Maritime Autonomy and Safety at Sea

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Synopsis

Safety at sea is the protection from harm to people, property and the environment. Safety assurance in the case of autonomous sea going vessels is nontrivial due to the pace of change in enabling technologies and their disruptive impact. Historically accidents and incidents at sea have often been attributed to human error but the safety implications of a machine rather than a human making decisions whether fully or in part, is yet to be understood. Although the development of regulation of autonomy at sea is in its early stages, there is much activity to address safety of autonomy in maritime and elsewhere, along with a wealth of established safety practices from before its advent with good read across. One recent and significant development is the European Maritime Safety Agency commissioned study into autonomous vessel safety risks and their assessment tool, ‘RBAT’. Meanwhile the umbrella body, MARITIME UK is up to the seventh edition of its code of practice for industry players and the major ship classification societies have each published guidance documents in the intervening period. Two general purpose guidance documents are the UK’s Safety-Critical Systems Club “Safety Assurance Objectives for Autonomous Systems” and the “Safety Assurance of autonomous systems in Complex Environments (SACE)” from the Assuring Autonomy International Programme. Leaning on earlier established principles and practice, management of safety risk to a tolerable level and subsequent demonstration of safety case remain pivotal to safety assurance of maritime autonomy. Functional safety is the mitigating risks of system or component failures that would otherwise cause harm. Here the well-established and general-purpose standard IEC 61508 applies and in addition, failure and hazard analysis techniques abound. Finally, where applicable, good practice should be read across from safety initiatives beyond maritime and self-driving road vehicles in particular are considered.

Keywords: Hazards, Risk, Uncrewed, Unmanned, Remote

1. Introduction

The maritime industry is experiencing a significant paradigm shift with the increasing adoption of autonomous technologies. Autonomous vessels, equipped with advanced sensors, Artificial Intelligence (AI), and automation systems are reshaping traditional maritime operations. This transformation is driven by the pursuit of improved efficiency, safety, and sustainability in maritime transportation.

The broad interpretation of autonomy assumed by the authors of this paper is a machine acting in place of the human although with the human potentially remaining in the loop to some variable degree either in situ or remotely. Numerous classifications of autonomy exist but no further consideration of these follows. Prevention of harm and the safety imperative remain front and centre irrespective of the "flavour" of autonomy.

Reflecting available maritime related literature, many of the references sources here that follow pertain to surface vessels and commercial shipping however the authors of this paper have sought to extract transferable principles rather than case detail.

1.1. Accidents aboard conventionally crewed vessels

Despite advancements in maritime safety practices, accidents and incidents continue to occur aboard conventionally crewed vessels; which highlights the inherent risk associated with maritime operations. The European Maritime Safety Agency Annual Overview of Marine Casualties and Incidents 2022 report (EMSA, 2022) considers all accidents and incidents occurring involving ships flying the flag of a European Union (EU)

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https://doi.org/10.24868/11174

member state and occurring in an EU Member State’s territorial sea or inland waters. Data presented in this report shows that of the accidents and incidents occurring at sea between 2014 and 2021, “Human Action” was the most significant event type, making up 68.3% of contributing factors. Contributing factors catalogued as Human Behaviour, and contributing factors related to human action accident events are considered as influenced by human behaviour. When considering contributing factors influenced by the human element, the study found that 81.1% of all contributing factors were influenced by the human element. Whilst autonomy is sometimes heralded as panacea to human error, its role in accidents and contribution to safety at sea can only truly be understood from experience over prolonged period of introduction and maturation. The significant use of technology to supplant the human may lead to many new and poorly understood causal mechanisms, different potential hazard events and demand added barriers to these then resulting in harm.

1.2. Safety nuances of autonomous systems

The introduction of autonomous systems in maritime operations brings new safety considerations and challenges. Unlike conventionally crewed vessels, autonomous vessels rely on sensors, algorithms, and communication networks to navigate and operate autonomously. While autonomy offers the promise of improved safety through reduced human error, it also raises concerns regarding system reliability, cybersecurity vulnerabilities, and regulatory compliance. The adoption of autonomous systems is relatively immature and their technology building blocks, AI for example, are still developing. As a result, operational insight of autonomy specific causes to hazards at sea, is severely limited. Several other nuances of autonomous systems are now discussed and their implication to safety at sea.

The scope of functionality for autonomous systems is much broader than conventional systems and so the safety analysis must go far further. As illustration, looking to the "SUDA" (Sense, Understand, Decide, Act) characterisation of system functionality, an autonomous system spans the entire spectrum whilst conventional systems do not and tend instead to fall at either end.

For a role of any complexity, the human must act in concert or team with the machine in a dynamic manner that is contingent on varying conditions of both the system and its operational environment. There is thus the potential for ambiguity over the delineation of responsibility between human and machine. Furthermore, the human factors of such teaming raises additional concerns well documented elsewhere with potential safety implication.

In maritime, a future blurring of responsibility is at odds with the historical delineation between the supplier focus on assuring that a system is safe to operate versus the user focus on assuring that the system is operated safely. Indeed, the overwhelming conclusion from workshops held by the UK’s Society of Maritime Industries (SMI) last year on assurance of autonomy was the pressing need for intimate collaboration between the two communities to achieve success (SMI, 2024).

Given that the blurring of responsibility is relatively recent, current regulation intended to impose safe operation has been written exclusively for human consumption and enaction. At the highest level these include International Maritime Organization (IMO) instruments such as the International Convention for the Safety of Life at Sea (SOLAS), the International Regulations for Preventing Collisions at Sea (COLREGs) and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). Two ramifications are firstly that without some interpretation they cannot be applied in isolation as written to autonomous systems and secondly, the widely adopted threshold is that they should then demonstrate equivalent safety to the human. This is potentially less familiar, more ambiguous or difficult to evidence whilst less demanding than the engineering convention of As Low As Reasonably Practical (ALARP).

With conventional systems, the handling of unforeseen circumstances typically falls to the human operator who adapts their use of systems at their disposal or otherwise mitigates the consequences. For safety assurance of autonomous systems and reduced human fallback, then increased emphasis is placed on identifying foreseeable excursions from the system's intended use or "Operational Design Domain". However, if adopting the well-established risk-based approach to safety then a safety related event of low likelihood and so not "reasonably" foreseeable that however has disastrous consequences, should not be neglected. Conventional bottom-up safety practice focuses on functional safety, so system faults or failures, and autonomous systems have given rise to the notion of functional insufficiency (particularly looking to self-driving and “SOTIF”, Safety of the Intended Functionality) as source of hazardous situations hitherto neglected.

Having asserted requirements have been correctly set for the autonomous system including the off-design performance just mentioned (so called validation) then demonstration that the system implementation correctly meets these requirements (so called verification) may be similarly fraught depending on technology choice.

Autonomous systems that learn on the fly and are opaque in underlying nature for instance, may be difficult to verify. In the case of autonomous systems, risk assessment must address far more software failures, for which failure rates are much harder to quantify if indeed they can be, than the equivalent for hardware. Software failures are a result of human error but frustratingly, these can occur anywhere in the lifecycle from requirement setting through to implementation.

Ensuring the safety of autonomous vessels requires a multidisciplinary approach that encompasses technological innovation, regulatory oversight, and risk management strategies. Addressing these safety nuances is essential to building trust and confidence in autonomous maritime technologies and realizing their full potential to revolutionize the maritime industry for the better.

2. Maritime autonomy and safety, significant position pieces

The following subsections summarise the status of key position pieces on safety in autonomy at sea and attempt to draw out their unique slants.

2.1. European Maritime Safety Agency (EMSA)

Undertaken by the consultancy arm of Norwegian classification society Det Norske Veritas (DNV), the EMSA has commissioned development of a Risk Based Assessment Tool (RBAT) for the autonomous and remote control of sea going vessels. Four reports are available with the fifth and final still outstanding. The fourth report (DNV, 2022) explains the current status of RBAT and describes its application to three hypothetical case study vessels with varying onboard autonomy: a short-sea cargo vessel, small passenger ferry and Ro-Pax ferry. Given the significant detail published and its endorsement by EMSA, a summary of component parts to RBAT now follows.

RBAT part 1 is the detailed description of the use of autonomous and remote control by subdivision of a vessel’s “mission” into phases, operations, control functions and control actions, and allocating both the undertaking and the supervision of these actions at the lowest level to human/machine and onboard/remote.

RBAT part 2 is then a hazard analysis of all control actions. Unsafe conditions are first identified by considering a provided list of control action deviations from design intent, similar to conventional HAZard and OPerability study (HAZOP) “guidewords”, such as the control action occurring too early. Causal factors which can trigger unsafe conditions are then identified with candidate categories provided to assist their identification. The worst foreseeable outcome of an unsafe condition/mode assuming no mitigation is then selected from a list of potential accident categories such as collision and flooding. The severity of the worst-case outcome is determined from tables of consequences such as fatalities/injuries and environmental damage.

Part 3 of RBAT is a mitigation analysis of part 2’s unsafe conditions. This entails understanding any Fault Detection, Isolation and Recovery (FDIR), particularly identifying independent prevention and mitigation measures and ranking their effectiveness. RBAT part 4 is a risk matrix evaluation and departs from the convention of considering event likelihood (given the difficulty in quantifying this) and consequence severity to instead consider consequence severity (from RBAT part 2) and mitigation effectiveness (from RBAT part 3). Each unsafe condition is thus ultimately categorised as high risk (intolerable), medium risk (tolerable) or low risk (As Low As Reasonably Practical, ALARP). RBAT part 5 is driving risk down to tolerable and ALARP by for example, increased control action integrity, introducing operational restrictions, and better mitigating the unsafe condition and the hazard severity.

The RBAT is effective in removing the need to assign a quantitative likelihood to risks relating to autonomous systems, instead looking to the effectiveness of mitigation layers. This allows for risks to be assessed where a quantitative likelihood cannot be reliably assigned. Furthermore, it is the authors’ opinion that the RBAT has a wide applicability which could as it is adopted by the industry, promote common understanding across all stakeholders involved in the maritime safety process, for example an equipment manufacturer’s safety work can be understood by any party who may want to install the equipment on their vessel.

The RBAT technique refers to mitigations that “for the assessed scenario can prevent losses regardless of failure cause”. This post failure mitigation aims at preventing the undesirable consequence once a failure has occurred. Standards such as IEC 61508 (covered later in the paper) could be used in conjunction with the RBAT, to developing a system to a safety integrity level which will give assurance that there is mitigation against the failure occurring in the first place.

2.2. *Horizon2020 AUTOSHIP*

Bolbot and Theotokatos (2021a) present the safety approach developed by EU Horizon 2020 collaborative project AUTOSHIP and its application to hypothetical cases studies of remote and autonomous operation of short sea shipping cargo vessel and inland waterways barge. They compare eleven different risk and hazard analysis methods and ultimately advocate Preliminary Hazard Analysis or HAZard IDentification (HAZID) citing its applicability irrespective of the maturity of design and its support from class societies. The AUTOSHIP safety analysis steps are similar to those endorsed by EMSA (DNV, 2022) and described above, indeed the use of similar HAZOP like guidewords are proposed (function provided wrong, not provided etc.). Several major departures of the AUTOSHIP from the EMSA approach are as follows. It considers security and cyber-security implications along with consequences beyond safety such as reputation, it does not specifically emphasise vessel control, and the final risk assessment is based upon the estimated frequency of unmitigated cause and its likelihood of becoming a hazard.

2.3. *Classification Societies and others*

On behalf of an industry collective, MARITIME UK (2023) describe a voluntary code of practice now in its seventh edition, signed up to by many suppliers and relevant other parties. In terms of safety of autonomy, the code steps back and proposes element of a safety management system to include policy, appropriate responsibilities, culture, risk management, procedures for safe operation and emergency response, personnel and training, equipment maintenance. It then offers good practice recommendations including systems that should be risk assessed (Table 1) for failure implication and perhaps uniquely, recommended sense and avoid capability according to vessel category. Numerous classification societies undoubtedly have a view on the safety of autonomy at sea with only a few notables commented on below. An overview of notable positions is presented in Table 1 but this is not comprehensive survey and other classification society positions are omitted.

Lloyd’s Register (LR) was early to develop a design and construction code for Unmanned Marine Systems (Lloyd’s Register, 2017). The LR code attributes required system “levels of integrity” in light of the consequence of system failure to people safety, namely high (unacceptable), medium (conditionally acceptable) or low (unconditionally acceptable). Although no specific criteria or guidance is given for deciding between integrity level, the degree of safety verification then imposed by LR matches these three categories and specific verification methods are distinguished in the code annex both for each category and each lifecycle stage from design through to in-service operation. Systems drawn out for consideration as represented by headings in the code are given in (Table 1) for comparison.

Bureau Veritas (BV) proposes potential hazard types associated with vessel functional groups (see Table 1) and define risk as an additive combination of indices for causal event frequency and severity of hazard consequence (Bureau Veritas, 2019). The former ranges from 1 (extremely unlikely) to 7 (frequent) whilst the latter ranges from 1 (negligible) to 5 (catastrophic) for implications to the human (injury and death), the ship (damage) and the environment (pollution). The selection of index in each case is aided by tabulated distinctions. Guidance is not however offered on the acceptability of resulting risk with responsibility for this placed on the relevant administration.

The American Bureau of Shipping (2021) assigns risk category of high, medium and low according to the consequence of a functional failure (distinguished as not dangerous, potentially dangerous and immediately dangerous) and both whether human supervision is onboard and remote, and whether it continuous, periodic or on-demand. The risk categorisation assumes that risk increases if human supervision is remote rather than onboard and as attention becomes less frequent. In addition to vessel generic hazards, the ABS suggest hazard types for oil and gas vessels so for example, topside production and underwater drilling.

DNV set out assurance expectations according to four areas of navigation, engineering/platform systems, remote control and communications (DNV, 2021) with contributing functional groups listed in Table 1. As DNV’s guidance pertains to both autonomous and remote operation, they are unique in advocating explicit analysis of human factors related risk via dedicated methods beyond the conventional. As the longest list of functional groups by item count, the entries against DNV in Table 1 are compared for consistency with items proposed by others as interpreted by the authors of this paper, a tick suggesting duplication and empty entry suggesting omission. Table 1 suggests a patchwork of safety topic coverage but also potentially inconsistency of terminology both of which should be carefully considered in any safety argument.

MARITIME UK	**LR**	**BV**	**ABS**	**DNV GL**
Platform control		✓		Remote control
✓		✓		Communication
Autonomy decision making	✓	Voyage, Navigation	✓	Navigation/ manoeuvring
✓	✓		✓	Propulsion
✓				Steering
Electrical connectors;	Electrical			Electrical power
Sensors, Actuators	Control	Detection		Control / monitoring
	Structure, Stability			Watertight integrity
Fuel / hydraulic	✓	Ship machinery		Fire safety
	Auxiliary		✓	Ballasting
			Environmental protection	Drainage / bilge
			Mooring, Docking	Anchoring
				Maintenance
		Cargo / passenger management	✓	Cargo handling
			Industrial processes	
		Security		

Table 1 Comparison of autonomous vessel functional or system groups

2.4. Regulation and Standards

The Maritime and Coastguard Agency (MCA) is responsible for implementing UK and international law and policy, with safety being central. Their Workboat Code applies to vessels in commercial use less than 24m in length and Edition 3 (MCA, 2023), specifically annex 2 addresses remotely operated unmanned vessels. This will dictate on regulatory compliance in UK waters until the Maritime Autonomous Surface Ships (MASS) Code of the IMO takes mandatory effect planned for 2028.

Workboat Code Annex 2 covers: general code exclusions by virtue of the vessel being unmanned (e.g. machinery space fans), equipment restrictions (e.g. no flame appliances), data requirements (e.g. positional information), equipment protection measures (e.g. fire containment, alerts), operational requirements (e.g. remote connectivity, checks, distress call obligations), navigational and anchoring stipulations (e.g. remote watchkeeping provision), and finally health and safety provisions for boarded personnel.

Overarching policy for safety management in UK defence is governed by JSP 815 with DSA02 DMR focussing on maritime defence. Defence regulations interpret statutory instruments such as the MCA code in a defence context and add military deltas and DefStan 00-56 then dictates how systems are acquired in response. The UK's Naval Authority and Technology Group (NATG) are actively considering rules for the certification of autonomy at sea.

Three key standards are briefly mentioned, the first already well adopted given the increasingly software intensive nature of complex systems and second much more recent but with significant future potential implication. IEC 61508 dictates Safety Integrity Level (SIL) for safety critical systems and the specification, design, implementation and testing processes that should be followed to ensure the required integrity is met. IEC 61508 was intended for the implementation of simple safety function and does not for instance deal with AI such as machine learning. The upcoming IEC 63187 standard is touted to build upon 61508 but with a defence and pan-lifecyle focus. ISO/IEC TR 5469 addresses the functional safety of AI systems and AI specific concerns such as transparency, explainability and adversarial attacks.

3. Safety of autonomy beyond maritime

The following two subsections cover positions on safety in autonomy that are first generic in nature and second originate from the ground-breaking automotive domain.

3.1. Domain independent safety assurance

Coordinated by the University of California Los Angeles, the Norwegian University of Science and Technology (NTNU) and the University of Stuttgart, the International Workshop for Autonomous System Safety (IWASS) has been running for several years and Correa-Jullian et al. (2023) put forward a scene-setting white paper for last year's event. These authors note that "safety cases" have been "central to the regulation of multiple safety-critical systems, including nuclear, railway, oil and gas, automotive, industrial automation, and aerospace" with maritime notably absent. Here, a safety case is "a structured argument and the corresponding evidence that a system can operate safely for a given context". Correa-Jullian et al. (2023) note limitations in the use of natural language to present safety cases in reports and adoption instead of graphical notations "CAE" (Claims, Arguments, and Evidence) and the similar "GSN" (Goal Structuring Notation).

GSN can be traced back to the University of York who have proposed "SACE" (Safety Assurance of Autonomous Systems in Complex Environments), a set of safety case GSN "patterns" to structure the safety argument of an autonomous system (Hawkins et al., 2022). The top-level goal or claim is that the autonomous systems will sufficiently mitigate all hazards both within and outside of its defined operating context and a recurring GSN pattern then applies at each level of system decomposition, that safety requirements are met and any potential hazardous failures are managed. The steps to SACE might be summarised as follows:

1. Operational domain (context) and scenarios (autonomous system activities) defined completely and correctly.
2. All hazardous scenarios identified by considering all autonomous system interactions with its environment.
3. Safety requirements or a reduced operational domain are determined sufficient to mitigate hazardous scenarios.
4. High level safety requirements are decomposed in a tiered manner to reflect design decomposition into its component parts.
5. The design at each tier ensures safety requirements are met, that decisions are appropriate, a process has been followed and the design has been checked.
6. Hazardous failures/deviations (by HAZOPS, FMEA) are identified and sufficient mitigations put in place.
7. The autonomous system is aware of excursions outside its operational domain and remains safe both when in this occurs and during transitions.
8. The meeting of safety requirements is sufficiently verified.

A third initiative of note is the UK's Safety Critical Systems Club (SCSC) and its Safety of Autonomous Systems Working Group (SASWG). The group proposes 46 safety principles across three categories: computational, architectural, and platform or vehicle related (SASWG, 2024). The first and largest category covers data, requirements (functional, performance and test), algorithms, software and hardware.

3.2. Driver-assistance and self-driving developments

The development of ANSI/UL 4600 Standard for Safety for the Evaluation of Autonomous Products has been led by Carnegie Mellon University's Professor Koopman with road vehicles predominantly in mind although with application beyond. Whilst not strictly a process, numerous assessment criteria are proposed to help determine the acceptability of a safety case. It covers process such as risk assessment, testing and tool usage along with solution specifics such as autonomy functions and environment interactions. ANSI/UL 4600 provides a potentially useful checklist of considerations to confirm the exhaustiveness of a safety case.

The automotive domain has led on handling hazards in the absence of equipment faults. The ISO/PAS 21448 SOTIF standard considers the mitigation of risk due to unexpected operating conditions, gaps in requirements and foreseeable misuse. Valuable safety insight is anticipated from the application of SOTIF to maritime autonomy. Clear bounding of a vessel's concept of operation has long been common precursor to safety assessment irrespective of particular method chosen and rigorously identifying foreseeable excursions beyond this boundary is the kick-start to such SOTIF thinking.

Beyond SOTIF, functional safety and hazard analysis, there are one or two safety topics raised within the self-driving sector that read across to maritime but not featured in the maritime autonomy safety literature covered earlier. The term "behavioural safety" adopted for instance by Waymo (2021) and Siemens (2020) is described as "basic and defensive" driving by Koopman (2022) and concerns following the expected norms including adhering to traffic rules. The parallel in maritime is observance of good seamanship and compliance with the COLREGs, which particularly the latter, has been keenly pursued as feature of autonomous navigation. A second topic is crash safety or crashworthiness and lessening the severity of harm, a collision having occurred. This safety topic has clear relevance to safety at sea but could be interpreted more broadly across the range of accidents that might occur and not merely limited to vessel collisions.

4. Conclusions

The increased adoption of autonomy at sea will introduce different specific hazards to seafaring and new causal event chains. Despite a prevailing view that autonomy will reduce accident occurrences that arise due to human error, there are multiple nuances of autonomous systems that make safety assurance more challenging than for conventional systems.

This paper has reviewed the safety assurance nuances of autonomy at sea, relevant responses across the maritime domain and key contributions from further afield. A coalescing of the different positions is advocated to ensure coverage and comprehensiveness of safety philosophy and practice. Ultimately, the adequacy of safety assurance can only be evidenced by continuous at sea operation free from incident and accidents. Given the disruptive impact of autonomy adoption, unsafe events are inevitable, and safety assurance must be iterated in response.

Current safety thinking is that with a shift of emphasis on the balance of responsibility between human and machine, then the well-established risk-based approach still serves its purpose. Promising steps forward have been taken on the European continent to tailor such an approach to the nuances of autonomy. Classification societies and similar are then forthcoming on prescribing levels of safety verification although the coverage of topics would benefit from alignment.

Drawing on different perspectives including from adjacent domains should continue to be exploited to ensure safety at sea remains as a forefront priority. Developments in the driverless car domain are good examples such as dealing with foreseeable excursions from intended functionality and accident severity management. A continued emphasis on safety assurance is essential to seeing that autonomy at sea serves its full potential.

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