Autonomous Surface Vessels and Design for Availability

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2 Synopsis

Availability is in simple terms the degree to which an equipment/ system/ vessel is in an operable state and depends on how reliable and maintainable its sub-systems are. Without a typical crew who are continuously on hand, Autonomous Surface Vessels (ASVs) require more thorough consideration in designing for availability than is currently practiced for conventional vessels. This requirement is exacerbated as ASVs become larger and more complex in nature and their roles increasingly longer in duration. Interrupted operation of a vessel due to equipment faults and failures can have a range of unwanted consequences from underperformance of its role through to hazardous events. Despite this, availability has been overlooked in research and development literature compared to other ASV topics. Equipment redundancy is an oft cited solution to ensuring availability but is just one of a number of reliability and maintenance strategies each with pros and cons. The specific choice of strategy and resulting "design for availability" requires the rigorous trading of these pros and cons that would benefit from decision support. As a novel contribution to the subject domain, the choice of strategy is framed as an exercise in mathematical multi-criteria optimisation. The justification for the use of such optimisation is given and potential steps for its application proposed.

3 Keywords

Uncrewed Ships, Reliability, Maintainability, Optimisation

4 Biographies

Eshan Rajabally is the Maritime Autonomy Technology Lead at BMT. Eshan is a chartered engineer with over twenty years of experience in research and innovation, technology development, and demonstrator prototyping.

Ian Savage is the Chief Engineer for Transversals and Technical Assurance at BMT. He has over twenty years of experience in Naval Engineering in both Surface and Sub-surface craft and specialises in Naval Recoverability and fire protection.

5 Introduction

Equipment faults and failures are generally tolerated more-so in surface maritime than in other transportation domains such as air, given the heightened safety-criticality of onboard equipment as compared to sea-going vessels. As a result, ensuring availability of a conventional vessel's equipment typically calls for frequent and varied planned and unplanned maintenance tasks to be carried out, particularly for long-duration operations and large or complex vessels. However, a future proliferation of Autonomous Surface Vessels (ASVs) demands a different philosophy to designing for availability without the benefit of a crew continuously on hand as in the conventional sense. This paper makes the case for an even more focussed and systematic treatment of availability, than conventionally considered, directed at the lack of onboard support, and a potential way forward.

The next section (6) is a summary of the status of ASVs and the potential future course of their development. This is followed in section 7 by key terminology definitions and justification of availability being a particularly important topic. As a pivotal enabler to availability, different maintenance strategies are considered in section 8 along with the difficulty of strategy selection with regards to ASVs. Recent thinking in ASV availability is presented in section 9, acknowledging that whilst there are good practice and emerging technologies, the strategy of redundancy is not a "silver bullet". Considering the multiple approaches to designing for availability, the case for applying mathematical optimisation is given in section 10 before conclusions in section 11.

6 Autonomy and its Application to Surface Vessels

The International Maritime Organisation (IMO) defines a full autonomy to be where "the operating system of the ship is able to make decisions and determine actions by itself". This they categorise as degree/ level

4 autonomy with a further 3 paraphrased as follows. Degree 1 concerns conventional ships with some onboard automation, degree 2 covers ships that are conventionally crewed but can be remote controlled and degree 3 ships are both remotely controlled and uncrewed. In practice autonomy at degree 4 can vary according to the scope of systems under consideration, the range of tasks or operation in mind and perhaps most importantly, the nature of human monitoring and intervention both in-situ and otherwise. There have been many earlier attempts to distinguish this variation further giving rise to a number of scales of autonomy from academia, class societies, industry, and interest groups (e.g Norwegian Forum for Autonomous Ships) including naval specific (e.g. the European Defence Agency's "SARUMS").

At varying degrees of uptake, proposed defence and security applications of vessel autonomy include seaborne targets, submarine hunting, minesweeping, Intelligence, Surveillance, and Reconnaissance (ISR), and border and littoral zone patrol. As has grabbed the headlines in recent times, ASVs have been employed in anger for offensive purposes with for example, reports of explosives laden drone boats used by Ukraine to attack the Russian naval port of Sevastopol in the Black Sea. Stepping up in vessel size, O'Rourke (2023) summarises the status of US Navy large ASV initiatives. Their medium displacement concept is a 45-190ft patrol sized vessel mooted for ISR and Electronic Warfare (EW) and their large displacement concept is a 200-300ft, corvette sized vessel mooted for Anti-Surface Warfare (ASuW). The Ghost fleet development programme to which these concepts belong include the prototype vessels under test, Overlord and Seahunter. Meanwhile, funded by the UK MoD's Defence and Security Accelerator (DASA), Intelligent Ship is a multi-phase innovation programme to develop and demonstrate human autonomy "teaming" with a future warship in mind and so demonstrating C2 decision making spanning the operations room, bridge and machinery control spaces (Cooke and Tate, 2023). The range of roles is telling of both the potential reach and ambition of autonomy in the naval domain.

A key takeaway from the initiatives described above is the wide range of application of autonomy in maritime and the potential for its growth in scope and adoption into larger and more complex vessels than is currently the case. Enabling technology development has perhaps pooled around situational awareness and navigation and as argued next, availability should not be neglected. In practical application it is difficult to divorce availability from its bedfellow topics of reliability and maintainability. Hence the three terms are first defined.

7 Availability, Reliability & Maintainability (AR&M) at Sea

Definitions of AR&M are taken from the UK MoD's Defence Standard 00-49. Equipment reliability is the ability to perform under given conditions for a given time interval. Maintainability is the ability of equipment to be retained in or restored to a state in which it can perform as required under given conditions. Maintainability is thus dependent on serviceability (the ease of conducting scheduled inspections and servicing) and repairability (the ease of restoring service after a failure). Equipment availability is the ability to be in a state to perform as required under given conditions and is therefore dependent on reliability and maintainability. Availability is required for uninterrupted functioning and so continuous performance of the task in hand.

In the case of ASVs, without crew intervention in the conventional manner, there is more scope for faults and failures (e.g. a sudden loss of steering) to lead to hazardous situations for the vessel itself and others in the vicinity. The obligatory assessment of operational safety will require focus and additional rigour to particular measures in the design for availability according to the risk posed from dangerous incidents and accidents. Defence Standard 00-45 advocates a Failure Mode, Effects & Criticality Analysis (FMECA) and proposes categories of hazard severity not only in terms of safety and environment, but also mission capability and cost. A criticality matrix is further proposed to classify the risk according to both the severity and the likelihood of the hazard. The implication of availability to safety of ASVs is a topic worthy of a paper in its own right.

Classification societies have issued guidance and, in some instances, goal-based rules, e.g. Lloyds Register's Code for Unmanned Marine Systems 2017. These focus on the safety requirements of the vessel and its control systems and included Classification Notations to support design assurance. Lloyds Register include notations such as 'Digital MAINTAIN', allowing remote / automated monitoring / analysis, decision making and adjustment, that when combined with more traditional Machinery Planned Maintenance and Condition Monitoring notations will allow conditioned based maintenance data to be used to support alternatives to survey, potentially, in addition to supporting remote or autonomous machinery monitoring. Use of such data should provide cost savings through life that may help to offset a higher procurement cost.

7.1 Availability, an Overlooked Topic?

There are a number of reasons why the topic of availability for ASVs now demands more attention than historically given particularly when contrasted with autonomous vehicles in the land and air domains. Redressing the following is paramount to successful expansion of maritime autonomy (see also Eriksen & Lützen, 2022):

- Interrupted operation of conventionally crewed vessels is tolerated more than for vehicles in the other domains given a lower likelihood of immediate danger to life and limb, and so the safety imperative has not been as pressing a driving force.
- In maritime, there has been a long-standing expectation of onboard engineers being both well trained and well equipped to remedy or mitigate faults and failures.
- The remoteness of operation at sea means there is a considerable delay and logistical difficulty to recovery if faults and failures cannot be self-remedied.
- A variety of large vessel type, complexity and purpose means no one-size-fits-all solution.
- A plethora of equipment and suppliers thereof particularly when cargo/payload handling and/or mission systems added to the plate.

7.2 The Mayflower, a Cautionary Tale

Led by Promare in collaboration with IBM and others, the Mayflower Autonomous Ship is a 50ft uncrewed trimaran built to recreate the iconic transatlantic crossing by the original Mayflower over 400 years ago. Over the course of two crossing attempts the first in 2021 and the second in 2022, three faults occurred as reported in the media, forcing the vessel to be recovered or diverted elsewhere. The modern-day Mayflower is propelled by electric motors and powered by solar panels, batteries and a backup generator. Mechanical and electrical faults associated with this drive line were reportedly unforeseen and remained undiagnosed until the vessel was recovered. Specific details on the faults are not openly available although Stanford-Clark (2023) mentions a broken flexible hose coupling within the exhaust system during the first crossing attempt and an earthing problem due to chaffing of electrical wiring during the second attempt. The authors of this paper are unaware of what AR&M modelling if any, such as fault and failure analyses, was performed during design and may have been of help. Despite ultimately failing to recreate the original Mayflower's voyage, the 2700-mile crossing from Plymouth, UK to Nova Scotia, Canada was nonetheless a significant achievement. The Mayflower experience illustrates the scale of the availability challenge, particularly that of the inevitably of faults and their high-consequence potential without timely human intervention.

8 Conventional Maintenance Strategies

Three maintenance strategies are often distinguished. Corrective or reactive maintenance is repair and replacement in response to damage, faults and failures. Preventative or proactive maintenance meanwhile can be time-interval or schedule-based and predictive or condition-based usually determined by Reliability Centred Maintenance (RCM) analysis. The former is conducted according to a pre-determined frequency whilst the latter according to measured indicators of equipment health status such as vibration of a bearing. Without the benefit of access to human intervention, the relative pros and cons of the maintenance strategies should be objectively compared to strike the best balance between them. The definition of ASV need not exclude onboard human presence and so a large ASV may or may not be crewed to some extent and for some or no time whilst at sea. Clearly, feasibility of hands-on maintenance by engineering crew at sea depends on the allowance for safe onboard access and hotel-services with significant potential implication to vessel size and cost. The three maintenance strategies fall on a continuum ranging from reactive to proactive where there is tension between cost and benefit, such as the lower procurement cost but longer downtime for the former case compared to the higher procurement cost but shorter downtime for the latter.

Determining the mix or balance of maintenance strategies is a non-trivial task for conventional vessels and is potentially made more complex with increasing adoption of autonomy. Although risking a break in continuous operation, corrective maintenance might be favoured for non-critical equipment or for functions with redundancy. Corrective maintenance may be less tolerable on an ASV than conventional vessel given fewer or no in-situ crew to undertake repairs and then a delay or difficulty in boarding crew at sea to do so. Condition-based maintenance is then seen as a step forward from schedule-based maintenance. The higher initial cost of condition-based maintenance from implementing condition monitoring compared to schedule-based maintenance can be offset over an extended period by savings from not intervening earlier than is necessary. The cost of the additional instrumentation and monitoring should be traded against benefits to other aspects of the design providing increased and importantly earlier indication of failure modes that could create fire, flood or capability loss. Kluijven et al. (2017) and Dragoș et al. (2021) consider pros and cons of the different maintenance strategies in the context of autonomous vessels. These authors thus illustrate the conflicts and trade-offs that must be resolved in any effective design for availability. Overarching approaches to effective maintenance strategy have been proposed such as Reliability Centred Maintenance (RCM). Applicable to all Defence environments, and optionally supported through Class Notations, RCM considers system and equipment functions, failure modes, effects and consequences, and the need for preventative or corrective measures.

9 Recent Thinking in Autonomous Surface Vessel Availability

For long duration unattended operation, addressing “holistic” health is the paramount challenge to ensure hull, mechanical and electrical availability. To address this challenge, a structured, comprehensive and detailed upfront analysis of equipment faults using a suite of techniques and backed up by modelling and real-world data can be used to focus the design effort around high-probability triggers and high-severity consequences. Brocken (2016) considers records of machinery failure aboard conventionally crewed but non-specific vessels in German waters over multiple years from 2001 to 2011 to glean lessons for future uncrewed vessels. He finds failures in the main engine (139 incidents), steering gear (75), fuel system (40), electrical system (32) and cooling water system (30) to represent 90% of the total number (359) of incidents. Brocken (2016) further analyses failures by severity, proposes potential design solutions and speculates that the cost of compelling reliability improvements on uncrewed vessels can be offset by the savings associated with accommodating humans.

Cost savings aside, design efforts should consider mitigations across the cause-effect chain and look to engineer-out single-points-of-failure whilst engineering-in fault recoverability e.g. degraded subsystems operating in concert with still healthy subsystems. There are 2022 media reports of US defence research agency, DARPA adopting a philosophy of graceful degradation for its first-of-a-kind medium sized ASV, NOMARS (No Manning Required Ship). Equipment redundancy is mooted to this end along with major system modularisation to enable rapid refit in any typical yacht yard. Looking ahead, modern and emerging technologies may be better exploited to augment condition monitoring such as Internet-of-Things based sensors, drone-based inspection, machine-learning based prognostics and augmented reality.

A cost-effective approach will require a structured focus to availability modelling and any associated engineering enhancements. Bartlett and Savage (2023) propose that the design is assessed against the ability to continue to provide essential safety functions and, where required by the concept of operations, to provide enduring mission capability. This, first and foremost, aims to allow the vessel to safely operate but also to ensure the vessel can recover itself to avoid burden or hazard to 3rd parties. Bartlett and Savage (2023) consider loss of aspects of the design against platform and mission system against the DNV Rules for Classification of ship framework and the requirements to maintain safety of function (in the case of ASVs to 3rd parties) such that a:

- Failure will not lead to danger
- Failure could eventually lead to danger / degrade mission
- Failure could immediately lead to danger / mission loss

Overlaying machinery failure historic data together with systems supporting essential safety / mission functions provides a means to focus availability modelling and design enhancement in a logical, justifiable and tailorable manner. This approach will also provide benefits to the survivability of the ASV.

9.1 Equipment Redundancy, Necessary but not Sufficient

Redundancy is the duplication of equipment so if one fails then another can take over and can be active (in simultaneous operation) or passive (held in standby until called upon). Historically but perhaps without due recognition and credit, the human is the redundancy of last resort. He or she can manually accomplish the machine's function after the final backup fails (Panter and Falcone, 2021). For example, after an automated fire suppression system fails, the human can and is expected to use manual firefighting methods.

Eriksen & Lützen (2022) present an example analysis of the implications of equipment redundancy on reliability of systems to which they belong. They consider loss of propulsion due to pump failures onboard a hypothetical single engine ASV using reliability data from the OREDA (Offshore and Onshore Reliability Data) handbook, a well-established information source for the oil and gas industry. Crucially, they compare independent and dependent failures, the former case being where the likelihoods of different failures occurring are unrelated to one another. In the latter case failures are related, can be common cause or cascading, and are not resolved by redundancy. Although there are strategies to reduce dependency between failures such as physical separation of equipment, Eriksen & Lützen (2022) observe that achieving true independence between failures is in practice, very difficult. Eriksen & Lützen (2022) consider pump failures in the fuel oil, lubrication oil and cooling water equipment assuming that just 1% of pump failures are dependent. They find that without the onboard crew to remedy equipment failures, then the effect of dependent failures despite being proportionally few, rapidly surpasses those of independent failures.

Opting for equipment redundancy can sometimes be the knee-jerk answer to ensuring ASV availability. However, it brings cost, weight and space penalty and as evidenced above, is not a panacea. Fortunately, equipment redundancy is one a of a number of alternative strategies that can be employed. The challenge then becomes choosing between competing strategies, but as described next, recent thinking is starting to address this challenge with the nuances of ASVs in mind.

9.2 The Promise of Decision Support

The application of mathematical optimisation in reliability and maintainability has been experimented with previously in maritime. By mathematical optimisation, the authors refer to algorithm-based search and comparison of alternative solutions as opposed to hand-performed iteration and selection, which is the convention. Crucially here, mathematical optimisation is proposed in support of rather than in place of such conventional practice that is well established in RCM and well proven in designing for availability. BMT have good reputation in such practice illustrated for example, by the acceptance of their reliability and maintainability case for the Queen Elizabeth Class.

Karatuğ et al. (2022) flag a few applications of mathematical optimisation of conventional vessel and offshore machinery and go on to apply discrete variable Multi-Criteria Decision Making (MCDM) to compare different mixes of maintenance strategy for different levels of vessel autonomy. Specifically, Karatuğ et al. (2022) compare different high-level combinations of corrective, time-based and condition-based maintenance for the 4 IMO autonomy levels, using MCDM techniques AHP/ TOPSIS (Analytic Hierarchy Process/ Technique for Order Preference by Similarity to Ideal Solution) and subjective expert ranking over 21 different criteria. Perhaps unsurprisingly, they conclude that corrective or time-based maintenance are each alone insufficient for increasingly autonomous vessels and that a hybrid solution is advocated that mixes in condition-based maintenance. As argued in the following section (10), the authors of this paper propose that mathematical optimisation can be exploited further to structure thinking and help determine the specifics of a design for availability in a particular ASV application.

10 Mathematical Optimisation of Reliability and Maintenance

Simply put, optimisation is the selection of the best solution to a problem from a number of alternatives. In the case of ASV reliability and maintenance, the following subsections explain why mathematical optimisation is warranted, how it could be put to task and finally, recent and proposed development.

10.1 Justification for Optimisation

Alternative “designs for availability” are defined by different reliability and maintenance strategies as illustrated in Figure 1 by a set of typical control levers or dials available to the designer in specifying equipment. Real-world optimisation problems typically relate to multiple objectives, criteria or attributes. Mathematical methods for multi-objective optimisation are many and varied, and are particularly advantageous where objectives are conflicting and so the problem is “non-trivial”. The two conflicting objectives in our case are availability and cost. Whilst it’s desirable to maximise availability this would be at the penalty of increased costs.

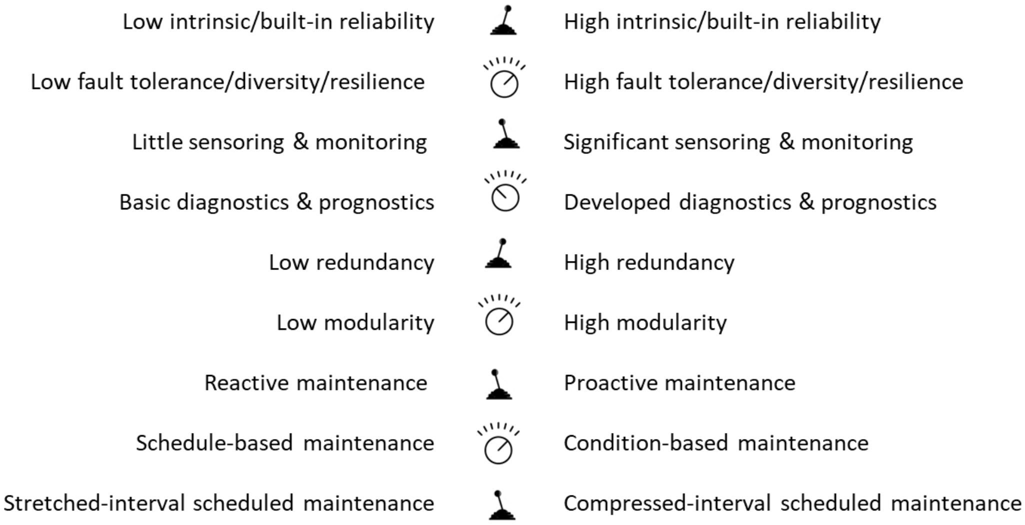

Figure 1 Typical Availability “Control Levers & Dials”

The role of mathematical optimisation in resolving the cost-availability conflict is in identifying the so-called “Pareto” front. A Pareto front is the set of non-dominated solutions where one objective cannot be improved without having a detrimental effect on the other (Figure 2). The Pareto front thus divides the solution space between feasible and infeasible solutions. In our case and the depiction below, the infeasible space includes the impossible utopian solution at the axis intersection that has zero cost and is always available. Dominated solutions are those where objectives can be simultaneously improved upon without having to sacrifice one in pursuit of another. Each combination of maintenance and reliability philosophy and position of the design levers and dials depicted above (Figure 1Figure 2), represents a unique “design for availability” solution in Figure 2. These solutions can apply at individual equipment level up to vessel specification as a whole and are many and varied. The identification and plotting of solutions and particularly those that belong to the Pareto front can be supported by well-established AR&M quantitative analysis such as System Availability Modelling.

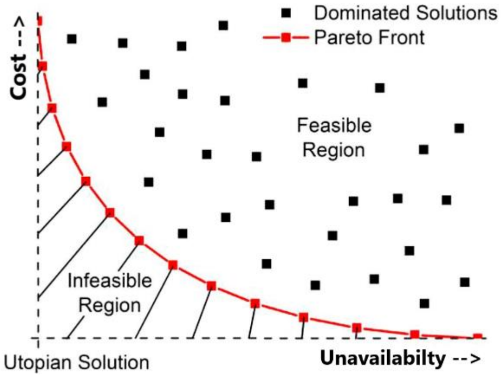

Figure 2 The Cost-Availability Pareto Front

10.2 *Application of Optimisation*

To cast or frame the “design for availability” task as one of mathematical optimisation, there are a number of basic steps irrespective of the specific optimisation approach adopted.

Firstly the relevant equipment and systems should be determined. Secondly the suite of variables that are under the designer's control and collectively determine the availability solution in the particular case of interest, such as those in Figure 1, must be down selected and defined. Equipment reliability in terms of Mean Time Between Failure (MTBF) for example, will be within the designer's influence to some degree as dictated by the intrinsic quality specified for components, factored if required by the environment in which the equipment will be operated. Thirdly the optimisation objectives, namely availability and cost at the highest level as illustrated in Figure 2, must be similarly defined as well as their relationships to controllable variables, the so-called objective functions.

The objectives themselves can be further broken down as Karatuğ, et al. (2022) proposes below (Table 1). Objective functions can be defined by theoretical (physics driven) or empirical data driven modelling. Here the fidelity of the modelling (i.e. real-world faithfulness) is pivotal to the effectiveness of the optimisation that then follows. Employing established and accepted approaches is paramount and any modelling must be subject to rigorous validation and verification. Indeed, validation and verification of the end-to-end application of optimisation is key to its adoption. Early steps have been made by way of initial case study as described in the next subsection (10.3) but more must follow.

The outcome of steps one to three will in the fourth step lend itself to a choice of optimisation method/s according to case specifics. For example, some of the Figure 1 levers and dials are for variables that prove strictly discrete rather than continuous in nature and may limit the choice of method. For step five, implementing and executing the method is not just a case of "turning a handle" and demands careful attention from the analyst. As the Pareto front suggests, a number of solutions may be generated for further down-selection to the winning "design for availability".

Main Criteria	**Sub Criteria**
Economic	Investment cost, Operational cost, Spare part inventories cost
Management	Awareness of shipping company for application of strategy, Expected impact on the energy efficiency of ship, Expected impact on the amount of fuel consumption and emitted emissions, Compliance with current policies for the maritime industry, Mission readiness, Adaptability level on existing ships, Adaptability level on new-built ships
Technical	Impact on the efficiency of maintenance operations, Impact on system reliability, Impact on system availability, Impact on the risk level of the system, Impact on the useful life of the system, Applicability of strategy from point of technological infrastructure, Spare part inventory availability

Table 1 Maintenance Strategy Selection Criteria (adapted from Karatuğ, et al., 2022)

10.3 Recent Proof-of-Principle and Next Steps

BMT has explored the potential for mathematical optimisation in supporting design for availability via hypothetical test case. The test case aimed to investigate the performance of algorithm-based optimisation over and above conventional hand-based iteration and selection of a design for availability. Here the variables of influence were active and passive redundancy of equipment in a simple propulsion system. The competing objectives were system reliability and cost over an increasing mission duration.

Random occurrence of failures at a fixed likelihood were assumed such that equations of reliability based on the exponential probability distribution and MTBF estimates could be adopted. The optimisation was performed in MS Excel using a built-in solver to minimize the cost of achieving a target reliability by comparing the delta achieved from adding redundancy to each equipment in turn. The promise of mathematical optimisation was demonstrated and further development is called for.

Having shown the potential of optimisation in a simple test case, the next steps are to evaluate the scaling up to real-world representative circumstances. The evaluation should seek to demonstrate feasibility (i.e. practical viability of the optimisation), validity (i.e. accuracy of the optimisation in determining the best availability design) and reproducibility (i.e. consistency of the optimisation under varying conditions). Evaluation through multiple test cases will contribute to good practice generation comprising procedures and tools that embody the application steps outlined in the preceding section.

11 Conclusions

Autonomy is set to increase in its breadth and depth of application to sea going vessels. With reduced or infrequent opportunity for human access, ensuring uninterrupted operation requires a different mindset to reliability and maintainability. Modern and emerging technology offers solutions to the availability challenge but no single solution in isolation will prosper in all cases. A rigorous approach to differentiating solutions is thus warranted and mathematical optimisation may offer the route to best down selecting the reliability and maintenance strategy that delivers essential safety and persistent mission functions. Such optimisation holds potential for the rigorous specification of reliability and maintainability strategy not only for future Autonomous Surface Vessels but also today's vessels both conventionally and lean crewed.

12 Acknowledgements

The BMT study into redundancy optimisation and referred to in this paper was conducted by university student, Timothy Powell during a Summer placement.

13 References

Bartlett, S., & Savage, I., 2023, "Naval Autonomous Surface Vehicle Recoverability", submitted to the 2023 IMarEST Engine as a Weapon International Symposium, Bristol.

Brocken, E.M., 2016, "Improving the Reliability of Ship Machinery", Master of Science Thesis at the Delft University of Technology.

Cooke, C., & Tate, A., 2023, "Intelligent Ship Phase 2, Summary Information to Support Phase 3 Proposals", DSTL/PUB148547 Version 1.0.

Dragoș, S., Purcărea, A., Cotorcea, A., Nicolae, F., & Coșofreț, D., "Naval maintenance. From corrective maintenance to condition monitoring and IoT. Future trends set by latest IMO amendments and autonomous ships", Proceedings of the International Scientific Conference SEA-CONF 2021, pp. 323-340.

Eriksen, S., Utne, I.B., & Lützen, M., 2021, "An RCM approach for assessing reliability challenges and maintenance needs of unmanned cargo ships", Reliability Engineering & System Safety, Volume 210.

Eriksen, S., & Lützen, M., 2022, "The impact of redundancy on reliability in machinery systems on unmanned ships", WMU Journal of Maritime Affairs 21, 161–177.

Karatuğ, Ç., Arslanoğlu, Y., & Soares, C.G., 2022, "Determination of a maintenance strategy for machinery systems of autonomous ships", Ocean Engineering, Volume 266, Part 3.

Kluijven, P.C., Broeders, B., Broer, D., Dijkhuizen, D., Bonder, F., & Prawoto, L., 2017, "Autonomous sailing Propulsion and Maintenance", The Maritime Symposium 2017: Autonomous Sailing, Rotterdam.

O'Rourke, R., 2023, "Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress", US Congressional Research Service Report R45757.

Panter, J., and Falcone, J., 2021, "The Unplanned Costs of an Unmanned Fleet", Available at https://warontherocks.com/2021/12/the-unplanned-costs-of-an-unmanned-fleet/.

Stanford-Clark, A., 2023, "Mayflower Autonomous Ship – the future of autonomous marine exploration", Autonomous Ship Reality Online Conference