Literature Review of Maritime Cyber Security: The First Decade

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Literature Review of Maritime Cyber Security: The First Decade

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ABSTRACT
This is a comprehensive review of the current body of work for cyber security in the marine and maritime sectors. Reviews are useful as a field develops, both for those new to the field, and those contributing to a section of the existing body of work. This looks at the phases of research, from exploratory and positional papers in the early 2010s, to the more recent experimental research, and how "maritime cyber security" has branched into subtopics addressing human factors, policy, law, cyber-physical security, and more. In addition to different topics of research, this comprehensive review summaries the focus of those papers, whether they are intended for crewed vessels, uncrewed vessels (above and below the surface), offshore structures (e.g., oil, renewable wind energy), and infrastructure like ports. As a newly developing field, compared to general cyber security or naval engineering, this review also examines the ratio of positional papers, papers that generate knowledge, and papers that summarise existing works to gauge the maturity of the field. This type of review relies on an expert understanding of the existing body of academic literature and its impact on industry and government, instead of applying prescribed systematic review methodology. This review of over three hundred articles concludes with overall findings and suggestions for future research to continue maturing and growing maritime cyber security research.

KEYWORDS
comprehensive review, maritime cyber security

1. Introduction

According to Google trends[1], the first mention of "maritime cyber security" ("maritime cybersecurity" was introduced a few years later), was first searched for in December 2013 (see Figure 1). Some of the earliest and most recognised academic papers were also published in 2013. Several of these earlier publications were positional papers, articles that began to describe the potential issues around cyber security of ocean-related technologies. Interest in the subject noticeably increased in 2016, and significantly again in 2020. In our examination of 319 maritime cyber security papers from 2013-2023, the first review articles in the field were published in 2017, which is early considering that there were only 15–20 maritime cyber security papers available for review around that time. In our analysis, later review studies had access to more articles, but selected a small subset for review. In contrast, this comprehensive review provides a high-level analysis of the first decade of research without exclusion, and an in-depth review of key works to establish the breadth, depth, and maturity of the body of research.

[1] https://trends.google.com/trends/

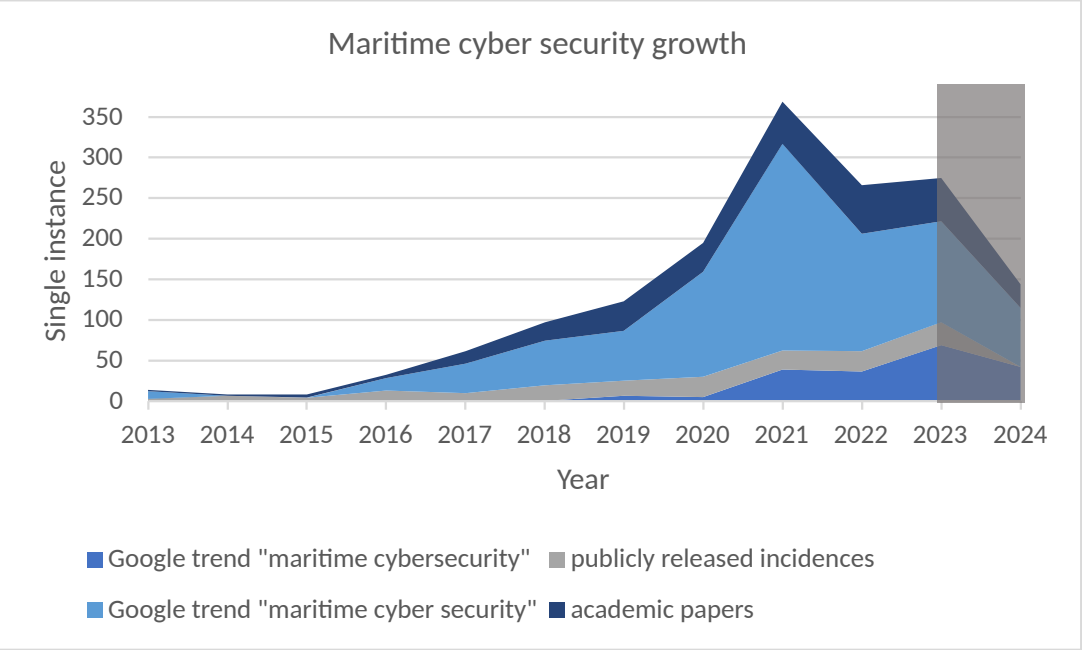

Figure 1.: Global public Google search trends[1] for two terms, number of academic papers, and public incidences (Fenton, 2024) from the start of 2013 to mid-2024.

1.1. Cyber Threat Impact on the Industry

As a billion-dollar industry, the maritime sector facilitates international trade and interconnects the world. In 2022, a total of 11 billion tons of goods were transported by ships, including 3 billion tons of crude oil and 3.3 billion tons of iron ore (UNCTAD, 2022). Maritime infrastructure, which includes ships, port infrastructure, and offshore structures, is an essential part of the modern world and its economic growth.

The traditional concept that maritime systems are air-gapped from land or the wider world is no longer true, across both operational and information technology (OT and IT). New technologies are becoming more networked, resulting in better communications, usability, and service, but they also introduce vulnerabilities when not secured appropriately. A 2021 US Coast Guard report claimed the number of reported cyber-attacks against maritime transportation systems increased by 68% since 2020 (US Coast Guard, 2022). Figure 1 combines Google search trends, public incident statistics from the Maritime Cyber Attack Database (MCAD) from Fenton (2024), and academic publications to show the overall growth in interest (public and academic) over the decade from 2013-2023, with the addition of incomplete 2024 statistics.

Cyber security for Critical National Infrastructure (CNI) gained huge attention, after the 2010 Stuxnet attack which targeted supervisory control and data acquisition systems (SCADA). More recently in 2017, the NotPetya Malware was used in a global cyber attack affecting systems worldwide. The global shipping giant Maersk shipping line was significantly impacted by this attack. According to Maersk, who have been congratulated on their response and transparency, suffered losses between 250-300 million USD revenue losses, IT restoration costs, and extraordinary operations costs (A.P. Moller - Maersk, 2017). This is not an isolated event, as denial of service and ransomware are the most frequently, publicly, reported attacks. However, there may be some bias as “publicly” reported attacks as these are easier to see and report than

attacks that manipulate data stealthily, like Stuxnet. While this is understandable, studies based only on public information should be open about this bias for the readers.

In 2022, German oil companies Oil Tanking and Mabanaft suffered an attack, which was thought to be a ransomware attack that caused huge distress to its loading and unloading systems, forcing the energy company Shell to reroute supplies to other depots (Greig, 2022). In the year prior, news of attackers threatening to publish data stolen from website and servers of the Port of Lisbon was made (Rahman, 2023). An attack on DNV's ShipManager servers affected more than a thousand ships worldwide (Page, 2023), attacks on Dutch maritime logistics company Royal Dirkzwager released potentially stolen data (Arghire, 2023), and attacks on Japan's port of Nagoya caused it to momentarily suspend their container operations (Robinson, 2023).

Denial of service (DoS) attacks have also been reported. The online website infrastructure of the Port of London Authority was knocked offline by a 'politically motivated' Distributed DoS (DDoS) attack in 2022 (Glover, 2022), while later that year, the inspection database of the Tokyo MOU, which coordinates port state control across the Pacific region, was attacked and taken down for several weeks (Maritime Executive, 2023). In another incident, Voyager Worldwide, a vessel management software and navigation services provider, took all of their systems offline (Chambers, 2022). Port DoS attacks in 2023 include two Israeli ports' websites (Haifa Port and the Israel Ports Development and Assets Company The Times of Israel (2023)), websites of three Canadian ports (Quebec City, Halifax, Montreal (Morrissette-Beaulieu, 2023)), the North Sea Port website that operates the ports of Vlissingen, Terneuzen and Ghent (Harreveld, 2023), and the websites of the Dutch port authorities of Groningen, Amsterdam, Rotterdam, and Den Helder (NL Times, 2023).

Earlier positional papers such as Jones et al. (2012); ESC Global Security (2015) and Tam and Jones (2018) hypothesised that cyber-attacks like denial of service and ransomware in the maritime sector could have an impact on physical operations and increase risks to safety, and these public 2020's incidences verified those predictions. Cyber attacks against the sector are motivated by a variety of reasons, such as egoism, espionage, financial gain, and political agendas Silgado (2018). According to (US Coast Guard, 2024), ransomware attacks increased by a further 68% between 2022 and 2023, on top of the significant increase the year before (US Coast Guard, 2022). Many of these reports were also about DoS or ransomware. From these known incidences and others, it is clear that the impact of disrupting the maritime operation is not confined to the sector itself but also impacts sectors and industries dependent on it, such as food supply, electronic manufacturing, oil and gas, and the wider supply chain.

In response to growing cyber security concerns, the International Maritime Organisation (IMO) passed Resolution MSC.428(98) to raise awareness about cyber risk threats and vulnerabilities. As of January 1st, 2021, all ship owners must comply with this resolution to continue their operations around the world (International Maritime Organization - IMO, 2017). Other documents that considered this problem include IMO's circular MSC-FAL.1/Circ.3 for guidelines on maritime cyber risk management, and Baltic and International Maritime Council's (BIMCO) cyber security for on-board maritime vessels document(International Maritime Organization - IMO, 2022; BIMCO, 2021). These documents emphasise the importance of identifying vulnerabilities in ship systems as well as installing countermeasures for cyber attacks (BIMCO, 2021).

It is important to continue supporting the cyber security and resilience of the sector with scientific findings that can also be fed into new solutions, policies, training, and governance. To do so, research publications require academic rigour both in individual

publications and in the larger body of work, which this review attempts to assess.

1.2. Review Structure

The aim of this comprehensive review is to examine the last decade of academic research on the topic of maritime cyber security. In our review of the literature, the first paper that examined maritime cyber security as one topic, and not a piece of a larger topic, was in 2013. The time frame for this review is therefore the complete years from 2013-2023, but also partial statistics from 2024 due to the time of publication.

We have considered (i.e, read all of) a wide range of papers. Generally, the mass majority of literature found were predominately conference papers, journal papers, and theses. This comprehensive review includes all these types of publications because, at the start of a field, many key journals and conferences will not accept positional papers or new topics not in their accepted topics list. Because of this, many previous survey papers missed high impact publications by limiting themselves to specific journals and conferences. In contrast, this review also considered articles published in many languages, although non-English publications were translated to English using Google translate.

There are two parts to this review, the first is to select key papers in specific topics to illustrate how maritime cyber security has branched out into subtopics. The second part of this review looks at 300+ papers from January 2013–June 2024, published in a range of venues and languages, to examine the maturity of the field after its "first decade" in existence. To do this, we divided the papers into three main categories:

(1) Positional: These articles often propose an area of research or state an issue with greater clarification than before. Some of these will also propose a type of solution, but not in detail, nor would they implement or test the solution.
(2) New knowledge: These papers add new knowledge to the body of knowledge. This can be further broken up into papers based on experiments and ones that propose new solutions (e.g., frameworks, simulations, testbeds) with more depth and verification than positional papers. In theory, in this category we would also consider papers that generate new knowledge by surveying or interviewing a wide range of experts. However, as most interview/questionnaire studies we examined lacked rigour (very few participants or did not fully disclose/verify the background of experts or methodology), the majority of these studies we classified as a review of people's opinions, instead of generating new knowledge.
(3) Surveys: Literature reviews including systematic reviews are included in this category. This includes reviews made by surveying experts instead of surveying papers, and combining expert opinions with existing frameworks.

These categories are subjective and some papers were borderline between categories. Others, particularly theses, contain enough material that multiple sections covered multiple categories. In those cases (0.5% of all papers), some articles had two classifications. Using the definitions above, we divided 319 papers into four categories to assess the growth of research, from positional papers to papers that create new knowledge, and then papers that summarised and contextualised that knowledge. All papers were found by searching google scholar, scopus, and ACM using "maritime cyber security" "maritime cybersecurity" and "maritime cyber-security". While we recognise this may not cover some papers peripheral to the subject, we have high confidence the sample pool is larger than previous studies and includes the most field defining and

significant papers in the first decade of this field. Figure 2 shows the distribution of these papers, and also which also correspond to Sections 2 – 5) of this article. The overall analysis of all papers is then explored in the Discussions (see Section 6) after reviewing key papers in the field, and of these categories.

In-depth analysis of sector-specific equipment is not the focus of this paper, but a few key systems that appear frequently in the literature are the Automatic Identification System (AIS), Integrated Bridge System (IBS), Integrated Navigation System (INS), Voyage Data Recorder (VDR), Human Machine Interface (HMI), Program Logic Controllers (PLCs), and controls for rudder, thrust.

2. Positional Papers

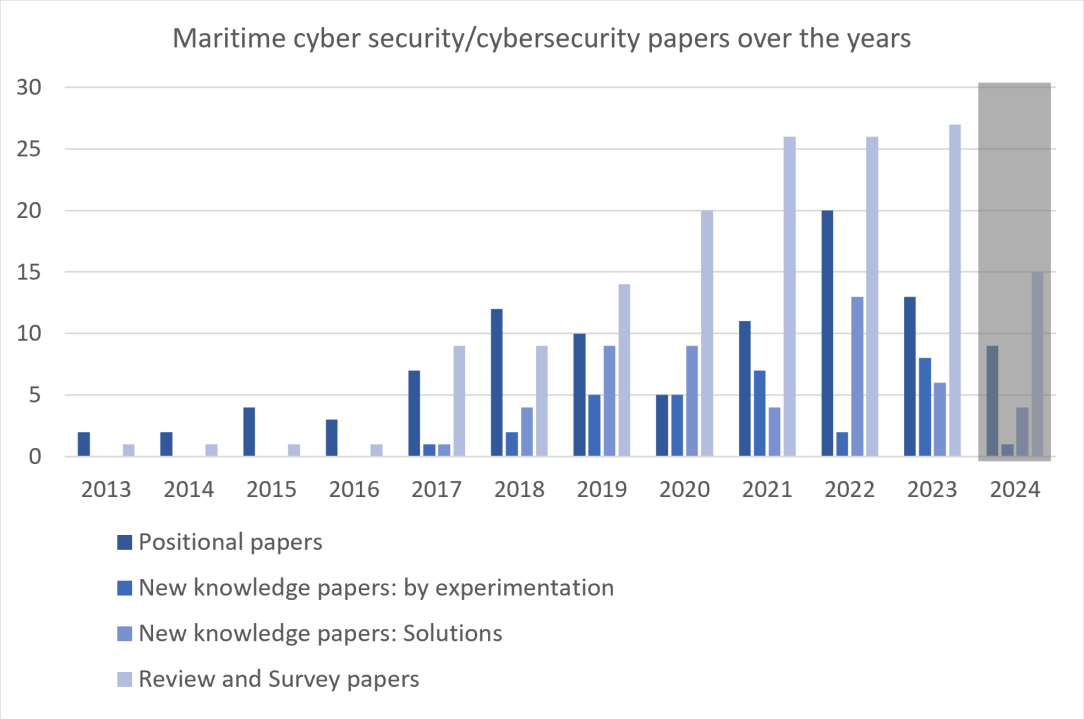

Figure 2.: Proportion of types of papers and relevant sections.

As a new area of research, there has been a steady number of positional papers from 2013–2024 as new subtopics were explored, as shown in Figure 2. Examining positional papers, often the first to detail a new subtopic, is a useful way to understand how the topic of "maritime cyber security" branched off into new topics. Typically, when examining the literature over the last decade, new subtopics of the umbrella term maritime cyber security began with a positional paper. That said, not all positional papers proposed new subtopics.

In our analysis of the literature, many of the more recent positional papers were for specific nations or sea regions. This highlights that, while this is a global issue, there are unique challenges for different nations, sea regions, ports, ships, and organisations. For example, the very first positional paper in 2013 was specific for the United States (US). Key positional papers for Australia, South Africa, Greece, Korea, Portugal,

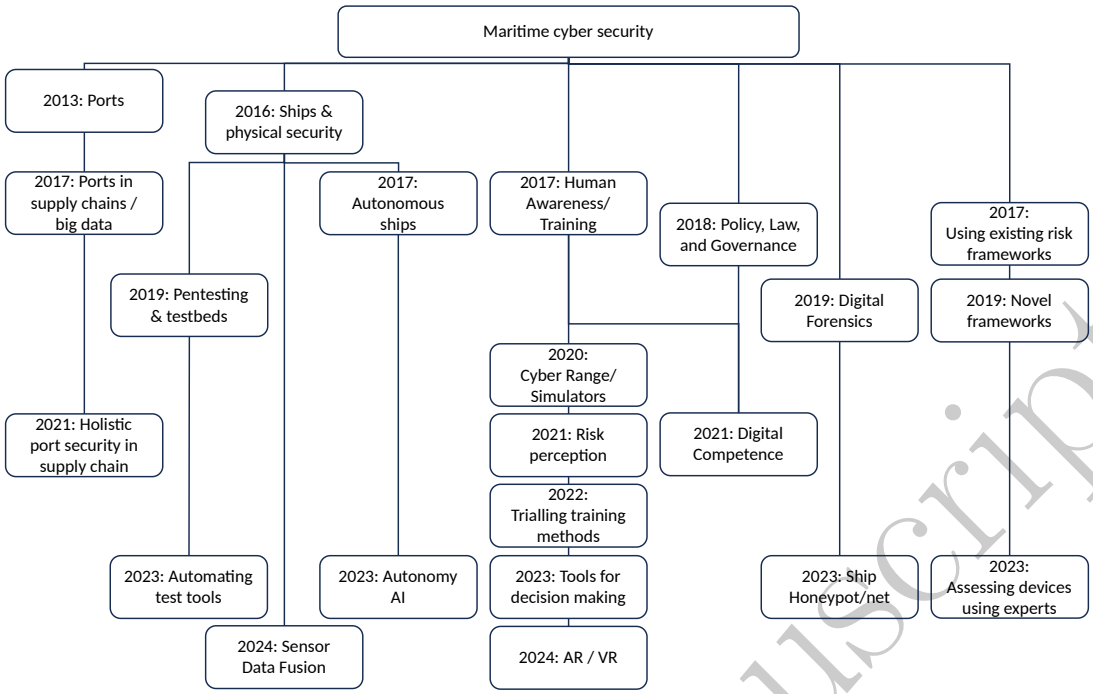

Figure 3.: Tree of positional papers and new topics of study.

Spain, France, United Kingdom, Norway, Indonesia, Bangladesh, Vietnam, and the Philippians were seen up to 2023. Some also focused on Navy challenges specific to countries over the merchant navy. Many positional papers also focused on sea areas, such as the Black Sea and the Malacca straits due to local threats.

Before 2019, the majority of publications were in the early-phase of predominantly positional papers (everything before 2017 was either positional or review). However, from 2019 until 2024, the number of survey papers has outnumbered positional papers. This raises concerns whether the body of research is more forward facing (positional) or backwards facing (review), which is discussed at the end of this paper. While the number of positional papers outnumbered the two new knowledge categories separately most years (the exception being 2020), when compared to the two new knowledge categories combined, they outnumbered positional papers in 2019, 2021, and 2023.

To better understand how the topics of maritime cyber security have grown in breadth and depth, Figure 3 shows positional papers 2013-2024 based on topics. From these articles, it is possible to look at when topics first began to emerge globally. This does exclude positional papers that are a variation of a global idea, for example, while maritime cyber security policy was first discussed in 2018 and is mentioned here, there have been many papers on policy for specific regions like the Philippians, which is not shown on this graph. From our analysis, "maritime cyber security" split into port and ship cyber security early in the field's development, between 2013–2016. 2016 also saw more discussion on OT security in addition to IT security. The research of "ships" also split fairly early in 2017 to crewed and different levels of autonomous vessels. While there have been some efforts to consider holistic security, ports and ships together, in 2021, most following articles have tended to address one or the other.

The human element of maritime cyber-security has generated many topics, since its first positional papers around 2017. After a few years of discussions around the need

for awareness and training, 2020 saw the first positional papers on teaching facilities like cyber ranges (CRs) and crew training simulators that can be adapted for maritime cyber security training. This was quickly followed by positional papers on how people in the sector perceived risk and trialling actual training sessions using cyber ranges, tabletops, and ship simulators. With a better understanding of the problem, 2023 and 2024 saw new positional papers on creating tools to aid human-made decisions and discussions on how to use more future digital technologies to improve training and cyber security awareness. In 2021, there was a cross between policy and the human element, when the discussion of digital competence was first discussed. Papers on cyber security codes and maritime law had its clearest beginning in 2018 like with Hopcraft and Martin (2018). Since then there have been a few papers that looked into the legal aspects of maritime cyber security and IMO regulations (Al Ali et al., 2021; Karim, 2022). The majority of papers in the period 2018-2023 summarised current state of affairs, and we did not see clear branches of subtopics prior to 2024.

Lastly, there is an area of work focused on capturing malicious behaviours (digital forensics, and tools to collect like honeypots) which started in 2019 but compared to other areas has not received much attention. This is also somewhat connected to risk assessment frameworks which started in 2017 using existing frameworks to assess risk, and some discussion on how to create novel frameworks in 2019. Since then, other frameworks like MITRE have been adapted for the sector and/or used to assess specific devices using expert opinions as input.

From Figure 3, it is possible to understand the growth of the body of work, and even make educated predictions on future areas of work (see Section 6). As the field continues to develop and mature the number of positional papers has decreased proportionally to other types of papers, and this trend is likely to continue, however for the field to grow a few key positional papers every few years is key for the next decade or two to expand on topics of research individually and cross-topics as well.

3. New Knowledge Papers: By Experimentation

This section focuses primarily on papers that generate new knowledge through experiments, as defined in Section 1. New knowledge papers that discuss solutions that are at least one step above a proposal follows this section. As surveys combine and comment on these types of papers, they are discussed last. Within this section, different types of experimental papers are discussed by their type, scope, and setups. Topics that are more positional for future work are not included in this section.

3.1. Types of Assessments

In our review of past literature, the majority of assessments made tended to be technical, vulnerability assessments. While training solutions have been published for people (see Section 4.4) there is a gap in research that evaluates these training solutions and learning. Similarly, most papers on policy/standards seem to be primarily positional statements. The one exception we saw of this, was an experiment assessing how well standards compliance actually provided digital security Vineetha Harish et al. (2024).

A vulnerability assessment identifies digital flaws, often reporting them with risk scores or mitigation steps. Some already existing vulnerability scanning tools have revealed more than 50,000 external and/or internal weaknesses in systems (Spivey, 2021). The purpose of a penetration test (pentest) is to then exploit these vulnera-

bilities as an attacker would and report the results. The UK National Cyber Security Centre (NCSC) recommends a well-scoped penetration test as a method of system hardening against threats (NCSC, 2022). For the interested reader, details on security audits, vulnerability assessments, and ethical hacking are differentiated in Chia (2019). This positional paper proposes the necessity of ethical hacking in the marine and maritime sectors, and urges shipping companies to deploy tests to check their cyber resilience. Another type of assessment is a security audit, which determines if policies and procedures are compliant with standards and regulations.

For IT systems there are several vulnerability assessment and penetration testing frameworks, but as of publication, there are very few established tools for the maritime industry, particularly the OT side of the sector. In a systematic literature review by Bolbot et al. (2022), out of the 144 papers examined from 2010–2022, only thirteen papers were attributed to penetration testing and vulnerability scanning. This more limited systematic review claimed that the majority of testing focuses primarily on IT testing, and not OT. These findings were confirmed in our wider comprehensive analysis of existing literature on vulnerability assessments.

Penetration tests of an off-the-shelf satellite communication device using commonly available tools and custom scripts were done in (Gurren et al., 2023). These tests also demonstrated side effects, such as extreme battery drainage. This was one of the few experimental papers that demonstrated the possible cyber-physical effects of a device. During Pavur et al. (2020)'s tests, four major Very Small Aperture Terminals (VSAT) networks were tested, all of which use the same underlying technology stack as more than 60% of the world's maritime industry. These streams were found to lack basic link-layer encryption and were susceptible to passive and active attacks such as eavesdropping and session hijacking, which exposed ship-to-shore communication to cyber risks.

Tests were also conducted on the security of Voyage Data Recorders (VDR), a system that stored evidence for incident investigations, by testing them for known and unknown vulnerabilities. Santamarta (2015) analysed the firmware and software of an in-market VDR and discovered vulnerabilities that were exploitable. Additionally, VDRs were found to be vulnerable to attacks involving malicious USB drives, leading to breaches, tampering, and deletion of data affecting the Confidentiality-Integrity-Availability (CIA) Triad principles (Vineetha Harish et al., 2022; Hopcraft et al., 2023). Attempts have also been made to secure VDRs to address these security challenges (Seong and Kim, 2019). In Balduzzi and Wilhoit (2014), the authors evaluated the security of AIS by identifying and introducing various software-based and radio-frequency based threats. These types of publications are examples of papers generating new knowledge through experiments.

3.2. Scope of Assessments

As most of the assessments were technical, that is the focus of this section. However, the scope of the assessment for policy would likely consider organisational, regional, and international scopes. This may also be narrowed to a type of asset or device, and possibly by age as well. The scope of assessment of training would also likely be tied to the participants and types of training, however, this is likely a future piece of work and therefore outside the scope of this literary review on previous studies.

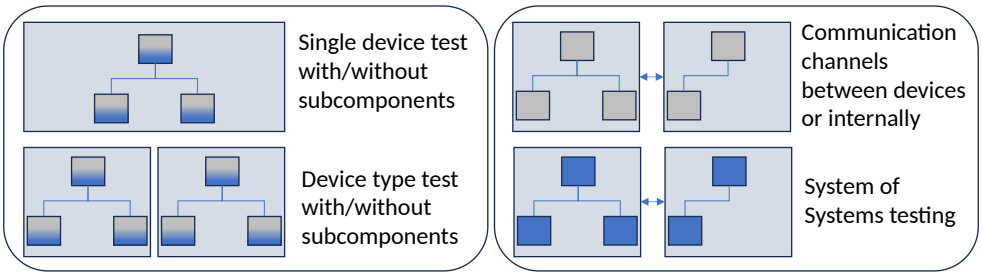

Figure 4.: Scope of assessment for technical assessment. Devices and device sub-components can also be divided into software/hardware components.

3.2.1. One Device Type

Most of the experiment-based literature revolved around testing a single device (see Figure 4). Some examples of VDRs and VSAT above took that approach. A few go even further, looking at only the software or firmware of a devices, often running in an emulator or virtual machine. For example, a software system used by almost one hundred container terminals worldwide was analysed in-depth by Eichenhofer et al. (2020) over the course of seven months. A low-level code review was included, which was unusual. However, despite being a single piece of the software, the testing did isolate two software modules for testing: a web application for communicating yard tractor jobs to operators and a web system with information about ship schedules, container locations, dangerous goods locations, and loading/discharge lists, and used for communicating port status and managing access to external stakeholders.

In a similar way that other studies have examined specific modules within a larger piece of software, tests on maritime system sub-components have been done. There have been on-bridge security tests, in which the sub-components of an ECDIS were tested to find vulnerabilities in third-party components (Svilicic et al., 2019b). Similar tests were performed on different other systems and sub-components like RADAR (Svilicic et al., 2020b, 2019a, 2020a). These experiment papers widen the scope outside one device, and the different vulnerabilities of a system's components.

Botunac and Gržan (2017) analysed several AIS configurations and introduced a software-based threat. These setups included nineteen combinations of hardware (AIS transponders, receivers) and software were tested in a controlled environment Khandker et al. (2022). This again expanded a single-device test, and sought to examine vulnerabilities of a type of system, expanding the scope. A total of eleven types of AIS attacks, including spoofing, jamming, alerts, data encoding, visual disruption, and denial of service, were tested against these setups, and most attacks were successful.

3.2.2. Device Communication Channels

Outside single devices, or a device and its sub-components, another aspect to consider is the communication between devices. For example, the work in Kessler (2021) explained vulnerabilities in the maritime Controller Area Network (CAN) bus communication protocol and NMEA 2000 standards in terms of the CIA triad of information security. In the study, it is mentioned that neither NMEA 2000 nor CAN Bus addresses confidentiality issues. CAN Bus does have bit integrity checks, but neither of them has time stamps, thus no timing checks. They also do not have any authentication mechanism and are susceptible to denial of service (DoS) attacks, however, this

could be improved by employing cryptographic encryption or network-based intrusion detection systems to filter out malicious messages.

3.2.3. Systems of Systems

The final and widest scope of assessment is often termed as system-of-systems. This is essentially a combination of the previous scopes, including multiple systems, their subcomponents, and multiple connectors and connector types. For example, Tam et al. (2021a) examined an attack chain that reached from the bridge of a ship to the steering mechanisms. While the system-of-systems can be any set of ship or port systems, another well-known term is the Integrated Bridge System (IBS) which is the system of all bridge systems and is often sold as a single unit to ships by single manufacturers. In an examination of IBS vulnerabilities, including individual components, Awan and Al Ghamdi (2019) found that 43% of the evidences were related to AIS, GNSS, and sailing directions, out of the 59 evidences collected. Work in Lund et al. (2018a,b) tested the security and integrity of Integrated Navigation Systems (INS), networks of interconnected navigational equipment. In another work around the INS, Svilicic et al. (2019c) tested a vessel's INS using a commonly available vulnerability scanner.

3.2.4. Time Frame

Another aspect of the scope of an assessment is whether it examines the past, or attempts to examine the future. While most horizon scanning tends to be positional papers due to the lack of information, these are often near-future assessment for emerging technologies. In the maritime sector, two worthwhile mentions are Maritime Autonomous Surface Ships (MASS) and Artificial Intelligence (AI). Several research studies have been recently conducted on using machine learning and AI in maritime systems, be it for traffic management, collision avoidance, or autonomous ship driving (Kretschmann et al., 2020; Munim et al., 2020). It is important to consider cyber security and testing of MASS and their systems while they are still in the research and development stage (Tabish and Chaur-Luh, 2024; Cho et al., 2022).

In Zagan et al. (2022), it claimed that Remotely Operated Vessels (ROVs) and MASS could have vulnerabilities in their hardware, software, firmware, and other interconnected component. It explores different types of MASS and their cyber vulnerabilities, and presents a case study of testing BlueROV from Blue Robotics including mapping its vulnerabilities to CVEs. In contrast, in article Walter et al. (2023), the authors experimented with adversarial AI attacks, testing how robust AI object detection can be against data poisoning, backdoor attacks, patch attacks, and model stealing. This was done both in a lab environment, and in situ with real MASS in sheltered waters. Additional tests in Walter et al. (2024) continued to test AI-based computer vision vulnerabilities from the vulnerabilities in the system training AI.

3.2.5. Human Machine Interaction (HMI)

Lastly, while machine-to-machine tests have been discussed, the human element is still prominent in the discussions about MASS and ROC. This often uses terms such as Human-in-the-loop (HITL), or Human-Autonomy-Teaming (HAT). For example, Misas et al. (2024) looked at trust in MASS environments from a human perspective, taking into consideration a reduction of Situational Awareness and HAT in remote operations. More generally, an assessment of the risk of MASS operations was conducted by Chang et al. (2021) by conducting reviews of the literature and expert

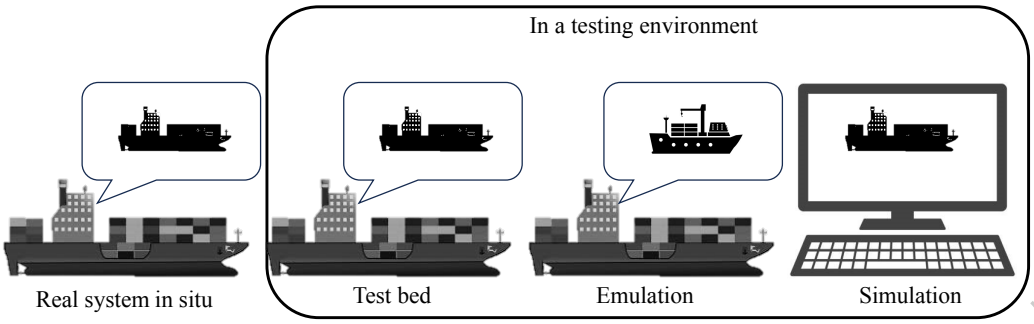

Figure 5.: Basic difference between real systems (software on intended hardware) emulation (hardware/software that enables a system to behave like another) and simulation, which a completely virtual version typically running on generic hardware.

interviews, followed by an analysis and quantification of data using FMEAs combined with Evidential Reasoning (ER) and Rule-based Bayesian Networks (RBNs). A similar study used a novel method of FMECA-ATT&CK-ATLAS (FAA) for the assessing the risks of autonomous cargo vessels. It combines Failure Modes, Effects, and Criticality Analysis (FMECA), MITRE Adversarial Tactics, Techniques, and Common Knowledge framework (MITRE ATT&CK), and Adversarial Threat Landscape for Artificial Intelligence Systems (ATLAS) (Yousaf et al., 2024).

3.3. Experimental Setups

Once the type (e.g., penetration) and scope (e.g., single device, software only) of the test have been chosen, there are a few more details to choose on how a technical test is conducted. To better facilitate testing in all scopes, research has been done on creating test beds and environments where penetration tests and vulnerability assessments can be conducted. This has shown to provide better monitoring, repeatability of experiments, and protection for both the devices in the test environment, and outside. There are several companies that offer maritime penetration testing services and consultancy on client ships Pen Test Partners (2024); Aptive (2024); SHIP IP (2024); Firesand (2024). While this can be useful, the risk to the ship means a smaller scope of testing is usually executed, yielding realistic results but a subset of the actual vulnerabilities. Tam et al. (2019) discussed this need for a risk-free environment for testing in 2019. Since then, more papers on new experimental environments have been published, discussing simulated, emulated, in situ and hardware testbed environments. Figure 5 shows the differences between real systems (test beds included) emulation and simulation in a lab, and real systems in situ, or in their normal operational context.

The work of Longo et al. (2023) presents a virtual environment that can simulate onboard sensors, IBS, and hydraulic systems and can be connected to external components like ship simulators. Work in Wolsing et al. (2022) modelled a simulated bridge environment using a radar unit, display, and various sensors and Sicard et al. (2022) developed an ICS physical testbed for French Naval Defence obscurity with a modelled warship with Human Machine Interface (HMI), PLCs for propulsion and artillery units and other SCADA systems. This setup is useful for testing a French Navy Ship; however, its setup and testing are limited to one configuration. A more configurable hardware testbed is proposed in Tam et al. (2019), which allows it to have many ship networks and devices to be connected the way ships of different types

and ages would. A list of software and equipment that could be used in a testbed for autonomous systems is first proposed in Amro and Gkioulos (2021).

In addition to the environment of the experiment, the tests themselves are critical. In other disciplines like structural and software engineering, there are often a suite of tests that are used to assess aspects of the subject. In a similar way, there have been proposals for cyber security tests for experiments, ranging from generic ones from other industries to sector/device/protocol-specific ones. The authors of Hemminghaus et al. (2021a) developed a tool to implement multiple cyber attacks, such as spoofing, AIS attacks, and Meanie in the Middle (MITM - originally Man in the Middle) attacks against Integrated Bridge Systems. The tool can be used to assess the security of these systems and identify vulnerabilities, but attacks are crafted and offered with the assumption that navigational data will be verified by humans and there will be a human in the loop. In spite of the tool itself not being a penetration testing tool, the attacks generated can be used to launch tests through its interactive HMI.

In Vineetha Harish et al. (2024), a sector-specific tool for the maritime bridge environment automatically identified and profiled devices for audits and tests. This brought more functionality to the testbed it was designed to work on, and is an indication of the sub-topic of the field maturing. The authors in Yi and Kim (2021) proposed a security testing approach for naval combat system, a complex software-based system, that connects various heterogeneous systems, including sensors, weapons, networks and navigation systems. The authors chose to develop a software-specific security testing framework as these systems were increasingly being used commercially. Studies researching training would need to be clear in their training environment (e.g., online, real time, real ship, simulation) however, previous studies have chosen these for experiments, not necessarily assessments of students or the training itself.

4. New Knowledge Papers: Solutions

As defined earlier, when a paper does more than provide a proposal within a positional paper, this paper considered it a new knowledge paper that provides a solution. This can be at several levels, at a minimum a solution is a more detailed proposal, but ideally these will have trailed a test case, or undergone more vigorous verification. In addition to the level of readiness, the type of solutions is critical. In our review of the existing literature, these tend to be frameworks (e.g., training, risk assessment) or research enablers (e.g., cyber ranges, test beds).

4.1. Existing Security Testing Frameworks

From 2013– June 2024, a small percentage of the existing literature focused on security testing and assessment frameworks for the maritime industry. Most of what is available relate to threat assessment in the maritime sector rather than actual security testing methods like pentesting or vulnerability assessments. The authors in Enoch et al. (2021) acknowledge that automated security modelling and vulnerability assessments can help improve cyber resilience in the sector, and given the differences in the environment and type of systems, current IT and Internet of Things (IoT) network assessments may not be able to seamlessly integrate into maritime. To address this issue, the authors present the Maritime Vessel-Hierarchical Attack Representation Model (MV-HARM), a graphical security model of ships. The model can be used to assess the effects of an attacker, both on single and multiple targets, identify potential

attack paths with attributes such as network configurations, vulnerabilities, systems, and connectivity and assess the effectiveness of defence strategies on the networks.

Similarly, Pitropakis et al. (2020) proposed a framework to collect and analyse maritime cyber threat intelligence, as a solution to the lack of threat awareness in the sector. The MAritime Threat Intelligence Framework, also known as MAINFRAME, collects and correlates data, audits data integrity using Hyperledger blockchain, and honeypots, performs threat intelligence using a Security Information and Event Management (SIEM) system, and machine learning models and is integrated into VERACITY, a commercial product from DNV GL. The authors Melnik et al. (2022) discuss the importance of vulnerability and security assessments for the maritime sector and propose a probabilistic assessment of a vessel's cyber security considering targeted and non-targeted cyber threats. Yoo and Park (2021) proposes a qualitative solution to determine item-specific vulnerabilities to identify cyber risks in the sector. They conducted a qualitative risk assessment with a group of six experts who reviewed twenty-seven risk factors divided into three groups of administrative risks, technical risks, and physical security risks, to derive cyber security improvement plan priorities. The study also emphasised the need to include quantitative vulnerability assessment of the elements to calculate quantitative risks.

While previous frameworks have provided solutions, many were manual paper-based exercise, not verified, or both. An example of a security tool that does this is the Bridge Attack Tool (BRAT), which implements several attacks against IBS to help in security assessments (Hemminghaus et al., 2021a). The authors point out that in the maritime sector, there is not a sector-specific tool, testers often use generic tools to carry out assessments and there is a need for maritime-specific testing framework. BRAT uses preconfigured attacks like AIS attacks against IBS and uses an interactive Human Machine Interface. Its results are not verified like, for example, on real hardware.

The types of papers above were popular in the early 2000's; however, as the state of the art grows, the novelty of these papers decreases. Due to this, as of 2023, more papers are now needed to expand the state-of-the-art by automating tools and/or verifying the results of the testing framework. A prime example of this is BridgeInsight mentioned previously (Vineetha Harish et al., 2024), which pushes the boundary of testing frameworks by both automating tests, moving away from manual inputs, and also verifying its results by testing the security vulnerabilities on real hardware.

4.2. Risk Assessment/Management

Within the last decade of maritime cyber research, risk assessment methods and crew awareness make up a significant section of frameworks proposed in literature. There is therefore a need to research and develop new and better tools and frameworks to test the systems, standardise, and regulate the frameworks across the sector.

One of the earlier maritime cyber-risk papers was concerned about maritime supply chains and critical infrastructures (Polemi and Papastergiou, 2015). The document itself was a review paper, but the projects it summarised were new solutions in the field, namely CYSM, Medusa, and Mitigate. These solutions examined a port's cyber-physical elements and supply chain risks (Polemi and Papastergiou, 2015). Between 2018–2022, a considerable number of studies like this were conducted.

In Polatidis et al. (2018), its authors conducted discussions about MITIGATE, the risk management system mentioned above, which is used to discover cyber attack paths and detect and address risks based on parameters such as entry points, target

points, attacker capability, and propagation length. In dynamic supply chain environments, attack path discovery helps identify flaws and can be fed into the wider risk management system. Authors also claimed this approach can be used to assess risks in SCADA systems as well Kalogeraki et al. (2018).

Tam and Jones (2019) introduced dynamic risk analysis through MaCRA (Model-Based Framework for Maritime Cyber-Risk Assessment) to quantify and assesses risks. Through MaCRA, maritime cyber risks can be quantified by modelling attributes such as attacker abilities, ease of exploit, attacker rewards, and target vulnerabilities. Results are projected on a simple risk quadrant. This framework has also been applied to profile and quantify risks in autonomous ships and maritime ports infrastructure. Authors provided fine-grained but theoretical assessments of the risks, and also the potential econometric and cascading cyber-physical impacts (Tam et al., 2021b).

While several of the academic literature discussed in this section either modified or created new solutions and knowledge due to limitations in adapting other methods to maritime, many other studies have used existing frameworks and then fed expert data into those frameworks for results. However, from our comprehensive review, many of these studies relied on a very small set of experts (see Figure 6) and/or do not disclose their metrics for "expertise" in sufficient detail. Therefore, while useful contributions, the authors considered papers of this nature to be a type of systematic review of expert opinions, rather than adding to new knowledge.

4.3. Technical Solutions

Previously, most solutions proposed have been self-labelled as frameworks and models. These are not technical in nature, but do address technical topics. In Jacq et al. (2018), the authors discuss the possible solutions to cyber security challenges by investigating the People, Process, Technologies (PPT) triad.

Considering the last decade of research, the maritime sector is still in the early stages of testing for cyber security, which means that there are limited technological solutions to the cyber security challenges it faces. Many papers are still positional papers, or early proposals for non-technical solutions. More technically, some research has been conducted to secure widely used protocols in the sector, such as the Automatic Identification System (AIS) and most of the solutions are based on cryptographic techniques and digital certificates Goudossis and Katsikas (2018). That research then proposed a secure AIS model that uses techniques like Identity-Based Public key cryptography and symmetric cryptography to encrypt AIS messages and anonymise data.

In a related study, SecureAIS, proposed by Aziz et al. (2020), is a software-based key establishment protocol designed to encrypt and authenticate messages between AIS transceivers using cryptography techniques such as the Elliptic Curve Qu-Vanstone (ECQV) implicit certification scheme and the Elliptic Curve Diffie-Hellman (ECDH) key agreement algorithm. The authors also demonstrated a proof-of-concept using SDRs and GNURadio. In their experiments, they observed that the solution reduced the time overhead by 20% using only twenty AIS time slots compared to traditional X.509 certificates. SIGMAR is a framework designed to add authentication to nautical datagrams using digital signatures based on asymmetric cryptography (Hemminghaus et al., 2021b). The authors of the framework have identified the issue that changing or replacing maritime systems can be expensive and difficult, and thus retrofitting features is the best way, especially when the systems have low computational power to perform intensive operations like encryption.

Solutions discussing attack detection and Intrusion Detection/Prevention systems are also becoming prevalent. Studies have been conducted to deploy such attack/threat detection solutions in IoT-based Maritime Transportation Systems (MTS) and these solutions are modelled using different learning algorithms (Liu et al., 2023; Gyamfi et al., 2023). Merino Laso et al. (2022) presents the idea and results from the European project ISOLA (Innovative and Integrated Security Systems on Board Covering the Life Cycle of a Passenger Ships Voyage) developed within the scope of the Horizon2020 program, with the aim of identifying threats, risks, and assessing them, as well as incorporating incident detection and reporting, focusing on cruise ships. There are several modules in the ISOLA platform, such as sensor data processors, artificial intelligence algorithms for dynamic vulnerability detection, intrusion detection systems, warning systems, and integration of open-source tools for finding flaws. The authors mention that the platform will provide insights to users during incidents and crises to help improve the response, and mention the need for a dynamic cyber security vulnerability assessment tool to be developed in the future.

4.4. Crew Awareness Training/ Frameworks

A critical part of ensuring resilience in the maritime sector is training crew members and operators in cyber awareness. With the increasing digitisation in the field and the integration of new systems into navigation and communication networks, it is crucial to educate people on how to better identify, respond and protect against cyber threats and attacks. Ship Bridge Simulator-based training is the most common method for cyber awareness training in the maritime sector, and there are several research that support this. As part of a maritime ship simulator-based exercise, students encountered cyber threats related to OSINT and digital footprint at sea, which helped them gain a better understanding of cyber hygiene and the use of technology at sea (Yousaf et al., 2024). Erstad et al. (2023) demonstrates the benefits of a Human-Centred Design approach when developing a simulator-based incident scenario for maritime cyber resilience training, and stresses the effectiveness of simulators as a learning environment. These were also tested in a real mariner training environment with a focus on Norwegian cadets.

Another popular method for maritime cyber awareness training is through cyber ranges. Tam et al. (2021c) discusses the use of cyber ranges, physical test beds, simulations, and emulations in training contexts and how they may have different pros and cons. This was written out of the Cyber-MAR EU project (CyberMAR, 2024). The same project also published in Pyykkö et al. (2020), which argued that a holistic model using cyber ranges with realistic scenarios can improve the efficiency of the maritime cyber operations. Cyber range-based training can be effectively executed by developing an architecture or model, designed to consider levels of simulation and realism according to the audience and scenario. A maritime cyber range has been proposed by Potamos et al. (2021), comprising simulated and emulated communication networks, administration tools, navigational equipment, and machinery, to assist in cyber awareness training by means of attack simulations. Additionally, it can be integrated into a larger Multi Domain Cyber Range Federation to share resources between geographically distributed cyber ranges and develop multi-domain cyber training scenarios. As explored more in a later section, this is a relative new subject within maritime cyber security, but one that has seen significant growth in just a few years.

5. Review Papers

Within the set of "review" papers published in the last decade, there were three distinct types. First, were general review papers where authors selected papers by region, subject, or out of interest. These were often self-labelled as reviews, surveys, and overviews. Other papers claimed themselves to be systematic reviews, which were reviews that adhered to more strict rules and systematic procedures. However, while many claimed to be systematic, in actuality, many were more accurately a general review paper, as discussed below. Lastly, the authors had previously defined papers that used existing frameworks and used them to process/review expert opinions that were limited (small) and/or without robust discussion on what they consider "an expert" and if the range of necessary expertise was involved. Instead of considering these as new contributions to knowledge, these have been classified as a review of opinions instead of a review of papers.

5.1. Limitations of Literature Reviews

While literature reviews of all kinds can add to the overall knowledge, there are several limitations to survey papers in maritime cyber security that should be considered. The first limitation, which is illustrated in the discussion, is that the majority of the papers in maritime cyber security in the last five years are overwhelmingly survey papers, reducing the novelty of each publication. In addition, due to how few papers, especially how few new knowledge papers there are, most if not all reviews published before 2024 were limited and biased due to a small set of available concrete research since 2013 but did not fully disclose this limitation, leading readers to potentially wrong assumptions. Many also restricted their set further by excluding articles in certain languages or from certain publication venues despite their impact or high citations.

Another significant limitation to many previous reviews, especially the systematic ones, is the frameworks tend to work best on distilling an extensive body of work that has established journals and common terminology. Those assumptions do not hold as well in a new body of research. Firstly, as we have seen in our analysis of the literature, most early positional papers before 2017-2018 were published in a wide range of conferences, journals, and venues. Therefore, excluding papers outside of high-impact journals, while reasonable for an established field, limits the understanding of a new growing research topic that has not been widely published. On the second point, as seen with Google trends, doing a systematic review based on terms at this point is also difficult, as many publications are early positional papers from different countries, subjects, and across academia, industry, and government. Common terms and phrases have not yet been well established. In this comprehensive review, all papers related to maritime cyber security, even if they use different terms (e.g., ship vs vessel, cybersecurity vs cyber security) have been considered.

Another important note to review papers listing previous, publicly known, attacks, is currently the majority of them are only focused on publicly released information and those released in a single language such as English. That is a concern, as Lund et al. (2018a); Mrakovic and Vojinović (2019) pointed out how under-reporting is a significant issue. This research also discuses on low awareness of what different types of cyber attacks look like, all of which indicates that the reports that are known are limited and often biased towards very easily recognised attacks like DoS and ransomware. This is one of the critical limitations of review studies based solely on public incidences

for information. Therefore, while useful indicators that cyber attacks are happening in the sector, it may not be fully representative of all the attacks happening.

While there are limitations applying systematic reviews to a new area of research, it is important to highlight limitations of a comprehensive reviews as well. A comprehensive literature review summarises a body of work, and while the freedom to choose key works is essential, there is a possibility of author bias. In this review, the authors attempted to mitigate this by using publication dates to highlight new, field-defining areas of research as they were developed and explored. However, there is possible bias towards research the authors are familiar with and should be considered by the reader. It should also be noted that the database used for the literature search is Google Scholar, which pulls articles from most of the academic databases like Semantic Scholar, Scopus and Web of Science. Google Scholar helped to understand the field, by gaining a broader understanding, as our review included not just academic articles, but also technical reports, thesis, and books.

5.2. Limitations of Expert Reviews

This review also includes the use of existing frameworks to rephrase information as a type of review, just a more formalised or systematic one. For example, the MITRE ATT&CK framework was used by Jo et al. (2022) to analyse and model cyber threats on ships, where the authors analysed four known cases from other literature. The cases were then analysed with the existing MITRE ATT&K model and were mapped to phases like initial access, execution, command and control. In another example, Kayisoglu et al. (2022) performed risk assessments of navigation systems using widely accepted frameworks are also popular to uncover vulnerabilities and threats. The same core authors that used Failure Modes and Effects Analysis (FMEA) to assess the risks on Voyage Data Recorders Soner et al. (2023), also conducted a quantitative human risk assessment on AIS data and systems using the Shipboard Operation Human Reliability Analysis (SOHRA) method Soner et al. (2024). The same core authors again in Kayisoglu et al. (2024) developed treatment and mitigation strategies for onboard RADAR systems using the CORAS framework to perform the risk assessment.

The limitation of many of existing reviews is that they often have very small groups of people, the groups are biased, or there are no essential details about the experts provided. In our survey of 319 papers, the smallest group of experts was four. The largest was 239; however, that was an anonymous online survey with no verification or assessment of the participant's expertise. Moreover, in our analysis, all papers with more than seventy responses reported collecting anonymous options and/or not verifying any responded details. Many other below seventy participants were also unclear or reported no verification or not assessing experts. As seen in Figure 6, while the average of participants in all papers interviewing or surveying people, the average is roughly seventy. However, about a third of all such papers have had less than ten participants, and if only looking at studies that claim (not necessarily verify) that participants are "experts", that average falls closer to twenty participants per study.

Another point of consideration is that several of these types of papers were published by the the same core authors, which makes it possible that the same group of experts might have been used for multiple studies. This is not made clear in the studies, and can unintentionally create bias in a body of work, especially when review articles make assumptions and over-state certain findings in its summaries and discussions.

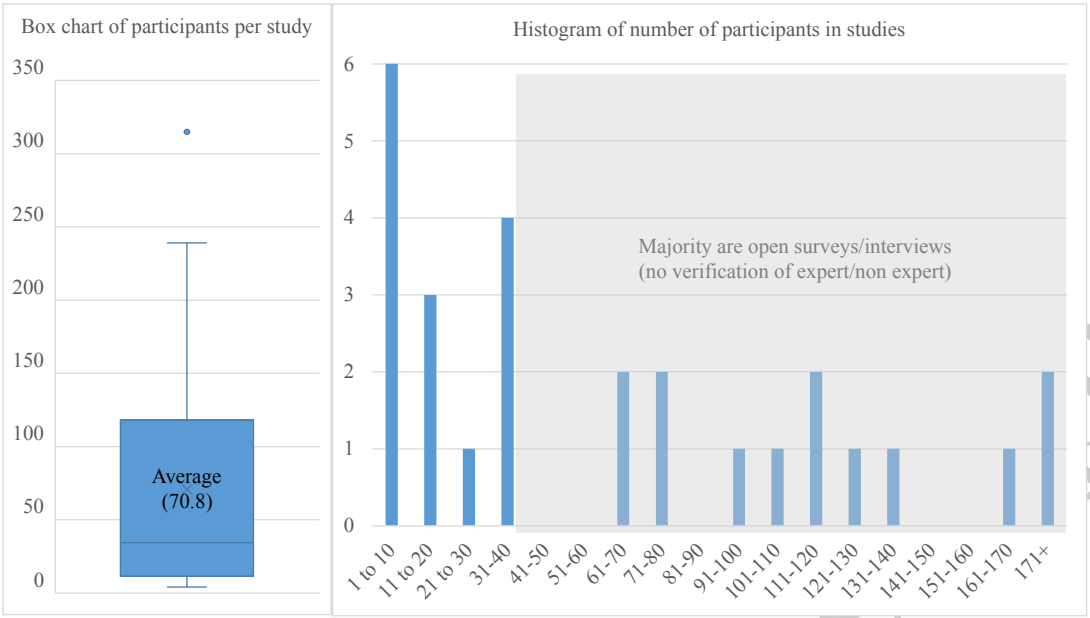

Figure 6.: Participants in past maritime cyber security surveys/interview studies

6. Discussion

This review aims to examine how maritime cyber security research has matured in its "first" decade of existence. This time frame was determined by looking for the first piece of literature that was dedicated to the concept of maritime cyber security, and not just a side note in another topic. It does not exclude papers based on the venue of publication or language, unlike similar works. As a result, this review considered 319 papers. While this did cover a wider range of papers from previous reviews, there are potential biases which we explained and tried to mitigate, as explained in Section 5.1). This review also had a clear cut-off for the end for 2023, future work would need to include publications in 2024 once that year has been completed. As the majority of these were positional and survey papers, we did not feel there was enough foundational articles to conclude anything about how secure the sector is, etc. However, this discussion can highlight some aspects of the maturity of this research area in a way that can help guide those just entering the field, those already working in it, and those looking for ways to progress the state of the art. These are summarised in the discussion points below:

(1) Global interest in maritime cyber security continues to grow both in academic research and in the public eye. A steady number of major, public reports of attacks on maritime assets globally and annually is likely a factor in this visibility and interest as discussed in the Introduction. Interestingly, many internal reports of cyber-attacks not publicly disclosed show a much more dramatic increase of incidences, up to 86% some years in some locations (US Coast Guard (2022)). This indicates that the sector still does not have a full grasp on how extensive cyber attacks are happening in the maritime sector, which also links back to both people's awareness and digital forensics.
(2) One concern is the ratio of review papers to other types of papers, as seen in Figure 2. From 2013–2016, in our comprehensive assessment, there were only

positional papers and review papers. Many review papers then were reviews of a few ideas, not facts or experimental results, and content from other sectors. Because of the ambiguity of the input, the results of many of these reviews were therefore unclear. There was a significant spike in review papers from 2017, with many of the earlier ones again more summary than a review because there were very few pieces of concrete studies to review as a body of work. From 2019 to the end of 2023, review papers were the number one type of publication. As discussed before, this causes some concern as it seems most papers in the field seem to be reviewing a very small number of foundational articles, reviewing other reviews, or including studies outside the field. Many of the reviews reduced the available number of papers in the review further with metrics that created bias (e.g., language). This situation is dangerous, as it can create echo chambers, bias, and ideas may eventually be reported as undisputed fact, when they have not been fully researched yet. The authors would urge researchers to focus more on generating new knowledge articles for growing a more scientific body of work.

(3) The breakdown of the umbrella topic of maritime cyber security into specialist areas (See Figure 3) has shown the research growing in terms of breadth and depth. Although not shown in the figure itself, many of the positional papers that helped broaden the scope and define sub-topics more clearly are from a wide range of researchers globally. Initially from 2013–2016 there were very few branches of maritime cyber security besides ports or a very high-level and generic view. In 2016 the discussion of ships was brought up separate from port security, and from 2017 to 2024 there have been multiple new areas proposed for research. Generally speaking, most of these positional papers have also had a following of new-knowledge papers, indicating growth. It is the authors' opinion that the breadth and depth of new knowledge papers is progressing well as a result of a comprehensive review of key papers that actively push the state of the art.

(4) In addition to proposing more new knowledge papers, it is also worth discussing how to increase the breadth of knowledge. The majority of experiments to test the cyber security of devices for example, have focused on AIS, ECDIS, and VDR with a few on RADAR or a PLC. All of these papers have mentioned that these are one device in a rich ecosystem of other devices, but the focus has continued to stay very narrow. There is also scope for more verification and assessment of the tools and frameworks being proposed. At the moment, most of the frameworks are manual, but ways to verify the frameworks work, verification for automated tools made, and verification for successful training would seem beneficial ways to grow the body of research further. It would also be beneficial to broaden research into other maritime infrastructure, such as underwater sea cables and offshore structures (e.g., oil, wind turbine).

7. Conclusions

Compared to other fields of research, maritime cyber-security is still a new area of research. In its "first decade" of existence, it has seen global interest, and that interest has defined and shaped it and its subtopics through positional papers, and then explored those topics with experiments, frameworks, and solutions in more depth and with scientific rigour. Literature reviews have also been published, attempting

to phrase the challenges and solutions to various audiences. This article provides a comprehensive review, as opposed to a general or systematic review, at an appropriate time, when the body of work was sufficiently mature enough. While overall the maturity of the field has clearly progressed in its early stages, there are areas of development and concern that are likely normal in a new area. These may resolve naturally, findings of this review on gaps in research and concern on research efforts globally are meant to help guide the next decade of maritime cyber security research productively.

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