WMU Journal of Maritime Affairs (2022) 21:233–266
https://doi.org/10.1007/s13437-022-00269-z

ARTICLE

# Autonomous ships and the collision avoidance regulations: a licensed deck officer survey

**Elspeth Hannaford**[1,2] · **Pieter Maes**[1,2] · **Edwin Van Hassel**[1]

Received: 4 May 2021 / Accepted: 27 April 2022 / Published online: 11 May 2022
© The Author(s) 2022

## Abstract

International interest in Maritime Autonomous Surface Ships (MASS) is on the rise. This exploratory research presents insights of a sample of licensed deck officers (LDOs) regarding the potential future of the Collision Avoidance Regulations (COLREGs) with the implementation of MASS. At present, there is much discussion in the maritime industry on if and how the COLREGs will need to be amended to be able to be applied to MASS. Limited research is published from the key perspective of the LDO. Qualitative and quantitative methods are used, including a literature review and a multiple-choice survey. Data is analyzed via descriptive statistics, and commonalities within the results are investigated as well as years of experience with practicing the COLREGs. Results show that many barriers exist when applying the COLREGs to MASS, and minor amendments to certain terms and definitions are recommended. Moreover, the COLREGs should not be quantified, and MASS should be identifiable from other vessels. LDOs with more experience with practicing the COLREGs are found to be slightly more open to changing the rules versus LDOs with less experience. When compared to the results of the International Maritime Organization's regulatory scoping exercise, the results of this study are found to be in congruence. This research provides valuable insights for the ongoing discussion of the future of MASS operation in the maritime industry.

**Keywords** Maritime Autonomous Surface Ships · COLREGs · Licensed deck officers · Regulatory scoping exercise

✉ Elspeth Hannaford
elspeth.hannaford@student.uantwerpen.be

Edwin Van Hassel
vanhassel@uantwerpen.be

[1] University of Antwerp, Prinsstraat 13, 2000 Antwerp, Belgium

[2] Antwerp Maritime Academy, Noordkasteel-Oost 6, 2030 Antwerp, Belgium

## 1 Introduction

Maritime Autonomous Surface Ships (MASS) are expected to be the next major step in the shipping industry (Sharma et al. 2019). Various autonomous shipping projects and technologies are continually being developed and tested around the world (Mallam et al. 2020; Fan et al. 2021; Kim and Schröder-Hinrichs 2021). As MASS research proliferates, International Maritime Organization (IMO) instruments such as the Collision Avoidance Regulations (COLREGs) need to be examined as barriers are created when these rules of navigation are applied to autonomous ships (Perera 2019; Chang et al. 2020; Zhou et al. 2020; Rivkin 2021). Current collision avoidance systems are not always fully COLREGs compliant (Lyu and Yin 2019), especially during complex navigation scenarios (Johansen et al. 2016). Amendments to the COLREGs are needed to allow for MASS operation (Komianos 2018; Timbrell 2019). Further guidance and clarification should be provided (Ringbom 2019).

The future of the COLREGs is unknown (Porathe 2019). Limited studies have analyzed COLREG barriers to MASS in great detail (Zhou et al. 2020). This study aims at filling this gap by contributing valuable insights regarding the future of the COLREGs with MASS implementation from the perspective of a sample of licensed deck officers (LDOs). This perspective is relevant as LDOs are COLREG subject matter experts (SMEs) (Silveira et al. 2021), and MASS will need to be operated by competent mariners (Ghaderi 2019). Mariners are the most important element for the safety of navigation of ships (Francis 2019). LDOs, among other stakeholders, should be included and collaborated with for MASS legal, training, and operational implications (Goerlandt 2020). During the time of this study, limited research has been published from this key perspective regarding the future of the COLREGs and MASS.

This research first uses a literature review to identify potential barriers to the COLREGs with MASS implementation as well as proposed solutions to these barriers. After having reviewed dozens of sources, eight references consisting of two reports, one thesis, and five journal articles were chosen based on subject relevance, method, data analysis, and research pool. Next, two to three SMEs discussed the findings of the literature review and created a multiple-choice survey specifically for LDOs to complete. This survey presented the original COLREGs and proposed amendments and asked participants which option is better at preserving the safety of navigation in a sailing environment that includes MASS operating at degree 3 or 4. Quantitative data from the survey was analyzed via descriptive statistics. Optional text boxes after each survey question added depth to the survey results. Majority, minority, and average survey responses across all questions were reviewed for commonalities, consistencies, and trends, and to see if LDOs are open to change or if years of experience with practicing the COLREGs have any impact on the results. Results are also compared to the results of the IMO's regulatory scoping exercise (RSE). The RSE has recently been conducted to assess how the COLREGs may be affected with MASS implementation by identifying all gaps, themes, and assumptions and provides guidance to identify further work (International Maritime Organization 2021).

This paper is structured as follows. In Sect. 2, background to this topic is given. Section 3 presents the research approach, and Sect. 4 provides the results. Section 5 presents the discussion, limitations of the research, and recommendations for further research. Section 6 offers the conclusion of this research.

## 2 Background

### 2.1 COLREGs

The COLREGs define compulsory navigational rules for vessels to avoid collision. The first recorded reference to a rule of sailing dates back to a signal book by Admiral Lord Richard Howe in 1776 (Kemp 1976). The following century, basic rules of navigation incorporating steamships were suggested by the London Trinity House Corporation (Kemp 1976). By 1864, the United Kingdom (UK) and the French government created a standard set of rules that were adopted by over 30 countries (Werner 2017). The COLREGs that we know today were adopted as a convention by the IMO in 1972 and put into force in 1977 to replace the older 1960 Collision Regulations (International Maritime Organization 2019b). There have been multiple minor amendments to the COLREGs since, which is the responsibility of IMO's Maritime Safety Committee (MSC). The latest set of amendments was adopted in 2013 and put into force in 2016. These amendments added Part F to rules 39, 40, and 41, which introduced definitions and regulation addressing audits and the IMO Instruments Implementation Code (International Maritime Organization 2019a).

Today, a total of 41 rules apply to "all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels" (USCG and US DOT 2004). They have been adapted by dozens of countries worldwide and cover everything from how to properly illuminate a vessel engaged in mine clearance operations to rules regarding the take-off and landing of wing-in-ground (WIG) craft. Six parts cover steering and sailing rules, lights, shapes, sound signals, and exemptions while four annexes detail topics such as the technical positions of lights and recognized distress signals to be used during an emergency (USCG and US DOT 2004). The COLREGs are also divided into international and inland rules. Inland rules have slight differences compared to the international rules and apply to vessels in inland waters of the USA as well as on the Canadian side of the Great Lakes (USCG and US DOT 2004).

The COLREGs are taught at maritime institutions around the world, often memorized verbatim by sailors in training. They are vital for the safety of navigation (Ugurlu and Cicek 2022) and should be properly executed to avoid collision (Perera 2019). As they are written as a legal document, the COLREGs can be considered ambiguous with some rules left up to interpretation. This can lead to human error (Demirel and Bayer 2015; Mohović et al. 2015).

### 2.2 COLREGs, navigational casualties, and human error

One of the main driving forces behind the promulgation of MASS is the possibility of reducing maritime accidents caused by human error (Ahvenjärvi 2016; Yoshida et al. 2021). Human error is a predominant factor in causing navigational casualties, which are characterized as collisions or groundings (Mohović et al. 2015). LDOs are found to be the primary cause of these types of accidents (European Maritime Safety Agency 2018). Fatigue of onboard officers is found to be one contributing factor (Rothblum et al. 2002).

Some experts also identify the misunderstanding, interpretation, or incorrect use of the COLREGs as another main contributing factor to navigational casualties (Demirel and Bayer 2015; Mohović et al. 2015). Seafarers with a poor theoretical knowledge of the COLREGs who were involved in an accident have a 233.8% higher probability of being involved in an accident of high severity (Wang et al. 2021). The Avoiding Collisions at Sea (ACTs) project, funded by the EU Leonardo Program and involving roughly 1500 participants from multiple countries, concluded that the rules are not easy to understand or apply (Ziarati et al. 2019). It was also found that experienced mariners have a better understanding of the COLREGs by 15% compared to inexperienced mariners (Mohović et al. 2015). Literature for learning the rules as well as the rules themselves should be clarified (Mohović et al. 2015).

The understanding and practice of the COLREGs is paramount to the mariner in order to avoid navigational casualties. Hence, it is important to keep LDOs in the conversation regarding the future of the COLREGs when applied to MASS.

### 2.3 MASS

Autonomous shipping is an important and significant topic for the maritime industry (Fonseca et al. 2019). Many maritime institutions are interested in how and when MASS will be fully integrated (Kim and Schröder-Hinrichs 2021). A study conducted in 2019 by the World Maritime University (WMU) predicted that human supervised autonomous vessels will reach between 11 and 17% of global shipping by 2040 (Schröder-Hinrichs et al. 2019). Aside from human error reduction, another main driving force behind MASS exploration is financial savings (Ahvenjärvi 2016). Technical or operational solutions such as building larger ships and reducing ship speed have reached their limitation to overcome economic, social, and environmental challenges (Gu 2019). MASS is a potential cure for current difficulties facing the maritime sector (Kretschmann et al. 2017). Moreover, societal advantages could be gained from autonomous shipping. It is believed that the potential flexibility of operations brought on by autonomous technologies could improve service coverage for distribution of goods (Gu 2019). The supply chain could be optimized; ship fuel usage could be reduced along with ship food waste, garbage disposal, and sewage; and there is potential for improved infrastructure for areas of dense traffic (Danish Maritime Authority 2017).

IMO's MSC has defined MASS and four degrees of autonomy. Degree 1 is a ship with automated processes and decision support with seafarers onboard that can take over control of the vessel. Degree 2 is a ship that is remotely controlled with seafarers on board that can take over the control of the vessel. Degree 3 is a remotely controlled ship without seafarers on board. Degree 4 is a fully autonomous ship that makes decisions on its own (International Maritime Organization 2021). It is generally agreed that MASS, while operating at degree 2, 3, or 4, can be monitored and controlled shoreside by a shore control center (SCC) (Zhou et al. 2020). SCC is synonymous with the term remote control center (RCC) (Dybvik et al. 2020).

A multitude of MASS projects are recently completed, ongoing, or being developed around the globe (Kim and Schröder-Hinrichs 2021). For example, NOVIMAR (Novel Inland Water Transport and Maritime Transport Concepts) has been developed for short sea shipping and inland waterways. This concept reduces manning and increases automation by using a vessel train concept where one fully crewed lead vessel (LV) is digitally linked to minimally crewed follower vessels (FV) via remote control (Colling and Hekkenberg 2019). Japan's Mitsui Osk Lines (MOL) is testing to improve autonomous docking/undocking operations of passenger ferries and aims at bringing autonomous shipping online as early as 2025 to reduce human error-related marine accidents and to relieve crews' workload (Bergman 2018). The zero emission battery-powered YARA BIRKELAND is designed for short sea shipping (Fonseca et al. 2019). It will be operational in 2022 (Nordal 2021) and aims at taking 40,000 trucks annually off the road in Norway (Kosowatz 2019). In 2021, the Belgian company Seafar conducted trials with its semi-autonomous vessel DESEO between Antwerp and Zeebruges. This small cargo vessel owned by Wennick has the capability of being controlled from shore via its RCC. During these trials, it still has minimal crew onboard for safety concerns (The Maritime Executive 2021). The "Designing the Future of Full Autonomous Ship" (DFFAS) project recently constructed a fleet operation center in Japan, where it will control MASS by 2025 (Zhang et al. 2021). China's 300 TEU containership ZHI FEI started sailing short distances between two of China's ports at the end of 2021. This vessel can be operated remotely, autonomously, or with people onboard. If trials are proven successful, the intent is to develop a larger autonomous ship of 10,000 TEU (Rivkin 2021). The UK's Mayflower Autonomous Ship (MAS) is in the process of recreating the original wooden three-mast Mayflower's historical journey across the Atlantic, but this time fully autonomous (Anderson 2020).

These projects among many others are helping to shape the future of the maritime industry. This sample list indicates that MASS projects vary greatly. They are being developed by different nations and by a multitude of institutions. Each project is on its own trajectory, but all MASS, as ocean going vessels, will have to follow the COLREGs (Perera 2019). LDOs should be familiar with the different types of projects that are currently underway as they may interact with them now at sea, as well as all parties involved in the process of amending the COLREGs to better shape the rules of navigation for the future.

### 2.4 COLREGs and MASS

Collision avoidance systems have the technology to navigate within the COLREGs (Ning et al. 2020; Shaobo et al. 2020). However, as the COLREGs are written for manned vessels, some of the current rules present problems (Porathe 2019; Pedersen et al. 2020). Many SMEs believe that the COLREGs need to be amended for MASS implementation as they cannot fully comply as they are currently written (Komianos 2018; Hirst 2020; Rivkin 2021). According to Zhou et al. (2020), they should be amended, but not substantially changed. On the other hand, as the first generation of MASS will be in a mixed environment of both humans and autonomous systems, some SMEs believe that MASS should simply follow existing rules (Perera and Bjorn-Morten 2019). Others believe that to further avoid collision, attention should be focused more on how COLREGs are taught and applied and less on how they should be changed (Hirst 2020).

One standing issue of applying the COLREGs to MASS is that the COLREGs are often ambiguous depending on the situation (Porathe 2018; Rivkin 2021). For example, the interpretation of "early," "substantial," "as soon as it becomes apparent," "finds herself so close that collision cannot be avoided by the action of the give-way vessel alone," "action as will best aid to avoid collision," and "if the circumstances at the case admit" are left up to the interpretation of the person navigating the vessel (Porathe 2019). Algorithms for COLREG execution have been known to be necessary to solve some of these issues and ambiguities, but proposed solutions vary and they are still in the research stage (Blanke et al. 2017). Many of these initial collision avoidance algorithms are applicable to single ship-to-ship encounters which can limit their use (Lyu and Yin 2019; Cho et al. 2020). MASS performance standards should be expanded upon to incorporate multiple ship scenarios (Perera 2019).

The MASS UK Code of Practice is currently used as a voluntary guide for MASS trials in the UK and in Europe. This code was created by the UK Maritime Autonomous Systems Regulatory Working Group (MASRWG), which engages with the IMO and aims at providing documents for eventual international adaptation (Maritime UK 2019). This code recommends that MASS control systems should be capable of compliance, should be able to maneuver within appropriate interpretation of the COLREGs, and should have proper sounds and shapes onboard. During failures and emergencies, MASS should maintain a safe course and speed as defined within the rules. Also, operators should have a clear understanding of all IMO instruments (Maritime UK 2019).

A report published in November 2020 by the Ministry of Transport and Communications in Helsinki, Finland, stated that the COLREGs present challenges for increased ship automation, and that it would be beneficial for certain parts to be clarified to address these challenges. Some rules that provide difficulties are the following: the ordinary practice of seamen (rule 2), maintaining a proper lookout (rule 5), and safe speed (rule 6) (Ringbom et al. 2020). This report does recommend that MASS comply with the COLREGs as any other manned vessel, and regulations governing MASS navigational systems should place COLREG compliance as a top priority (Ringbom et al. 2020).

The COLREGs need to be further investigated with the implementation of MASS. As LDOs have first-hand experience with practicing the COLREGs, and will most likely control MASS as remote control operators (RCOs) from an RCC (Burmeister et al. 2014), it would be prudent to investigate their point of view.

### 2.5 Regulatory scoping exercise

IMO decided that it will take a proactive role when it comes to MASS development and regulation (International Maritime Organization 2017). Their strategic plan for 2018–2023 includes the integration of "new and advancing technologies into its regulatory framework" (International Maritime Organization 2018). IMO's MSC, the subgroup responsible for all safety, security, and human element issues within IMO's scope, periodically establishes sessions to address these issues. MSC's 99th session validated a framework to execute a two-step RSE to address IMO conventions and MASS (International Maritime Organization 2020).

This two-step RSE addresses a large range of issues including maritime safety, security, human factors, marine environmental protection, port interaction, and liability regarding autonomous shipping (International Maritime Organization 2021). The first step of the RSE was to identify all gaps, themes, and assumptions of MASS for all degrees of autonomy within applicable IMO codes and treaties (Jo et al. 2020). The COLREG instrument was reviewed by multiple Human Factors Working Groups (HFW) from the Marshall Islands and from the supporting member states, being China, Japan, Singapore, Spain, Sweden, and the USA. The first step of the RSE was completed and presented at the IMO headquarters in London, England, on 2–5 September 2019 with 44 Member States in attendance (International Maritime Organization 2019c). Also present were the European Commission (EC), the International Hydrographic Organization (IHO), the International Mobile Satellite Organization (IMSO), and many members from other non-governmental organizations (NGOs). The second step of the RSE was to determine recommendations for the gaps, themes, and assumptions that were found in step one (International Maritime Organization 2021). This step was completed by MSC's 103rd session which concluded on 14 May 2021. This session approved the "Outcome of the RSE for use of MASS," which assesses how existing conventions may be affected with MASS implementation. It also provides guidance to identify further work. This second step identified the COLREGs as a high-priority instrument, and the following common potential gaps and/or themes were established: meaning of the terms master, crew, or responsible person; watchkeeping; and terminology within the COLREGs (International Maritime Organization 2021). The RSE used the following four statements to describe the most appropriate ways of addressing MASS operations at each degree of autonomy within the COLREGs (International Maritime Organization 2021):

I. equivalences as provided for by the instruments or developing interpretations; and/or.
II. amending existing instruments
III. developing a new instrument; or

IV. none of the above as a result of the analysis

Degree 1: I—onboard operations and watchkeeping may result in distortion and ambiguity regarding the COLREGs. This degree is the least disruptive of the four degrees; hence, statement I is the most appropriate way of addressing MASS operations. Potential gaps/themes that require to be addressed are terminology; lights; shapes and sound signals; and the role of the master.
Degree 2: I–II—same as above, but as control may be shifted remotely, I and II are the most appropriate ways of addressing MASS operations within the COLREGs. Potential gaps/themes that require addressing are the same as degree 1, with the addition of the responsibility of the remote operator.
Degree 3: I–II—this is the largest shift and will require amendments to COLREGs, and I and II are the most appropriate ways of addressing MASS operations. Furthermore, the COLREGs as they are currently written should retain as much of its current content as possible. Potential gaps/themes that require to be addressed are the same as degree 2 with the addition of distress signals.
Degree 4: II—as this is the concept the furthest in the future, amendments to COLREGs are necessary although they should still retain as much of its current content as possible. Potential gaps/themes that require to be addressed are the same as degree 3.

## 3 Research approach

A literature review and a multiple-choice survey are used for this exploratory research. The purpose of this study is to first identify barriers that the COLREGs present with MASS implementation via the literature review. Second, the aim is to identify proposed solutions from the literature review and to formulate proposed amendments to the COLREGs via the SME discussion. Third, the objective is to explore LDO insights via the survey regarding these barriers and proposed amendments. The operational degree that MASS is operating at for this research is degree 3 or degree 4.

### 3.1 Literature review

At the time this literature review was conducted, much literature was found on the theory and technology behind collision avoidance systems and how they implement the COLREGs, as well as the legal challenges of MASS, specifically the issue of liability. However, limited in-depth research is found regarding barriers to the COLREGs with MASS implementation that include potential solutions and/or proposed future amendments. Google Scholar, Research Gate, Semantic Scholar, and Web of Science are employed using the following descriptors: “collision avoidance regulations,” “autonomous shipping and navigation,” COLREGs and MASS,” “implementations of COLREGs with automation,” and “regulation of autonomous ships.”

References that focus on individual rules are sought out. Only references published within the last 5 years (2017–2021) are considered for recency. Eight literature references consisting of two reports, one thesis, and five journal articles are chosen based on subject relevance, method, data analysis, and research pool used. Many of these chosen references include a large, varied, and relevant international research pool, which helps to justify the limited amount of used references. A list of these references is found in Table 1.

### 3.2 Survey

The COLREGs that are found to have barriers with the implementation of MASS as found from the literature review are used to create the survey questions. Proposed solutions that are derived from the findings of the literature review are discussed among two to three SMEs to derive the amended COLREGs. A list of the specific COLREG, its issue with MASS implementation, the proposed solution based on the literature review, and proposed amendment in form of Option B in the survey is summarized in Table 2. The COLREGs used in this study can be found in their entirety in Online Resource 1. Not all rules in the COLREGs are discussed as only the rules that according to the literature review present barriers with MASS implementation are addressed.

The survey was created by Qualtrics™ and consists of 50 multiple-choice questions with forced responses. It is found in Online Resource 2. Non-probability sampling, specifically convenience sampling and snowball sampling, was used to find participants in the merchant marine industry. LDOs with sailing experience were targeted. This purpose-driven sampling approach used professional maritime networks such as the Nautical Institute along with other maritime organizations such as pilot associations, Maritime Education and Training (MET) institutions, maritime unions, and personal contacts to recruit participants. The survey was answered anonymously in accordance with GDPR by 562 participants from 17 January to 31 March 2021. The distribution of this survey results in a completion rate of 271, or 48.2%. Only complete responses where the participants have the occupation of LDO are used. This results in a sample with $N = 223$. The occupation of LDO includes all deck officer ranks, including third mate, second mate, chief mate, captain, or pilot. In the survey, "Pilots" are an option for profession as the survey was available to multiple pilot associations. These results are included under the occupation of LDO.

Survey questions are organized into multiple parts. Part One, "General Questions," identifies participants' occupation and number of years working with the COLREGs. Part Two explores participants' knowledge of MASS and is omitted from this study as it does not fall under the scope of this research. Part Three, "Rating the Effectiveness of COLREGs Taking MASS into Account," presents the COLREGs that may be affected with the implementation of MASS and the proposed solution derived from the literature review. For each survey question, participants had to choose which option is more effective in preserving the safety of navigation when applied to MASS. Choices were: Option A, Option B, or Option A = Option B. Option A was the original COLREG that presents a barrier to MASS

**Table 1** Literature review reference list

| Reference type | Reference title and author/source | Method and analysis |
|---|---|---|
| Report | "Analysis of Regulatory Barriers to the Use of Autonomous Ships," Danish Maritime Authority (2017) | Analysis of Danish regulation and law relating to shipping to identify and systematize potential barriers to MASS in commercial shipping. Interviews with stakeholders (Danish Shipping, Maersk, etc.) and workshop to assimilate conclusions and recommendations. The report can be used as knowledge base for amendments to international and national regulations |
| | "A Pre-Analysis on Autonomous Ships," Blanke et al (2017), Technical University of Denmarks | Pre-investigation to describe the MASS potential based on international MASS activities |
| Journal article | "The Autonomous Shipping Era. Operational, Regulatory, and Quality Challenges," Komianos (2018), The Nautical Institute, London, UK | Literature review. Examines operational, regulatory, and quality assurance challenges of MASS by reviewing current regulations, operational procedures, and quality assurance standards for MASS and introduces possible approaches and solutions |
| | "Maritime Autonomous Surface Ships (MASS) and the COLREGS: Do We Need Quantified Rules or Is "the Ordinary Practice of Seamen" Specific Enough?" Porathe (2019), NTNU | Discusses unmanned and manned vessel interaction with prevailing and suggested regulation from a literature review. Focus on whether the COLREGs should be quantitative |
| | "A Study of the Application Barriers to the Use of Autonomous Ships Posed by the Good Seamanship Requirement of COLREGs," Zhou et al (2020), Journal of Navigation | Literature review and SME interviews (scientists and deck officers) for the COLREGs |
| | "Regulating Autonomous Ships—Concepts, Challenges and Precedents," Ringbom (2019), TransNav | Study of existing instruments and current projects to clarify MASS key features and terminology |
| | "Autonomous Maritime Collision Avoidance: Field Verification of Autonomous Surface Vehicle Behavior in Challenging Scenarios," Kufoalor et al (2020), J Field Robot | Field test and discussed results from sea trials (verification exercise) for ASV using a Model Predictive Control collision avoidance system (Dutch project with selected companies) |
| Thesis | "Unmanned Ships: Technical, Economic, and Legal Aspects," Heymans (2017), University of Antwerp | Literature review of legal documents. Presents current positions and proposed conclusions to include MASS |

**Table 2** Rules, issues, solutions, and COLREG survey amendments

| Rule | Issue | Solution | Survey Option B |
|---|---|---|---|
| 2a—addresses the responsibilities of the master, crew, and owner of a vessel regarding the neglect of complying with the COLREGs or the neglect of precautions required by the ordinary practice of seamen | Seamen are characterized as those who work on ships (Danish Maritime Authority 2017). Legal responsibility includes master, crew, and ship owners (Zhou et al. 2020). MASS operating at degree 3 or 4 would not have master or crew onboard. The responsibility of a vessel's actions would have to be transferred elsewhere which needs to be delegated | As MASS is operated from shore, these responsibilities could transfer to an RCC where the RCO could take responsibility (Komianos 2018). RCOs should be obliged to possess the knowledge equal to that of the ordinary practice of seamen (Komianos 2018). Emphasize who is controlling the ship, not from where (Danish Maritime Authority 2017). The RCC should be liable for actions of a MASS (Zhou et al. 2020). Navigation can potentially be performed through a data link to shore (Blanke et al. 2017) | Master and crew may be onboard *or ashore* and the responsibility of the ordinary practice of seamen *is transferable to the responsible party ashore* |
| 2b—defines when one should depart from the rules to avoid immediate danger | Ambiguity exists on when one can deviate from the rules (Porathe 2019). If no one is physically onboard, the question arises on who is responsible for making this decision | Define when one can deviate from the rules (Porathe 2019) | Quantify Closest Point of Approach (CPA) to 0.5 nm and Time to Closest Point of Approach (TCPA) to 6 min based on discussion with SMEs and keeping in mind a normal vessel's CPA/TCPA while underway in all conditions |
| 3a—defines the term vessel, which includes every description of water craft<br>3b—defines the term power-driven vessel | The current definitions do not include MASS (Komianos 2018) | The current definitions do not exclude MASS (Komianos 2018)<br>A MASS should be regarded as a power-driven vessel (Zhou et al. 2020) | Adds the term *MASS* to the definition of a vessel<br>Adds: *whether crewed or uncrewed* |

**Table 2** (continued)

| Rule | Issue | Solution | Survey Option B |
|---|---|---|---|
| 5—addresses proper lookout, that it should be maintained at all times by all available means, which includes sight and hearing | Physical presence of crew onboard is needed to fulfill visual observation and hearing (Zhou et al. 2020) | It is possible that a human lookout can be replaced by technical means (Danish Maritime Authority 2017; Zhou et al. 2020). Sensors can possibly change lookout procedures, potentially removing physical presence onboard (Blanke et al. 2017)<br>MASS requires an appropriate system to detect, identify, classify, and predict all factors and situations (Kufoalor et al. 2020) | Adds the words *physical or non-physical sight and hearing* to the definition of a lookout |
| 6—identifies safe speed, which is defined as when a vessel can take proper and effective action to avoid collision and be able to stop within a distance appropriate to the present circumstance | No value of speed is given in the COLREGs (Zhou et al. 2020) | Provide general characteristics of a MASS sailing under determined sea states that must stay clear of any other vessel at distance *A* when underway at speed *B* (Komianos 2018). Quantify speed for every situation into algorithms for autonomous systems to determine safe speed (Heymans 2017). Port authorities can design dedicated channels for MASS and define safe speed (Zhou et al. 2020) | For simplicity, the survey adds: *MASS safe speed is predetermined based on location* (*ex. approaches to ports and dense traffic areas will have compulsory speed limitations for MASS*) |
| 7a—risk of collision. Every vessel shall use all available means to determine if risk of collision exists | No precise definition for risk of collision in miles or minutes (Porathe 2019) | Quantify parts of the COLREGs, but this would not cover all situations (Porathe 2019)<br>Risk of collision could be determined by persons ashore (Komianos 2018)<br>A useful way of quantifying risk is needed (Kufoalor et al. 2020) | Quantifies CPA of 0.5 nm and TCPA of 6 min to remain consistent with previous quantification<br>Adds: risk of collision can be determined by *crew onshore or offshore* |

**Table 2** (continued)

| Rule | Issue | Solution | Survey Option B |
|---|---|---|---|
| 8a, b, d—actions to avoid collision. Vessels should make positive, timely actions to avoid collision while observing good seamanship. Course and speed changes should be large and readily apparent, and actions taken to avoid collision should result in a safe passing distance | No concrete definitions for many terms such as good seamanship, timely, too close, safe distance, vessel is clear, readily apparent, and sufficient distance; these can be left open to interpretation (Heymans 2017) | One can find meaning of definition based on what it is not. For example, good seamanship can be defined as "not making a nautical mistake" (Heymans 2017) | Adds: *not making a nautical error* to the definition of good seamanship<br>Quantifies course change to at least 15 degrees, does not address speed for simplicity. 15 degrees is used based on the course change in a published study (Kufoalor et al. 2020)<br>Quantify safe distance to 0.5 nm or greater. Distance chosen based on previous amendment to maintain consistency |
| 9a—safe navigation of vessels in narrow channels | Term narrow channel is difficult to define and left open to interpretation (Heymans 2017) | Channels to be pre-determined and identified on nautical charts (Heymans 2017) | Adds: *narrow channels are predetermined by the IHO and are indicated on nautical charts*. IHO is chosen as this is an intergovernmental organization that surveys and charts the word's navigable waters (International Hydrographic Organization 2021) |
| 10b—defines navigation for traffic separation schemes (TSSs) | MASS would be navigating in the vicinity of manned vessels, which could cause confusion (Porathe 2019) | Separate TSS for MASS (Porathe 2019) | Add: *special traffic lanes predetermined by the IHO and indicated on nautical charts are compulsory for MASS and optional for other vessels*. IHO is chosen as this is an intergovernmental organization that surveys and charts the word's navigable waters (International Hydrographic Organization 2021) |

**Table 2** (continued)

| Rule | Issue | Solution | Survey Option B |
|---|---|---|---|
| 16—every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear | Definitions of "early" and "substantial" are ambiguous (Porathe 2019) | Defining and quantifying these terms by conducting deep learning studies using automatic identification system (AIS) information (Porathe 2019). It is possible to assess risk of collisions via known AIS data (Blanke et al. 2017)<br>If a collision avoidance system is correctly programmed with a quantified CPA and TCPA, it can interpret the meaning (Ringbom 2019) | Adds the quantification of taking action at 1 nm in restricted waters and 2 nm in open waters, which is stated as a general guideline from the Nautical Institute (Porathe 2018) since a deep learning study is out of the scope of this research. Adds: *restricted and open waters are to be defined by the rules* |
| 17aii—actions required of a stand on vessel to avoid collision. A vessel may take action to avoid collision by its maneuver alone, as soon as it becomes apparent that the other vessel that is required to keep out of its way is not taking appropriate action to do so | Definition of "as soon as it becomes apparent" is qualitative (Porathe 2019) | Same as above. Also, last-minute maneuvers need to be determined quickly; a vessel operated remotely must ensure reliable communication with the shore to be able to make these decisions in a timely manner (Komianos 2018) | Quantifies when a stand on vessel shall be required to take action, specifically making a CPA of 0.5 nm and TCPA of 6 min to remain consistent with quantification from previous survey questions |

**Table 2** (continued)

| Rule | Issue | Solution | Survey Option B |
|---|---|---|---|
| 19a, e—addresses vessels not in sight of one another and the actions to be taken when a vessel hears the fog signal from another vessel | How MASS would determine whether a vessel is in sight if no one is onboard and how it determines if it is in an area of restricted visibility (Heymans 2017). "Hears" implies human presence onboard (Komianos 2018) | Use of technology and onboard sensors to determine if a MASS is in an area of restricted visibility as the human eye is not the only means to determine if a vessel is in sight or not (Heymans 2017). It has been proven that sensors can adequately hear fog signals; having a person physically onboard is not necessary to hear (Komianos 2018). Fully enclosed bridges are currently in use on COLREG-compliant vessels and there are no issues with onboard personnel hearing fog signals (Ringbom 2019) | Adds: *for MASS, technological means can determine whether or not a vessel is in sight*<br>Adds: *for MASS, hearing may be accomplished by sensors or other technical means* |
| 23a—defines the lights required by a power-driven vessel | Question if MASS should have additional identifying lights required by the COLREGs (Porathe 2019) | Add an all-around purple colored light on the mast. The color purple is chosen because it is not currently used as a color in the COLREGs to identify vessels (Porathe 2019). The identification of vessel type in a COLREG situation is key for collision avoidance (Zhou et al. 2020) | Adds: *MASS shall exhibit an all-round light of a color that is not currently used as another identifying light within COLREGs*. Follow-up question offers either purple or turquoise as color options, which is recommended by the automated car industry (Rouchitsas and Alm 2019) |

implementation. Option B was the proposed amendment to the same COLREG. The third choice was Option A is equal to Option B. This was presented so participants were not forced to choose one option over the other simply because there were no other options. Each survey question in this section was also followed up by an optional text box to provide the opportunity for participants to add more in depth opinions to the survey questions.

### 3.3 Data analysis

Survey results were analyzed via descriptive statistics using SPSS to find the mode for each survey question. This analysis was conducted to see if the LDOs preferred the proposed amendments over the original rules. Next, the variable "years of practicing the COLREGs" was analyzed to see if this variable had any correlation to the survey responses. Survey results were then reviewed to see if any commonalities, consistencies, or trends existed among the chosen or rejected amendments. This was done by analyzing the majority, minority, and average survey responses across all survey questions. Lastly, an analysis via an excel heat map was conducted to see if participants who rejected one COLREG by choosing the amendment were more or less likely to reject another COLREG. This was done to see if any correlations existed within the rejected rules. As participants had a third option of choosing Option A is equal to Option B, for simplicity, these responses were combined with the responses of choosing the original rule.

## 4 Results

### 4.1 Survey results, rule by rule

In this section, the results of the survey are presented, rule by rule. First, the rule and its issue with MASS implementation are explained. Second, the solution from the literature review and the formation of the survey's Option B are shown. This is followed by the results of the survey, including comments from the optional text box that followed each survey question. A summary of the results of each rule is displayed in Table 3 where the frequency of the participants' answers and the mode for each survey rule are displayed.

#### 4.1.1 Rule 2a

This rule addresses the responsibilities of the master, crew, and owner of a vessel regarding the neglect of complying with the COLREGs or the neglect of precautions required by the ordinary practice of seamen. A main issue that arises from this rule with MASS implementation is that the rule refers to the responsibility of actions taken onboard a vessel by her master and crew. Seamen are typically characterized as those who work onboard ships (Danish Maritime Authority 2017). Vessels

**Table 3** Survey results rule by rule

| | Rule | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Survey option | 2a | 2b | 3a | 3b | 5 | 6 | 7a | 7a 2nd | 8a | 8b | 8d | 9a | 10b | 16 | 17ii | 19a | 19e | 23a |
| A | 82 | 178 | 68 | 101 | 125 | 150 | 202 | 138 | 189 | 208 | 196 | 138 | 82 | 186 | 186 | 123 | 89 | 47 |
| A = B | 28 | 11 | 41 | 34 | 29 | 16 | 2 | 34 | 13 | 2 | 8 | 24 | 29 | 9 | 8 | 24 | 43 | 15 |
| B | 113 | 34 | 114 | 88 | 69 | 57 | 19 | 51 | 21 | 13 | 19 | 61 | 112 | 28 | 29 | 76 | 91 | 161 |
| Mode | B | A | B | A | A | A | A | A | A | A | A | A | B | A | A | A | B | B |

operating at degree 3 or degree 4 would not have personnel onboard; hence, the responsibility of the vessel's actions would have to be transferred elsewhere.

If MASS is operated from the shore, these responsibilities could be transferred to an RCC where the remote control operator (RCO) could take the responsibility of a vessel (Komianos 2018). RCOs should be obliged to possess the knowledge equal to that of the ordinary practice of seamen (Komianos 2018). The survey question addressing rule 2a utilized this presented solution from the literature review via Option B. This option added to the original rule that the master and crew may be onboard *or ashore* and the responsibility of the ordinary practice of seamen *is transferable to the responsible party ashore*. This amendment gives the option to keep the responsibility on the master and crew, regardless of where they are located (Danish Maritime Authority 2017).

The percentage of participants who chose Option A is 38.6%. Only 12.6% decided that either option was the best answer by choosing Option A is equal to B. Option B is the mode as 50.7% of the survey participants decided that the original rule should include these amendments. Participants noted in the comments section that the definition of master and crew should be clarified and expanded upon. One noted that if a master and crew can be defined as aboard or ashore, then no change is needed in the rule. Others state that if a shore-based operator is remotely operating a vessel, they need to be fully accountable as if they were operating the vessel from aboard. Addressing shore-based crew, specifically how to name and define these staff members, is important for the COLREGs, particularly for liability and legal reasons. There is room in the definition of crew to be expanded upon to include shore-based personnel. Overall, participants found that it is important to address these terms with the implementation of MASS and the introduction of shore-based crew.

#### 4.1.2 Rule 2b

This rule addresses when one should depart from the rules in order to avoid immediate danger. An issue with this rule is that ambiguity exists on when one can deviate from the rules. There is also an issue that if a vessel is unmanned, who is actually responsible for making decisions concerning the ship to maintain safety of navigation?

The proposed change in Option B adds a distance of a vessel's Closest Point of Approach (CPA) and Time to Closest Point of Approach (TCPA) to define when one can deviate from the rules (Porathe 2019). This quantifies part of the rules to CPA of 0.5 nm and TCPA of 6 min. The latter issue is addressed in rule 2a. This distance and time was chosen after discussing with SMEs, keeping in mind a normal vessel's CPA while underway in open waters and in congested areas.

The majority of survey participants, 79.8%, decided that quantifying CPA and TCPA was not the best option as they chose the original rule without quantified times or distances. Only 4.9% chose that Option A is equal to Option B, while 15.2% participants chose quantifying CPA and TCPA by choosing Option B. From the comments section, it was clear that the majority of participants were strongly against any type of quantification of the COLREGs. For example, most commenters agreed that CPA and TCPA cannot be quantified because they vary depending on the

situation. This includes the location, speed, and type of vessel among other things such as the weather, visibility, and congestion. They should be left up to the interpretation of the navigator. Quantifying these terms is impractical and may lead to more collisions. Many vehemently stated that it is dangerous to quantify any of these terms. It is also noted that time and distance are not universal. The rules should be left ambiguous as every situation can be different.

#### 4.1.3 Rules 3(a) and 3(b)

Rule 3a defines the term vessel. A vessel includes every description of water craft, including "non displacement craft and seaplanes, used or capable of being used as a means of transportation on water" (USCG and US DOT 2004). A potential issue is that the term vessel may not include MASS. The same issue lies with rule 3b which defines the term power-driven vessel, which is a vessel propelled by machinery.

From the literature review, it was found that the current definition of a vessel in rule 3 does not specifically include MASS, but it also does not exclude it (Komianos 2018). For rule 3a, Option B adds the term *MASS* to the definition of a vessel. For rule 3b, Option B adds the words *whether crewed or uncrewed* to the definition of a power-driven vessel to be inclusive of MASS at degree 3 or degree 4.

For rule 3a, 30.5% of participants chose Option A. This is followed by 18.4% choosing Option A is equal to Option B. The mode is Option B as 51.1%, chose to add the term *MASS* to the definition of a vessel. For rule 3b, the majority of participants, 45.3%, chose Option A. This is followed by 15.2% choosing Option A is equal to Option B. The remainder of 39.5% of the participants chose the alternative, Option B. From the comments section, many believed that the word "vessel" is already inclusive in the word "MASS," but the majority still preferred to add it specifically to the definition. Some comments note that the term MASS itself needs to be defined in the COLREGs, as well as the degrees of automation. Many thought that adding the additional verbiage in rule 3b is unnecessary as it does not matter if a vessel is manned or not, it is still a vessel.

#### 4.1.4 Rule 5

Rule 5 addresses proper lookout. "Every vessel shall at all times maintain a proper lookout by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision" (USCG and US DOT 2004). The barrier with rule 5 is how to accomplish the role of a lookout via sight, hearing, and all available means when there is no human onboard.

It is possible that sight and hearing can be accomplished with no one onboard, as the duties of a lookout can be replaced by technical means such as cameras and infrared technology (Danish Maritime Authority 2017). The MUNIN project, which is a conceptual bulk carrier, has proven that the use of digital cameras, computer vision technology, and onboard systems such as radar, AIS, and infrared can provide a safer lookout than a human one (Blanke et al. 2017). All of these means combined is called an advanced sensor module (ASM) (Heymans

2017). In addition, based on the studies of the Advanced Autonomous Waterborne Applications (AAWA) Initiative, ships that are using various degrees of autonomy can use sensors and computer technology to replace human lookouts (Danish Maritime Authority 2017). It can be proposed to amend rule 5 to allow technical means to fulfill the role of lookout (Zhou et al. 2020). Thus, Option B adds the words *physical or non-physical sight and hearing* to the definition of a lookout.

Survey results show that the majority of the participants, 56.1%, chose the original rule and did not find this amendment practical. Those choosing Option A is equal to Option B accounts for 13.0%, and 30.9% chose the proposed amendment Option B. From the comments, it was noted that many do not think that cameras and sensors are able to fulfill the requirements of a proper lookout. Some disagree and simply argue that "all available means" already cover these technologies; therefore, the extra wording is not necessary. Many did not like how the addition was phrased, stating that it was too ambiguous or complicated the simplicity of the original rule.

#### 4.1.5 Rule 6

Rule 6 identifies safe speed. The COLREG definition of safe speed is when a vessel can take proper and effective action to avoid collision. It also states that a vessel must be able to stop within a distance appropriate to the prevailing circumstance. The issue with MASS implementation to this rule is how a MASS will determine safe speed.

One possible solution is to amend this rule by providing general characteristics of a MASS sailing under determined sea states that must stay clear of any other vessel at a stated distance when underway at a stated speed (Komianos 2018). Another suggestion is that concrete speeds for every situation can be implemented along with location, weather conditions, ship maneuvering specifics, and traffic among others into algorithms for autonomous systems to determine the vessel's safe speed for any given situation (Heymans 2017). As it would be difficult to address all of these conditions within one survey question, for simplicity, the survey Option B adds the following words: *MASS safe speed is predetermined based on location* (*for example*, *approaches to ports and dense traffic areas will have compulsory speed limitations for MASS*).

The majority of participants, 67.3%, chose Option A, deciding not to amend this rule in this way. Next, 7.2% chose Option A is equal to Option B, and 25.6% chose the proposed amendment Option B. From the comments section, many argue that this definition is too limiting. Safe speed is not only based on location on a multitude of complex characteristics. Other factors determining safe speed include current, ship maneuverability, ship size, weather, and visibility among others. It is also mentioned that MASS speed should not be defined in the COLREGs, but by individual vessel safe practices. Furthermore, restrictions on vessel speed, if any, could be made in local regulations and should not be addressed in the COLREGs.

### 4.1.6 Rule 7a

Rule 7a addresses the risk of collision. It states that every vessel shall use all available means appropriate to the prevailing circumstances and conditions to determine if a risk of collision exists. It also states that if there is any doubt that a risk of collision exists, it shall be deemed that it does exist. The issue with this rule is that there is no precise definition for risk of collision. According to the literature review, one possible solution is to better define the risk of collision for MASS. The factors of vessel speed, distance, and if the vessels are crossing can determine if a risk of collision exists, and it can be constantly interpreted by advanced sensor modules (Heymans 2017). An argument against this is that it would be difficult for collision avoidance software to cover all situations, as there would still be occasional black swans. It may be helpful to the software programmer to quantify parts of the COLREGs, but even this would still not cover all situations (Porathe 2019). Another possible solution is that the risk of collision could be determined by persons ashore (Komianos 2018). This is similar to the solution to rule 2a, which moves the responsibility of a vessel to the RCO ashore.

To explore the option of quantifying parts of the COLREGs, Option B of rule 7a quantifies CPA and TCPA to 0.5 nm and 6 min, respectively. These quantifications were chosen to maintain consistency, as these numbers were used previously for rule 2b. A second question to rule 7a was also included. This added to rule 7a: risk of collision can be determined by *crew onshore or offshore*.

The mode for this rule is Option A as the majority of participants, 90.6%, did not want to add stated quantifications to this rule. Only 0.9% chose Option A is equal to Option B, and only 8.5% chose Option B. Comments reflect the same opinions against quantification of the rules as found in rule 2b. Some stated that any type of quantification is dangerous and impractical. Half a mile CPA for a sailboat creates a very different scenario compared to half a mile CPA for a very large crude carrier (VLCC) that is fully loaded. Some participants stated that it would be nice to have a defined CPA and TCPA, but admitted that it would not be logical for all situations.

For the second survey question for rule 7a that added determining the risk of collision by *crew onshore or offshore*, the majority of the participants, 61.9%, chose Option A. Next, 15.2% chose Option A is equal to Option B, and finally, 22.9% chose Option B. The majority of the respondents did not choose this amendment because they thought that risk of collision cannot be determined by the crew onshore as well as by the crew onboard, while others argued that this phrase is redundant or not necessary.

### 4.1.7 Rules 8(a), 8(b), and 8(d)

Rule 8 is a lengthy rule addressing actions to avoid collision. In summary, vessels should make positive, timely actions to avoid collision while in observance of good seamanship. Course and speed changes should be large and readily apparent, and actions taken to avoid collision should result in a safe passing distance.

As this rule has multiple parts and varied potential issues with MASS implementation, three survey questions were used to address it. One issue with respect to this

rule is that no concrete definitions exist for many of the stated terms, which leave them open to interpretation. This includes the definition for good seamanship, as well as timely, too close, safe distance, vessel is clear, and sufficient distance (Heymans 2017). One proposed solution from the literature review is that one can find the meaning of the definition based on what it is not. Looking at past legal actions that were characterized as "bad seamanship," the meaning of "good seamanship" can be interpreted as what is not "bad seamanship." It can also be defined as "not making a nautical mistake" (Heymans 2017). To utilize this proposed solution, Option B of rule 8a adds *not making a nautical error* to the definition of good seamanship. Results show that the mode is Option A, where 84.8% of the participants were in favor of keeping the original rule and did not like this addition. Only 5.8% of participants chose Option A is equal to Option B, and 9.4% chose Option B. From the comments, many stated that "nautical error" needs defining. Most stated that this definition does not fully or adequately address the definition of good seamanship, and that this term cannot be simply defined.

The next survey question addresses rule 8b, which states that a course and/or speed change shall be large and readily apparent. Option B quantifies this course change of at least 15 degrees and does not address speed for simplicity. This question was quantified based on the course change used in a study conducted by Kufoalor et al. (2020). As a result, the majority of participants, 93.3%, chose Option A. Only 0.9% chose Option A is equal to Option B, and 5.8% chose Option B. The comments restate that no part of the rules should be quantified as all situations can be different.

A third survey question addresses rule 8d, which describes safe distance. Option B proposes a quantification of 0.5 nm or greater as a safe distance. The majority of 87.9% chose Option A. This is followed by 3.6% of the respondents who chose Option A is equal to Option B and 8.5% who chose Option B. Comments reflect previously stated opinions against any quantification of the rules.

#### 4.1.8 Rule 9a

Rule 9a describes the safe navigation of vessels in narrow channels. An issue with this rule is that the term narrow channel or narrow waterway is not previously identified and may be difficult to define. It can be left open to interpretation by the LDO. Literature review suggests that these channels or waterways can be pre-determined by an appropriate institution and identified on charts (Heymans 2017).

Option B adds to this rule: *narrow channels are predetermined by the International Hydrographic Organization* (*IHO*) *and are indicated on nautical charts*. This eliminates the mariner from the responsibility of determining whether an area is a narrow channel or not. Results show that the majority of participants, 61.9%, chose Option A. Only 10.8% chose Option A is equal to Option B, and 27.4% chose Option B. Some commenters stated that this amendment would clarify these definitions, but that this is not the duty of the IHO. Narrow channels can be defined by port or other local authorities. Arguments against this amendment agree that defining narrow channels is not practical and is not the same for every vessel, as the size of the vessel matters. Further definition should be kept out of the COLREGs.

#### 4.1.9 Rule 10b

Rule 10b defines navigation for traffic separation schemes (TSSs). As written, MASS would be interacting with manned traffic, creating a "mixed traffic" situation. This could cause confusion from the manned vessel's perspective. A proposed solution is for regulatory bodies to identify separate TSS for MASS which can be made compulsory for use (Porathe 2019).

Option B adds: *special traffic lanes predetermined by the IHO and indicated on nautical charts are compulsory for MASS and optional for other vessels*. Only 36.8% of the participants chose Option A. Next, 13.0% chose Option A is equal to Option B. The majority, 50.2% of the participants, chose Option B. Some argued that worldwide designated traffic lanes are not feasible. It was also stated that if TSSs are compulsory for MASS, manned vessels should not have the option to be able to use them. Some think that it is unrealistic if MASS would use certain TSSs as fishing and recreational vessels could cause problems with traffic. However, many stated that MASS and manned vessels should be separated as much as possible as a good measure for safety, and they agreed with adding this amendment.

#### 4.1.10 Rule 16

Rule 16 states that every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear. The issues with this rule is that the definitions of "early" and "substantial" are ambiguous and left up to the interpretation of the LDO. Possible solutions from the literature review include defining and quantifying "early" and "substantial." To determine quantified terms, researchers can conduct large MASS deep learning studies using AIS information (Porathe 2019; Rivkin 2021). If correctly programmed a quantified CPA and TCPAI, a MASS a collision avoidance system can interpret the wording and meaning of the COLREG terms (Ringbom 2019). They can be determined based on an algorithm to include all factors such as size and maneuverability of the MASS (Kufoalor et al. 2020).

Option B adds the quantification of taking action at 1 nm in restricted waters and 2 nm in open waters, which is mentioned as a general guideline from the Nautical Institute (Porathe 2018). This is also common practice among some mariners, but depends on ship type among other factors. Option B also adds that *restricted and open waters are to be defined by the rules* so there is no ambiguity on what is considered restricted or open waters. Option A is the mode with a total of 83.4% participants. Only 4.0% chose Option A is equal to Option B, and 12.6% chose Option B. The comments reinstate that the rules should not be quantified.

#### 4.1.11 Rule 17aii

This rule addresses the actions required of a stand on vessel to avoid collision. It states that this vessel may take action to avoid collision by her maneuver alone, as soon as it becomes apparent that the other vessel that is required to keep out of her way is not taking appropriate action to do so within compliance of the rules (USCG

and US DOT 2004). The issue with this rule is that the definition of "as soon as it becomes apparent" is not concrete and may be interpreted differently by different people. MASS operating at degree 3 must be able to have quick and reliable communication with shore-based RCCs to make these decisions in a timely manner, as last minute maneuvers must be determined quickly (Komianos 2018).

A possible solution for this rule, as with the previous rule 16, is to quantify CPA and TCPA. Option B quantifies when a stand on vessel shall be required to take action, specifically making a CPA of 0.5 nm and TCPA of 6 min to remain consistent with the quantification from previous survey questions. Most participants did not choose changing this rule as Option A is the mode. While 83.4% of participants chose this option, only 3.6% chose Option A is equal to Option B, and 13.0% chose Option B, the proposed amendment. Comments mimic previous comments that do not support quantifying the rules.

#### 4.1.12 Rules 19(a) and 19(e)

Rule 19a addresses vessels not in sight of one another when in restricted visibility. Rule 19e addresses the actions to be taken when a vessel hears the fog signal of another vessel. Some issues with MASS implementation include that if restricted visibility applies to MASS, there is no one onboard to "see" the visibility conditions and how MASS would determine if it is in an area of restricted visibility. Moreover, how MASS can "hear" a fog signal from another vessel if there is no one onboard. Possible solutions to these issues include using technology such as weather inputs, sensors, and cameras to determine if a MASS is in an area of restricted visibility. The human eye is not the only means to determine if a vessel is in sight (Heymans 2017). Furthermore, it has been proven that sensors can adequately "hear" fog signals, so having a person physically onboard is not necessary to fulfill this specific rule (Komianos 2018). Fully enclosed bridges are already in use, where officers must be able to determine sound signals and their direction without leaving the enclosed space (Ringbom 2019). Option B for rule 19a adds: *for MASS, technological means can determine whether or not a vessel is in sight*. For rule 19e, Option B adds: *for MASS, hearing may be accomplished by sensors or other technical means.*

For rule 19a, the mode is Option A. Specifically, 55.2% of the participants chose to keep this original rule. Only 10.8% chose Option A is equal to Option B, and 34.1% chose Option B. Some commenters bring up the argument: "what if the manned vessel considers it to be in sight and the MASS does not?" Others state that there is no definition of technological means, or that this phrase should be reworded, or that the addition is not necessary at all. Others state that technology cannot replace a person onboard using their own sight.

For rule 19e, 39.9% of participants chose Option A. Next, 19.3% chose Option A is equal to Option B. The mode results in Option B, with 40.8% of the participants choosing this option. Some respondents stated that it is not necessary to add this wording in the COLREGs because "hearing is hearing," and it does not need to be further elaborated on. However, it is mentioned several times in the comments that hearing is already accomplished by vessels with enclosed bridges. As it is previously practiced in the industry, technological means have already proven to be an

acceptable way to hear; thus, the addition to this rule is practical. Some participants were concerned with what would happen if hearing sensors fail. Two commenters stated that this rule is antiquated and should be removed. Others thought that this was a concise, positive addition, but the definitions of sight and hearing should be elaborated on, or the terms physical and non-physical should be reworded.

#### 4.1.13 Rule 23a

Rule 23a defines the lights required by a power-driven vessel. It is up for debate whether or not MASS should have additional identifying lights. It is possible that MASS could require a colored identifying light that is not already used in the COLREGs, for example, a purple all-around light on the mast (Porathe 2019). In the survey for this rule, Option B adds to the required lights of a power-driven vessel the following: *MASS shall exhibit an all-round light of a color that is not currently used as another identifying light within COLREGs*.

The majority did not choose this original rule, as only 21.1% chose Option A. This is followed by 6.7% choosing Option A is equal to Option B. Option B is the mode with 72.2% of participants choosing this option.

The follow-up question to rule 23a was only available to participants who chose Option A is equal to Option B or Option B from the previous question. Hence, this question was available to 176 participants. Only 169 participants answered this question as this question did not force a response ($N = 169$). Participants were given the option of choosing an identifying colored light that is not currently in use by the COLREGs. The first option is a purple colored light as previously mentioned, or a turquoise colored light which is proposed by the automated car industry (Rouchitsas and Alm 2019). The majority of the participants, 59.8%, chose the purple colored light, while 40.2% chose the turquoise colored light. The majority of the participants stated that adding an identifying light is a good suggestion. It was also stressed that it is very important for MASS to be easily identifiable from other vessels, and the respondents would like to know if another vessel operating in their vicinity is manned or not. Others added that the color of the light should be explicitly stated in the COLREGs. Many suggested that this light should be flashing, and that a day shape should also be added.

### 4.2 Years of experience with practicing the COLREGs

The number of years of experience with practicing the COLREGs was asked to see if the survey results differed according to this variable. Participants had to indicate which of the following best represents their experience in years with practicing the COLREGs: 0–5 years, 5–10 years, 10–15 years, or 15 + years. Results show that 10.8% of the participants have 0–5 years of experience, 22.9% have 5–10 years of experience, 20.2% have 10–15 years of experience, and the majority, 46.2%, have 15 + years of experience. The participants with 0–5 years of experience chose the original rule in the survey questions 88.9% of the time, respondents with 5–10 years of experience chose the original rule 72.2% of the time, the ones with 10–15 years

of experience chose the original rule 77.8% of the time, and those with 15 years of experience or more chose the original rule 72.2% of the time.

### 4.3 Participant responses across all survey questions

As there are 18 survey questions, choosing the original rule for 10 or more questions is considered the majority and choosing the original rule eight times or less is considered the minority. While 174 participants, or 78%, chose the original rule for the majority of the survey questions, 35% participants, or 15.7%, chose the amended rule for the majority of survey questions. Only 14 participants (6.3%) showed equal results by choosing the original rule nine times and the amended rule nine times.

Survey results also show that 30 participants, or 13.5% of the respondents, always chose the original rule. Whereas 25 participants, or 11.2%, rejected only one original rule, 50% of the participants agree with more or less 80% of the original rules, and 84% of the participants agree with at least half of the original rules. On the other hand, only three participants, or 1.4%, always chose the amended rule. Only one participant rejected 17 of the 18 original rules. This shows that if a participant rejects one original rule, they do not necessarily reject another as the data is varied across all rules. This is displayed in the heat map in Table 4.

This table shows the percentage of participants that rejected a particular original rule and the percentage of participants rejecting another original rule. For example, out of the participants that rejected rule 2a, 22% also rejected rule 2b, while 85% also rejected rule 23a. Rules 10b and 23a show the highest result of choosing the amendment. Both of these rules pertain to separating MASS from manned vessels, physically and visually. The next strongest amendment chosen is rule 19e, which allows for the accomplishment of hearing to include sensors or other technical means. This is followed by the amendment for rule 19a which adds that for MASS, technological means can determine whether or not a vessel is in sight.

**Table 4** Survey response heat map

| | | Percentage of respondents that also answered B to question number: | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2b | 3a | 3b | 5 | 6 | 7a | 7a-ii | 8a | 8b | 8d | 9a | 10b | 16 | 17aii | 19a | 19e | 23a |
| Of those who answered B to question number: | 2a | 22% | 67% | 50% | 47% | 37% | 10% | 34% | 12% | 8% | 10% | 34% | 65% | 17% | 19% | 50% | 58% | 85% |
| | 2b | | 94% | 77% | 57% | 66% | 40% | 63% | 20% | 17% | 37% | 66% | 86% | 49% | 63% | 69% | 77% | 91% |
| | 3a | | | 66% | 47% | 45% | 15% | 44% | 16% | 11% | 17% | 42% | 74% | 22% | 21% | 50% | 61% | 89% |
| | 3b | | | | 52% | 49% | 15% | 49% | 19% | 13% | 19% | 43% | 72% | 26% | 25% | 52% | 61% | 88% |
| | 5 | | | | | 51% | 19% | 51% | 22% | 13% | 17% | 45% | 74% | 28% | 26% | 67% | 77% | 86% |
| | 6 | | | | | | 28% | 56% | 30% | 21% | 33% | 61% | 88% | 44% | 37% | 72% | 81% | 95% |
| | 7a | | | | | | | 63% | 53% | 37% | 58% | 84% | 89% | 63% | 68% | 68% | 79% | 89% |
| | 7a-ii | | | | | | | | 24% | 16% | 25% | 51% | 76% | 31% | 33% | 69% | 78% | 96% |
| | 8a | | | | | | | | | 38% | 48% | 81% | 86% | 52% | 38% | 76% | 81% | 95% |
| | 8b | | | | | | | | | | 77% | 77% | 85% | 69% | 46% | 77% | 85% | 100% |
| | 8d | | | | | | | | | | | 84% | 100% | 79% | 68% | 74% | 89% | 95% |
| | 9a | | | | | | | | | | | | 87% | 38% | 39% | 62% | 70% | 84% |
| | 10b | | | | | | | | | | | | | 24% | 24% | 54% | 64% | 88% |
| | 16 | | | | | | | | | | | | | | 75% | 68% | 86% | 93% |
| | 17aii | | | | | | | | | | | | | | | 72% | 86% | 86% |
| | 19a | | | | | | | | | | | | | | | | 91% | 89% |
| | 19e | | | | | | | | | | | | | | | | | 89% |

## 5 Discussion

### 5.1 To change or not to change, that is the question

The COLREGs are currently written for manned vessels, and their future is unknown (Porathe 2019). Many believe that amendments are needed to allow for MASS operation (Komianos 2018; Timbrell 2019; Allen 2021) and they should be updated with the evolution of technology (Ziarati et al. 2019). Research at the testing stage has proven that collision avoidance systems and algorithms are capable of conforming to the COLREGs (Ning et al. 2020; Shaobo et al. 2020). However, it is also proven that challenges exist when they are applied to MASS and to these algorithms (Porathe 2019; Pedersen et al. 2020). The results of the conducted literature review support this, as many barriers to the COLREGs with MASS implementation were found. Survey results also revealed that some amendments were preferred over the original rules, indicating that amendments to the COLREGs, even if minor, may be necessary in the future.

Survey results show that participating LDOs prefer the original COLREGs for the majority of the rules, specifically 13 out of 18 survey questions, or 72.2% of the time. As most LDOs prefer to keep the COLREGs as they are written for the majority of the rules by choosing Option A and not choosing Option B, this potentially reflects a common acceptance that the maritime industry is slow to change (Manuel et al. 2019; Babica et al. 2020; Casareale et al. 2021). Some participants may not be ready or willing to embrace changes with automation; apprehension from the industry has kept autonomy at bay (Francis 2019). In addition, many mariners are worried about autonomous shipping (Allen 2021). Survey results may also reflect that many LDOs believe that MASS should simply follow the COLREGs as written (Perera and Bjorn-Morten 2019). Another possible reason is that participants chose Option A for the majority of their responses simply because they did not agree with the specific wording or meaning of the proposed amendments as a multitude of ways exist to word Option B in the survey. Many comments proved the opinions on the use of one word over another are varied and that any phrase can be slightly altered to affect its meaning. However, even though the original rules were overall the clear majority, approximately 75% of the participants chose more than one amendment over the original rule. This may indicate that LDOs *are* open to *some* change, and that some minor amendments may be necessary.

Option A equals Option B was the least favorable answer for all survey questions, averaging only 9.22% of the participants' responses. Since this opinion was never the majority response, this could reflect that LDOs had strong opinions either for the original rule, for the proposed amendment, or against the proposed amendment. It is also possible that those who chose this answer did not feel strongly for either option and chose this as a default.

Another result of this study was the strong opposition of not quantifying any part of the rules. Within the survey, six questions, which addressed rules 6, 7a, 8b, 8d, 16, and 17aii, presented an Option B that included a quantification for

one of the following: CPA, TCPA, safe speed, course change, and distance to take action. All of these amendments were rejected by the majority of the participants. Five out of six of these questions received the highest percentage of the participants choosing Option A. It was agreed by the majority of the commenters that these terms can *never* safely be quantified. It is agreed upon by Woerner et al. (2019) that MASS must be able to incorporate visibility, traffic, ship handling characteristics, and weather among others to determine these terms. The COLREGs are not quantified because the ambiguity of the COLREGs leaves room for mariner interpretation for all situations (Demirel and Bayer 2015; Rivkin 2021).

Amendments were preferred in five of the rules: rules 2a, 3a, 10b, 19e, and 23a. This is in line with Hirst (2020), Komianos (2018), and Szłapczyński and Ghaemi (2019), who state that MASS cannot comply with the COLREGs as written and they should be amended. The amendment in rule 2a adds that the responsibility of the ordinary practice of seamen is transferable to the responsible party ashore. Rule 3a adds the term MASS to the definition of a vessel. Rule 10b's amendment proposes to designate TSS for MASS that are optional for manned vessel use and TSS would be pre-determined and marked on navigational charts. This is agreed by Rivkin (2021), who suggests designated ocean routes similar to TSS for MASS. Rule 19e adds that hearing may be accomplished by sensors or other technical means. Rule 23a adds an all-around colored light for MASS to the required lights of a power-driven vessel. This is also suggested by Woerner et al. (2019), who state that MASS may need special lights and shapes to operate. The two survey questions with the highest percentage of the amendment chosen pertained to separating MASS from manned vessels, physically and visually. Many of the respondents stated that they did want to know if a vessel is manned or unmanned. This potentially shows a distrust in autonomous technology (Tam et al. 2021).

Overall, results of this research show that many barriers to the COLREGs exist with MASS implementation. While the majority of the rules were chosen to remain the same, some amendments were strongly preferred, indicating that the COLREGs in the future may need to be amended for MASS.

### 5.2 Results in comparison to the regulatory scoping exercise

The results of the IMO's RSE regarding the COLREGs for degree 3, which is MASS that is remotely controlled with no personnel onboard, concluded that some amendments will be required (International Maritime Organization 2021). It also stated that they should retain as much of its current content as possible. Interpretations should be developed and/or amendments should be made. Potential gaps/themes that were found to require to be addressed are terminology; lights; shapes and sound signals; and the role of the master and the responsibility of the remote operator. For MASS operating at degree 4, where a MASS is fully autonomous with no one onboard, the RSE also concluded that some amendments are necessary. Potential gaps/themes that require addressing are the same as degree 3, with the addition of distress signals (International Maritime Organization 2021).

RSE results are generally in line with the results of this research as the majority of participants chose the original rule for the majority of the questions, but revealed that some minor amendments are needed, as stated in Porathe (2019), Ringbom (2019), and Zhou et al. (2020). The definition of the ordinary practice of seamen from rule 2a was found to be a concern in the RSE, as did the results of this research's literature review and survey. In the COLREGs, this term is left undefined (Rivkin 2021), and hence, it would be difficult to be applied to MASS. The terms master and crew were also found to be issues in the RSE and in this research. The implementation of MASS operation would redefine the roles and responsibilities of master and crew (Kim and Schröder-Hinrichs 2021). Current manned MASS scenarios do not have defined or proven crews (Kim and Mallam 2020). Survey comments suggest that terms related to crew operating MASS from ashore need to be defined, as did the RSE. The RSE also found that the lighting of MASS needs to be addressed. There is a possibility of adding lights for MASS, as well as finding a way to address sight and hearing (Jo et al. 2020). This is in line with the results of the survey, where adding a required colored indicating light to MASS as found in rule 23a had the highest majority of participants in support of this amendment. Lastly, the survey and RSE results did not result in any quantification of the rules. The COLREGs are written vaguely to encompass a multitude of collision avoidance scenarios without being overly restricted (Woerner et al. 2019).

### 5.3 Limitations of the research and recommendations for further research

The proposed changes to the COLREGs presented in the survey were limited by the literature review conducted and by how Option B was worded. Specifically, quantifications chosen for the amendments could be investigated in greater detail. Proposed quantifications can be based on extensive machine learning using large amounts of AIS data (Porathe 2019), which did not fall within the scope of this research. Furthermore, this research was limited to MASS operating at degree 3 or 4. It would be beneficial to expand this research to cover all degrees of automation as was conducted by the RSE.

The survey completion rate (slightly below 50%) could be improved upon as the completion time averaged 1 h and 18 min. This may be considered too long for a survey as participants typically would be willing to spend this much time only if they found the survey of utmost importance to them (Kitchenham and Pfleeger 2002). Streamlining the survey to make it shorter and faster to complete would be beneficial as the survey length was 50 questions. Some feedback received from survey participants included that they did not finish the survey in one period of time because of the length.

As this research covered the entirety of the COLREGs based on a limited literature review, it would be beneficial to focus on each rule as a separate study to produce more in-depth results. By doing this, a survey could be distributed with multiple amendments to one rule that would result in a thorough analysis on the participants' opinions of each rule.

Results from this research show that those with 0–5 years of experience with the COLREGs chose the original rule more frequently than any other experience group. Those with 15 years of experience and over chose the alternative more frequently. This potentially shows that LDOs with more experience are slightly more open to change than those with less experience. Further research about the number of years of experience with the COLREGs and its effect on participant's answers is recommended.

Many LDOs stated that MASS should be treated as any other vessel; hence, many of the proposed amendments are not necessary. However, the majority of participants in the survey agreed that MASS should use separate TSSs and that it should be identifiable by an additional light. Many participants stated that they *did* want to know if a vessel was manned or not. This brings up the point that if MASS were to be treated as any other vessel, it should not have to be distinguishable from other vessels nor should other vessels in the vicinity need to know if a vessel is unmanned or not. The concept of whether MASS *should* be treated as any other vessel is an interesting topic that deserves further study.

## 6 Conclusion

Recent years have seen a surge in research and development in the field of autonomous shipping. There is no one current answer to how instruments such as the COLREGs will be amended, if at all, for MASS application, but it is an important topic of conversation in the maritime industry. The purpose of this exploratory research was to first identify the barriers that exist to the COLREGs with MASS implementation and to identify proposed solutions found from the literature review. Second, the aim was to formulate amendments to the COLREGs and to present them to a sample of experienced licensed deck officers via survey. Third, the objective was to explore the insights of the participants regarding these amendments. Survey data was analyzed via descriptive statistics. An analysis of the majority, minority, and average results across all survey questions as well the utilization of an excel heat map was used to find commonalities, trends, and consistencies among the results. The number of years of experience with practicing the COLREGs was also investigated to see if any correlation to the survey results was found.

Results show that many barriers exist with the COLREGs with MASS implementation. The original COLREGs were preferred by the majority of the participants for the majority of the rules, but minor amendments were preferred for some of the rules. These results are generally in line with the results of the IMO's regulatory scoping exercise. Preferred amendments included adding or clarifying definitions to terms such as master and crew, the ordinary practice of seaman, crew ashore, and lookout. Adding separate traffic separation schemes that are compulsory for MASS was also preferred, as was an all-around colored identification light for MASS. The strongest preference found was that no part of the rules should be quantified. Participants proved to be open to some change as approximately 75% of participants chose more than one amendment over the original rule, but results across all survey questions are varied. Participants with more experience with practicing the COLREGs

showed that they are slightly more inclined to choose the amended rules versus participants with less experience.

This exploratory research from the key perspective of a sample of licensed deck officers adds valuable insights to the ongoing discussion of the future of the rules of navigation with the onset of autonomous shipping. As the maritime industry embraces autonomy, it is important that MASS and its impact on the COLREGs and other IMO instruments are further investigated now to better prepare mariners for the future.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s13437-022-00269-z.

**Funding** This study was funded by the BOF (Special Research Fund) University of Antwerp and Antwerp Maritime Academy, Academization Projects 2020, Nautical Sciences. This funding source will cover the costs of this publication.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

## References

Ahvenjärvi S (2016) The human element and autonomous ships. TransNav: Int J Mar Navig Saf Sea Transp 10:517–521. https://doi.org/10.12716/1001.10.03.18

Allen CH (2021) Why the COLREGS will need to be amended to accommodate unmanned vessels. https://ssrn.com/abstract=3854220. Accessed 3 February 2022

Anderson M (2020) Bon voyage for the autonomous ship Mayflower. IEEE Spectr 57:36–39. https://doi.org/10.1109/MSPEC.2020.8946308

Babica V, Sceulovs D, Rustenova E (2020) Digitalization in maritime industry: prospects and pitfalls. Lecture notes in intelligent transportation and infrastructure. Springer International Publishing, Cham, pp 20–27

Bergman J (2018) MOL autonomous shipping project targets 2025 for 'practical use' of vessels. https://www.rivieramm.com/news-content-hub/news-content-hub/mol-autonomous-shipping-project-targets-2025-for-practical-use-of-vessels-23778l. Accessed 7 March 2019

Blanke M, Henriques M, Bang J (2017) A pre-analysis on autonomous ships. DTU. https://www.semanticscholar.org/paper/A-pre-analysis-on-autonomous-ships Summary/4eabcca691a52956f697f560dca3c1ce942781d8. Accessed 20 March 2020

Burmeister H, Bruhn W, Rødseth Ø, Porathe T (2014) Can unmanned ships improve navigational safety? Transport Research Arena, Paris

Casareale C, Marincioni F, Kendra J (2021) Smoothing the corners of hierarchy: integrating shared leadership to mitigate maritime disasters. Int J Disaster Risk Reduct 64:102471. https://doi.org/10.1016/j.ijdrr.2021.102471

Chang YC, Zhang C, Wang N (2020) The international legal status of the unmanned maritime vehicles. Mar Policy 113:103830. https://doi.org/10.1016/j.marpol.2020.103830
Cho Y, Han J, Kim J (2020) Efficient COLREG-compliant collision avoidance in multi-ship encounter situations. IEEE Trans Intell Transp Syst 23:1899–1911. https://doi.org/10.1109/TITS.2020.3029279
Colling A, Hekkenberg R (2019) A multi-scenario simulation transport model to assess the economics of semi-autonomous platooning concepts. In: Proceedings of the 18th conference on computer applications and information technology in the maritime industries. COMPIT, Tullamore, Ireland, pp 132–145
Danish Maritime Authority (2017) Analysis of regulatory barriers to the use of autonomous ships. https://dma.dk/find?query=Analysis%20of%20regulatory%20barriers%20to%20the%20use%20of%20autonomous%20ships. Accessed 31 January 2020
Demirel E, Bayer D (2015) Further studies on the COLREGs (collision regulations). TransNav: Int J Mar Navig Saf Sea Transp 9:17–22. https://doi.org/10.12716/1001.09.01.02
Dybvik H, Veitch E, Steinert M (2020) Exploring challenges with designing and developing shore control centers (SCC) for autonomous ships. In: Proceedings of the design society: DESIGN conference. Cambridge University Press, Cambridge, pp 847–856
European Maritime Safety Agency (2018) Annual overview of marine casualties and incidents 2018. European Maritime Safety Agency, Europe
Fan C, Montewka J, Zhang D (2021) Towards a framework of operational-risk assessment for a maritime autonomous surface ship. Energies 14:3879. https://doi.org/10.3390/en14133879
Fonseca T, Lagdami K, Schroder-Hinrichs JU (2019) Emergent technologies and maritime transport: challenges and opportunities. In: Proceedings of the 20th commemorative annual general assembly of the international association of maritime universities. IAMU, Tokyo, Japan, pp 14
Francis CFJ (2019) A review of the current collision regulations to accommodate multiple ship situations and MASS. J Phys Conf Ser 1357:012011. https://doi.org/10.1088/1742-6596/1357/1/012011
Ghaderi H (2019) Autonomous technologies in short sea shipping: trends, feasibility and implications. Transp Rev 39:152–173. https://doi.org/10.1080/01441647.2018.1502834
Goerlandt F (2020) Maritime autonomous surface ships from a risk governance perspective: interpretation and implications. Saf Sci 128:104758. https://doi.org/10.1016/j.ssci.2020.104758
Gu Y (2019) Autonomous vessels: state of the art and potential opportunities in logistics. NHH Dept. of Bus and Manage Sci Discussion Paper No. 2019/6.
Heymans H (2017) Unmanned ships: technical, economic, and legal aspects. Unpublished Master's Thesis, University of Antwerp, Antwerp, Belgium
Hirst H (2020) COLREGS: still fit for purpose? The maritime executive. https://www.maritime-executive.com/editorials/colregs-still-fit-for-purpose. Accessed 7 March 2020
International Hydrographic Organization (2021) About the IHO. International Hydrographic Organization, Monte Carlo, Monaco
International Maritime Organization (2017) Report of the maritime safety committee on its ninety-eighth session. International Maritime Organization, London, United Kingdom
International Maritime Organization (2018) Strategic plan for the organization for the six-year period 2018–2023. International Maritime Organization, London, United Kingdom
International Maritime Organization (2019a) COLREG—preventing collisions at sea. Maritime safety. International Maritime Organization, London, United Kingdom
International Maritime Organization (2019b) Convention on the international regulations for preventing collisions at sea, 1972 (COLREGs). IMO Conventions. International Maritime Organization, London, United Kingdom
International Maritime Organization (2019c) ISWG/MASS maritime autonomous surface ships. International Maritime Organization, London, United Kingdom
International Maritime Organization (2020) Maritime safety committee (MSC), 99th session 16–25 May 2018. International Maritime Organization, London, United Kingdom
International Maritime Organization (2021) Outcome of the regulatory scoping exercise for the use of maritime autonomous surface ships (MASS). International Maritime Organization, London, United Kingdom
Jo MC, Lee AR, Kim YD, Seo JS (2020) Study on the potential gaps and themes identified by IMO regulatory scoping exercise (RSE) for the use of maritime autonomous surface ships (MASS). IOP Conf Ser Mater Sci Eng 929:012014. https://doi.org/10.1088/1757-899X/929/1/012014

Johansen TA, Perez T, Cristofaro A (2016) Ship collision avoidance and COLREGS compliance using simulation-based control behavior selection with predictive hazard assessment. IEEE Trans Intell Transp Syst 17:3407–3422. https://doi.org/10.1109/TITS.2016.2551780

Kemp JF (1976) Two hundred years of the collision regulations. J Navig 29:341–349. https://doi.org/10.1017/S0373463300039308

Kim TE, Mallam S (2020) A Delphi-AHP study on STCW leadership competence in the age of autonomous maritime operations. WMU J Marit Aff 19:163–181. https://doi.org/10.1007/s13437-020-00203-1

Kim TE, Schröder-Hinrichs JU (2021) Research developments and debates regarding maritime autonomous surface ship: status, challenges and perspectives. In: Ko BW, Song DW (eds) New maritime business. Springer International Publishing, Cham, pp 175–197

Kitchenham BA, Pfleeger SL (2002) Principles of survey research: part 3: constructing a survey instrument. SIGSOFT Softw Eng Notes 27:20–24. https://doi.org/10.1145/511152.511155

Komianos A (2018) The autonomous shipping era. Operational, regulatory, and quality challenges. TransNav: Int J Mar Navig Saf Sea Transp 12:335–348. https://doi.org/10.12716/1001.12.02.15

Kosowatz J (2019) Sailing toward autonomy. Mech Eng 141:30–35. https://doi.org/10.1115/1.2019-SEP1

Kretschmann L, Burmeister HC, Jahn C (2017) Analyzing the economic benefit of unmanned autonomous ships: an exploratory cost-comparison between an autonomous and a conventional bulk carrier. Res Transp Bus Manag 25:76–86. https://doi.org/10.1016/j.rtbm.2017.06.002

Kufoalor DKM, Johansen TA, Brekke EF, Hepsø A, Trnka K (2020) Autonomous maritime collision avoidance: field verification of autonomous surface vehicle behavior in challenging scenarios. J Field Robot 37:387–403. https://doi.org/10.1002/rob.21919

Lyu H, Yin Y (2019) COLREGS-constrained real-time path planning for autonomous ships using modified artificial potential fields. J Navig 72:588–608. https://doi.org/10.1017/S0373463318000796

Mallam SC, Nazir S, Sharma A (2020) The human element in future maritime operations—perceived impact of autonomous shipping. Ergonomics 63:334–345. https://doi.org/10.1080/00140139.2019.1659995

Manuel M, Ghalwash G, Elbawab ME, Ahvenjarvi S, Nakazawa T, Farag YBA, Ibrahim AMM, Rowihil M (2019) Global maritime professional book of knowledge (GMP-BoK). Japan International Association of Maritime Universities, Tokyo, Japan

Maritime UK (2019) Maritime autonomous surface ships industry conduct principles and code of practice version 4. Maritime, UK

Mohović Đ, Mohović R, Barić M (2015) Identifying skill gaps in the knowledge and teaching of COLREGs. In: 17th international conference of transportation science. ICTS, Shanghai, China, pp 339–348

Ning J, Chen H, Li T, Li W, Li C (2020) COLREGs-compliant unmanned surface vehicles collision avoidance based on multi-objective genetic algorithm. IEEE Access 8:190367–190377. https://doi.org/10.1109/ACCESS.2020.3030262

Nordal K (2021) Yara to start operating the world's first fully emission-free container ship. YARA. https://www.yara.com/news-and-media/press-kits/yara-birkeland-press-kit/. Accessed 19 November 2022

Pedersen TA, Glomsrud JA, Ruud EL, Simonsen A, Sandrib J, Eriksen BOH (2020) Towards simulation-based verification of autonomous navigation systems. Saf Sci 129:104799. https://doi.org/10.1016/j.ssci.2020.104799

Perera LP (2019) Deep learning toward autonomous ship navigation and possible COLREGs failures. J Offshore Mech Arct Eng 142:031102. https://doi.org/10.1115/1.4045372

Perera LP, Bjorn-Morten B (2019) Possible COLREGs failures under digital helmsman of autonomous ships. In: OCEANS 2019. IEEE, Marseille, France, pp 1–7

Porathe T (2018) Interaction between manned and autonomous ships: automation transparency. ICMASS 2018 SINTEF proceedings. SINTEF Academic Press, Blindern, pp 41–46

Porathe T (2019) Maritime autonomous surface ships (MASS) and the COLREGS: do we need quantified rules or is "the ordinary practice of seamen" specific enough? TransNav: Int J Mar Navig Saf Sea Transp 13:511–518. https://doi.org/10.12716/1001.13.03.04

Ringbom H (2019) Regulating autonomous ships—concepts, challenges and precedents. Ocean Dev Int Law 50:141–169. https://doi.org/10.1080/00908320.2019.1582593

Ringbom H, Viljanen M, Poikonen J, Ilvessalo S (2020) Charting regulatory frameworks for maritime autonomous surface ship testing, pilots, and commercial deployments. MOTAC, Helsinki

Rivkin BS (2021) Unmanned ships: navigation and more. Gyroscopy Navig 12:96–108. https://doi.org/10.1134/S2075108721010090

Rothblum A, Wheal D, Withington S, Shappell SA, Wiegmann DA (2002) Improving incident investigation through inclusion of human factors. United States Department of Transportation, United States

Rouchitsas A, Alm H (2019) External human–machine interfaces for autonomous vehicle-to-pedestrian communication: a review of empirical work. Front Psychol 10:2757. https://doi.org/10.3389/fpsyg.2019.02757

Schröder-Hinrichs JU, Song DW, Fonseca T, Lagdami K, Loer K (2019) Transport 2040: automation, technology, employment—the future of work. World Maritime University, Malmö

Shaobo W, Yingjun Z, Lianbo L (2020) A collision avoidance decision-making system for autonomous ship based on modified velocity obstacle method. Ocean Eng 215:107910. https://doi.org/10.1016/j.oceaneng.2020.107910

Sharma A, Nazir S, Wiig AC, Sellberg C, Imset M, Mallam S (2019) Computer supported collaborative learning as an intervention for maritime education and training. In: Nazir S, Teperi AM, Polak-Sopińska A (eds) Advances in human factors in training, education, and learning sciences. Springer International Publishing, Cham, pp 3–12

Silveira P, Teixeira AP, Figueira JR, Guedes Soares C (2021) A multicriteria outranking approach for ship collision risk assessment. Reliab Eng Syst Saf 214:107789. https://doi.org/10.1016/j.ress.2021.107789

Szłapczyński R, Ghaemi H (2019) Framework of an evolutionary multi-objective optimisation method for planning a safe trajectory for a marine autonomous surface ship. Pol Marit Res 26:69–79. https://doi.org/10.2478/pomr-2019-0068

Tam K, Hopcraft R, Crichton T, Jones K (2021) The potential mental health effects of remote control in an autonomous maritime world. J Int Marit Saf Environ Aff Shipp 5:40–55. https://doi.org/10.1080/25725084.2021.1922148

The Maritime Executive (2021) Semi-autonomous sailings start aboard shortsea vessel in Belgium. MarEx. https://www.maritime-executive.com/article/semi-autonomous-sailings-start-aboard-shortsea-vessel-in-belgium. Accessed 25 October 2021

Timbrell W (2019) Can the prospect of unmanned ships stay afloat under the current collision regulations. Southampt Stud Law Rev 9:49

Ugurlu H, Cicek I (2022) Analysis and assessment of ship collision accidents using fault tree and multiple correspondence analysis. Ocean Eng 245:110514. https://doi.org/10.1016/j.oceaneng.2021.110514

USCG, US DOT (2004) Navigation rules international and inland. https://www.navcen.uscg.gov/pdf/navrules/navrules.pdf. Accessed 17 November 2021

Wang H, Liu Z, Wang X, Graham T, Wang J (2021) An analysis of factors affecting the severity of marine accidents. Reliab Eng Syst Saf 210:107513. https://doi.org/10.1016/j.ress.2021.107513

Werner CJ (2017) The history of the rule of the road—sailing vessel history. All at Sea. https://www.allatsea.net/the-history-of-the-rule-of-the-road/. Accessed 2 November 2020

Woerner K, Benjamin MR, Novitzky M, Leonard JJ (2019) Quantifying protocol evaluation for autonomous collision avoidance. Auton Robots 43:967–991. https://doi.org/10.1007/s10514-018-9765-y

Yoshida M, Shimizu E, Sugomori M, Umeda A (2021) Identification of the relationship between maritime autonomous surface ships and the operator's mental workload. Appl Sci 11:2331. https://doi.org/10.3390/app11052331

Zhang X, Wang C, Jiang L, An L, Yang R (2021) Collision-avoidance navigation systems for maritime autonomous surface ships: a state of the art survey. Ocean Eng 235:109380. https://doi.org/10.1016/j.oceaneng.2021.109380

Zhou XY, Huang JJ, Wang FW, Wu ZL, Liu ZJ (2020) A study of the application barriers to the use of autonomous ships posed by the good seamanship requirement of COLREGs. J Navig 73:710–725. https://doi.org/10.1017/S0373463319000924

Ziarati R, Djani M, Ivce R, Mohovic R, Baric M (2019) A need for some changes in the COLREGs, its teaching and learning for preventing collisions at sea. In: The 26th international maritime lecturers association conference (IMLA 26), modern challenges in maritime education and training. IMLA, Batumi, Georgia

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.