspections remains generic to a vessel class across which there can be significant differences in design detail & operational environment.

Whilst offering robust assurance for hull integrity, these historical approaches will rarely be the most efficient for a specific asset and operating conditions. This is a missed opportunity for the potential to optimise the way risk is managed, increase operational availability and capability as well as reduce cost and avoid unnecessary HSE exposure for inspectors carrying out high risk work.

Types of maintenance and inspections

Five stages of the evolution of maintenance applicable across all industries are shown at a high level in Figure 1. Maintenance approaches can range from mainly reactive right up to a sophisticated system able to predict failures before they arise. For hull structure this level of sophistication could consist of tailored risk-based inspections fed by live data (motions, stresses, load cycles etc.) and managed in a combined data and analysis digital twin.

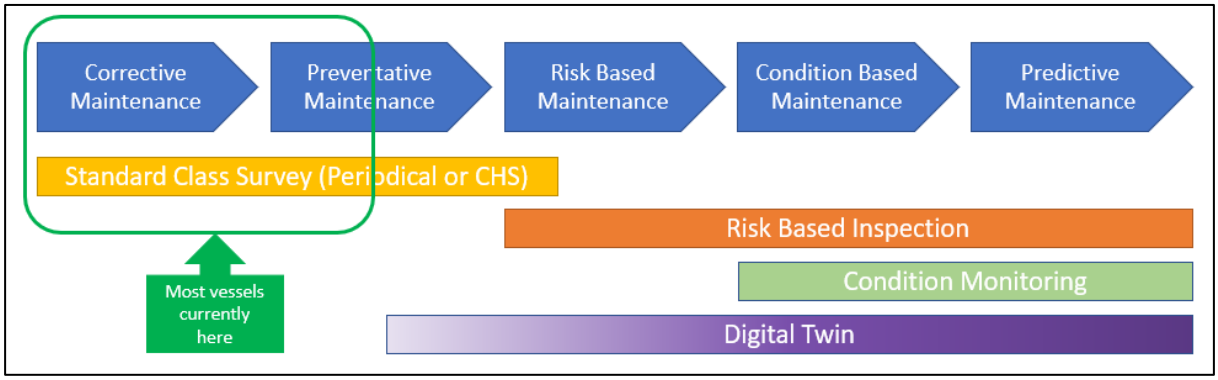


Figure 1 Evolution of maintenance

Although most vessels in Class today are still operating under a corrective / preventative maintenance approach, for floating offshore units (e.g. FPSO and FLNG vessels) Classification Societies have introduced the framework for the development and implementation of Risk Based Inspection schemes [6], [7], [8]. This approach enhances the traditional periodic approach, considering actual degradation mechanisms for each structural element for a specific asset and service conditions. Inspection effort is prioritised based on risk severity, derived from the potential for and consequence of failure. The enhanced understanding of defined risks and failure modes enables a tailored and targeted inspection frequency and scope to be specified to mitigate these risks. For a specific item this may mean more or less inspection than the default prescriptive approach. The more generic wisdom from standard Class inspection requirements is not lost in this process as it forms an additional input to be considered in determining the final inspection scope.

Inspection methods and technology

Most regulations have typically been written around traditional human inspection methods. These generally consist of inspectors physically carrying out visual inspection and non-destructive examination, for example ultrasonic thickness measurements of corrosion, or magnetic particle inspection of cracks.

Technological developments of recent years have led to significant improvements and cost reductions in inspection data capture and deployment technologies. Technologies include high resolution optical cameras (visual / infrared / thermal), 3D photogrammetry, laser point cloud scanning (e.g. LIDAR), phased array ultrasonic testing, pulsed eddy current and time of flight diffraction (TOFD). Many of these can now be delivered using Remote Inspection Techniques (RIT), for example with the use of underwater Remotely Operated Vehicles (ROVs), Unmanned Aerial Vehicles (UAVs) or magnetic crawlers.



Figure 2 Example of a UAV [9], an ROV [10] and a crawler [11] used for hull structure inspection

Importantly, regulatory frameworks now exist for the use of such technologies [12], [13]. Traditional inspection scopes written for human execution however typically need some modification to be suitable for RIT deployment.

The effectiveness and value of such technologies should be carefully considered and depends on the situation, nonetheless their availability for use in hull integrity management opens up new possibilities for the way in which inspections can be carried out and how the risk of defects can be managed.

4. ENGINEERING

Traditional approach to engineering optimisation

Traditionally engineering optimisation is mainly carried out at the design stage. In service inspection, maintenance and repair regimes tend to follow standard prescriptive or empirical approaches without any optimisation.

Under traditional Class Rules, little to no engineering knowledge or effort are required to determine hull inspection scope and frequency, perform inspections and carry out repairs. Acceptance criteria are designed such that a surveyor with no detailed knowledge of actual stress levels for a particular vessel can identify anomalies and specify repairs which are typically ‘like for like’ in accordance with IACS 47 [4].

This system and the rules, regulations and guidance that govern the standard rule-based methodology are based on years of accumulated experience and knowledge and serve the

maritime industry well. This approach is reflected in the make-up of engineering support at the design vs operational stage.

Aspect	Design	In service
Personnel	Large pool of dedicated specialist design engineers.	Limited technical support / capability (e.g. one superintendent for multiple ships). Generalists rather than specialists.
Information available	Large volumes of recently created information, authors often still available or within the organisation. Large databases with easy access to critical documents (drawings, design reports, analysis models etc.).	Variable amounts. Sometimes no information is available. Even when available content awareness / understanding may be low (e.g. personnel unfamiliar with difficult to access legacy information).
Optimisation	Significant effort into understanding stress & fatigue, reducing weight, increasing propulsion efficiency etc. Studies and analysis conducted to explore and justify departures from rule minimums.	Rule based acceptance criteria. Repairs to "as built" condition. No design change based on updated service conditions. Limited budget available.
Timescales	Allowances made up front in schedule for analysis and optimisation.	Asset operating schedule drives the quickest solution in a reactive situation.

Figure 3 Comparison between typical design vs in-service engineering support

Engineering optimisation in service

The introduction of additional engineering support in operation enables operators to move beyond the traditional approach. With a better understanding of a specific asset under distinctive operating conditions, inspection scope, frequency and methods as well as remediation of issues can be tailored to better suit the particular needs of that asset.

The optimum level of engineering in support of a particular asset depends on several factors. For example, a simple prescriptive approach may be most appropriate for a young asset, with a long life ahead of it, easy access to a shipyard for low-cost repairs and an adequate allowance for platform downtime. In contrast, for an offshore oil and gas unit which cannot readily proceed to a shipyard, incurs high labour costs, additional safety risks and significant platform downtime for any offshore work, the cost of engineering to reduce the operational impacts of inspection and repair work can be more easily justified. The same can be said of a naval asset for which platform availability and capability are critical. Figure 4 shows some of the tools that can be used to apply increasing levels of engineering sophistication to optimise inspection and risk mitigation efforts in operation. The 'optimum' level of engineering will be different for each asset and depend on many factors some of which are shown at the bottom of the figure.

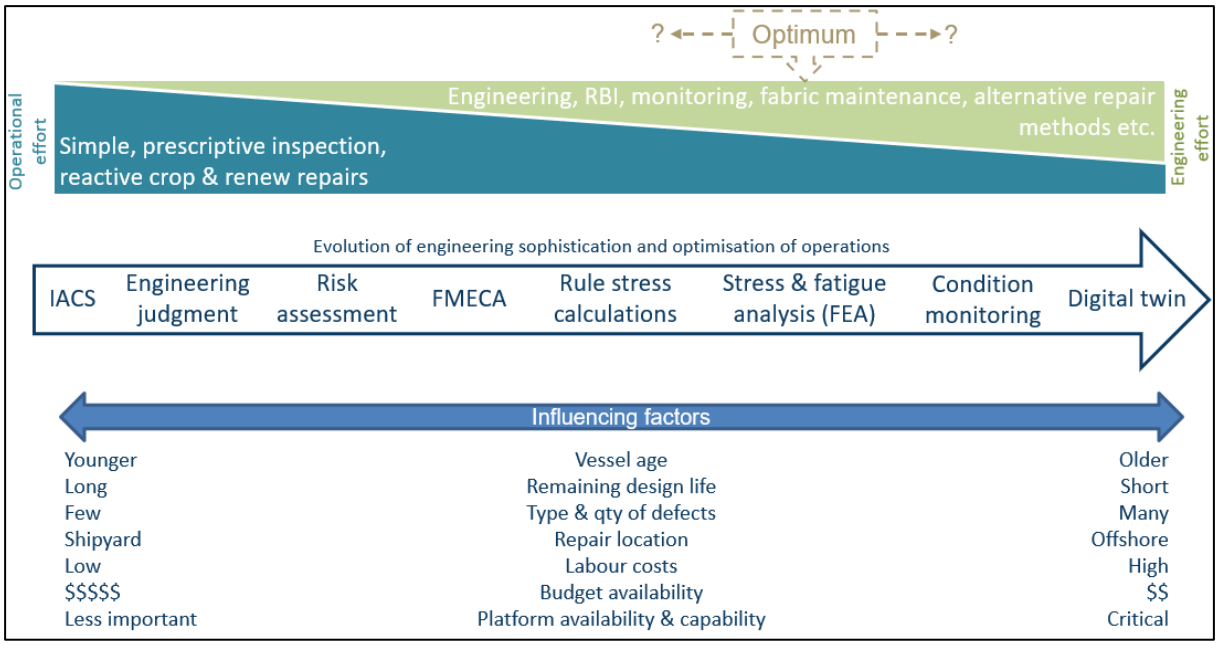


Figure 4 Tailoring of level of engineering depending on influencing factors

IACS: This refers to any repair completed in accordance with the baseline recommendations of the International Association of Classification Societies (IACS). IACS recommendation No. 47 [4] contains a list of recommendations and guidelines for completing the repairs. These are typically 'like for like' also referred to as 'crop and renew' repairs.

Engineering judgement: This is when suitably qualified and experience personnel with knowledge of the asset and its operations tailor a repair or risk mitigation solution. This is normally closely aligned with the original structure as built or IACS 47 [4] and may not involve supporting calculations.

Risk assessment: Using simple techniques, the likelihood and consequence of failure from a defect are assessed to inform risk mitigation and repair decisions.

FMECA: Failure Mode Effects and Criticality Analysis (FMECA) differs from a standard risk assessment in that it considers likelihood, consequence, and detectability of a failure. Where applicable, this facilitates monitoring of defects to become part of a defect management solution.

Rule stress calculations: Using the formulas contained within Class rules and first principles, the capacity of degraded structure with anomalies is calculated. Depending on the defect location and type there can be significant redundancy in hull structures. For example whilst corrosion of a beam may exceed the standard allowable % thickness diminution (typically 20-25% [1], [2]), if the corrosion is localised and at a low stress point on the beam span, stresses and buckling capacity may remain well within allowable limits. A simple stress and buckling calculation can potentially demonstrate that the corrosion is acceptable provided it does not progress any further. In this example arresting the corrosion (e.g. coating repair) and regular monitoring to ensure no further deterioration may be preferable to a repair.

Stress and fatigue analysis: These are more sophisticated approaches than rule-based stress calculations, in that Finite Element Analysis (FEA) and fatigue spectral direct calculation procedures are used to determine structural hot spots and fatigue life [14], [15], [16]. This can be used as part of an overall assessment or for specific anomalies as an input to determine the optimum risk mitigation methodology in a similar way to the example provided for Rule stress calculations above.

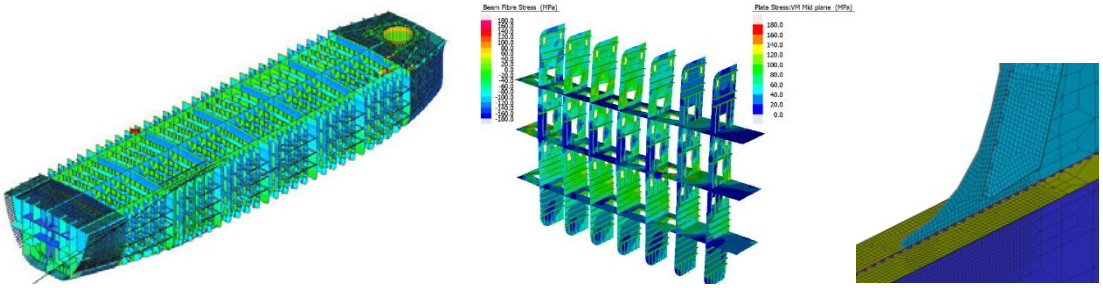


Figure 5 Finite Element Analysis (FEA) models

Condition monitoring: This involves the measurement of live data such as global and local hull strains, wave impact pressures, motions, accelerations, draft and trim, tank levels and metocean conditions to determine the actual material state of an asset as well as loads experienced.

Digital twin: A digital twin is a virtual model designed to accurately reflect a physical object. In the context of hull structures it can be a 'data' twin and / or an 'analysis' twin. The level of definition / data included varies depending on requirements as do the amount, types and frequency of live or static inputs. An example of a hull structure digital analysis twin could be a full ship FEA model updated with live wave conditions from a metocean buoy, live global stress levels from strain gauges, and periodical updates of hull structure with inspection findings (corrosion, cracks etc.). Such a model can provide rapid and up to date understanding of the performance of a hull structure [17], [18], [19].

5. RISK MITIGATION

Under traditional Class Rules, the risk of a failure arising from a structural defect is typically addressed by permanent 'like for like' repair (although there is some provision for temporary repair). The increased level of understanding of hull structural condition achieved using the engineering optimisation techniques described above opens up the following variations of repair or monitoring techniques:

Alternative welded repairs: 'Like for like' repairs may not be the best solution particularly if they do not solve the root cause of an issue (e.g. poorly designed fatigue connection which may fail again). In this case an improved design detail would be preferable.

Cold repairs: These do not involve any welding or 'hot work' and include bonded plates or composite laminate repairs of vessel structure. Regulations exist for bonded steel plates [20], [21] however pure composite repairs still require assessment and approval on a case-by-case basis.

Arrest and Monitor: Where engineering assessment has demonstrated that a corroded structure still maintains adequate strength, that assessment will remain valid provided corrosion does not progress any further. 'Arrest and monitor' typically involves removal of corrosion back to sound metal, grinding sharp edges smooth, repairing the coating and then regular monitoring to ensure the condition does not degrade further. Recent reductions in inspection & monitoring costs through the use of unmanned inspection techniques such as ROVs, UAVs and remote cameras have resulted in this approach becoming cost effective and a realistic consideration for day to day inspections.

Operational changes: Operational limits can be imposed on an asset (e.g. sea state, speed, tank loading etc.) to ensure that the vessel remains within its operating envelope which may be modified to account for structural defects.

6. REGULATORY ENVIRONMENT AND CONSTRAINTS

Civilian statutory considerations

Although at a high level, there is a trend within regulatory regimes to move towards a goal-based approach [22], [23], in practice especially for hull structure, detailed implementation of regulations and acceptance criteria in service are based on and constrained by prescriptive approaches. These are usually centred around a periodical survey [1], [2], [24].

An example of a practical regulatory approach that allows for tailoring within inspection, engineering and repairs is the Australian (civilian) regulatory situation for Oil and Gas vessels as defined within Marine Order 47 [25].

This Marine Order specifically makes provision for deviation from the traditional prescriptive regime that defines the extent and frequency of inspections if the proposed regime is at least as effective as the default prescriptive regime.

An example given is for Performance Based Inspection (PBI) which is acceptable to AMSA so long as it is approved by a Recognised Organisation (e.g. LR, DNV, ABS and BV amongst others [26]).

Naval regulatory position

The nature of Naval Assets and their certification, means that there is a long history of tailoring standards for individual platforms or classes of assets. For many NATO aligned navies, the regulatory position is defined by ANEP 77 [27]. This is a goal-based code derived from civilian international conventions that enables a Naval Administration to certify its assets. Throughout ANEP 77, there are regular references to tailoring including guidance on developing a "tailoring document" within the "standards plan".

Specifically, Part 3 Regulation 6 of ANEP 77 deals with surveys (extract below).

> *"Surveys shall be conducted at a periodicity appropriate to the design, construction, material state and usage of the ship at intervals aligned with those required for merchant shipping regulated by international convention unless determined otherwise by the Naval Administration. In the event that the Naval Administration agrees alternative arrangements for the periodicity for a specific*

ship, the Naval Administration is encouraged to share the particulars and reasons with other Naval Administrations for their information."

Although ANEP 77 does provide a high-level regulatory mechanism for optimising inspections, what it does not provide are detailed guidelines for the practical implementation of this for hull structures.

An example of how a specific administration implements inspections is given by the Royal Australian Navy Publication 4412-4315 [28]. When considering the extract from ANEP 77 above, it can be seen that the RAN approach is more sophisticated than simplistic IACS repairs (see Figure 4). This is facilitated within the RAN guidance as the risk assessment of defects is specifically codified. However, the full range of techniques available to optimise inspections and repairs are not quoted or codified.

Class rules including Naval Class

In general, when considering optimisation of physical repairs, alternative repairs are accepted under traditional Class Rules provided that any proposed alterations to hull structure are approved by Class and are to the satisfaction of the attending surveyor.

When considering optimisation of inspection periodicity, within LR Naval Ship Rules [24], although alternative arrangements for survey periodicity of structure will be considered "upon request", no detailed guidelines are given as to what evidence needs to be provided for any such change. This reflects the approach taken within the ship rules. It should be noted that for items covered by Machinery Class Notations, there are well established rules and procedures around implementing Reliability Centred Maintenance or other forms of condition monitoring.

Overall, there is some leeway within regulations to deviate from prescriptive approaches. One example is where at surveyor discretion the extent of ultrasonic testing can be reduced for structural coatings that are in "good" condition [29]. Others include using "surveyor discretion" and adopting "temporary repairs" [1], [2], [6]. There are also clauses within LR Ship and Offshore Rules [1], [6] allowing original scantlings to be changed. It is also possible to defer repairs using defect criticality assessment methods such as FMECA to demonstrate the effectiveness of any alternative risk mitigation measures (refer Section 5).

Explicitly, if the LR Offshore Rules are considered [6], Part 1 Chapter 6 provides specific "Guidelines for Classification using Risk Based Inspection Techniques". Also available is a guidance note for "the risk-based inspection of hull structures" [7]. This provides a clear framework and a route to approval with a purpose written set of regulations.

7. CASE STUDIES

Case study 1: FPSO Risk Based hull inspection regime

FSC were engaged to develop a Risk Based Inspection (RBI) regime for the hull structure of an ageing FPSO. This AFRAMAX tanker originally built in 1981 and converted into a disconnectable FPSO in 2008-2009 had been operating in Australia under a periodical inspection regime since conversion. The vessel had recently completed Special Survey VIII in 2020.

The driver for change was the fact that unless any optimisation were completed, the survey regime would fall under the IMO ESP code requirements [3]. For a vessel of this age, this would require a full 5-year special survey scope to be carried out every 2.5 years instead of every 5 years; a doubling of the inspection requirements. For trading vessels which dock at regular intervals and have limited ability to apply more sophisticated inspection regimes, this is an appropriate way to ensure the increased integrity risk that comes with vessel age is accounted for. However, for an FPSO the operational implications of this requirement are a significant increase in personnel safety risk (many inspections involve human entry to confined spaces and working at height), and the significant cost of offshore inspections including knock on effects on production uptime.

A Risk Based Inspection regime was therefore developed in accordance with LR guidelines [7]. A high level flow chart for the development of the RBI is given in Figure 6. Initially a detailed RBI basis of design was developed to collate historical data, verify sufficient technical knowledge and identify areas where more work (e.g. inspection or analysis) was required to develop a fit for purpose RBI plan. Subsequently additional analysis was carried out, and condition prediction reports created. These summarised all key insights from past data, current condition as well as predicted condition for corrosion, buckling, cracks & fractures, fatigue and stress. These reports as well as input from key stakeholders during the RBI workshop formed the key inputs to the qualitative risk assessment. Using the operator's corporate risk matrix, defined inspection and monitoring methods and inspection frequency tables, suitable inspection and monitoring scopes and frequencies were determined to mitigate identified risks to an acceptable level whilst working within operational constraints.

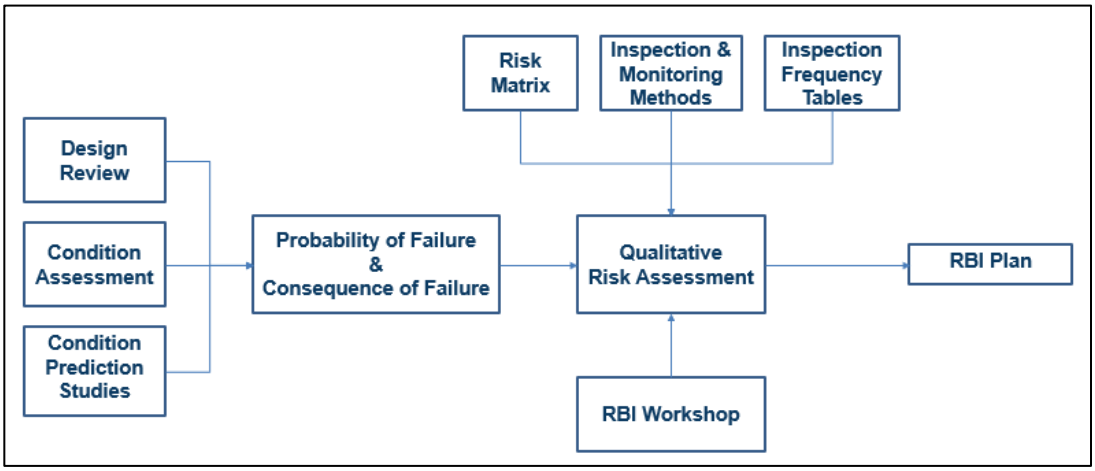


Figure 6 Simplified hull RBI development process flowchart

The resulting RBI plan provided the operator and Class with a far better understanding of the specific risks applicable to the asset. This understanding was founded on an extensive and clearly documented evidence base, enabling tailored inspection scopes and frequencies to be implemented, increasing asset availability, and significantly reducing risk and cost.

Inspection frequency for most tanks was halved compared to ESP requirements. The clearly defined inspection scopes for each tank directly address the relevant risks. This increases the efficiency of the actual inspections in terms of the value of the data obtained. Formal costs

savings are not available, however the following provides an order of magnitude. Considering 21 cargo oil and water ballast tanks and an average offshore inspection cost of approximately $0.5M per tank, savings over five years are of the order of $10.5M. Some tank inspections also required production shutdown, therefore additional production related savings in addition to the quoted number were also achieved.

Case study 2: Operational availability increased through drydock schedule reduction

The emergence of a significantly higher level of hull structural anomalies than expected during the Special Survey inspection carried out offshore for an FPSO lead to hull structural repairs becoming the critical path activity for the subsequent drydock campaign. This risked delaying the planned date for return to field and production startup. FSC applied a combination of inspection, engineering and risk mitigation optimisations to achieve significant reductions in shipyard repair scope. This took hull structure off the critical path and brought the schedule back on track.

Over a 22-month period, in parallel to the offshore inspection and drydock campaigns, several of the techniques discussed earlier were employed.

Figure 7 shows the total steel renewal weight on completion of all inspections if a standard IACS 47 [4] 'crop and renew' approach was taken (248t). The impact of the optimisations that were carried are shown in the green 'waterfall' steps.

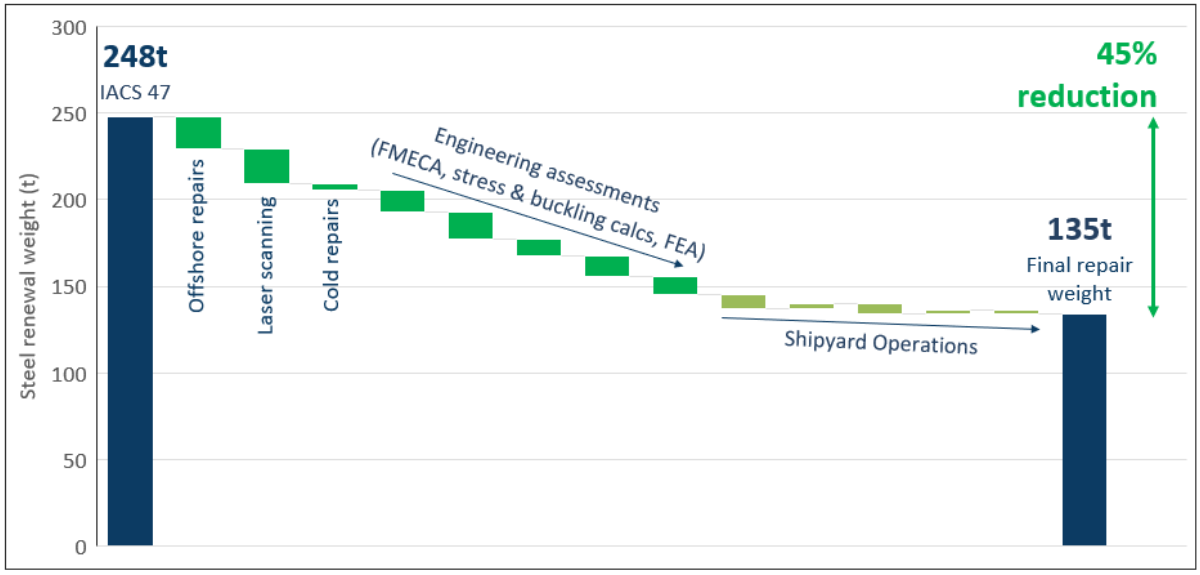


Figure 7 Inspection and engineering optimisation – repair steelweight waterfall chart

The final repair steel weight was reduced by 45% compared to that required with simple application of IACS 47 requirements, with a corresponding reduction in manhours, cost & shipyard schedule of approximately 30-40%. This clearly demonstrates the benefits of the approaches described in this paper.

Case Study 3: Naval patrol boats – unlocking maximum value from stress monitoring

To better understand and manage hull structures for the new RAN Cape Class Patrol Boats (CCPBs), a study was carried out into the implementation of a fit for purpose real time hull structural health reporting system.

The challenge in implementing such a system is not only what data to measure and what equipment to install to collect that data, but how the data will be used, and integrated into the wider hull and overall vessel integrity management system. This includes looking at how maximum value can be extracted from the data by enabling findings to feed back into the fleet inspection and maintenance programme.

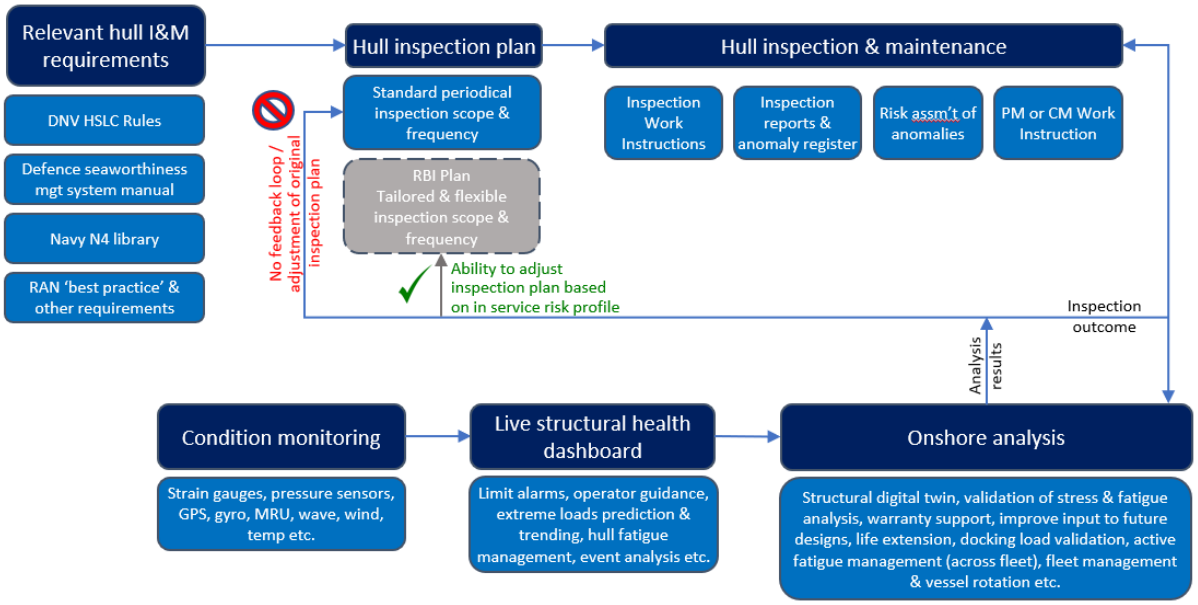


Figure 8 Example hull integrity management framework for RAN Patrol Boat

Figure 8 shows a high-level overview of a potential RAN Patrol Boat hull integrity management framework, under a standard Class / Naval periodical inspection regime. Recording live data such as global stresses, local stresses at known stress hotspots and fatigue cycles can bring significant benefits to the understanding of how an asset is performing, both immediately to the crew, but also back onshore with a wealth of potential uses for the information.

Under current DNV HSLC [5] and RAN [28] inspection frameworks there is no clear guidance for the use of this knowledge to influence inspection frequency and scope. To unlock maximum value from the data a condition monitoring system provides, an alternative regulatory framework for inspection is required (refer Section 6).

If an RBI plan can be used in lieu of standard Class and Naval inspection scopes, that will bring two key benefits to the CCPBs. The first is that initial inspection scope and frequencies can be tailored to match the specific risk profile for the vessel based on design assumptions. The second and arguably more significant is that risk profile changes through the life of the asset informed by live data on stress levels and environmental conditions can be used to tailor inspection requirements. For example, where stress levels or fatigue cycles are lower than design assumptions and inspection data show no issues, it may be possible to extend inspection intervals for certain high stress or fatigue critical details. Conversely if the fluid properties or temperature, or indeed the inspection findings (e.g. coating breakdown) for tank indicate a higher corrosion risk, inspection frequency and scope may require increasing to ensure the risk is managed.

The flexibility of this mechanism ensures inspections are only undertaken where required, rather than just because a standard prescribes it. Likelihood of failure is also reduced through a better understanding of structural behaviour and the ability to target areas of concern more accurately. Both these benefits as well as lowering overall risk are likely to increase availability and operability of the platform.

8. APPLICABILITY IN A NAVAL CONTEXT: INCREASING CAPABILITY AND OPERABILITY OF FRONT-LINE NAVAL ASSETS.

Similarities between naval and floating offshore units assets that adopt RBI

When considering commercial assets that adopt RBI as compared to Naval assets, both seek customised certification and survey regimes that reflect the vessel's operational envelope. For Naval Vessels this can be highly tailored [23], [27], [28].

Both also normally have a greater availability of engineering resource (in house, subcontracted or otherwise) to support the more detailed considerations of such an optimised approach.

A further similarity is that in both cases assets with long life spans and multiple through life extension plans are being operated.

Situations where Naval Assets may benefit from optimised inspection and maintenance approaches

If it can be shown that a naval asset need not be inspected, or if during an inspection that a particular defect need not be repaired to complete the intended mission, then it may be possible to increase capability and availability. By quantifying the effects of the defect, it may also be possible to avoid any operational restrictions that reduce capability. Or indeed avoid disconnection of mission critical systems to effect structural repairs.

From the authors' knowledge and understanding of existing Naval practices [23], [27], [28], [30] it is suggested that there could be scope to use the same techniques deployed in the Oil and Gas sector to tailor the inspection periodicity and engineering evaluation of structural defects in a systematic way to improve availability and capability. This could be further improved should condition monitoring data be collected and used effectively.

For example, with effective condition monitoring and risk based inspection, a deployed frigate or destroyer may not need to make a long transit to a home port. Instead, it could stay on station at a high level of readiness or put in to a commercial port for far more targeted, shorter and less intrusive maintenance without any increase in risk. Another example could include not needing to disconnect essential parts of the combat system or chilled water system to inspect and repair primary or secondary structure. This could maintain or increase availability of a front-line asset whilst providing evidence that its structural capability has not degraded.

When anomalies do require repair, rather than simply re-instating the 'as-built' detail, an enhanced understanding of risk can enable the repair to be tailored to the latest operational requirements of the vessel considering repair capabilities, location and scheduling.

9. CONCLUSION

Several techniques have been established and proven for optimising the in-service inspection and maintenance of hull structures. As demonstrated in the case studies above, these can deliver multiple benefits for the right sort of asset and supporting organisation.

Engineering optimisation of repair methods and risk mitigation is already accepted by Class subject to review and approval. To facilitate a change from traditional prescriptive inspection and repair regimes, purpose written regulations are required.

Within the Australian Oil and Gas sector the regulatory regime is in place for risk-based inspection with detailed guidelines available and several vessels already operating under this framework.

Within the Naval context, the regulatory regime exists under ANEP 77 [27] to apply tried and tested techniques to optimise the maintenance regimes of Naval Assets. Although in specific cases, inspections and repairs are already subject to optimisation, a more comprehensive and wholesale adoption of regulations and techniques used in the civilian context could provide multiple benefits. These include increased clarity, understanding and standardisation of the methods involved, improved assurance of the asset's ongoing ability to safely deliver the required capability, and more rigorous evidence for regulatory compliance.

In summary a better understanding of the asset's hull structure under a fit for purpose regulatory regime can enable optimisation and efficiency gains in inspection and maintenance. This provides the flexibility required to improve the availability and capability of the platform.

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Innovative Concepts within LCM Analytics

Author: Tomas Eriksson, CEO, Andrew Perkins, Country Manager Australia

Affiliations: Systecon Group AB

Email: tomas.eriksson@systecongroup.com

ABSTRACT

The capability and complexity of Naval Vessels are increasing quickly which composes a challenge that too often results in poor availability and escalating costs. These risks can be mitigated or avoided by using the proper methods to underpin decisions in design of system and support from the concept phase to end-of-life. System oriented Life Cycle Management provides the methods and tools to do this.

Strong analytics is essential for successful Life Cycle Management. An organization's ability to continuously meet the main LCM objective, cost effectiveness, throughout the system life cycle, is dependent on its access to timely and dependable decision support. LCM Analytics, what is increasingly called "data driven approach to LCM" has been a critical success factor for decades. But new developments in different fields means new possibilities and application areas and LCM analytics is on the verge of opening up on a new scale.

One of the drivers of this development is digitalization, which enables new innovative approaches to achieve the LCM objectives. In everything from more computational power, better integration, improved visualization, automated data gathering, new approaches to optimization, simulation, heuristics, and AI there are novel opportunities that complements and strengthens the analytic abilities. These sets our community up for more clarity in decision making, quicker analytical turnaround and opportunities to answer new sets of questions.

BACKGROUND

Naval Vessels are among the most technically complex systems that exists in the world. They are essentially a platform with multiple different subsystems that shall operate in unison, in challenging environments, autonomously over long time periods with quickly shifting operations, objectives, and supply chain. This shall be accomplished in cooperation with other systems and be able to do that over a life length of 30 years and beyond. It is important for the vessels to be able to provide their intended capability continuously over time and adapt to changing requirements, operations, and environment, all of which should be accomplished without breaking the budget. In addition to building highly capable systems that can respond to threats and challenges these vessels also must be designed so that they have a high availability at the lowest possible cost. To achieve this an analytical approach should be applied throughout the design of the system, it´s support system and continuously in operations and upgrades. The analytics should be able to provide answers on future outcome so that the right decisions can be made in every step of the process.

LCM ANALYTICS

The purpose of System oriented Life Cycle Management and LCM Analytics is to increase fleet performance, to build confidence in that the right decisions are made, control costs and to drive increased quality. In the end this saves taxpayer dollars, frees up budgets for further investments and ensures successful projects over time.

The core of the analytical approach is to make sure that each organization has the capability to turn available data into knowledge that can provide direction for the program. The analytical approach brings value in every phase of the life cycle of the system from conceptual design to termination. It helps the organization to control materiel projects, managers to make the right decisions as well as helping the analysts in tasks ranging from spares optimization to fleet planning. Decisions on everything from which supplier choose to identifying key downtime drivers or optimize the on-board spares assortment and plan maintenance is enhanced by the analysis.

The type of decisions that LCM Analytics underpins ranges from early conceptual design, through technical design, support system design, bid-development, acquisition evaluation, contract negotiations, maintenance-, support- and supply-concept as well as dimensioning of maintenance resources and spares packages.

The analytical approach requires the capability to turn complex scenarios characterized by complex technical systems with a complex support system having complex operational requirements into a pertinent model that can be used to predict the long-term implications on cost and effectiveness from chosen designs and dimensioning. By having the ability to predict the outcome it becomes possible to weigh alternatives against each other and to apply optimization techniques to find the best possible alternative and thereby making the right decisions throughout the process.

Methodology for LCM Analytics

Naval program management is a complex science that requires methods that are up to the task. It involves thousands of people and multiple organizations, long time horizon and has huge monetary as well as capability impacts. This obviously calls for methodology, standardization, and work procedures, all of which are in place to various degrees. These are all invaluable and the foundation for building and operating great platforms. To enhance the performance in the long run it is important to also add the capability to predict the long-term performance and to optimize the various design parameters at hand for cost-effectiveness.

To be able to predict the readiness over time and life cycle cost is crucial for building, buying, and operating a great ship. In addition to the ensuring that the technical capabilities of the system are provided; propulsion, fire power, sensors, command, and control, it is also crucial to be able to ensure that these capabilities are available and ready when needed. All of this shall also be accomplished to an acceptable life cycle cost and done so with confidence.

Effective life cycle management analytics must provide these capabilities. It must be able to accommodate and accurately model the complexity of the system of systems, the multifaceted operational requirements and the intricate multilayered support organization

and produce relevant and reliable predictions and optimizations. It should be the crystal ball that helps you to move from hope to confidence in that you are making the right decisions.

The aspects of analytical

To reap the benefits of the analytical approach you need to make sure that there are five aspects that are covered within the organization.

- The first one is simple but perhaps the hardest. That is to embrace the thought that through-life cost-effectiveness is important and that it can be used to improve the long-term performance of the system. This is important because it makes you ask the right questions, and it drives increased quality, higher performance, and lower costs.
- The second aspect is that you need to be able to describe your system in operations to the right level of detail. This means that you need a model of your technical system, your maintenance and support system and operations. However, it does not mean that you need to describe all details of every bolt, nut, or sortie.
- The third aspect is that you need to be able to get data to support the model you have built. A common misunderstanding is that you need extensive and perfect data. This is simply not true. What is true is that you need to use the data you have and let the usage of the data drive improved data quality.
- The fourth aspect is that you need to be able to use the model and the data at hand and through mathematics, simulations and effective algorithms provide insights into how your system will perform.
- The fifth and probably the second most important aspect is to be able to get the results of the analysis into the hearts and minds of the decision makers. This is accomplished through making the results easy to understand, quickly available and to have the decision makers act, but also learn from the results produced.

The good news is, that in many organizations, the second and third, often even the fourth aspects are often already largely in place and the important efforts are to get the first and fifth aspect into place.

WHEN TO USE LCM ANALYTICS

Analytical LCM is a methodology that supports Material Projects throughout the lifecycle of the system. It helps from concept to termination through providing cost and effectiveness as a clear evaluation criterion that helps guiding in decision as well as identifying missing, faulty, or ambiguous data. Analytical LCM provides value continuously in the life cycle but is accentuated when changes occur, the bigger the change the more important the analysis becomes.

In the early phases the analysis is often made on novel data but as the life cycle progress then the analytics are either based on new types of analysis needed or due to changes. The types of changes that should trigger analysis includes the following

- Material State, e.g., such as modification, change proposals, mid-life upgrades, new data delivered

- Operations, e.g., Rate of Effort has changed, operations ramping up, changes to deployment, changes to operations
- Support system, e.g., Supply lead times worsening, need for endurance during crisis, improved maintenance capabilities
- Budget revisions, e.g., Lowered budget, Budget increases
- Contracts, e.g., acquisition, maintenance contracts, power by the hour contracts

The changes above will potentially lead to substantial impacts on the cost and effectiveness, which must be identified, and should also trigger changes to dimensioning of the maintenance resources, spares and should be done even when changes are anticipated to understand the effect before it comes into place.

We have seen that tasks performed throughout the lifecycle in the Maritime Arena is made with greater confidence, control, and increased performance through the application of LCM Analytics for System Project Offices, SPOs, and Contractors alike.

In the conceptual studies the analysis should focus on a high-level model to ensure that operational readiness is considered in addition to the capability requirements desired. In the design phase focus is initially on the technical system/platform. It is then important to influence the design by the application of ILS, LSA and LCM Analytics. When getting closer to the roll-out and delivery the design of the support system and operations comes into focus, and then dimensioning becomes important and is often the key usage for the LCM Analytics. When the systems are in operation it is important to continue with the analysis to ensure that the strategic decisions made are adopted to a changing environment and to adopt to better data generated from the operations. In the termination phase important timing decisions on phase out of the fleet, phase in of the replacing capability as well as when maintenance and repairs should be ended and how cannibalization can be used on retired systems.

DIGITALIZATION AND LCM ANALYTICS

The continuously increases in computational power, digital integration, data gathering and storing, and the implication thereof on the generation of business value greatly enhances the value provided by LCM Analytics.

Nearly every aspect of our lives, personal as well as professional is touched by the increased digitalization. This ongoing transformation, sometimes referred to as the fourth industrial revolution, provides opportunities for increasing the value generated by the analytical approach.

The benefit from digitalization to Analytical LCM comes from combining the strengths of readily available data, integrated information systems, computational power, and new algorithms to provide better results, quicker that involves more of the organization and the decision maker in an agile and iterative approach that brings huge value now and over time.

In the evolving digitalized landscape, work procedures could, and should, be enhanced to a much larger degree by cutting edge analytics.

Data availability – More accurate input
Data is key to making good decisions and the growing data availability therefore increases the effect of Analytical LCM. The more accurate input both because more data is gathered, and it is available quicker.

The amount of available data grows quickly. This includes predictions as well as experienced data and sensor data. In the integrated world we live in, it is possible to share data more easily which is important take advantage of. It ensures that the vast amount of existing data also is made available to and used in the work with Analytical LCM.

One example is sensor data. Sensors onboard systems now continuously gathers information on the health and usage. The vast amount of data is being stored in extensive data lakes that can be used, for example through machine learning, to get useful understanding on everything from representative failure rates to predicting when maintenance is needed. The sensor data, and machine learning results, becomes available once the system is in operation and can then help as input to the Analytical LCM.

Another example is the ability to share machine readable data more easily between supplier and buyer of systems using integration interfaces and evolved standards, such as the ASD S-Series for ILS.

Large scale computing – More knowledge from data
Great analytical capability is key to getting the most knowledge out of the data gathered. Faster answers to more complex scenarios using existing and new algorithms brings significant power.

The fast and relentless increases in computational power makes calculation intensive algorithms feasible also within LCM analytics. Large scale computing thereby opens opportunities to solve problems that have been impossible using traditional mathematical methods. These new methods include the application of heuristics such as differential evolution for solving complex optimization problems and AI/machine learning to extract processed information from large datasets.

Mathematics and simulation techniques that have been used since long in Analytical LCM also benefits from the increased computational power since they now can be applied to bigger and more complex scenarios.

Combined does the growth in capability for existing methods and the use of new algorithms broaden the field significantly for the types of questions that the Analytical LCM can be applied to.

The opportunity to use the models as digital twins that can live along the platform itself also provides great opportunities for using the Analytical LCM throughout the system lifetime.

Integrations – Quicker turnaround and iterative analysis
Quick turnaround from changed conditions or new data until it influences decisions increases the quality and accuracy of the Analytical LCM. It also enables more professionals to get involved in understanding and developing the results which greatly enhances the results.

The capability to integrate with different systems and to incorporate the analytics in a digital network helps to reduce the time needed to transfer data between data storages and analytical tools. This helps in making it possible to get much quicker turnaround for the analytics loop, from question to answer.

Traditionally a huge part of the time for analysis has been absorbed by the data gathering. By freeing up this time, the analyst can instead put more efforts into better understanding and to quicker supply answers into the decision making.

Visualizations, information sharing – Greater impact

To be able to easily share results in a format that is easily understood by the recipient greatly enhances the impact from the results. One of the key aspects is to ensure that all stake holders understand the results and their implications, and to be able to quickly present results in an intuitive and understandable way brings huge value.

As mentioned earlier one of the most important steps in getting value from an analytical approach is to ensure that the results are actually available, understandable, and used by the decision makers who is affected by them. Visualizations such as dashboards helps provide this kind of clarity and makes it easier, and quicker, for the decision makers to digest results. This also helps them the decision maker to become more active in the development of the results rather than a passive bystander.

SOME APPLICATIONS

The following are examples from maritime scenarios from three different nations where active use of LCM Analytics has made significant impact:

Example 1, Delivery of Frigates

A Navy was procuring new Frigates. These new frigates were from a new design and with several subsystems that were novel to the Navy. The availability under different types of missions was one key requirement that was made part of the contract. It was also considered in the contract that the contractor should show prior to delivery that the Frigates would be able to meet the requirements. To do this the contract also stated that it should be shown through simulation that the requirements were met. This made it necessary to build a model that considered the ship as a whole and all its sub-systems and key parts. The model also needed to take maintenance, support and supply into account as well as being able to replicate complex operational scenarios and various operational modes for system, subsystem, equipment, and parts. A key requirement for the model was also to be able to replicate the behaviour in various types of complex redundancies. The simulation could prove that the ship would be able to meet the requirements, given the design and reliability of the ship in combination with maintenance, support and supply concepts.

Example 2, Bidding process

A Navy was procuring new Frigates. In the bidding phase the Navy wanted to ensure that the bids submitted had a high quality, that they were comparable, and that the Navy could confidently evaluate and ensure that the bids would meet cost-effectiveness requirements and that the bids contained all data necessary to underpin the conclusions. The Navy included

requirements that the bid should include input based on technical design and maintenance concept and that these should be compiled into a model which could be evaluated in regard to the availability and cost requirements. This meant that all the bids were easily comparable and that the contractors were able to provide much higher quality bids. In addition to this it also made the contractors aware of the influence their design decisions and maintenance concept decisions made, and they could thereby provide better bids that were certain to meet the requirements.

Example 3, Control in a delivery project

A navy was procuring a system that would be utilized for several branches of the armed forces. The project was under risk of having significant cost overshoot and there were also concerns that the systems would not meet the high readiness requirements. This project was already in the delivery phase and the first systems were being delivered. To ensure that the project could take control, reduce the risk for cost overshoot and ensure that readiness was met, analytical lcm was applied as one of the key tools. A model was built to model the phase in of the new delivered systems. The technical system was modelled as well as the maintenance concept and a complex support system. The delivery of systems was to be done over several years, so the model needed to be able to accommodate that. To ensure that the results were up to date with the latest data an integration was set up to easily generate models from multiple data sources. Suggested improvements in design of system and support system were then set up as alternatives and evaluated to ensure that the most effective actions were taken. This was done in close cooperation between the navy and the contractor to ensure that both sides understood both the actions taken but also why they were taken and what type of effect that was anticipated from the actions. The efforts in identifying improvements and the subsequent use of analytical lcm ensured that the navy could get confidence in having control over the project from a cost effectiveness perspective as well as identifying improvements that meant huge savings.

CONCLUSIONS

Ships are highly complex systems in every aspect, from how they are constructed to how they are maintained and supported and how they are operated. In the development, as well as in the operation of, the ship design and dimensioning, decisions should be based on an analytical LCM approach with the aim of increasing operational availability and lowering cost.

LCM Analytics should be tightly engrained in the work procedures to ensure that these results are considered for all decisions. All major decisions should be understood in respect to how they influence the cost-effectiveness of the system.

In the organization it is important to have a broad understanding and commitment to the value of LCM Analytics, to be able to model your platform, to ensure that available data is used, to evaluate the model through analytics and finally to ensure that the results reach the decision makers so that it has an impact.

LCM Analytics brings value in all phases of the life cycle. The characteristics of the analytics changes with the phase of the life cycle. Typically, the Analytics should be performed

continuously but should especially be used when changes to system, support or operations occur.

Digitalization brings great opportunities to further the impact of the analysis by making data more readily available, improving analytics capability with greater calculation capability, improving the speed of the process through integration and gives more impact from the result by making them more readily available to all stake holders.

SESSION 18

Ship Design / Shipbuilding

GMA welding ARC ID designation: using welding Arc acoustic signatures
Refereed

Propeller dynamometer wake modification using a 3D printed wake device for behind-hull-condition testing
Refereed

Naval promas system

imc 2022
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INTERNATIONAL CONVENTION CENTRE
SYDNEY, AUSTRALIA

ANNEX C

GMA Welding ARC ID Designation: using welding Arc acoustic signatures

Malcolm Rigby[a], Sipei Zhao[b] and Xiaojun Qiu[b]

[a] Expert Investigator industry partner Sound Institution (trading as Open Welding) for Australian Research Council ARC Linkage grant LP160100616 Partnering with University of Technology Sydney UTS 2016. malcolm@openwelding.com

[b] Centre for Audio, Acoustics and Vibration, Faculty of Engineering and Information Technology, University of Technology Sydney. sipei.zhao@uts.edu.au

1. ABSTRACT

There has been years of research into the form, structure and phenomena of Gas Metal Arc Welding (GMAW) which uses consumable electrodes to melt and fuse with compatible metals by using an electrical generated open arc as the delivery method.

The International Institute of Welding (IIW), the Welding Institute (TWI), American Welding Society (AWS), Weld Australia and a host more associations, plus supplier companies have participated in research conducted by numerous global educational institutions to investigate GMAW's output dynamics to develop an arc ID designation that matches its droplet transfer modes . The purpose of the paper is to propose an Arc ID designation scheme that has advantages over the current descriptive method of Arc ID. It notes that GMAW acoustic signature feature is one mechanism of achieving an Arc ID designation that is quantifiable and non-subjective.

2. INTRODUCTION

Why do we need to develop improved welding process control techniques [1]? That question feeds into a national desire for countries to form things from metal. The ability to improve brings value in revenue and contributes to GDP [3, 4].

However, a global challenge exists in the availability of welding skills for both mature and developing markets today.

Welding associations and research institutions are constantly collaborating to make easier the understanding of GMAW processes and improve welding skills to meet that challenge of skill availability.

This paper puts forward a GMAW arc ID designation scheme to overcome diminishing welding skills availability by improving:

- Transference of welder skills.
- Compliance validation.
- Clear interpretation of Welding Procedure Specifications (WPS).

In choosing an arc ID discriminator, for designation purposes, this paper has incorporated one of GMAW natural phenomenon known to industry, its acoustic emission during the welding process.

It has been reported that expert GMAW welders can direct the welding arc type based on its welding sound, and psychoacoustic experiments show that welding performance is significantly degraded without using the acoustic feedback to welders [7].

In addition, identifying metal transfer modes based on welding sound is critical for automatic GMAW process monitoring, quality control and as a training pathway for competency [5].

It was proposed in 1976 (IIW) to identify welding arc by classification using descriptive terms [2].

This paper builds on that work and other academic arc classifications [6] to arrive at a designation scheme using a non-subjective medium that can be recognised in Industry.

3. METHOD OF DESIGNATION

Arc acoustics are used as feed-back from Input Welding Parameters (IWP) a configuration of both fixed and adjustable parameters [7]. The range in acoustic variation lends itself to correlate with an arc ID designation scheme, discussed later in the paper. Arc sound variation can now be numerically modelled with 98%$^{+}$ accuracy [8]. This novel application allows comparisons between Process Qualification Records (PQR) acoustic signatures and on-the-job welding arc signatures.

3.1. Transfer Types

The electrical slope for GMAW in Figure 1 shows segments in which different transfer modes reside, based on IWP [7].

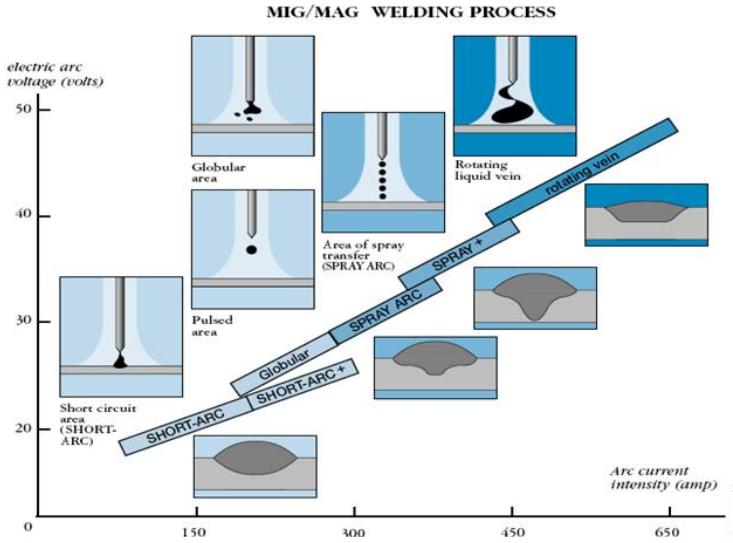


FIGURE 1 Illustration of different metal droplet transfer modes corresponding to arc current and voltage.

Based on the type of droplet detachment in each segment a corresponding acoustic signature can be identified. Those segments can be placed acoustically into three specific groups [8].

Industry uses common descriptions for these segments. As more transfer modes are identified clear thresholds between transfer modes are needed. An arc ID designation must be available to accommodate descriptively those transfer modes [10]. A meaningful description can be clumsy and complex in its use.

3.2. Existing Numbering Systems

The IIW system of arc ID designation in Table 1 was developed to help address International concerns of welder skill availability [1]. These designations have been expanded and mainly used by academics to act as reference markers in welding research [6]. Evidence of Industry take up is difficult to find and could be considered informally used.

The disadvantage/shortcomings of the existing descriptive systems would be its comprehension. It contains terms not normally used outside the academic community.
It relies on arc designation by description and that supports subjective interpretation [9].

TABLE 1. Original IIW metal transfer classification

Transfer types	Sub Group	Example
1.0 Free Flight		
1.1 Globular	1.1.1 Globular drop	Low Current GMAW
	1.1.2 Repelled	CO2 Shielded GMAW
1.2 Spray	1.2.1 Projected	GMAW above transition
	1.2.2 Streaming	Medium to high current GMAW
	1.2.3 Rotating	High current extended CTWD
Added Later	1.2.4 Drop Spray	At transition in GMAW
2.0 Bridging		
2.1 Short Circuit		Low current GMAW
2.2 Bridging without interruptions		Welding with wire additions
3.0 Slag protected Transfer		
3.1 Flux walled guided		SAW
3.2 other Modes		SMAW (MMAW), FCAW

For Industry take up of an arc ID designation a scheme should be considered that assists Industry engagement and can deliver benefits.

3.3. Proposed Arc ID Designation Scheme

It is proposed that arc designation be grouped then uses a matrix scheme that arranges, Transfer type and Droplet transfer, into separate designations as in Table 2. The scheme has been built upon arc ID designations given in reference papers [6, 9]. To view the full proposed scheme, see Table 3

ID designation has three steps:

Step 1 Group droplet transfer by its dominate electrical characteristics, electrical conditions where welding wire metal transfers by either short circuit, or free flight, or electrical conditions applied to welding wire to transfer metal droplets by other methods.

Step 2 Nominate the droplet transfer; such as contact, spray, globular and explosive means.

Step 3 Select droplet forms found during its transfer process as forced, projected, pure or repelled form.

When an arc ID is more representative of its actual profile there is a likelihood of its optimal use and avoidance of arc misalignment.

The challenge is keeping designations at a comprehensive level to ensure Industry engagement.

The proposed scheme arranges mode segments into groups. These groups are proven to have unique acoustic characteristics that can be directly attributed to a transfer type [8].

3.4. Groups Defined

Group 1: Contact Transfer

Electrode welding wire comes into contact with base metal and delivers an electromagnetic pinch effect, (different from Cold Metal Transfer*) to detach molten droplets. Acoustic signature in this group presents high sound pressure, and asymmetrical impulse intervals and event durations.

Group 2: Free Flight

Electrode welding wire droplet detachment occurs at the end of the electrode without contact on base metal. The droplet accelerates through an open plasma column to the base metal. The acoustic signature shows medium to low sound pressure and irregular impulse intervals with long durations between events.

Group 3: Controlled

Electrically, and in some cases, mechanically controlled droplet development and detachment. It has both Contact and Free Flight modes of transfer in this group. Acoustic pulses are regular, sound pressure consistent and predictable with impulse intervals and event durations symmetrical.

Within each group there are other arc ID designations that can be established [9]. Those designations are more pronounced if transitioning from Group 1 to 2 and within Group1 and 2 on its own. Group 3 stands independent of other groups.

Table 2 divides the transfer processes into two functions [12]. Industry commonly refers to the first as transfer types; the other designation is the droplet form under transfer conditions [13].

TABLE 2 Arc ID metal transfers Descriptive scheme for letter and number designation

Process type			
Transfer type	**T**	**Droplet Transfer**	**D**
Liquid	q	Bridging	1
Short-circuit	sc	Pure	2
Contact	c	Forced	3
Globular	g	Repel	4
Pulse	p	Double pulse	5
Spray	s	Projected	6
Streaming	t	Rotating	7
Explosive	e	Gasless	8
Other	o		

There are common descriptive terms used in all three groups which can segment into transfer type of the droplet and type of droplet form. However, the designation also needs to accommodate any group's unique terms. Once a description is selected, a letter and or number can be allocated to that description combination.

Example of converting an arc description into a designation, would be, Free flight, spray transfer in pure droplet from becomes designation **2s2**, defined as Group **2** (free flight), **s** Spray (transfer type) and **2** Pure (droplet form) also described as optimised droplet form.

TABLE 3 Proposed scheme for arc ID designation

Arc ID Scheme

Natrual	**Contact Group**		**1**
Transfer type		**Droplet**	
Liquid bridge	b	Pure	2
Contact	c	Forced	3
Globular	g	Repel	4
Explosive	e	Gasless	10

Natrual	**Free Flight**		**2**
Transfer type		**Droplet**	
Globular	g	Repel	4
Spray	s	Forced	3
Stream	t	Pure	2
Explosive	e	Gasless	10

Controlled (Pulse/Synergic)	**Other Group**		**3**
Transfer type		**Droplet**	
Contact	c	Pure	2
Pulse	p	Forced	3
Spray	s	Projected	7
Explosive	e	Gassless	10

Outside range			**0**
Type Transfer	0	**Droplet**	0

The advantages of the proposed designation scheme for the welding community are; it selects from three known and understood groups. The transfer mode letter is linked to an understood mode segment and only the droplet form needs explanation with its relation to heat energy development on base metal [7].

3.5. Arc ID Case Study with Scheme Applied

Two Welders of the same ability with 10^{+} years experience were asked to deliver a 6 mm fillet for a PQR. IWP needed to conform to AS/NZ1554.1 GP Welding Procedure Specification (WPS). Compliance confirmed by destructive testing. IWP's were noted and a macroscopic inspection taken at the same point for each welder.

TABLE 4

Input Welding parameters

Welder	Transfer mode	∅Wire	Shield gas	T/Speed mm/min	Average Current	Average Voltage	Average Arc energy kj/mm	Weld size mm
a)	Pulse Forced	1.2	SG-ACHe-15/10	364	257	29.7	1.26	7.5
b)	Pulse Pure			230	185	28	1.38	7.9

The weld outcome was different for each welder.

The mode difference and IWP may be caused by historical interpretation of what is normal to each welder.

Case study has welder **a)** delivering a weld that needs further investigation for fusion compliance and welder **b)** over weld design requirements.

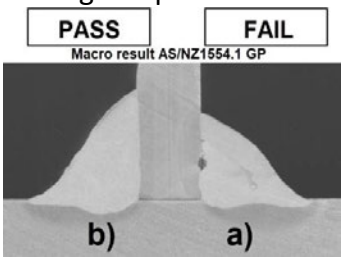


FIGURE 2 weld macroscopic view

The difference between weld settings such as current and travel speed are large and not reflected in an Arc ID description; Free flight/Spray/Drop Spray.

In contrast arc audio is much different, illustrated in Figure 3.

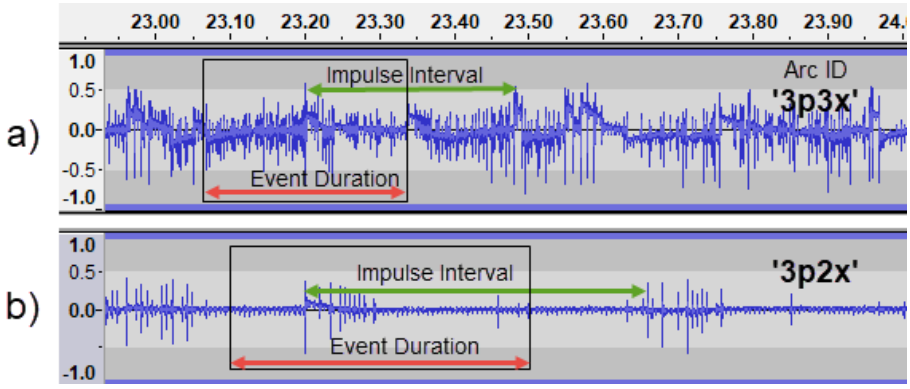
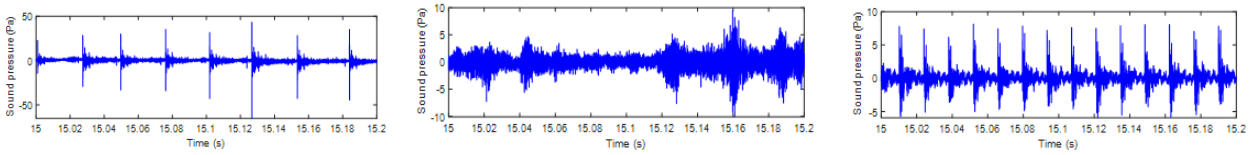


FIGURE 3 Acoustic signature wave forms

Welder a) Controlled/Pulse/Forced 3p3x. Welder b) Controlled/Pulse/Pure 3p2x.

4. WAVE FORM VERSE ARC ID GROUP

Recent studies have shown a correlation between sound wave forms and Arc ID Groupings [8]. A statistical analysis looked at three features, Sound Power, Impulse Interval and Event Duration to distinguish an Arc ID Grouping. It also found within each Group there are additional sound features that are also unique. Statistically the wave form can be numeric modelled which supports an Arc ID designation scheme.



Contact Group Free Flight Group Controlled Group

FIGURE 4 Typical acoustic envelops for each Arc ID Group

When wave forms are compared, as in the case study FIGURE 3, it can be seen that within the Controlled Group there are clear differences acoustically and as a consequence a difference in weld outcome due in part to arc energy.

5. DISCUSSION

By applying a statistical algorithm to the acoustic characteristics of a welding arc it has been proven possible to link GMAW acoustics to an arc designation [8]. Arc Grouping is clearly defined via peak sound pressure, impulse interval and event duration. Further sound feature comparisons can be made to determine sound envelop similarities. The comparison can be modelled numerically. The outcome is a number value representing how similar the sound is to a PQR benchmark. These benchmark welds would be designated by number and letter.

For the Case Study, clearly arc ID 3p2x would act as the benchmark and 3p3x is outside acceptance.

5.1. Industry Demands

What exacerbates arc misalignment is a global trend of available welding skills to interrupt welding requirements, due in part to age attrition, or lack of institutions to instruct in new skills and supply chains unable to support complex welding systems [3].

Traditionally, reversing such trends requires extra training to increase skill levels, to meet the demands of complex welding [11]. That ambition although welcome by Industry is not practical in its execution *"Where have all the welders gone!"* (Wall Street Journal, Aug 2006). The timeline to train for experience does not meet the needs of markets/countries wanting to create value by forming things in metal. The welding supply chain goes some way to address skill gaps by making equipment compensate for variation in user's skill and having consumables with broader compatibility. Even metal can made weld friendly. However, gaining experience without personnel interpretation is difficult and presents a challenge for industry.

6. STANDARDS

Within welding standards ISO [14] and AS/NZ [15] it has no mention of a tolerance around arc transfer modes, only IWP essential variables. There are on occasions a reference to transfer types by description, but not designation. It is expected in Industry if IWP's are true and correct arc profile should be accounted for. This is not the case in practice, due to condition of machinery, at the time of welding, and skills/experience of the welder to understand the outcome of arc misalignment.

6.1. Industry Benefit

In Industry if an arc mode miss-aligns there are visible and hidden impacts (downstream/upstream) for metal forming process such as:

a) Productivity
b) Weld quality
c) Cost control
d) Skills available
e) WEL safety (Work Exposure Levels)

What this paper endeavours to do is link an arc ID designation scheme to a known GMAW phenomenon that is quantifiable so Industry benefits.

Allowing for arc misalignment, as in the Case Study, brings a logical conclusion that corrective action would need to take place to gain compliance. This would incur additional production costs. When a transfer mode is identified, in a non-subjective way using its acoustic signature, it becomes beneficial to deliver consistency and weld compliance.

If welding systems have IWP configured to match a PQR, the output should be a metal transfer mode matching arc energy and metal fusion requirements. That resulting mode should be unambiguously identified by designation to either a novice, or an experienced welder (5^{+} years).

6.2. Future Work

This paper introduces the proposed three part numerical/letter scheme, but not include the interchangeable or mixed modes, which will be expanded in the future. The future scheme should contain an arc ID numeric/letter designation that represents the arc's true technical behaviour.

Arc behaviour for one mode can change to another mode and group by means of droplet growth size/duration and detachment interval [13]. With these changes arc energy on base metal can also vary. Its significance would depend on weld acceptance thresholds. The difference between sound waveforms is obvious, so it is advantageous to use acoustic signature as the key identifier for those occurrences. Therefore the designation number/letter should accommodate mixed arc mode transfers (interchangeable metal transfer [6]) and a more consistent weld outcome can be delivered.

7. CONCLUSIONS

There have been previous attempts to classify GMAW metal transfer modes for Industry and research purposes. That ambition was to identify an arc transfer mode reference which was common across any GMAW welding.

This paper proposes a comprehensive, but simple arc ID designation scheme, which makes it quicker, but with more confidence to identify metal droplet transfer modes during GMAW.

Compared with the existing descriptive methods, the advantage of the proposed arc ID designation scheme can be found in:

- GMAW acoustic signatures codified to an arc ID designation.
- The designation signature can be digitised and made transferable.
- A non subjective designation that does not relying on interpretation by mode description.
- New future pathways to refer arc ID mode in WPS or PQR's.
- Brings focus to droplet detachment dynamics and its role in fusion welding.
- Moves welding operator to a higher level of understanding of the GMAW process.

Future work also includes identifying the Arc ID from acoustic signatures automatically with advanced signal processing techniques.

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Dynamometer wake modification using a 3D printed wake device for behind-condition propeller testing

Thomas Keith[1,2], thomas.keith@dst.defence.gov.au
Daniel Butler[2]
David Clarke[2]
Chris Ellis[2]

[1] Cavitation Research Laboratory, University of Tasmania
[2] Maritime Division, Defence Science and Technology Group

ABSTRACT

A first-of-kind, 3D printed wake device, designed to improve propulsor testing in the behind-condition was manufactured and tested in the Australian Maritime College (AMC) cavitation tunnel. Testing of model scale propellers in the open-water condition is often insufficient to obtain accurate performance characteristics for a propeller designed to operate in a wake. This is because the flow into the propeller does not replicate the thickened, spatially varying wake experienced by the propeller during operation. For this reason, behind-hull condition testing, with the dynamometer upstream of the propeller, is preferred if a representative, thickened wake can be generated. The dynamometer body only generates a thin wake and so is usually insufficient to represent the wake produced by the hull and appendages. A hull-like body may be placed upstream of the propeller to generate a more representative wake; however, this method generally requires a large facility to carry out testing without making considerable compromises to the accuracy and usefulness of the experiment. The 3D printed wake device, tested here, was designed to provide a solution to this problem, generating arbitrary wakes in smaller facilities without making the same compromises.

The measured wake of the 3D printed wake device exhibited considerably improved agreement with the wake of a typical underwater vehicle, in this case the model-scale Joubert generic underwater vehicle design. The wake device increased the measured nominal wake fraction to 0.19, approaching the desired goal of 0.26 for the Joubert geometry, a significant improvement compared to 0.04 for the bare dynamometer. The results show significant modification of the wake, indicating that the use of 3D printed wake devices designed to produce controlled artificial wakes is feasible.

INTRODUCTION

There are two configurations that may be used when testing a model propeller with a dynamometer in a cavitation tunnel. The first is an open water test, where the propeller is located at the upstream end of the dynamometer. The second is a behind-condition test, where the propeller is located at the downstream end. Open water tests are common as they minimise experimental variables such as non-uniformity in the inflow, and the results can be used with standardised procedures such as those provided by the International Towing Tank Conference (ITTC) [1]. However, open water testing cannot determine if the wake adaption of a propeller designed to operate in the wake of hull and appendages was successful. Behind-condition tests introduce a wake field; however, without a full hull model, the

wake field is not necessarily representative of the wake seen in operation. The accuracy of testing in the behind condition may thus be improved by altering the wake of the dynamometer to be more representative.

The wake in a behind-condition test may be altered using various methods, each having advantages and disadvantages. One method is to fit a scaled hull and any appendages to the dynamometer upstream of the propeller. This may be feasible for a large cavitation tunnel with the hull producing a low blockage, but not necessarily feasible for smaller tunnels. It is not advisable to reduce the size of the propeller [2] to allow the use of a smaller scaled hull as the performance of model scale propellers is known to be dependent on the blade Reynolds number, especially when the Reynolds number is low [3].

For smaller tunnels, a method whereby a porous blockage (e.g. a gauze or mesh) is inserted upstream of the propeller can be used. The drag through the porous material creates a localised pressure drop, and hence decreases the momentum of the flow near the dynamometer. Previously, this has been accomplished using combinations of wire gauzes combined into a wake screen [4]. This method produces less blockage as the velocity profiles do not rely on the large body required to grow a sufficiently thick natural boundary layer. This method has a few disadvantages. Firstly, it can only produce a nominal wake, that is, a wake that has not been modified by the propeller, and so any effects on the wake caused by the propeller such as hull suction are ignored. Secondly, as only the velocity profile is tailored for, the static pressure, static pressure gradients, and velocity gradients in the streamwise direction are not guaranteed to be accurate.

A first-of-kind wake device was 3D printed and tested at the Australian Maritime College (AMC) cavitation tunnel. These tests determined the effectiveness of the wake device as a means of producing thickened wakes on a dynamometer during behind condition testing in a controlled manner in order to match the desired wake of an underwater vehicle. This paper discusses the design and testing of the wake device, and its implications on future experiments.

EXPERIMENTAL SETUP

Test section setup

The test section of the AMC cavitation tunnel is 0.6 m wide and 0.6 m tall at the entrance with a length of 2.6 m. The bottom of the test section slopes down towards the exit at an angle of 0.44° to account for typical boundary layer growth and as such provide a constant freestream velocity over the tunnels operating range of 2 m/s to 12 m/s [5].

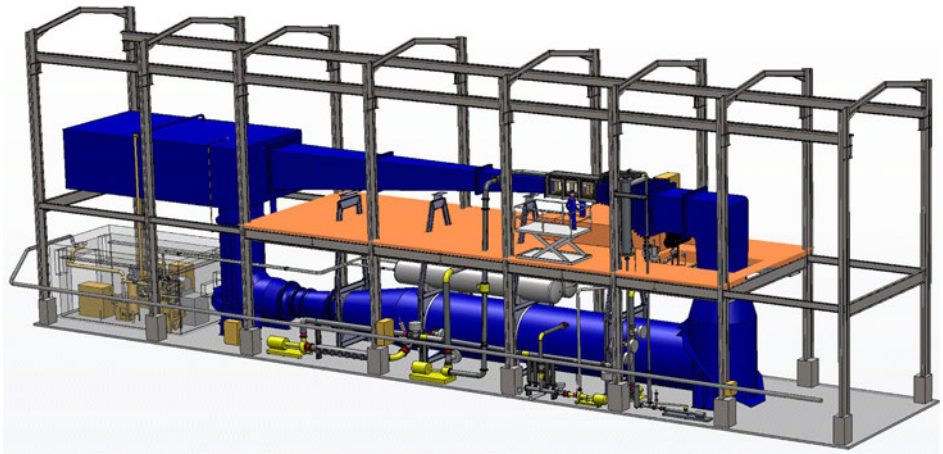


Figure 1: Schematic of the AMC Cavitation Tunnel [6]

The propeller dynamometer is installed through the top of the tunnel so that it lies along the centreline of the tunnel and as such is pitched at 0.22° to lie parallel to the freestream flow direction.

When attached, the wake device is located 25 mm upstream of the foremost point of the dynamometer support strut as shown in Figure 2. The wake device is fitted on to the front of the cylindrical section of the dynamometer by removing the nose cone, fitting the wake device to the main body of the dynamometer, and then re-attaching the nose cone to the front of the wake device. Thus, the length of the cylindrical section of the dynamometer is extended slightly by the wake device thickness.

A propeller was not fitted for any of the experiments. Instead, a cylindrical blank hub was attached, with dimensions typical of the hubs used on this dynamometer.

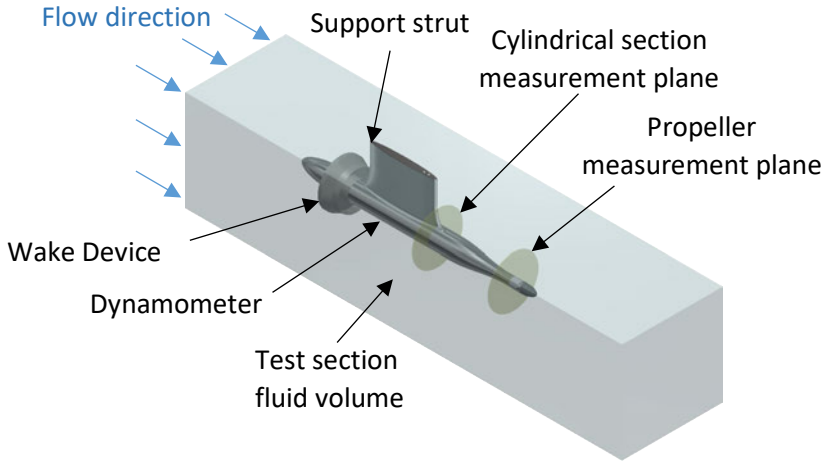


Figure 2: Dynamometer arrangement for behind-condition testing in AMC's cavitation tunnel

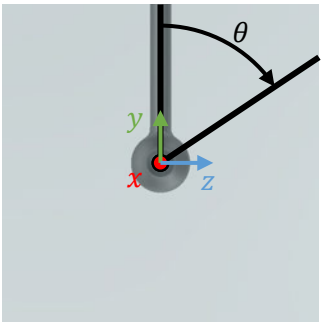


Figure 3: Dynamometer coordinate system and azimuthal datum as viewed from downstream

Measurement system

Wake profiles were measured using a 1.2 mm static pressure probe, and 0.5 mm total pressure probe, attached to a 3D traverse mounted through the side of the tunnel. The pressure was measured using a TE Connectivity EPB-B0-1 differential pressure sensor. The reference pressure line was plumbed via a diaphragm to the top of the test section. The sensor was calibrated in-situ by altering the tunnel static pressure. The static pressure probe is known to exhibit sensitivity to Reynolds number, and is thus calibrated over the operating velocity range of the tunnel.

Measurement points

Two measurement planes were investigated in this experiment. The first, the cylindrical section measurement plane, was located 475 mm downstream of the wake device near the end of the cylindrical main body of the dynamometer, just upstream of the end of the support strut (see Figure 2). The second, the propeller measurement plane, was located at the interface of the propeller hub and the tail cone, 925 mm downstream from the wake device. This second plane represents the location at which flow is considered to enter a fitted propeller.

Measurements were taken on radial lines at azimuthal angles of 45°, 90°, 135°, and 180° (see Figure 3 and Figure 9), where the top of the dynamometer is at 0°. As the flow around the support strut was thought to be more complex, additional measurements were taken on radial lines at azimuthal angles 0°, 5°, 10°, 15°, 20°, and 30° for the propeller plane measurements. The 3D traverse has a

measurement range of approximately ±100 mm from the centreline of the tunnel in x and y directions, with the z direction being limited by the model and the support for the probe stem. Measurements were taken to the maximum radius afforded by the traverse at the 0° position at all other angles as shown by the circles in Figure 2, except for at 135°, where the profile was taken to the extreme-most corner of the measurement area. A reference measurement was taken at approximately every 100 samples at the extreme-most corner of the measurement area at 45° to account for sensor drift.

Wake device

The 3D printed wake device is shown in Figure 4. The current design is azimuthally invariant, with the aim of making an axisymmetric wake, but varies with radius in order to tailor the velocity profile in the radial direction. The thickness profile of the device was determined by the estimated velocity deficit at each radial position required to match the wake of a Joubert axisymmetric model [7], scaled to suit a 250 mm diameter propeller. The equivalent Joubert hull required to produce this wake would be approximately 485 mm in diameter.

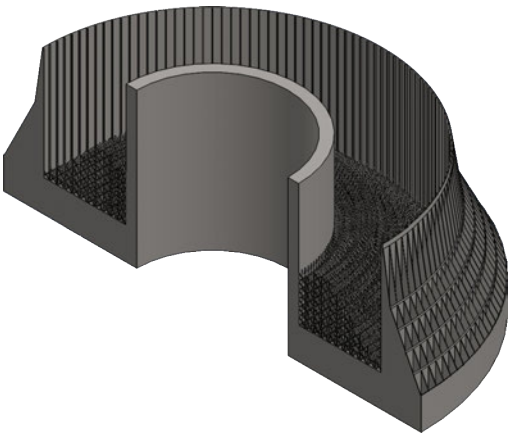


Figure 4: Wake device cross section showing central bore for fitting to the dynamometer

The wake device was 3D printed from Grade 17-4 PH Stainless Steel using a Selective Laser Melting process followed by post-machining. The overall diameter is 272 mm, with a maximum axial dimension of 100 mm.

As shown in Figure 4 and Figure 5, two types of geometric building blocks were used in the design of the wake device. The first is a quasi-rectangular cross section “honeycomb”, and the second is a spaceframe-like 3D lattice (see Figure 6). It was thought that the use of two distinct types of geometry may allow for a decoupling of the pressure loss over the device and the amount of turbulence generated which may be of concern in future work. The wall thickness of the “honeycomb” and diameter of the lattice bars are 0.4 mm. The two geometry types are combined to form a cell row which is designed to produce a specific pressure loss in fluid passing through. There 16 cell rows equally spaced at 5 mm across the radius that are repeated 160 times around the circumference and for a total of 2560 cell rows. The front face of the wake device consists of square section “honeycomb”. A lattice structure is then built from the rear face of the “honeycomb” in the region nearer the wall. Nearer the circumference of the device, the “honeycomb” from the front face is extended to the rear of the device.

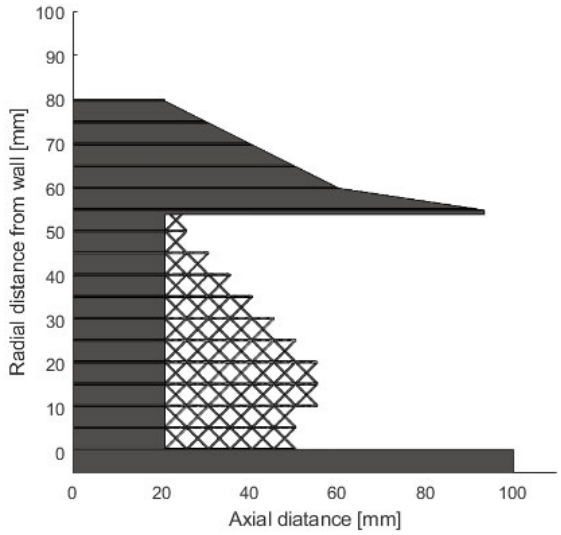


Figure 5: Wake device cross section showing the 16 radial cell rows

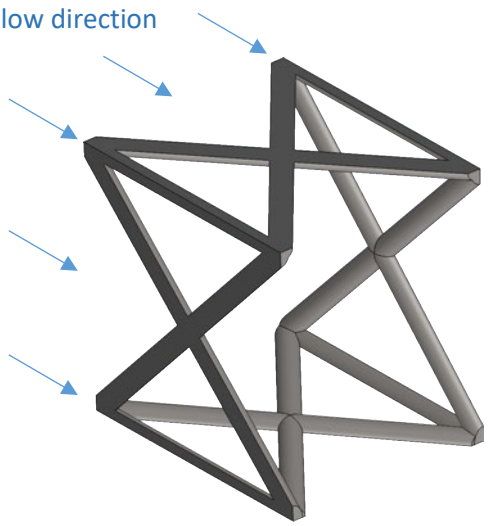


Figure 6: Typical Lattice unit cell used in the wake device

RESULTS

Data reduction

The results presented are non-dimensionalised for ease of interpretation. This has been done using the tunnel inlet velocity and water density. The normalised velocity ($\tilde{v}$) is then,

$$\tilde{v} = \frac{v}{v_\infty} \qquad , (1)$$

where v is the local velocity and v_∞ is the inlet velocity.

The static pressure coefficient is,

$$C_p = \frac{p_s - p_{s,ref}}{\frac{1}{2}\rho v_\infty} \qquad , (2)$$

where p_s is the local static pressure, $p_{s,ref}$ is the test section reference pressure, and ρ is the water density. Where applicable, the fraction of propeller radius is provided on the auxiliary axis. The propeller radius (R) used is 125 mm. This was based on the typical propeller size tested in the AMC cavitation tunnel.

Wake device performance

A comparison of the dynamometer wake with and without the wake device, and the target Joubert body wake, are plotted in Figure 7 against the wall normal distance from the surface of the hub, and the propeller radius fraction r/R. The velocity profile achieved by the wake device is considerably closer to the desired wake of the Joubert hull. The overall shape of the achieved velocity profile nears the desired shape in the first order, but there are still artefacts from the wake screen, visible as inflection points, at several points along the profile. The nominal wake fraction [8],

$$w_{nom} = \frac{2}{1-\left(\frac{r_h}{R}\right)^2} \cdot \int_{\frac{r_h}{R}}^{1} r \cdot \tilde{v}\, dr \qquad , (3)$$

where r is the radial distance, r_h is the radius of the hub, increased from 0.04 for the bare dynamometer, to 0.19 with the wake screen fitted, approaching the goal wake fraction of 0.26 for

the Joubert hull. The fractions were calculated from the single velocity profiles at θ = 135° which are assumed to be constant with azimuth, as they are the only profiles which span the entire propeller radius across all the experiments, and hence allow for direct comparison.

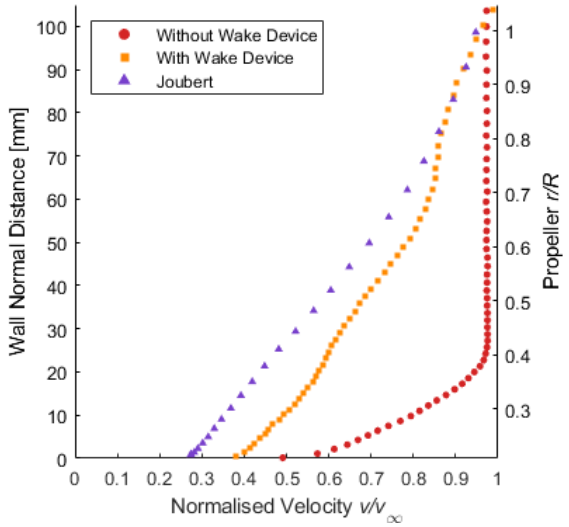


Figure 7: Comparison between goal Joubert wake, the unmodified dynamometer wake, and the wake as modified by the wake device. Dynamometer measurements taken at the propeller measurement plane. θ = 135°, v_∞= 4 m/s, R = 125 mm

The mean and standard deviation of the measured wake profiles at a given radius are shown in Figure 8. The tests where a wake device is fitted show a velocity dependency, with the deficit of the mean profile at a given radius increasing between the 6 m/s and 8 m/s tests. The shape of the 4 m/s test with wake device shows a slightly different shape, having a greater deficit closer to the wall than the 6 m/s test, and a slightly smaller deficit than the 6 m/s test far from the wall. For all speeds, the standard deviation, indicating the variability of the flow experienced by a blade through a rotation, is greater for the tests with the wake device than the without the wake device far from the wall, but is similar below a wall distance approximately 7 mm.

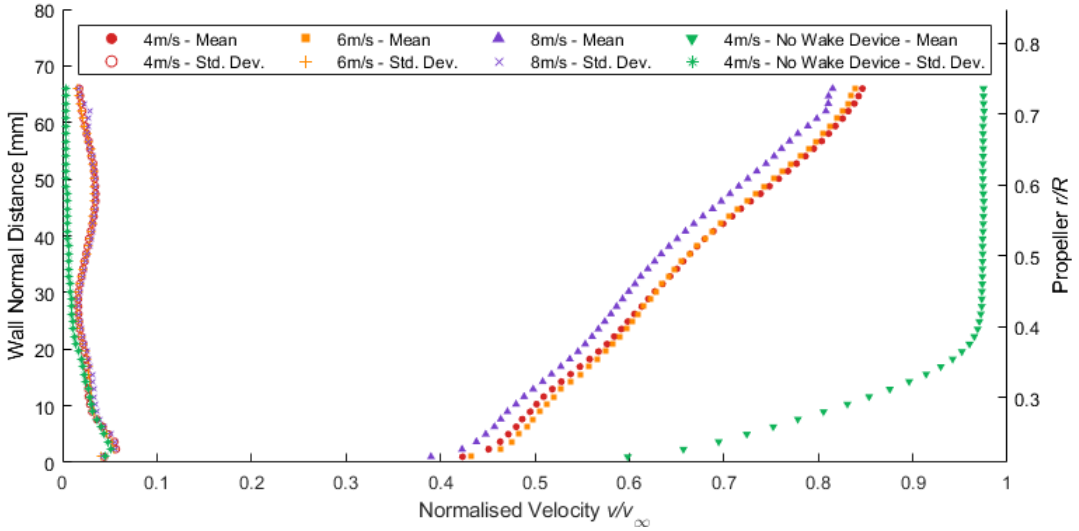


Figure 8: Mean and standard deviation of normalised velocity around the circumferential direction at a given radius, with and without the wake device fitted. Taken at the propeller measurement plane. R = 125 mm.

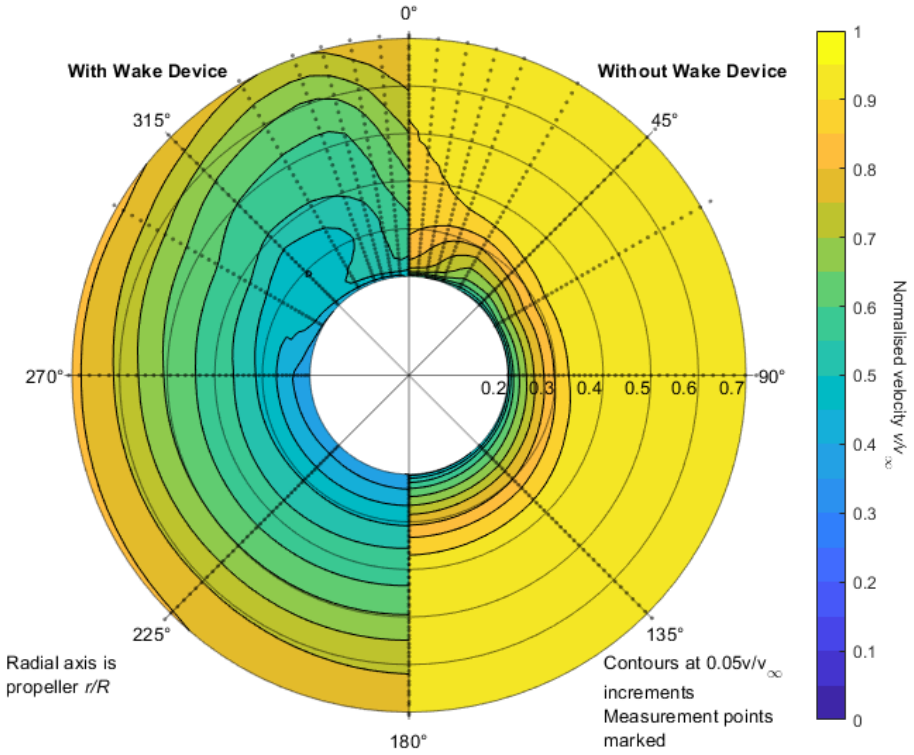


Figure 9: Normalised velocity comparison of the dynamometer wake with (left side) and without (right side) the wake device. Taken at the propeller measurement plane. v_∞ = 4 m/s, R = 125 mm.

A comparison of the dynamometer wake with and without the wake device fitted is shown in Figure 9. The wake produced by the bare dynamometer body reaches the freestream velocity at a radius fraction of approximately 0.35R. With the wake device added, the freestream velocity is not reached within the propeller disk area, with a normalised velocity of 0.96 reached at the maximum radius of the propeller blade (see Figure 7).

Radial velocity profiles at the cylindrical section measurement plane

Figure 10 shows velocity profiles taken at the cylindrical section measurement plane, 475 mm downstream of the wake device. Distinct changes in the velocity profiles that approximately correlate with changes in the wake device thickness are observed. The region of greater loss associated with a thicker lattice section is seen immediately outside of the naturally occurring boundary layer, between approximately 5 mm and 20 mm. The linear increase in velocity from 20 mm to 40 mm also aligns somewhat with the linear change in the lattice thickness. There is a significant drop in the velocity behind the thickest honeycomb section, indicating that the wake device produces too high of a pressure drop at this point. These areas are not quite aligned with the geometry that generated their respective deficit, indicating that the wake has begun to diffuse. The shape and magnitude of the profiles are consistent at all four azimuths measured around the dynamometer.

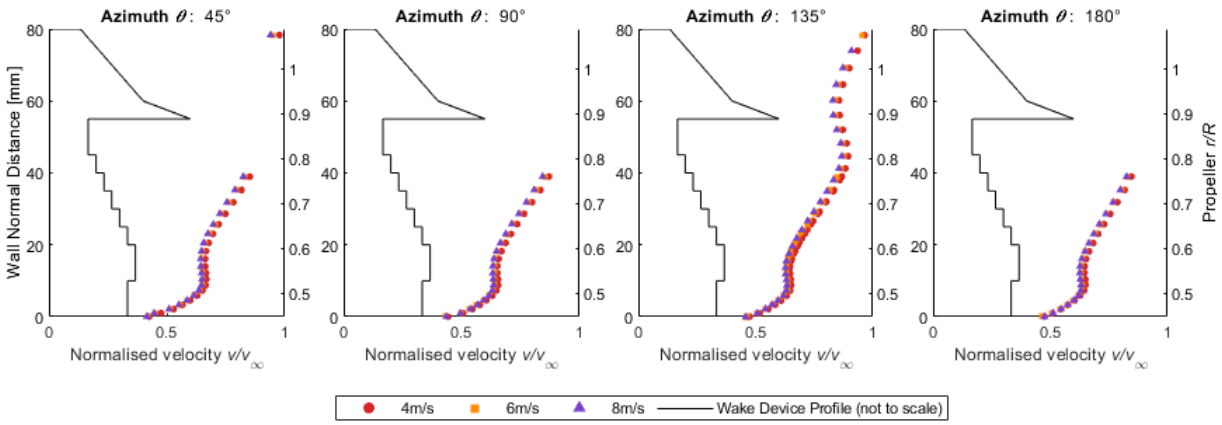


Figure 10: Normalised velocity profiles at the cylindrical section measurement plane. The cross-section of the wake device thickness is indicated with a black line. R = 125 mm.

Static pressure at the cylindrical section measurement plane

The static pressure coefficients measured at the cylindrical section measurement plane are shown in Figure 11. For all azimuths, the static pressure coefficient at the wall decreases with increasing tunnel inlet velocity and does so in a non-linear fashion. The range of near-wall static pressure coefficient reduces with azimuthal position, such that the difference between 8 m/s and 4 m/s static pressure coefficients at 45° is approximately 0.13, whereas at 180° it is only 0.03. Additionally, the static pressure coefficient decreases with increasing radius, with this effect being more pronounced at increased azimuth. The combination of these factors means that for the 135° and 180° azimuths, the static pressure coefficient for the 4 m/s test near the wall is greater than at greater velocities and progressively decreases with radius to below that of the 8 m/s test by the 35 mm and 20 mm mark for each azimuth respectively. This behaviour is also seen in the 6 m/s test results. The near-wall static pressure coefficient shows an increase with azimuth, with the largest change seen between 45° and 90°. The dependence on azimuth points to an interaction between the newly formed wake and the support strut indicating that the formation of the junction vortex is affecting the measured static pressure coefficient around the dynamometer body to a significant radius.

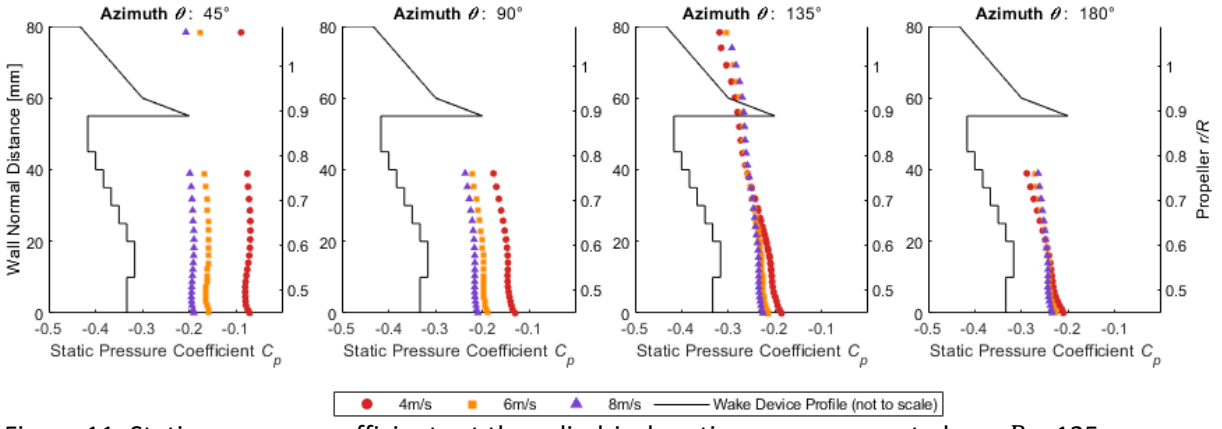


Figure 11: Static pressure coefficients at the cylindrical section measurement plane. R = 125 mm

Velocity deficit at the propeller measurement plane

Figure 12 plots the velocity profiles taken at the propeller measurement plane, 925 mm downstream of the wake device. It shows that the wake loses most, but not all, of the distinct velocity changes seen previously in Figure 10, indicating that the wake has begun to recover, but is still evolving. This is also demonstrated by the presence of inflections along the profiles. The velocity deficit near the wall is

greater at the propeller measurement plane compared to the cylindrical section measurement plane, which may be ascribed to the dilation of the flow and adverse pressure gradient over the tail cone combined with the thickening of the boundary layer due to the reduced diameter of the dynamometer.

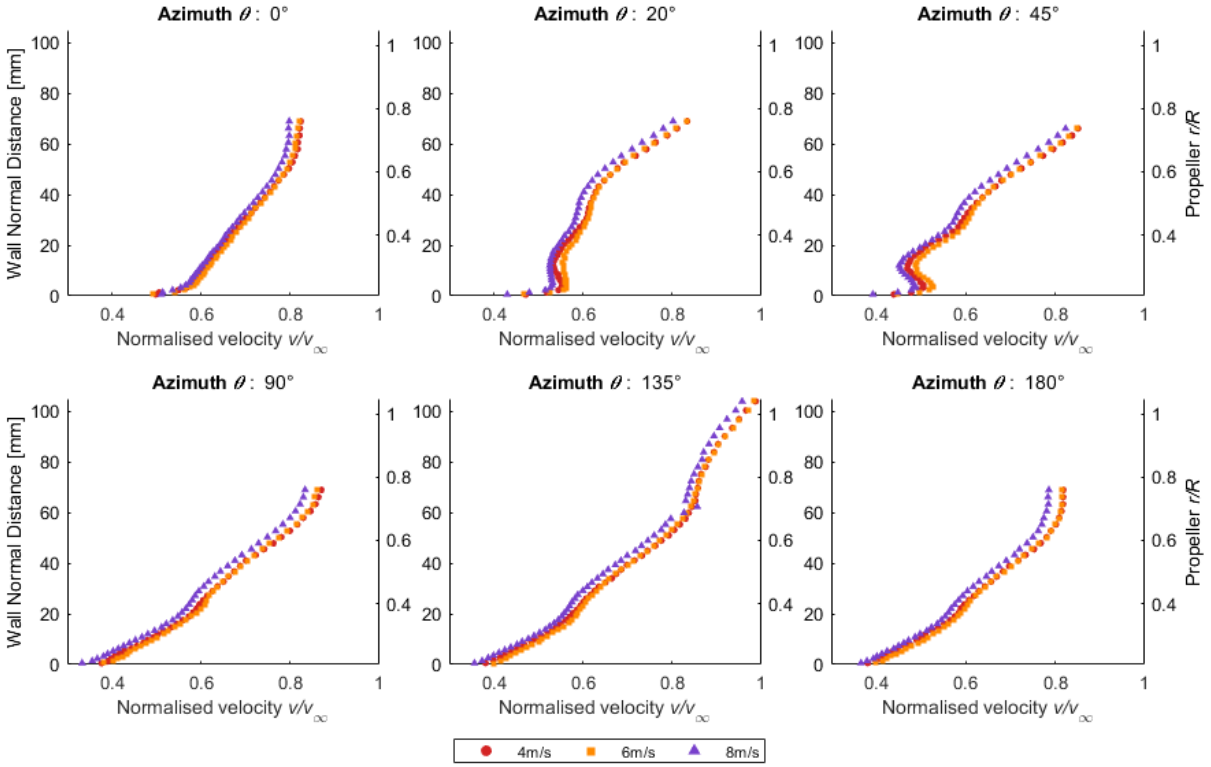


Figure 12: Normalised velocities at the propeller measurement plane. R = 125 mm.

Figure 12 and Figure 13 show a small velocity dependence. The 8 m/s test shows a smaller normalised velocity over all regions than the 4 m/s test. As observed previously in Figure 8, the shape of the 4 m/s normalised velocity profiles shown in Figure 12 differ slightly from the shape of the 6 m/s and 8 m/s normalised velocity profiles. The profiles do not show a monotonic change with changing freestream velocity.

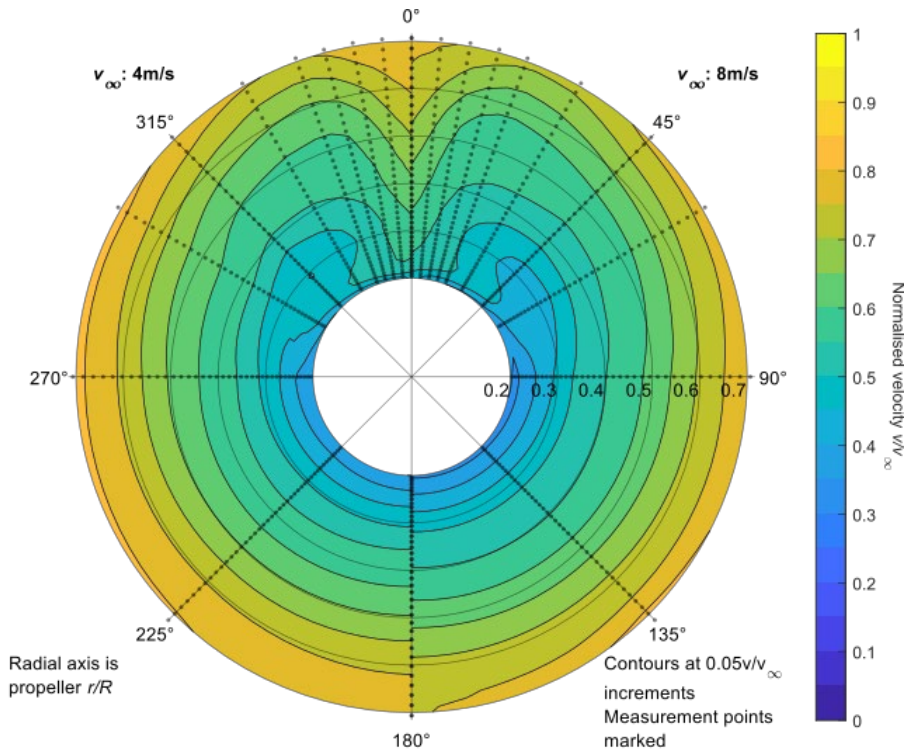


Figure 13: Comparison of the wake at 4 m/s (left side) and 8 m/s (right side) with the wake device fitted. Taken at the propeller measurement plane. R = 125 mm.

DISCUSSION

Whilst the exact target velocity profile of the Joubert hull was not achieved; the wake device was effective at reducing the velocity near the wall and producing a considerably thickened wake. The almost five-fold increase in wake deficit from 0.04 to 0.19 represents approximately 68% of the required additional velocity deficit to reach the goal deficit of 0.26. The magnitude of the velocity deficit achieved indicates that an accurate tailoring can be achieved using this method.

The shape of the velocity profiles at the propeller plane shows properties that are desirable for tailoring wakes. The controllability of the wake depends on two key factors: The amount of shear that is dissipated; and the amount of external flow influence. If too much shear is dissipated, then the boundary layer will quickly return to its natural shape, determined by the pressure gradients downstream of the wake device, instead of by the wake device itself, meaning that only one shape can be achieved. If there were significant external influence on the downstream wake then the tailoring may be overshadowed by these external effects. The observed velocity profiles maintain the inflection points, meaning that both of these factors are sufficiently small that a tailored profile may be preserved over the distance from the wake device to the propeller. This means that the wake's shape is controllable and so may be altered by a wake device such as the one fitted in the current experiment.

Variation of the non-dimensionalised measurements behind the wake device with velocity was not unexpected. As the wake develops downstream of the device the growth will depend on the velocity in a manner similar to a natural boundary layer. What remains unexplained is the change in shape of the wake at 4 m/s. The lack of progressive change indicates a fundamental change in behaviour between 4 m/s and 6 m/s, for which testing between 4 m/s and 6 m/s would be needed to discern. Despite these irregularities, the change in velocity deficit between tested velocities is small compared

to the range of velocity deficits that are achieved. This insensitivity means that a single wake device may be used at a range of operating velocities and still achieve the desired profile. This allows for the flow rate through the propeller to be precisely set in-situ, rather than requiring a wake device for individual settings.

CONCLUSION

A series of experiments were carried out at the AMC cavitation tunnel testing the performance of an axisymmetric, 3D printed wake device, designed to produce a representative wake of an underwater vehicle. The wake device significantly thickened the wake, achieving a wake fraction appreciably closer to the desired profile.

The results provide an increased understanding of how the wake device altered the wake, and guidance to continue developing and refining wake device design in order to enable improved testing of wake adapted propellers in behind-condition testing. The use of 3D printed wake devices, designed to produce controlled artificial wakes, is feasible.

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Naval Promas System

Joakim Hirvonen Grytzelius, Kongsberg Maritime Sweden AB, joakim.grytzelius@km.kongsberg.com
Henrik von Wendt, Kongsberg Maritime Sweden AB, henrik.vonwendt@km.kongsberg.com
Kristoffer Kleppestø, Kongsberg Maritime AS, kristoffer.kleppesto@km.kongsberg.com
Patrik Kron, Chief of Naval Systems, Kongsberg Maritime Sweden AB, patrik.kron@km.kongsberg.com

1 ABSTRACT

This paper presents the results from computational fluid dynamic (CFD) calculations and experimental model tests in which the propulsion manoeuvring system (Promas) has been compared to a conventional system with an off-centre rudder, normally used on navy ships.

The CFD calculations and model tests show the effect from the Promas system on the cavitation, propulsion efficiency, underwater radiated noise, and pressure pulse levels for a ship speed up to 25 knots. The cavitation inception speed (CIS) were model tested for the two configurations.

Results from the experimental in behind condition show an increase in propulsion efficiency between 5.0 % to 6.3 % for the Promas setup. This is in good agreement with the CFD calculations which show an improvement close to 6%.

The measured pressure pulse (PP) levels were lower with the Promas setup compared to the conventional system. The noise levels were lower for the Promas system at frequencies below 1 kHz.

The cavitation inception speed for the Promas setup is like the result for the conventional system. The Promas setup has equal or slightly better pressure side tip vortex (PSTV) inception while the conventional system results in a slightly better suction side tip vortex (SSTV) inception.

2 INTRODUCTION

Previous studies and experiments done at Kongsberg Hydrodynamic Research Centre (KHRC) has shown that Promas have several hydrodynamic advantages compared to a conventional propeller/rudder system. One of the main advantages of Promas is that the propeller (with its hubcap) and rudder (with its Costa bulb) is treated and designed as one propulsive unit. The propeller is designed to achieve the best possible system efficiency and the rudder includes an adapted twist specially designed for the propeller slipstream. In addition to increased propulsive efficiency, Promas will also improve low speed maneuvering and reduce the hull induced pressure pulses (PP), see Figure 1 for a short summary of Promas advantages.

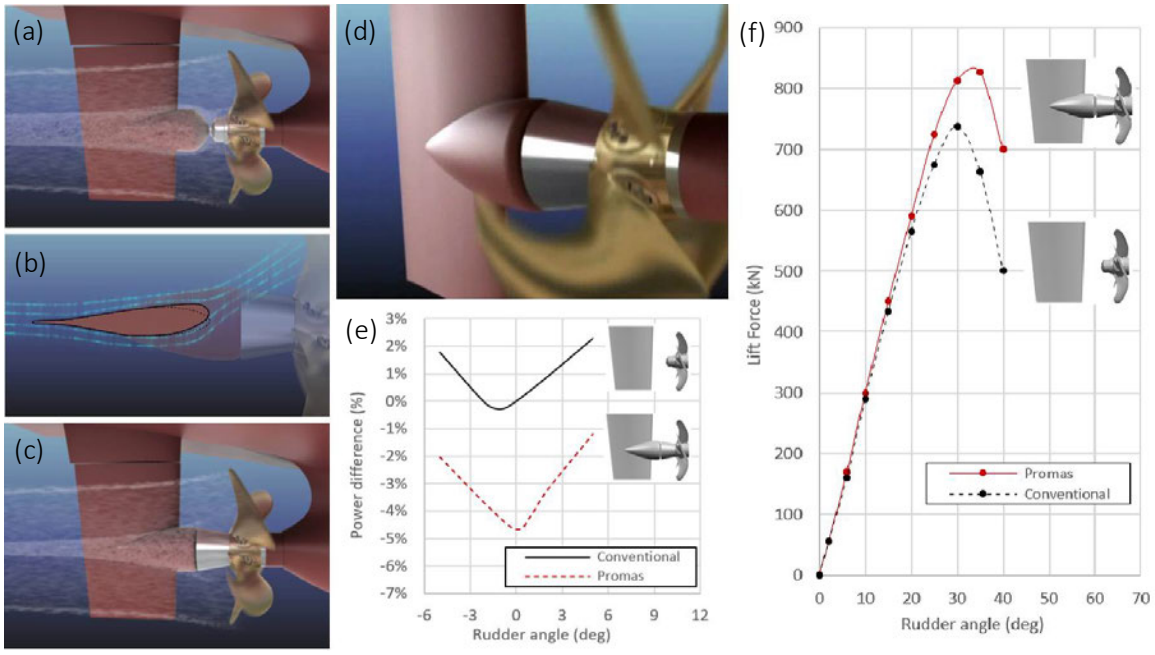


Figure 1: (a) Rudder with Costa bulb regaining energy from the propeller slipstream. (b) Illustration of adapted rudder twist. (c) Illustration of the Promas system with hubcap, Costa bulb, and adapted rudder twist to regain energy from the propeller slipstream. (d) Illustration of Promas with a steering angle of -5 degrees. (e) Efficiency improvement is maintained at rudder angles between ±5 degrees (commercial vessel at 16 kn). (f) Diagram showing that Promas has higher total lift compared to the conventional system at bollard pull condition.

In the commercial shipping industry, Promas has mainly been used to save fuel. The reduction of greenhouse gases (GHG), decreased pressure pulse levels, and lowered radiated noise has come as a bonus when choosing to install Promas. However, in recent years there have been much more focus also on ''Green shipping'' and how it's affecting the marine life, here Promas plays an important role with its benefits of reduced PP and radiated noise levels. For more than 15 years the Promas concept has contributed to a better marine life and been successfully installed in more than 200 new sale and upgrading projects.

The interest in sustainability and GHG reduction are also growing in the naval market, where increased operational range is of high priority. Today, with focus on combination of small crews with remotely operated and autonomy vehicles, we are seeing an interest to reduce ship speed to increase operational endurance.

Most naval twin-screw vessels use conventional rudders which is placed off-center from the shaft centerline. Historically this configuration is mainly used to allow the shaft to be pulled out without removal of the rudder blade. However, for high speed vessels like Corvettes/Frigates the cavitation performance at high speed is also an important design requirement and might have played an important role when placing the rudder off-center.

For naval vessels with a top speed between 20-25 knots the results in this paper will be of great interest with regards to the significant increase in system efficiency and good results for cavitation inception speed, pressure pulse-, and radiated noise levels.

As the cavitation modelling from the CFD calculations is still not validated with satisfactory accuracy, one of Kongsberg's cavitation tunnels has been used for the present study of cavitation inception speed, pressure pulse- and radiated noise- levels. These results are then compared towards the CFD calculated values to evaluate and improve our methods.

The test setup consisted of a typical naval aft ship dummy designed for installation of both the Promas bulb-rudder and the conventional off-center rudder. It consists of an open shaft configuration with V-bracket and high shaft inclination angle to produce a typical wake field for a naval twin screw vessel.

The four main goals were to investigate the following:

- Cavitation inception speed.
- Propulsive efficiency.
- Underwater radiated noise.
- Hull induced pressure pulses.

The cavitation inception is determined by visually observing when cavitation occurs on the propeller blade.

3 CFD CALCULATIONS

As mentioned in the earlier section, CFD calculations has been performed to increase the hydrodynamic insights, to improve the simulation methods, and for the validation of the experimental results. A full-scale 3D model of the aft ship, shaft line, V-bracket, rudders, and propeller were configured in our own developed CFD tool, HullProp, which is based on in-house standardized methods utilizing the commercial tool Siemens Simcenter StarCCM+. The propeller forces and induced slipstream were calculated by using a propeller model utilizing a sliding mesh approach i.e. a rotating propeller region with a sliding mesh interface. The propeller induced slipstream propagates downstream and the rudder interaction are studied in a transient manner. The calculated rudder forces are averaged levels of the last propeller revolution simulated when a stabilized and converged solution are established.
The results from the CFD calculations are post-processed into forces and cavitation pattern estimated through single phase iso-surfaces detection and is used to compare the systems performance in regards of propulsive efficiency, pressure pulses, and cavitation.

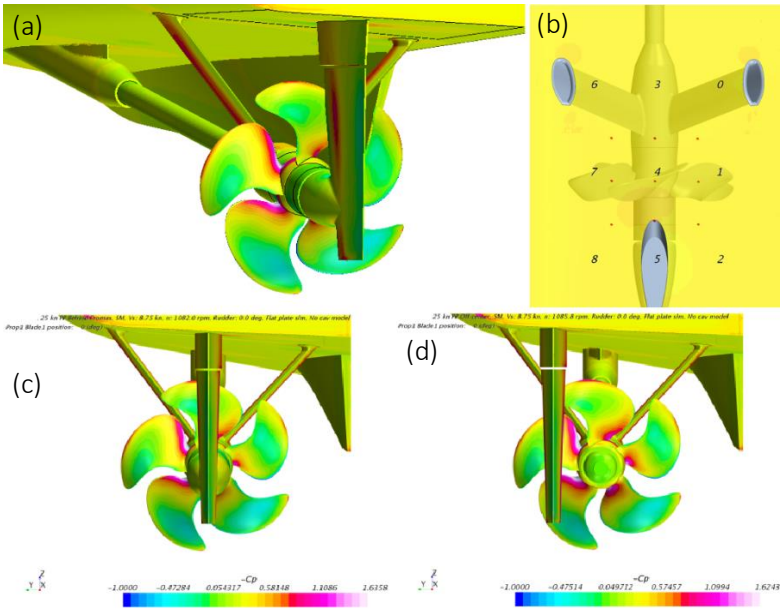


Figure 2: (a) Illustration of the 3D model used in the CFD calculations. (b) Top view of the model showing the positions of the pressure transducers. (c) Aft view of the Promas system. (d) Aft view of the conventional propeller-rudder system.

As Promas is a combined propulsion and maneuvering system it is also important to compare the maneuvering forces between an off-center rudder system and a Promas setup. In a cavitation tunnel this is a very time-consuming task. However, there exist a well proven and validated method for calculating rudder forces (a simplified CFD setup with a virtual propeller disc) which is used for this comparative study. The results were used to create rudder lift curves and a lift/drag relationship. With thoughts of the operational profile of a naval vessel the maneuvering forces were calculated at three different speeds. Max speed at 25 kn, transit speed at 15 kn, and 6 kn. To represents slow speed and harbor maneuvering the calculations were also performed for bollard pull.

4 MODEL TEST

4.1 Experimental setup

The setup used for all tests was a minimalistic hull dummy to represent the port side of a twin-screw navy vessel. The rig was mounted in cavitation tunnel T-31 (Kempf & Remmers) as illustrated in Figure 3.

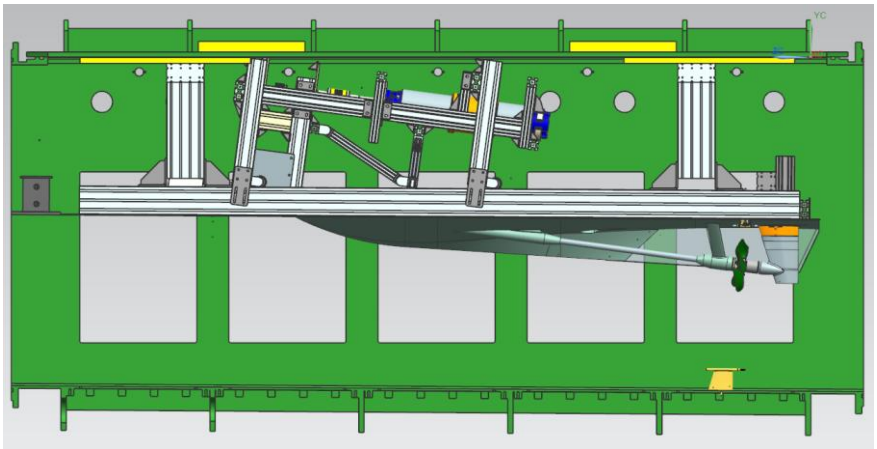


Figure 3: CAD view of the mounted test setup in KHRC cavitation tunnel T-31.

The dummy model shape is designed by KHRC to generate a representative wake for a navy vessel with open shafts and V-brackets, operating at a speed up to 25 knots. Notable for the model is the open propeller shaft with an 7.5° vertical inclination and its modular design makes it easy to change the setup between a conventional off-center rudder system and a Promas configuration. There is also an integrated camera in the hull dummy facing towards the suction side (SS) of the propeller to study the cavitation in more detail. Figure 4 (a)-(d) show detailed views of the two different systems mounted in the cavitation tunnel.

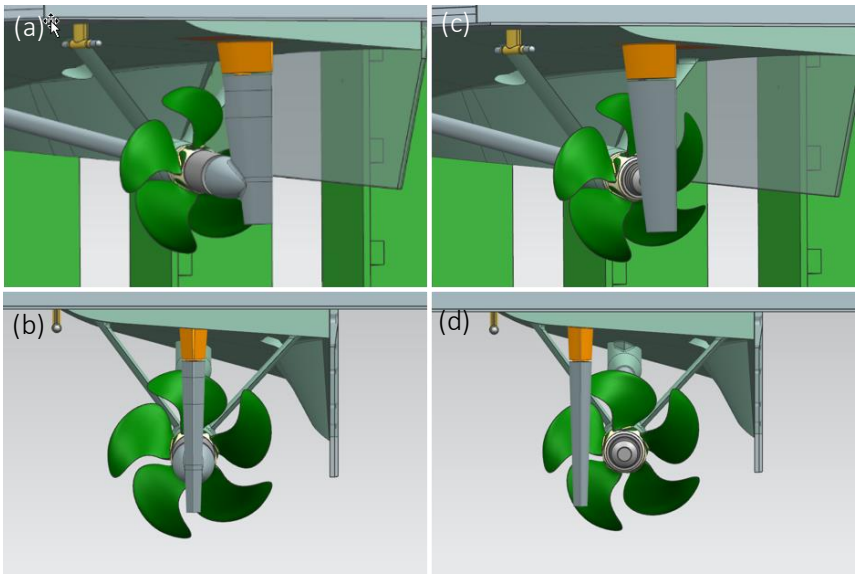


Figure 4: Images showing the two configurations used in the calculations. (a) and (b) show side- and aft view for Promas and (c) and (d) for the conventional setup.

To make the results more relevant, we used a NACA-66-20 profile for the off-center rudder and KM's standard profile for the rudder included in the Promas setup. The rudder for the Promas setup was designed with a KM standard twist, minimal fairing and no toe-out/in. This to give an unbiased result and as a reference for future optimization.
Both rudder blades were produced in aluminum and anodized to give a smooth and strong surface (Figure 5).

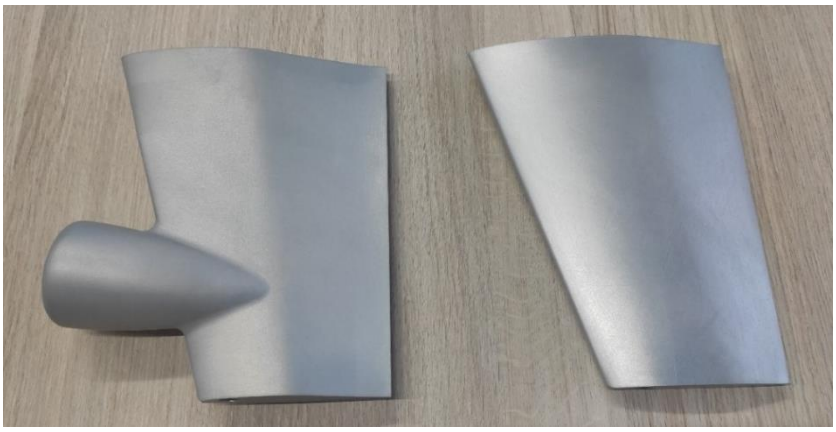


Figure 5: Photograph of the two rudders used in the test. Rudder with bulb used for Promas (left) and conventional rudder (right).

The same propeller model is used in all the experiments and is a typical Navy propeller, designed for high CIS, efficiency, and low-pressure pulse levels. The basic propeller data is presented in Table I below.

Table I: Details of the propeller model.

Full scale			
Type of propeller		CPP	
Number of blades	Z	5	
Blade area ratio	A_E / A_0	0.76	
Design pitch ratio	P_0 / D	1.38	
Prop. diameter	D_S	3.60	m
Hub diameter	d_S	1.02	m
Skew angle	θ_S	35	deg
Model scale			
Scale factor	λ	14.4	
Prop. diameter	D_M	250	mm
Hub diameter	d_M	70.83	mm

4.2 Measurement devices

A total of 8 pressure transducers was mounted flush into the hull above the propeller to measure pressure pulses. The mounting in the hull is illustrated in Figure 6 (a). Noise was measured with three underwater B&K 8103 hydrophones. Two of them mounted on the top plate and one mounted at the bottom, as illustrated by Figure 6 (b). The pressure transducers and hydrophones were sampled at 51.2 kHz and each measurement was recorded for 7.5 seconds.

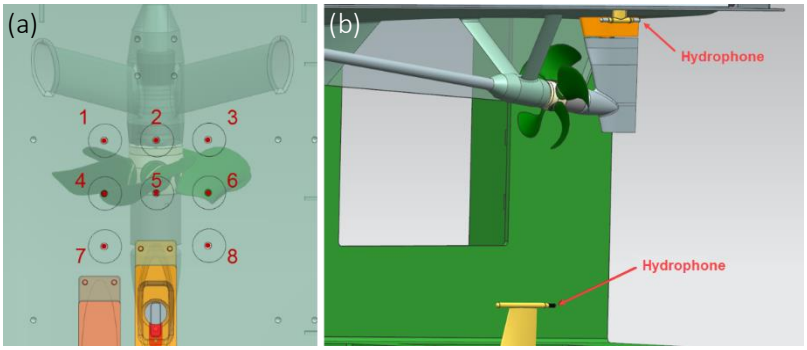


Figure 6: (a) Illustration of pressure transducers mounted into the hull. (b) CAD view of the hydrophone positions.

The propeller thrust and torque was measured with a 2-component dynamometer mounted between the propeller and propeller shaft. Rudder drag was measured with a 1-component dynamometer mounted at the rudder stock position.

4.3 Wake Simulation

To create a realistic wake field a wire mesh grid was mounted on the hull (Fig. 7 (a)), and to measure the water velocities at the propeller disc a special hub was used, see Figure 7 (b). The resulting wake was measured by the aid of an LDA (Laser Doppler Anemometry, Dantec Dynamics) instrument and is shown in Figure 7 (c).

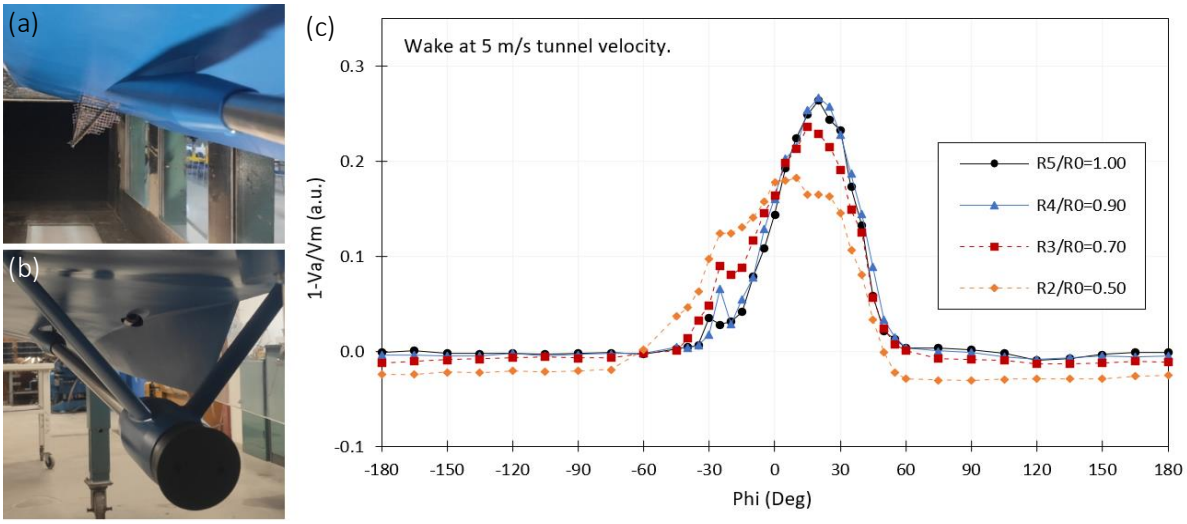


Figure 7: (a) Image of the wire mesh grid attached to the hull which is used to create a realistic wake field. (b) The special hub mounted on shaft to measure the wake at the correct position. (c) show the resulting wake field at the propeller disc.

5 RESULTS AND DISCUSSION

5.1 CFD

The system performance is evaluated by adding the rudder drag to the propeller thrust to get a total propulsive force. It is further normalized toward the ship-hull resistance and an in-house force balance method. The results from the calculations are summarized in Table II and shows that Promas will reduce the power consumption with approximately 6 % at a ship speed of 25 kn. The calculated pressure pulse level was expected to decrease for the Promas system, as earlier seen in other projects. However, the results showed to be the same for both systems which shows that further work is needed to refine our calculation method regarding pressure induced hull forces.

Table II: The propulsive results from the CFD calculation shown as total efficiency.

25 kn	η_{tot}	Efficiency Gain (%)	Pressure pulses (kPa)
Conventional system	0.640	-	1.7
Promas system	0.678	5.98%	1.7

The rudder forces were calculated at three different speeds and at bollard pull (BP). Except for the BP condition, the lift curves and lift/drag relation show the same trend, therefore only the 25 kn condition will be presented here.

Figure 8 (a) show the resulting lift forces versus rudder steering angles from the 25 kn condition. Compared to the conventional system the maximum lift force is increased by approximately 30% for the Promas system. The stalling angle is unchanged. The lift/drag relation, figure 8 (b), show that Promas has less drag at small rudder angles and a higher lift at larger angles.

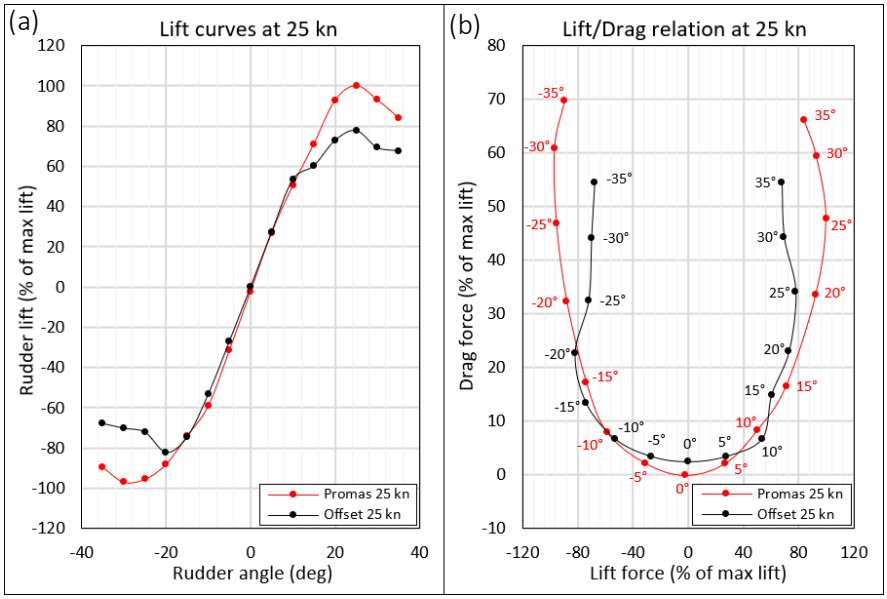


Figure 8: (a) Comparative rudder lift vs rudder angle curves between conventional- and Promas- systems at 25 kn. (b) Lift/drag comparison between the same systems as in (a).

In the bollard pull condition Promas has higher lift force at all rudder angles, figure 9 (a), and the maximum lift force is increased by approximately 140%. The lift/drag relation, figure 9 (b), shows that Promas, already at rudder angles of ± 10 degrees, has equal lift force as the conventional systems at 35 degrees.

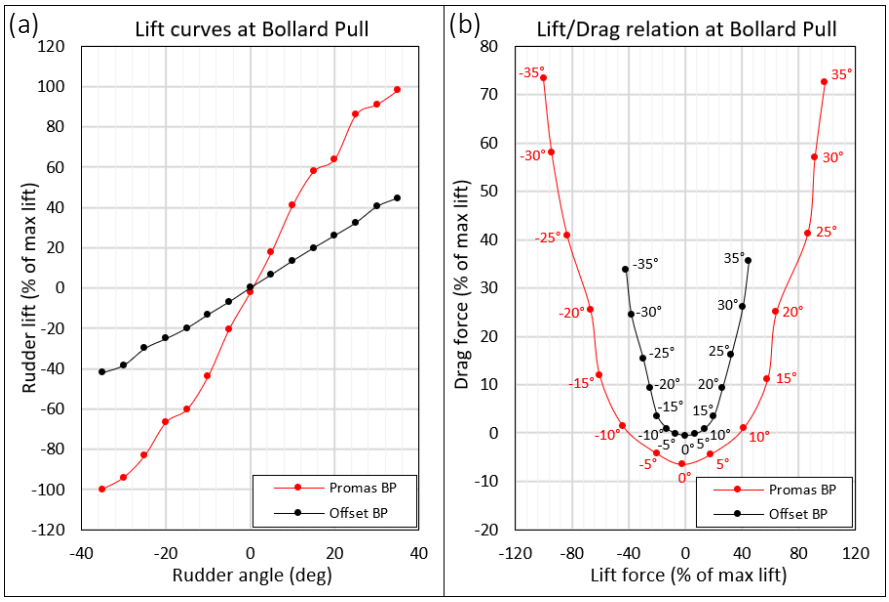


Figure 9: (a) Comparative rudder lift vs rudder angle curves between conventional- and Promas- systems at bollard pull. (b) Lift/drag comparison between the same systems as in (a).

The large increase in rudder forces for Promas will improve steering at slow speed and harbour maneuvering.

5.2 Model test

5.2.1 Cavitation inception speed

Cavitation inception speed is determined by visually observing when cavitation occurs on the propeller blade. In this case there were three different individuals present at the test, all judging the cavitation inception individually.

The model test results are scaled to full scale by using McCormick's law with a McCormick factor of 0.4 and plotted as the cavitation number (σ_A) versus the advance number (J):

$$\sigma_A = \frac{P - P_V}{0.5 \cdot \rho \cdot {V_A}^2} \quad (1)$$

$$J = \frac{V_A}{n \cdot D} \quad (2)$$

where P being the pressure in undisturbed water, P_V the vapour pressure, ρ the water density, V_A the speed of advance, n the propeller revolution, and D the propeller diameter.
As seen in figure 10, the conventional off-centre system has a slightly better suction side tip vortex (SSTV) inception while the Promas setup has slightly better pressure side tip vortex (PSTV) inception.

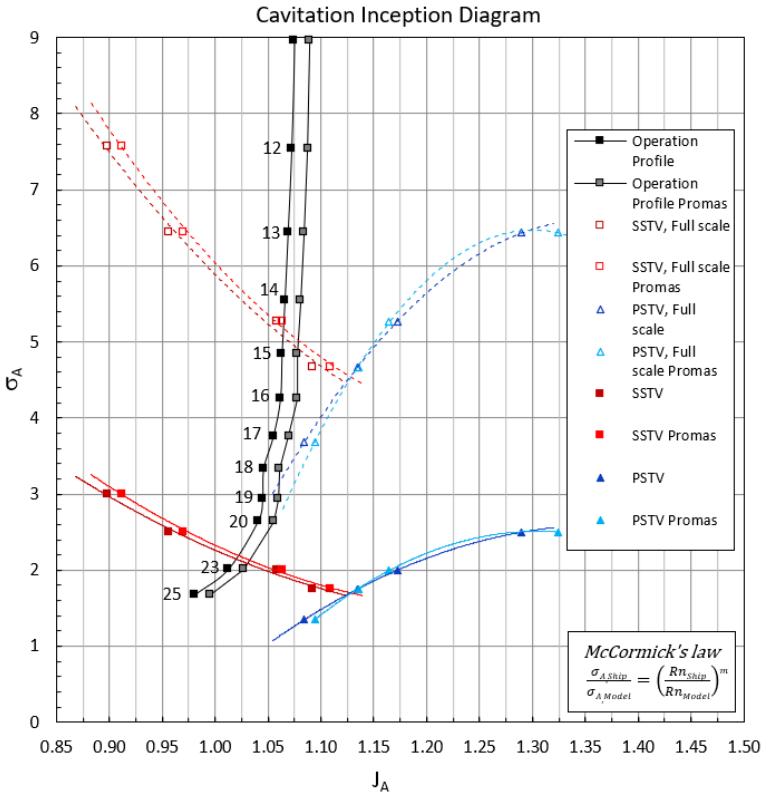


Figure 10: CIS diagram showing the results from the comparison between the conventional and Promas systems.

The most obviously change between the two systems is the change in operational profile. Compared to the conventional system the operational profile for Promas is shifted horizontally towards higher propulsion number (J). This is however reasonable when considering that Promas has higher propulsive efficiency i.e. the propeller is less loaded at the same speed.
If considering, the error margin relative to the measurements it is plausible to conclude that the CIS properties for the two configurations are the same.

5.2.2 Propeller cavitation

At 25 knots, the cavitation patterns on the propeller blade was similar for both the conventional system and the Promas setup. There is however a clear difference at the propeller root section. Figure 11 (a) and (b) clearly show the root cavitation close to the blades trailing edge for the conventional system. The same area for the Promas setup, figure 11 (c)

and (d), has notable less cavitation and appears more sporadic. This is expected since Promas, with its bulb and hubcap, reduces the slipstream contraction and as a direct consequence there is reduced water velocities around the propeller hub. It is worth mention that the root cavitation is a common feature for a highly loaded CP propeller and the most important is to control it to be non-erosive.

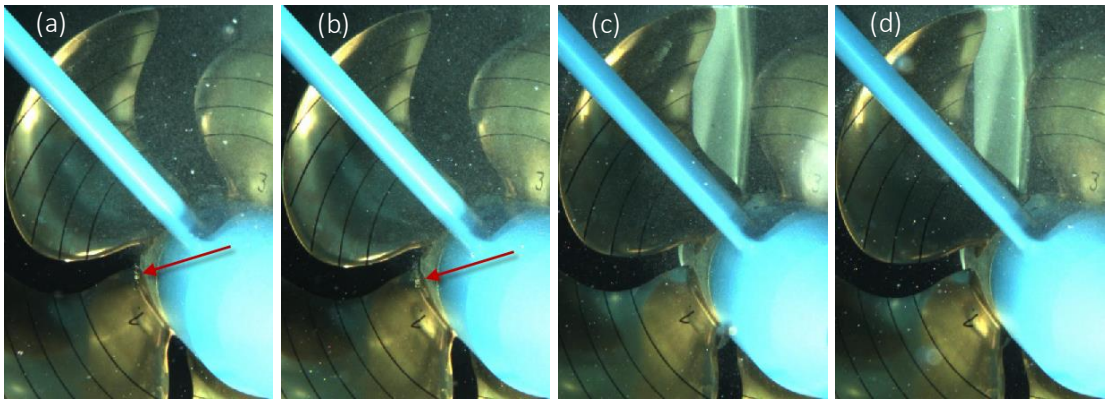


Figure 11: (a)-(b) Root cavitation at 25 knots for the conventional system. (c)-(d) The same root area as for the conventional system shows reduced root cavitation.

5.2.3 Rudder cavitation

Figure 12 (a)-(f), show the cavitation patterns on the bulb-rudder from the Promas setup at steering angles -5, 0 and +5 degrees and ship speed of 20 kn. The bulb-rudder was free from cavitation at 20 kn and 0° steering angle (figure 12 (b)). At -5°, a small vortex appeared on the port side of the rudder, starting at the bottom close to the thickest section (figure 12 (a)). With a steering angle of +5° a sporadic cloud cavitation is observed on the starboard side close to the fillet between the rudder- bulb and blade (figure 12 (f)).

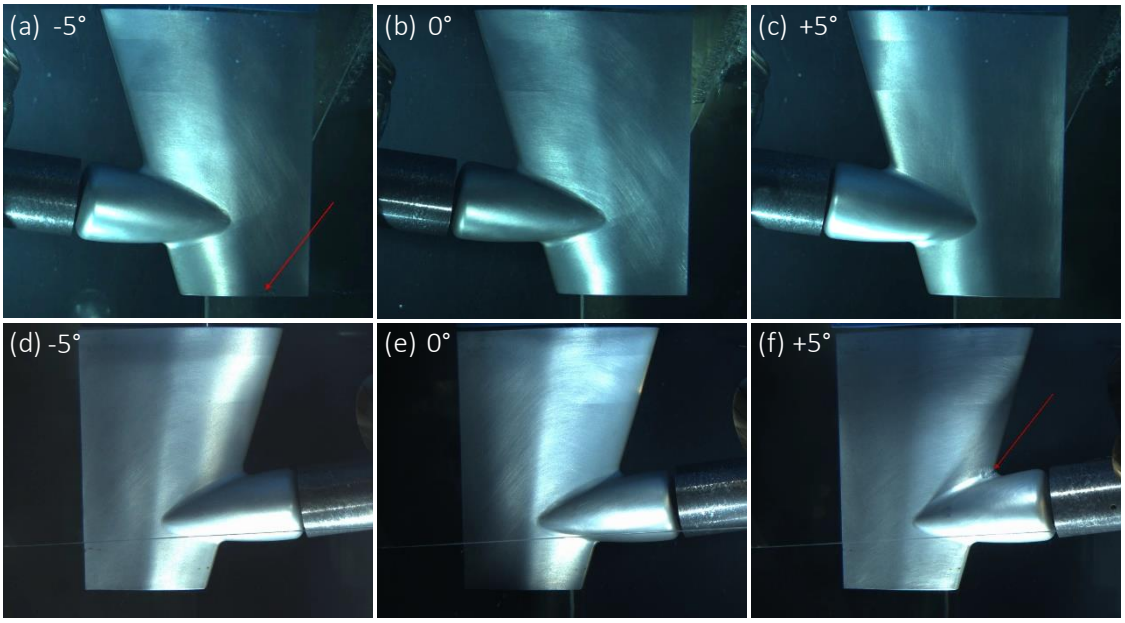


Figure 12: (a)-(c) Port view of Promas systems rudder at 20 kn and rudder angle -5°, 0°, and +5°, respectively. (d)-(f) Starboard view of Promas systems rudder at 20 kn and rudder angle -5°, 0°, +5°, respectively.

At 25 kn and 0° rudder angle (figure 13 (b)) a small vortex appears on the port side of the rudder, triggered at the thickest section. The small vortex at is strengthened when the rudder angle was set to -5° and disappearing at +5°, figure 13 (a) and (c), respectively.

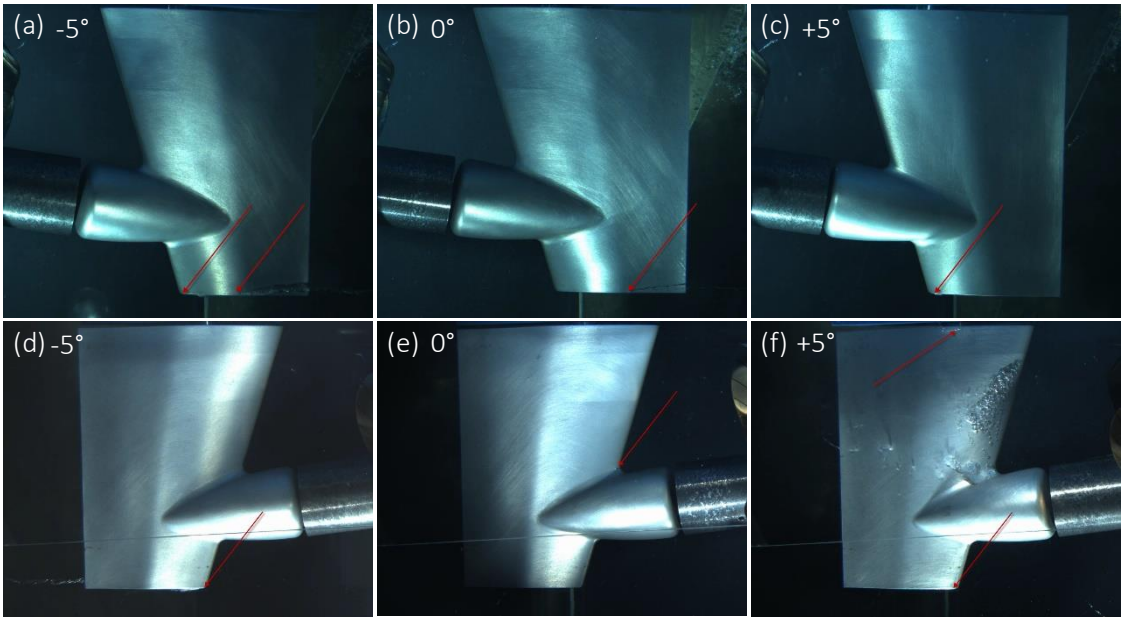


Figure 13: (a)-(c) Port view of Promas systems rudder at 25 kn and rudder angle -5°, 0°, and +5°, respectively. (d)-(f) Starboard view of Promas systems rudder at 25 kn and rudder angle -5°, 0°, +5°, respectively.

At the bulb fillet on starboard side (figure 13 (e)) a sporadic cavitation appears. At +5° rudder angle (figure 13 (f)) a considerable bubble cavitation was present on the rudders upper part on the starboard side. A small vortex was also visible at the top of the rudder blade. The sporadic cavitation at the bulb fillet develops into cloud cavitation at +5° rudder angle. Cavitation was also triggered by the sharp edge at the bottom of the rudder at ±5°.

5.2.4 Efficiency in behind

To compare the system efficiencies i.e. both rudder and propeller, the rudder thrust component (drag) is added to the propeller thrust. The results are presented the same way as a propeller open water curve and scaled to full scale according to ITTC-78, as seen in figure 14. The operating points of interest is then calculated according to KQ/J3 analysis.

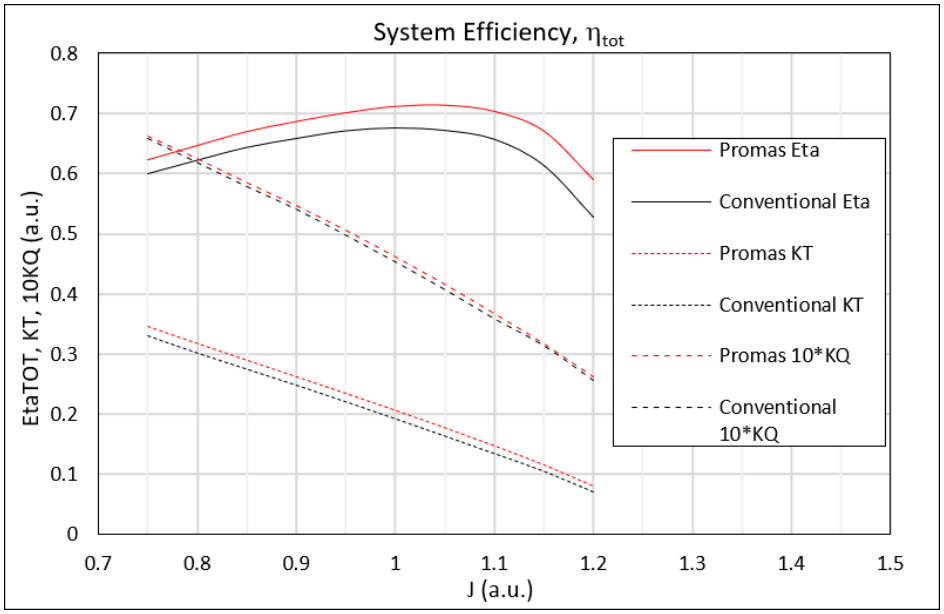


Figure 14: Efficiency characteristics in behind, Promas vs conventional vs conventional off-centre rudder.

The system efficiencies are compared at 25 kn, 20 kn, and 15 kn and the results are presented in table III. The analysis shows that Promas will increase the systems performance between 5.0–6.3 % depending on ship speed.

Table III: Comparison between the system efficiencies between Promas and conventional setup.

	25 kn		**20 kn**		**15 kn**	
	η_{tot}	η_{tot} gain	η_{tot}	η_{tot} gain	η_{tot}	η_{tot} gain
Conventional system	0.676	-	0.674	-	0.670	-
Promas system	0.709	5.0 %	0.714	5.9 %	0.713	6.3 %

5.2.5 Pressure pulses

Pressure pulses was measured for the harmonics of propeller passing frequency by eight transducers, integrated in the hull above the propeller. Position 1 to 8 refers to the setup shown in figure 6 (a) and position 9 refers to hydrophone located on the side of the rudder (figure 6(b)).

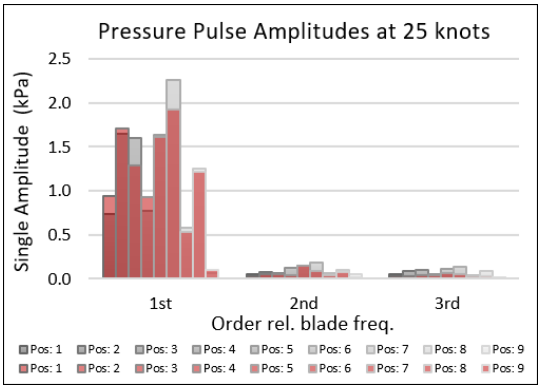


Figure 15: Pressure pulse amplitudes at 25 kn for Promas (red) and conventional (grey) systems.

The first order single amplitude pressure pulse at 25 kn is approximately 15% lower for the Promas system (figure 15). For the blade passing frequency and the second and third harmonics, Promas results in lower levels compared to the conventional system.

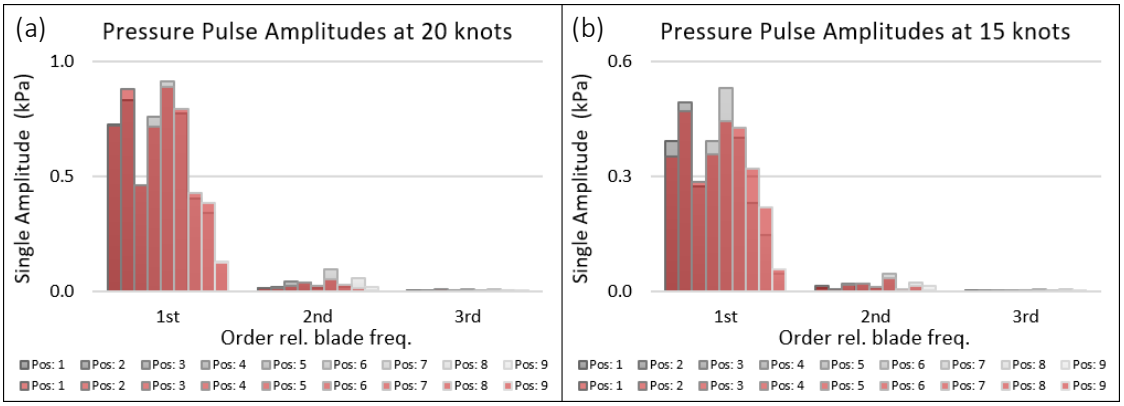


Figure 16: Pressure pulse amplitudes at 20 kn (a) and 15 kn (b) for Promas (red) and conventional (grey).

The 20 kn and 15 kn conditions (figure 16 (a) and (b)) shows a similar trend as for the 25 kn conditions. However, the reduction is somewhat smaller at the 20 kn condition. The results are presented in Table IV.

Table IV: Calculated single amplitude full-scale pressure pulses at 25, 20 and 15 kn

	25 kn		**20 kn**		**15 kn**	
	5^{th} Amp [kPa]	10^{th} Amp [kPa]	5^{th} Amp [kPa]	10^{th} Amp [kPa]	5^{th} Ampl [kPa]	10^{th} Amp [kPa]
Conventional system	2.26	0.18	0.91	0.09	0.53	0.05
Promas system	1.92	0.15	0.89	0.05	0.47	0.03

5.2.6 Radiated Noise

Noise level are only presented for 25 kn because at lower speeds the measured signal matches the background noise. The measurements presented here was recorded with the hydrophone positioned at the tunnel floor below the propeller, see figure 6 (b). Noise is presented as full-scale narrow band power spectral density (PSD) diagrams and as 1/3-octave band sound pressure level (SPL).

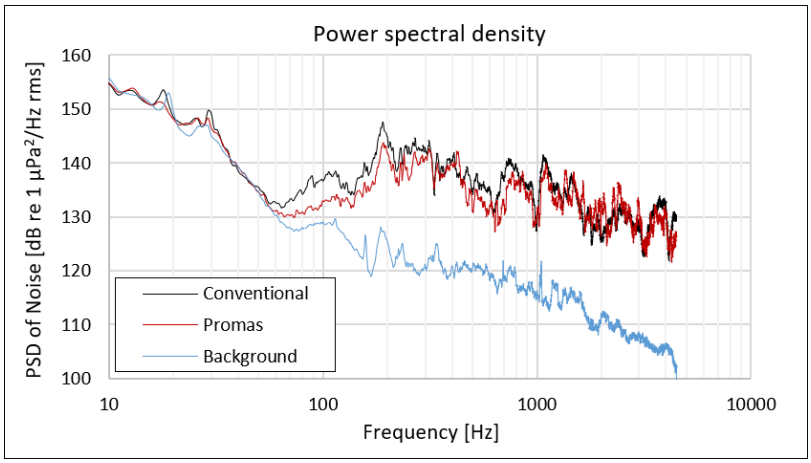


Figure 17: Radiated noise measurements, scaled to full scale and presented as PSD. Conventional system (black), Promas setup (red) and background noise (blue).

The diagram in figure 17 show the measurements as PSD versus noise frequency for Promas and the conventional system. At frequencies lower than 1 kHz, Promas radiates less noise, while at higher frequencies it radiates slightly higher noise. It is plausibly to conclude that this is caused by the small tip vortex triggered on the bulb-rudder.

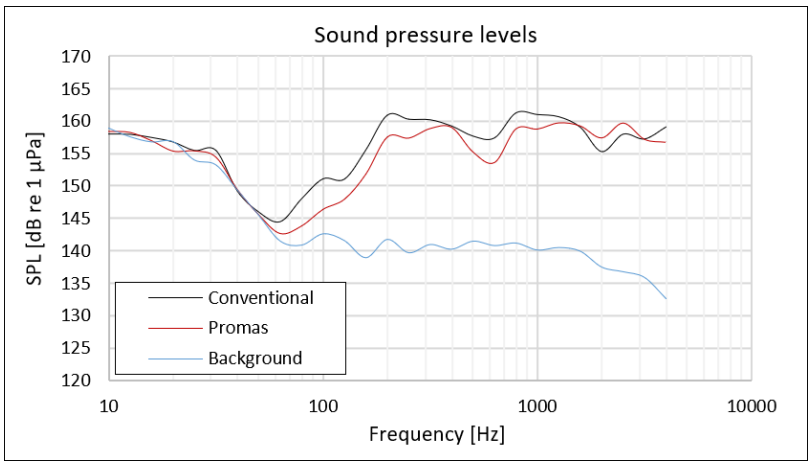


Figure 18: Radiated noise measurements, scaled to full scale and presented as SPL. Conventional system (black), Promas setup (red) and background noise (blue).

Figure 18 show the measurements as SPL versus noise frequency for Promas and the conventional system.

6 CONCLUSION

In conclusion, the propulsive properties of a conventional navy propulsion system (propeller with offset rudder) and Promas (rudder integrated with propeller) has been compared in detail by means of propulsive efficiency, rudder forces, cavitation inception speed, cavitation, pressure pulses, and noise levels.

The experimental results show an increase in system performance between 5.0 – 6.3 %, depending on vessel speed, for the Promas setup. This is in good agreement with the CFD calculated results which showed an improvement close to 6%.

Based on the calculated rudder forces, the bulb-rudder used for Promas, has 30 % higher lift at 25 kn compared to the conventional rudder. At the bollard pull condition the bulb-rudder has higher lift at all rudder angles with a maximum increase of approximately 140 % at +35° steering angle.

The measured cavitation inception speed (tip-vortex inception) showed to be the same for both systems. The propeller blade cavitation showed to be unchanged, however, at the blade root the cavitation was improved for the Promas setup and is explained by reduced water velocities around the propeller hub.

The CFD calculated pressure pulse amplitudes for the two systems showed to be similar. However, the experimental results showed a decrease with approximately 15% for Promas and agrees with our earlier findings regarding Promas.

The measured noise levels showed that for frequencies below 1 kHz Promas radiates less noise, at higher frequencies Promas radiates slightly higher noise levels. It is reasonable to believe that these higher levels are caused by the rudder tip vortex triggered at the rudder nose.

Except for the improved propulsive performance, which will increase the operational range, the rudder forces are much higher and will improve the slow speed and harbour manoeuvring. Reduced pressure pulse and noise levels leaves room for further efficiency improvements or a more silent operation.

The unbiased Promas design used here leaves room for further improvements regarding reduction of the rudder tip vortex, causing noise at frequencies above 1 kHz, as well as a tailormade twist design to reduce bubble and cloud cavitation on the rudder blade.

Furthermore, calculation for alternative Naval adapted Promas propellers, indicates that there is room for further improvements regarding efficiency and values well above 6% could potentially be reachable.

Conclusively, the above results clearly show that Promas has a great potential to be a suitable solution also for the naval segment.