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Review

The Vagueness of COLREG versus Collision Avoidance Techniques—A Discussion on the Current State and Future Challenges Concerning the Operation of Autonomous Ships

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Abstract: With the development of Maritime Autonomous Surface Ships (MASS), considerable research is undertaken to secure their safety. One of the critical aspects of MASS is collision avoidance, and multiple collision avoidance algorithms have been developed. However, due to various reasons, collision avoidance of autonomous merchant vessels appears to be far from resolved. With this study, we aim to discuss the current state of Collision Avoidance Methods (CAMs) and the challenges lying ahead—from a joint academic and practical point of view. To this end, the key *Rules from International Regulations for Preventing Collisions at Sea (COLREG)* have been reviewed with a focus on their practical application for MASS. Moreover, the consideration of the COLREG Rules in contemporary collision avoidance algorithms has been reviewed. The ultimate objective is to identify aspects of COLREG requiring additional attention concerning MASS developments in terms of collision avoidance. Our conclusions indicate that although a lot of progress has been achieved recently, the feasibility of CAMs for MASS remains questionable. Reasons for so are the ambiguous character of the regulations, especially COLREG, as well as virtually all existing CAMs being at best only partly COLREG-compliant.

Keywords: Maritime Autonomous Surface Ships (MASS); Collision Avoidance Methods (CAMs); COLREG; maritime practice; maritime transportation safety

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1. Introduction

Nowadays, the maritime industry is facing a disruptive change consisting of the implementation of autonomous and uncrewed merchant vessels. These are projected to employ various technologies including remote and autonomous control [1], data fusion, artificial intelligence, and others—depending on the design and actual operational conditions [2]. In light of this concept being relatively new and few prototypes existing (as of November 2022), details of both design and operational aspects of autonomous ships remain unclear. However, due to potential benefits related to the implementation of this technology [3] it is expected that such implementation will at some point occur [4]. Therefore, some safety-critical aspects of it shall be carefully addressed beforehand.

Collision avoidance is one of the most widely discussed aspects of operations of prospective autonomous merchant vessels [5–7]. Numerous scholars contribute to the topic by investigating past accidents, legal frameworks [8], and algorithms. There may be at least two reasons behind the attractiveness of this topic. Firstly, collisions at sea constitute a noticeable portion of maritime accidents [9,10] bringing sometimes catastrophic (health, economic, environmental) outcomes. Secondly, the behavior of vessels can be modeled using various techniques [11] including game or field theories, ship domains, as well as other related concepts [12–16], in addition to high-level considerations on accident analysis, and human factors involved [17,18]. The (negative) human element often refers to the safety of navigation, as it is being sought (and, in most cases, achieved) nowadays, in the era of manned shipping [19,20]. This variety of efforts dedicated to a single problem causes different approaches [21], ideas, and concepts to mix resulting in, sometimes, surprising outcomes. Even if they are all interesting contributions, at the same time they may be mutually exclusive, while only some of them are feasible to implement—under specific conditions and in certain circumstances.

Meanwhile, the issue of collision avoidance of Maritime Autonomous Surface Ships (MASS) shall be resolved one way or another, if those vessels are to be considered safe by industry stakeholders [22]. Being perceived at least as safe as modern-day manned shipping is a prerequisite for the successful acceptance, certification, and implementation of its autonomous variant. Therefore, it is important and beneficial to summarize currently taken approaches to collision avoidance of autonomous ships from various viewpoints, including technical and legal as well as practical ones.

The following discussion and critical literature review is by no means intended to present a full scope of approaches taken, the works carried out, or the results achieved. Instead, its objective is to present, pinpoint, discuss, and critically analyze practical insights on some of the existing contributions. To this end, scholarly and non-scholarly sources along with their relevance to the currently binding COLREG (*International Regulations for Prevention of Collisions at Sea*) are analyzed. It is widely acknowledged that the shipping industry is on the verge of the implementation of MASS and sufficient attention shall be paid to their ability to avoid collisions efficiently. This includes issues related to remote sensing of the environment, navigational situation identification and resolution, as well as compliance with traffic regulations. All these issues shall be resolved beforehand to prevent potential, far-reaching consequences should the MASS technology be hastily implemented.

The remainder of the manuscript proceeds as follows. Firstly, sources of publications on maritime collision avoidance belonging to scientific and grey literature are discussed in Section 2. Thence, Section 3 elaborates on issues arising from COLREG and reviews, compares, and discusses modern CAMs that could be potentially utilized in MASS. Lastly, two sections discussing the findings and concluding the topic close the paper.

2. Information Sources

2.1. Grey Literature

As collision avoidance is crucial from the viewpoint of maritime safety, it is scrutinized by numerous institutions interested in it. Among these, the most prominent is the International Maritime Organization (IMO) which is responsible for formulating the legal framework, to which the prospective automated ships would adhere. The IMO started an organized work on this topic around 2018 when a need for performing a Regulatory Scoping Exercise (RSE) was put forward. It aimed to analyze the possibility of implementing automated vessels under the existing legal framework or identify potential conflicts. Various legal instruments have been reviewed including COLREG. Finally, in February 2020 the IMO provided the outcomes arising from the completed RSE.

As a result, it has been found that numerous passages of COLREG require clarification [23], mainly because human presence and participation in the process have been justifiably assumed when the Rules were drafted in the 1970s. Furthermore, challenges were identified in thirteen aspects, including:

- General COLREG compliance;
- The role and responsibilities of the master;
- Terminology within COLREG;
- Lack of clarity;
- Detection of signals (i.e., remote sensing);
- The role and responsibilities of the remote operator.

Eventually, it has been postulated that the COLREG itself shall be amended to incorporate MASS. Interestingly, it was not brought forward that a new legal instrument shall be introduced to cover collision avoidance of MASS, perhaps because it would create additional confusion for mixed traffic conditions (with MASS and fully manned vessels sharing the sea). The major problem, in this case, appears to be the human-to-machines ratio that will differ significantly from today's shipping. In collision avoidance between two, as well as multiple ships, watchkeepers need to account for the potential of unexpected actions of their counterparts (see COLREG Rule 2b) [24,25]. Such risk would be difficult to calculate by autonomous vessels, which would expect other ships to act according to a prescribed or AI-derived collision avoidance algorithm, no matter the sometimes surprising nature of maritime traffic.

Moreover, it was clearly stated during the discussion at IMO's Sub-Committee on Navigation, Communications, and Search and Rescue session in 2020 that at least ships carrying dangerous cargo and passenger vessels will be traditionally operated in the foreseeable future with a complete conventional crew on board. By this, a long transition period is foreseen during which vessels manned in the traditional way and MASS with different degrees of autonomy will meet at sea.

The topic of collision avoidance was also studied by national maritime authorities, such as Danish Maritime Authority. Therein, it was raised that autonomous vessels will act based on adequate sensing of the environment overlayed on pre-programmed choices and considerations (i.e., algorithms). At that time (2017) it was suggested that a new legal instrument should be drafted to cover collision prevention of fully autonomous vessels. The rationale was that their behavior may differ greatly from this of ships having the benefit of continuous human control and decision competence [26]. As can be seen, the discussion on how to handle the issue legally appears to be far from a conclusion, but the difficulties originating from applying a different set of rules in the same geographic area appear to be acknowledged by various stakeholders.

In addition to works carried out under the auspices of international and national governing bodies, collision avoidance was also in the spotlight of some other organizations including classification societies including Bureau Veritas [27] and DNV-GL [28]. These only contained very general guidance on how the process shall be handled to ensure its safety.

As can be seen, collision avoidance is among the most-discussed issues within the MASS domain. It is also a subject of numerous scientific studies.

2.2. Scientific Sources

The scientific literature on autonomous ships has been increasing in recent years [29]. In principle, contributions can be divided thematically into two major groups. The first of them is focused on investigating high-level considerations involving collision avoidance, while the second looks at the development of (potentially) implementable algorithms for collision avoidance. Herein, the reliability and accuracy of sensors supplying data to algorithms are either carefully considered or their perfect operation—tacitly assumed.

Firstly, it has been easily identified that ensuring the overall safety of MASS is among the most important goals of their implementation. To this end, various techniques have been applied to evaluate the expected levels of risk or safety or analyze them somehow differently [30]. The Bayesian Belief Networks [18], System-Theoretic Process Analysis [31,32], and expert-based studies [33] have been applied among other methods in an attempt to produce the initial (not based on real-world experiments) results. Most of the studies undertaken included considerations on collision avoidance.

These mainly revolved around the issue of gaining and maintaining situation awareness (SA). SA is defined as a perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future [34]. A widely raised issue was whether the MASS control system would be capable of correctly observing the environment and producing decisions on how to proceed in given circumstances [35]. Moreover, since some level of supervision or remote control by a human is expected, similar was studied with respect to the SA of a remote operator [36–40]. Unsurprisingly, it was concluded on numerous occasions that the ability to maintain the SA by remote operators depends on many factors, including their experience, system design, and ability to properly and timely switch between the degrees of autonomy [41].

Another set of scientific documents focuses on the legal aspects of collision avoidance. Herein, the issue of interpreting or amending the COLREG has been raised. It is sometimes assumed that autonomous ships will always follow COLREG [42] just like any other machine following its instructions.

Sometimes, the navigational status of the MASS is contested as differing from the vessel underway using engine. For instance, it has been argued that an autonomous ship shall be considered as *not under command* if her sensors fail [43] or as *restricted in her ability to maneuver* [44]. As a matter of fact, whether unmanned marine vehicles can be considered vessels under COLREG Rule 3a has also been challenged [44]. Some technical solutions are also proposed to highlight the fact that the behavior of MASS may differ from manned vessels [42], but the suggestion does not appear to be based on anything but the opinion of the original author.

Moreover, it is often argued that maritime autonomy remains a spectrum in which an autonomous merchant vessel may, in fact, operate various processes on a different level of human involvement at the same time. In principle, the spectrum ranges from direct manual control to fully autonomous operation and includes concepts such as remote control or periodical supervision. Various approaches to this issue are being discussed in legal and technical documents produced by various stakeholders of the maritime industry. Nevertheless, since it is postulated that the machines would run the vessel most of the time or control most of the processes, both scientific and industrial efforts focus on the development of control algorithms. This is also apparent in maritime collision avoidance: a process to which simple logic and algorithms can be easily and successfully applied (at least at a first glance).

3. Autonomous COLREG

Regardless of the amount of work devoted to ensuring the safety of navigation, in terms of collision avoidance COLREG remains the most important and legally binding instrument. It was drafted some five decades ago before any meaningful research on automated shipping could result in the actual feasible large-scale implementation of the technology. However, it remains the root of any knowledge on how to perform collision avoidance at sea, scrutinize operational procedures, and analyze potentially dangerous situations. Although it is advocated that the evolution of MASS calls for implementing a brand new legal instrument to cover all matters related to it [45], whether collision avoidance shall be part of it remains undecided. Regardless of the outcome of the discussion, manned ships will remain in operation for quite some time even after a successful implementation of MASS. This allows for using COLREG as a bottom-line for all considerations related to collision avoidance, regardless of the magnitude of human involvement in it. It is simply that any new regulation on automated shipping must not be different from COLREG to the extent that MASS would behave in a manner incomprehensible for human seafarers, and vice versa.

Therefore, certain aspects of COLREG shall be reviewed with a primary focus on its practical applications for MASS.

3.1. Steering and Sailing Rules

COLREG, or any other collision regulations, are primarily concerned with how to ensure vessels at sea pass each other without colliding. Guidelines on how to achieve that are known as *Steering and sailing rules*, with which certain issues can be associated as given below.

3.1.1. Vagueness of Rules

As pointed out by many authors [46–51], the vagueness of COLREG makes it difficult to transform into a machine-readable form [52]. Codifying exact values of certain parameters was and still is deemed unnecessary as humans can rather easily apply their experience to situations involving these. For instance, experienced human seafarers can *judge* whether their ship is in a narrow channel. Meanwhile, an algorithm would need to detect such a situation based on a set of criteria (such as under keel clearance, the distance between respective buoys, distance from banks, etc.) [23] and using installed sensors.

The two aspects of COLREG in which reliance on crewmember's experience is the most apparent is the use of two closely related terms: the ordinary practice of seamen and good seamanship. The former is one of the criteria for assessing the situation around own vessel under Rule 2, while the latter shall be taken into account when taking action to avoid collision (as per Rule 8). The main issue is that terms so vague and non-easily programmable are to be taken into account by a machine. This is especially important in a safety-critical process where decision making may create a mismatch between the interpretation of the respective rules. While human seafarers gain their experience constantly, the same cannot be said about the machines, which are expected to follow exactly the instructions preprogrammed. Moreover, it has been raised that those who actually create the instructions or perform the research that is oriented on it may be lacking the understanding of seamanship whatsoever [53,54].

The only case where the machine can gain anything close to experience is through machine learning. Herein, it has been pointed out that the application of artificial intelligence (AI) solutions can be helpful, provided they meet certain conditions, such as trustworthiness and explainability [55] related to the non-deterministic nature of machine learning. This means that the structure of the algorithm (including collision avoidance) may be to some extent dynamic, thus producing different outputs from the same inputs [56], a feature unknown in deterministic, traditional programming. Moreover, it must be kept in mind that AI would have to be fed with data, perhaps reflecting the real behavior of ships in a certain geographical area. This data may include not-readily apparent situations in which COLREG Rules or good seamanship were violated, as violations (or *departures* under Rule 2b) are not uncommon in the real world [57]: *garbage in, garbage out*. By learning from situations in which violations of the Rules were made for any reason, AI itself might learn to make violations. With the limited explainability of artificial intelligence and the inability to analyze its hidden layers *line by line* [58], these departures may come as a surprise.

It is also unclear to which level these terms (*good seamanship* and *ordinary practice*) apply to remote operators [43]. Working mainly ashore, they may not have extensive seagoing experience, while they may need to apply it in remotely steering the vessel, to avoid collision, as well as other accidents.

3.1.2. Safe Passing Distance and Wheel-Over Point

Passages of COLREG that do produce some misunderstandings even now refer to the execution of collision avoidance itself.

One of the terms used concerning identifying the head-on type of an encounter, *reciprocal or nearly reciprocal courses*, has already been widely discussed with some solutions brought forward [48,59]. These were mainly based on the visibility sectors of sidelights, and especially their practical intensity cut-off in the forward part.

However, COLREG includes more statements that may have far-reaching consequences while being unclear to software-based agents. To this belong the instructions on how ships shall act to avoid collision. Herein, *safe speed*, *distance appropriate to the prevailing circumstances and conditions*, *proper use*, *scanty information*, *ample time*, *readily apparent*, *safe distance* can be listed, but other examples could also be found.

From the practical point of view the most important fact is that some distance shall be kept between the vessels at all times, and how to secure such distance. To this end, Rules do not prescribe a crisp value of what the safe distance between two vessels passing each other shall be. This is of utmost importance as nearly all algorithms likely to be implemented in autonomous collision avoidance are based on maintaining minimum separation between hulls or domains built around them. There is a multitude of arguments about what that distance shall be, which stems from the fact that it has not been legally imposed. Its value depends on the size of the ship and its maneuverability, available maneuvering space, weather conditions, traffic congestion, visibility, and the professional experience of the person making the decision. This is very different from aviation, where exact values are given [60].

Thus, how great should the passing distance be, and what should it depend on? Executing an evasive maneuver in advance would sometimes be necessary to avoid a close-quarter situation. The COLREG rules leave a wide berth for interpretation in this respect, too. The ambiguity reveals itself in leaving the decision makers to assess the value of the distance between two ships at which the give-way ship should perform a collision-avoidance maneuver. Moreover, and simultaneously, the stand-on ship may and later shall undertake such a maneuver (see Figure 1) and thus has to make similar decisions without having clear instructions on how to do so (Rule 17). This creates certain problems, particularly in a meeting situation of two ships with very different maneuvering characteristics or when decisions are made on these ships by OOWs (officers in charge of the navigational watch) with different professional experiences. This again leaves room for interpretation and may be managed in different ways by different persons in charge, let alone algorithms designed and certified by different companies.

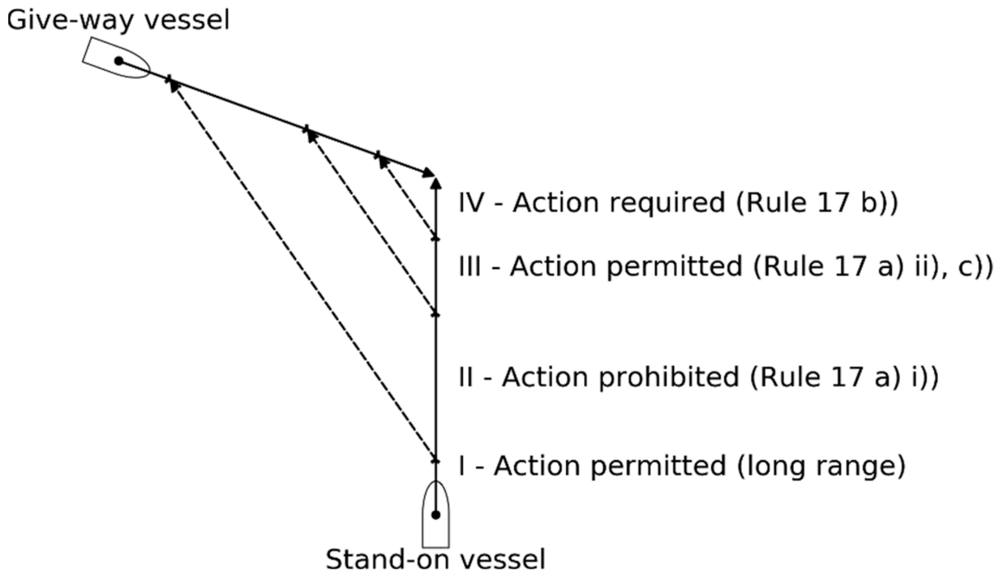

Figure 1. The stages of a crossing encounter under the COLREG Rule 17, as given in [61] and inspired by [62].

Therefore, the above instructions may be more or less clear for humans. However, computers do need an exact set of commands to follow, so that a set is not ambiguous. On the other hand, manned vessels do collide even nowadays. Thus, this advocates that humans also do have trouble interpreting or implementing the COLREG rules.

3.1.3. Giving Way

Furthermore, COLREG introduces two types of giving way: *not impeding* and *keeping out of the way*. As prescribed by Rules 13–16 as well as 18, certain vessels shall *keep out of the way* of others by taking early and substantial action to avoid the collision. However, certain passages of Rules 8–10, as well as Rule 18, stipulate that these other vessels shall at the same time *not impede* the (safe) passage of the former. As discussed in [62], the fact that a passage of a certain vessel is *not to be impeded* does not mean that she is a stand-on vessel and shall maintain her course and speed (to a certain point, as outlined in Rule 17).

Rather, she shall, depending on circumstances, give way and *keep out of the way* of the vessel expected and required to *not impede* her. A common example may be a vessel constrained by her draught that shall *not be impeded* but is not a stand-on vessel by definition. Note the overlapping and at the same time mutually exclusive requirements, lack of crisp criteria and definitions. As a matter of fact, experience and context play a major role whenever contradicting guidelines are in use—both being virtually unavailable to machines.

The issue of mutual responsibilities between the vessels (Rule 18) could be handled using currently installed onboard devices like AIS (*Automatic Identification System*), as it obligatorily transmits the navigational status of the ship. It should be mentioned, however, that even if the autonomous algorithms will follow different decision-making processes depending on the statuses of both own and target ship, the issue of the human factor will still exist. As the status is set manually by the OOW during different stages of the sea passage (at least on manned vessels), there is always a possibility of mistakes that would lead to misinterpretation of the situation by the autonomous system. A similar situation can also occur when remote control will be used, and a shore-based operator will wrongly change the navigational status. An additional issue is the fact that according to SOLAS (*International Convention for the Safety of Life at Sea*) the AIS is not mandatory for all vessels [63], but only for larger ones or of a specific type (passenger ships). Last but not least, AIS remains invisible to COLREG as if it did not exist. Drafted before a concept of AIS was developed, COLREG rules do not mention it otherwise than indirectly under Rule 5: *maintain a proper look-out by [. . .] all available means* (other than specified).

3.1.4. Restricted Visibility

The COLREGs also do not provide the value of visibility expressed in nautical miles, considered to be restricted. Therefore, Rule 19 applies to ships not in sight of one another when the meeting situation is assessed, and a decision is made only based on indications of technical means of observation. For correct usage and interpretation of Rule 19, the crucial statement is also given in its paragraph a, especially in the part *when navigating in or near an area of restricted visibility*. This means that a ship can be physically located outside the area of the restricted visibility, but Rule 19 and resulting instructions apply to her anyway.

Moreover, this Rule introduces a partially different principle of performing an evasive maneuver than in the case when two ships are in sight of one another. If two ships were in sight of one another and one of them has the other ship that is higher in the priority hierarchy in front of the own ship's beam on the port side, it should alter her course in such a manner to safely pass behind the stern of the privileged ship. When they are not in sight of one another, both of them are expected to alter their courses to pass at safe distance. The OOW can assess the meeting situation and decide on avoiding action based on radar observation or data presented by AIS, but the type of maneuver depends on whether the target ship or its navigation lights are *visible by sight* at the time of assessing the situation and beginning the maneuver. Therefore, another question arises: does a remote look-out via cameras count as *visual sight*?

In relation to the above, it should be noted that there is a sudden transition from one legal regime (Rules 10–18) to another (Rule 19) once the target vessel comes within sight. Further note the assumption that contemporary vessels are usually not equipped with technical means of look-out other than radar (Rule 19d: *a vessel which detects by radar alone the presence of another vessel*) and the fact that autonomous ones will likely employ a wider set of sensors, possibly even thermal-imaging cameras [35]. Having different resources to assess the situation, ships can reach different conclusions and act differently.

3.2. Look-Out

3.2.1. Sources of Information about Other Ships

The COLREG Rule 5 stipulates that every vessel shall, at all times, maintain a proper look-out by all available means to make a full appraisal of a situation around her. When the Rules were drafted it was justifiably presumed that this will be done by human senses with an aid of technical resources: radar. Nowadays, additional aids are used including AIS and ARPA (Automatic Radar Plotting Aid). However, it remains a good seamanship practice to rely on the sight and hearing of the look-out.

Whatever the sensory setup of autonomous ships is going to be, the advantage of human sensory abilities will be lost, at least for their crewless types. The ability of the vessel to analyze the situation around her and detect potentially dangerous objects would depend on the technical specification and reliability [64] of the sensors and data processing algorithms, including data fusion [65]. Only after this is completed can the decisions on evasive actions be taken with sufficient reliability. However, a difficult task is not only detecting the dangerous encounter, but also interpreting it based on, i.e., lights, day signals, or other visual properties. Given the fact that even AIS data can be flawed in many ways [66], the reliability and trustworthiness of any signals transmitted by any vessel and any kind of device (including navigation lights) can be questioned [67,68].

Another level of complexity is added by the fact that not only visual sightings are to be detected and interpreted. They should also be compared with information collected by radar, AIS, and sound signals—both detected directly by microphones installed on board, but also transmitted by radio. As for the latter, that would include information exchange on very-high frequency radiotelephones between humans not always following the *Standard Marine Communication Phrases* and using different dialects [69–71]. Although coordination of evasive maneuvers is strongly discouraged [72], it is also quite frequent and shall be taken into account. However, it can also be found incomprehensible by the control system which may need to call for the assistance of a human operator located in the SCC (*Shore Control Center*). If every voice communication should be interpreted by the operator (not only those conversations directly involving the vessel in question) then a lot of data transfer would be required, as well as the permanent attention of the operator, especially when traversing congested waters or those affected by abnormal refraction.

Speaking of an operator, it shall also be raised whether such a person qualifies as a potential look-out since (s)he would only rely on the data transmitted from the ship's sensors to the SCC, which could be distorted or delayed. If so, then would it be in line with good seamanship to employ one operator to conduct the look-out and to operate all the other systems of the vessel?

3.2.2. Lights, Shapes, and Signals

The need to identify the priority level of the encountered vessel based on its day shapes and navigation lights (at night) is emphasized in present-day COLREGs, for instance in Rule 18d,/and i. A lack of AIS recognition within the Rules makes lights, shapes, and sound signals the only acceptable way of learning the status of the target vessel. However, there are numerous problems related to it. Firstly, shapes and their sizes are not adapted to the size, maneuverability, and operating speed of modern merchant ships. Secondly, some issues, for instance identifying the side of a vessel engaged in dredging or underwater operations which other ships may pass, do not have a corresponding message within the AIS. Thirdly, the identification of the navigation lights by optical systems has not been put to a rigorous test to date, especially with their rather limited minimum ranges of visibility (as prescribed by Rule 22) [40].

Finally, sound signals differ between good visibility (maneuvering signals, Rule 34) and restricted visibility (fog signals, Rule 35), which provides further complexity to navigate, especially in the latter conditions. Further, considering the difficulty in identifying which of the vessels in the vicinity transmitted the received signal, relatively small audibility range, and a need to fuse these data with those from other sensors, one can get a loop of mutually exclusive information—useless and perhaps only interpretable by an experienced human.

Needless to say, only the properly processed data can serve as input to collision avoidance algorithms themselves. As aforementioned, the most challenging in designing collision avoidance algorithms for MASS is the ambiguity of the rules. Every machine needs a clear procedure for its operation, and thus many algorithms have been proposed in the literature to date. These still have their drawbacks and limitations, as no one covers COLREG at an even satisfying level. However, some of them are a good way to develop initial ideas and increase the extent of considered Rules.

3.3. Collision Avoidance Methods Considering COLREG

Finding feasible and collision-free solutions that will bind the initial configuration of the vessel with the desired one is among the main tasks of various ship collision avoidance methods. In recent years, various ship CAMs have been proposed which support manned and unmanned ships to prevent collisions with moving obstacles (e.g., target ships) or unexpected obstacles (e.g., in unknown navigation environments) [73]. One obvious tendency is introducing edge-cutting techniques from other research fields to solve the problem, such as robotics, modern control, artificial intelligence (AI), etc., [74–76] and the ship collision problem is usually modeled as an optimization problem with respect to utility functions and obstacles [77–79].

From three review papers made since 2009 [73,80,81] we could observe the developments of CA algorithms in the past 20 years. Many limitations of CA algorithms have been overcome by the newly introduced techniques, while some new challenges emerge.

As mentioned by [80], traditional collision avoidance algorithms ignore the own-ship dynamics, neglect the environmental disturbances, assume semi-dynamic obstacles, and disregard COLREG. These limitations, however, have to some extent been handled by currently existing algorithms. To this end, many algorithms have incorporated ship dynamics in collision avoidance [82,83]. The ship's maneuverability is considered by using non-holonomic motion models that can describe the movement of the ship. Meanwhile, environmental disturbances are usually taken into account by two means. Specifically, the environmental disturbance is either modeled as noise in the ship dynamics model [84] or some constraints in the optimization problem [85]. The moving obstacles are allowed to change their speed and course, such as [79,86]. The considerations of navigational rules (especially COLREG Rules 8, 13–17) in collision avoidance methods (CAMs) have also become popular recently [80,87–89].

To analyze the existing CAMs concerning previously discussed issues of ambiguities related to COLREG, a literature review has been conducted.

3.3.1. Method—Literature Review

The consideration of COLREG in existing CAMs mainly falls into three types:

- COLREG is incorporated in the evaluation of collision risk, helping the machine judge different encounter types and guide collision-avoidance actions [48,89,90];
- COLREG has been seen as a constraint in finding a collision-free solution [83,86];
- COLREG has been applied to design the penalty of different actions in the deep reinforcement learning framework [91].

The above approaches have been further elaborated through a structured literature review performed on high-quality scientific papers. Herein, the issues of COLREG as raised in Section 3.1. and Section 3.2., along with the COLREG Rules, have been used as a starting point to perform the analysis. To achieve this, a total of 108 documents were retrieved using the Web of Science Core Collection (SCI-Expanded), which is a popular and recognizable database of high-fidelity scientific sources [92,93]. The initial sample was collected as a result of the search query made in the middle of March 2022. The query combined the occurrences of MASS and COLREG among the paper's title, abstract, and keywords as follows:

TS = ((autonomous OR unmanned) AND (COLREG$ OR "collision regulations" OR "international regulations for preventing collisions at sea")).

The dataset consists of the documents published by the end of 2021. Of these, 79 papers met the eligibility criteria, that is, discussing allegedly COLREG-compliant CAMs claimed to be feasible for MASS (or USVs, Unmanned Surface Vehicles). The review articles or discussions were rejected from the original data sample as they do not present a standalone method for collision avoidance of MASS.

After completion of the final sample, a manual review was carried out concerning the COLREG Rules as well as the issues emphasized in Section 3.1. and Section 3.2. The documents were proportionally divided and distributed among the co-authors of the paper and then reviewed. Besides verification of paper compliance with a certain Rule or consideration of a certain issue, observed limitations of the CAM in the reviewed document as well as the type of the method(s) or algorithm(s) used were noted.

3.3.2. Results and Analysis

The results of the review are given in Figures 2 and 3. In Figure 2, the percentage of CAMs compliant and partly compliant with the particular COLREG Rule is depicted. As can be seen, most of the CAMs are, at least partially, compliant with Rules 7 and 8, as well as with Rules 13–17. However, a large portion of them do not take into account Rules as important (if the importance of the Rules can even be differentiated) as 2, 6, 18, and 19. These results largely re-affirm those achieved in a parallel study published recently [94]. To some extent, it is understandable that Rule 12 is often neglected as it only applies to sailing vessels—a case that is not normally studied with regard to MASS (although this fact is rarely stated explicitly).

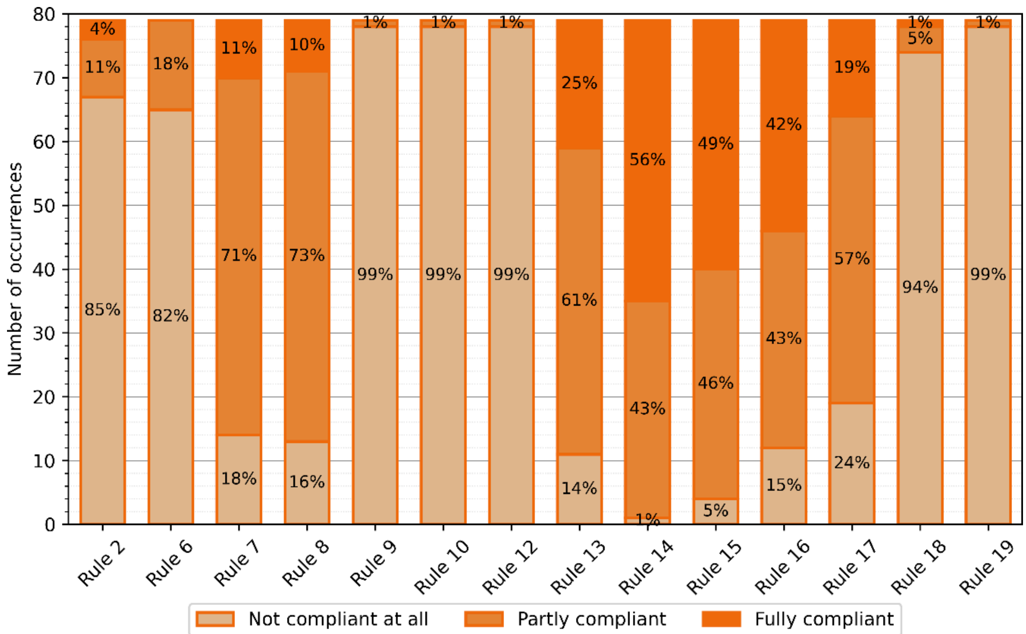

Figure 2. Distribution of COLREG Rule considerations in the reviewed collision avoidance methods.

Meanwhile, Figure 3 depicts the extent to which the issues raised in Section 3.1. and Section 3.2. have been addressed in the reviewed studies on collision avoidance methods. Herein, the categorization pertains to the given issue as follows. It was marked as *ignored* whenever authors of a given paper failed to acknowledge the fact that COLREG introduces a level of vagueness to the way vessels should act to avoid collision. Similarly, the issue would be marked as *acknowledged* if the authors mentioned the fact that it exists within COLREG and collision avoidance practice. Finally, the issue would be *resolved* if the authors provided a resolution to the previously discussed issue. Should the authors give a solution without discussing the issue of vagueness, the issue would be marked as *ignored* as it was the vagueness that was the focus of this study, not the solution. As can be seen, most of the issues are marked as *ignored* as if crisp values of certain parameters could be easily established or as if they were somehow prescribed.

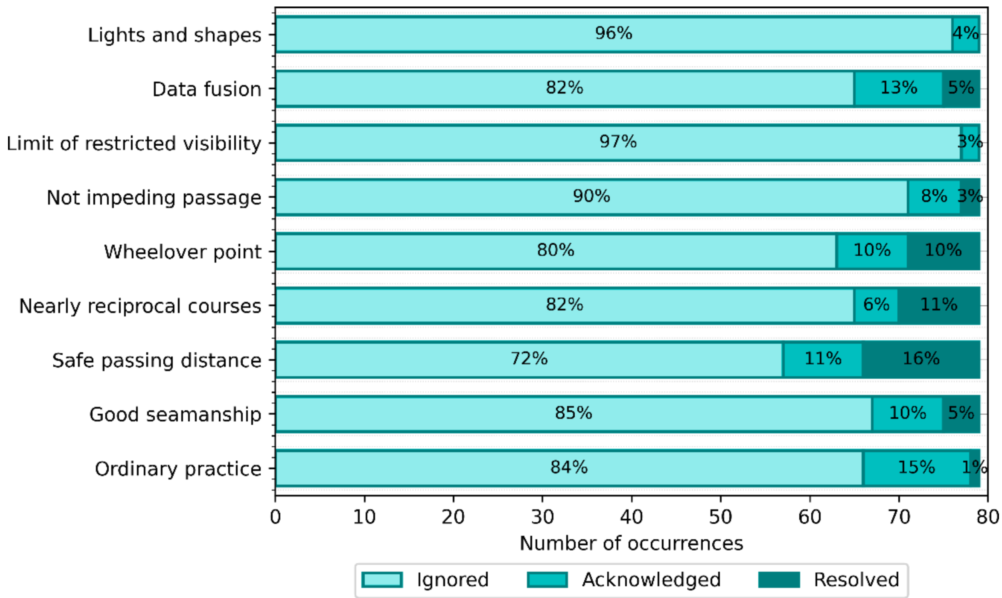

Figure 3. Distribution of the COLREG-related issues considerations in reviewed collision avoidance methods.

In summary, none of the studies incorporated the entire COLREG in CAM and few MASS have the capability of rule inference. It means that MASS can only handle limited scenarios that have been set by researchers. When unexpected changes or unrecognized scenarios occur, the actions taken by MASS might not be rule-compliant. Moreover, the vast majority of the algorithms fail to implement some important Rules that do not explicitly state the operational procedure for avoiding the collision, but do provide higher-level guidelines on how vessels should act at sea (e.g., proceed at a safe speed, or cross the traffic lanes on a heading as nearly as practicable at right angles to the general direction of traffic flow, or depart from the Rules).

Interestingly, it can be noted that even if a specific issue is directly related to a given Rule (like the issue of *reciprocal or nearly reciprocal courses* is related to Rule 14) and the vast majority of the papers touched upon this very Rule (no matter in partial or full compliance–99%), the issue is at the same time ignored by most of the researchers (82%). This phenomenon may suggest that even if the Rule is considered in the CAM for MASS, the essential issues in terms of vagueness and difficulty in implementation/algorithmization are not taken into account. In this case, most of the reviewed algorithms failed to analyze how to approach the intrinsic ambiguities, including those related to what is understood as *nearly* reciprocal courses but nevertheless implemented the relevant Rule. This was achieved, for instance, through labeling the encounter as *head-on* if one crisp parameter was met, e.g., when the target ship was found within the 5° sector from the own ship's bow. Further considerations related to, e.g., masthead light/sidelight observability or aspect comparison as well as Rule 14c were not pursued. This can lead to incorrect, incomplete, or inconsistent implementations and interpretations.

Despite it being challenging to strictly define a type of the algorithms used within CAM due to penetration of various methods, usage of hybrid approaches, or unclear description of the solution, an attempt was made to outline a general overview of the methods utilized by the researchers. Among these used for MASS collision avoidance considering COLREG, a few major types of algorithms can be listed [95]. The most popular approaches to CAMs identified during the review are VO-based (*Velocity Obstacle*) algorithms. Together with their improvements, they comprise almost 20% of the papers reviewed. These include the application of *linear VO* [96], *nonlinear VO* [97], *generalized VO* [86], and other *modified VO* [98]. Not much less frequently used by the researchers were various forms of deep learning (about 15%). These include, for instance, *Deep Re-*

inforcement Learning [91], *Deep Convolutional Neural Networks* [99], *Deep Q-Network* [100], etc. With a similar share of approx. 15% geometrical approach may be listed, including modified ship domain concepts [101,102]. Moreover, the solutions based on the potential field theory (mainly *Artificial Potential Field*) were notably popular (~10%), e.g., [103]. There were, however, many hybrid solutions comprising more than one algorithm, and those were usually combined with some path-(re)planning solutions, [104,105]. It is of note that the researchers also utilized other CAMs to finally find the best/optimal one. Therefore, among the documents reviewed there were also papers where only a single attempt to utilize a certain algorithm or method was made; examples of solutions were *Cuckoo Search Algorithm* [106], *Fast Marching Square* [107], and *Null-Space-based Behavioral* [108].

3.4. Limitations

The eligibility criteria for the review of the papers were transparent, the search query related to the subject of the study, and the scientific database selected for gathering the sample is commonly recommended. There are, however, some limitations related to the method selected that are inevitable when experts' knowledge and experience are utilized, as these always bring an issue of subjectivity.

Despite the review being carried out by the researchers and practitioners having insight into the field of the study, there is always a possibility to interpret by them the assumptions of the study, as well as the content of the papers browsed, in a different manner. This subjectivity bias can occur when different investigators are reading and interpreting the content of the papers and that may affect the results obtained. In this study, the assumptions were discussed in detail among co-authors involved in the review, with the consensus achieved before it was performed. Moreover, the quantitative results between the authors showed similar distribution patterns and share of the issues and/or Rules included among the documents browsed. Therefore, it may be assumed that the results achieved are reliable, while potential flaws should not impact the outcomes of the study, so do its findings.

More importantly, the discussion of the ambiguous issues related to COLREG, although inspired by various scientific sources and grey literature, consisted in outlining practical aspects of autonomous collision avoidance. Being a foundation for the literature review, it does not constitute a complete list of potential issues, but rather those most notable in the literature and subjectively considered the most urgent to resolve by autonomous CAMs.

4. Discussion

The above presentation on both scientific and practical aspects of autonomous maritime collision avoidance revealed several issues related to autonomous maritime collision avoidance. These may be found relevant by both developers of autonomous maritime systems as well as their operators. These are outlined in Section 4.1. below, while Section 4.2. elaborates on future challenges faced by the worldwide community researching CAMs.

4.1. Current State

Although it has already been widely acknowledged that COLREG is written in a non-machine-readable form, new instances of such drawbacks can be found. It is understandable since the Rules were drafted by humans and for humans in times when no other actor could be expected to interpret and apply them. Vagueness and ambiguity can easily be found in almost each of the Rules, but it is their potential applications that can cause a serious challenge for both designers and operators of the MASS, especially given the fact that numerous Rules can be applied at the same time to a given situation, and these can be mutually exclusive. See, for instance, contradicting directions of Rules 16 and 17 when more than two vessels meet in the restricted waters so as to involve the risk of collision. Faced with a necessity to apply their common sense, human navigators might find a solution based on their experience and assessment of the risk associated with any potential solution. In this sense, COLREG can be treated merely as guidance on collision avoidance, leaving the OOW some degree of freedom in decision making under Rule 2b. The difference between *guidance* and *regulation* would again be incomprehensible to a machine, which would rather need to detect a Rule-based conflict and call for human assistance. This can be a particularly demanding task given the fact that most of the CAMs do not address COLREG holistically, but rather only incorporate its certain parts. Even for humans, choosing proper action can be difficult if (s)he only knows part of the rules governing the process, let alone computers. And that is without even trying to delve into *departure from the Rules* as permitted by Rule 2b [46].

Furthermore, the review of scientific literature on collision avoidance at sea leads to an unexpected finding. Namely, the vast majority of the published studies (and all of those included in the review) claim that the algorithms and methods developed or presented therein are at least partially COLREG-compliant. This is understandable since COLREG provides a global legal framework for collision avoidance at sea, and it has been argued that the compliance itself can be difficult to quantify [53]. Nevertheless, there are instances where studies written, reviewed, and published by academics (and likely by practitioners, at least in some cases) are exactly the opposite. Some solutions presented therein are clearly in contradiction to the COLREG Rules to the point where it might be dangerous to apply them in a real environment. To these belong, for instance, wrong interpretation of angular sectors defining the kind of ship encounter that (during the night in good visibility conditions) should be made based on the navigational lights (and only on such grounds that is also usually omitted). It could be noted that some of the authors ignored Part C of COLREG, and especially Rule 21, where the visibility sectors of the navigational lights are provided, and these should be used as a base for further definition of a type of encounter and a certain Rule that should be in force. Moreover, an even smaller group of authors appreciated the existence of COLREG Annex I where technical details about the positioning of navigational lights including their practical cut-offs are provided. All these aspects directly affect the selection of encounter type, the behavior of the ships during a close-quarters situation, and therefore the safety of navigation.

A few first Rules of the COLREG are also rarely interpreted correctly. This can be usually noticed in conjunction with the application of Rule 18 (a lack of its application may be also an indicator). The navigational status of the ship is therein sometimes not in line with Rule 3, which changes completely the interpretation of the regulations and other Rules, let aside CAMs in which only certain passages of the Rules are neglected, including Rules 13d, 17c, or 7d. For the latter, the risk of collision is often calculated to initiate the collision avoidance algorithm, but seldom is the guidance prescribed therein applied. It is also astonishing to note that Rules as important for a seamanship practice as Rules 6, 18, and 19 are seldom taken into account. The effect of these Rules on the conduct of vessels both in sight of one another and in restricted visibility cannot be underestimated. Rarely do the authors of papers acknowledge the fact that Rules 18 and 19 exist but they decided not to comply with them for a certain reason. More often, they appear to turn the blind eye on these aspects which, when applied to a safety-critical process of collision avoidance at sea is hazardous in itself. Regarding wrong or a lack of consideration of Rule 18, the vast majority of the methods ignore the fact that all considered encounter-related Rules 14–15 are dedicated to two *power-driven vessels*. However, if the other navigational status of one of the ships involved in the close-quarters situation is in force, the priority is changed regarding the hierarchy provided in Rule 18 as to ship behavior. When it comes to Rule 19, the behavior of the vessels also differs from this, usually presented in the papers about CAM concerning COLREG for MASS. However, almost none of the methods presented takes into account an assumption about good visibility conditions and that two vessels are in sight of one another.

Taking into consideration all of the abovementioned, the following rhetorical question arises: how can the machines, thinking algorithmically, understand and correctly interpret ambiguous COLREG Rules if the academicians and practitioners publishing in the high-quality research sources have the same problem with the legal act having been in force for almost 50 years?

One potential answer to this question may be some level of simplification and unification of COLREG. To keep the Rules as close to workflow or process as possible, reduce the ambiguity and finally handle some of the issues discussed in this paper, so the conning actor's (human or machine) behavior could be unified across different visibility conditions (that means merging Rules 11 through 18 with the Rule 19). Such a significant change would lead to the unification of the collision avoidance actions taken—no matter if the ships are in sight of one another or not—and no matter who is in conn: a man or a machine. If presently Rule 19 forces a completely different way of taking evasive actions (theoretically in worse environmental conditions), perhaps this workflow could be also applied when the lights of the ships are visible. However, the question of the priority of ships with different navigational statuses (Rule 18) and the designation of a stand-on vessel would remain open. On the other hand, nowadays this prioritization does not exist in restricted visibility, and it is still possible to maintain safe shipping and take effective evasive actions. Therefore, the feasibility of this potential amendment shall be thoroughly investigated prior to implementation.

4.2. Future Challenges

Having asked this, another question may be formulated whether the same level of oversight might happen to algorithms implemented on ships that are put into a full-scale, commercial operation. It may be expected that such algorithms are tested and certified by classification societies or flag state administrations, but a similar expectation can be formulated with regard to a review process of scholarly publications. If reviewers failed to point out flaws in the algorithms, so can (potentially) the authorities. By that, CAM which is not compliant with COLREG (or its substitute/annex relevant for MASS, if implemented in the future) [40], can be certified as compliant—which would constitute a serious threat to maritime safety. That means the attendance of human operators in the control loop of the MASS is still required in the foreseeable future. As noted before in Section 2.1., with the human-to-machines ratio decreasing in the maritime domain, humans might lose/reduce the opportunity to step in and correct the flaws implemented in software or hardware. These shall therefore be mitigated on every level of system development. It has been raised that employing seafarers with hands-on experience can be beneficial to the process [53]. Moreover, due to the limited chance of interference by human operators in MASS, it is also important to study the design of human–machine interaction/cooperation, which could increase the efficiency and effectiveness of human interference. To date, many CAMs directly offer optimal solutions for MASS without explanation [109], which might not be friendly for human operators, to interpret the intention of the machine or to judge the rule compliance. Thus, given the developments in AI techniques, the challenge of developing CAMs not only includes finding feasible, optimal, and rule-compliant solutions but also explainable methods and user-friendly human-machine interactions.

The practical experience so important in today's shipping can only be implemented on the opposite sides of the process: in the concept of leading safety indicators and during remote assistance (control). Whatever is in between is left to either a machine or its developer. Neither of them needs to understand the practical nuances of the COLREG as the only legal instrument governing the conduct of vessels at sea.

Nowadays, almost all the decision making related to collision avoidance is performed by the OOW. (S)he is presumably highly trained and experienced enough to handle the situation or call for the assistance of someone higher in rank if (s)he fears failure. Note that the same process of calling for (remote) assistance is envisioned in most of the literature on the safety of MASS. Therein, however, it would be a machine *fearing* failure. If that fear were to be felt, certain criteria shall be pre-programmed to initiate it. These can take the form of operational leading safety indicators [2], which again need to be pre-programmed.

Additionally, a challenging (and seldom touched upon) level of difficulty can be foreseen with the occurrence of mixed traffic conditions, that is, in which a certain number of vessels in the same area and time are commanded by a human, and the others by a machine. The COLREG-as-guidance vs. COLREG-as-regulation distinction can be difficult to grasp by different actors in the already complex, multi-vessel environment. Moreover, with autonomous vessels expected to dynamically transition between modes of operation (or autonomy levels/degrees) [110], that is in fact a transition from human to machine control and vice versa, as any vessel can suddenly change its behavior. Such change might result merely from the change of actor in command of the vessel, similar to a watch handover between OOWs, but without the benefit of discussing the planned maneuvers and predicted paths; additionally, and even more importantly, without a forbidden watch hand-over during any safety-critical action [111]. Having discussed the vagueness of the Rules, (partial) lack of COLREG compliance by the majority of CAMs, and knowing that it takes time to build situation awareness [112], one can easily imagine the potential consequences of the vessel involved in collision avoidance maneuver suddenly changing her understanding of COLREG—without any warning.

Even apparently less-demanding situations can be challenging. The very process of avoiding the collision (i.e., maneuvering to not collide) would be based on pre-programmed algorithms or the application of artificial intelligence. Therefore, the success would depend on at least the following:

- Correctness of the algorithms, meaning that these are properly designed in a pre-operational phase of the system;
- Feasibility of the algorithms (i.e., their applicability to the given situation) and the ability of the system to implement their output;
- The ability of the system to observe the surroundings, as well as to collect input data required by the algorithms to properly calculate and execute the maneuver [113].

5. Conclusions

The objective of this discussion paper was to present, discuss, and critically analyze some practical insights on the contributions toward autonomous maritime collision avoidance. To achieve this, a critical analysis of the ambiguous aspects of *International Regulations for Preventing Collisions at Sea (COLREG)* Rules as well as a review of scientific literature on collision avoidance methods (CAMs) have been performed.

To this end, it can be raised that although the process of collision avoidance is based on the COLREG, the document itself is ambiguous to the extent that its current interpretations can lead to hazardous actions taken by prospective Maritime Autonomous Surface Ships (MASS). On the other hand, its alterations in the direction of easier interpretation by automated systems can make it incomprehensible to humans.

By overviewing the state-of-the-art CAMs, it has been noted that numerous researchers have undertaken a challenge to incorporate COLREG into their CAMs while attempting to handle their limitations, such as the neglection of ship dynamics, environmental disturbances, and uncertain movement of other ships. Specifically, many algorithms incorporate some of the COLREG Rules (e.g., 8, 13–16) for identifying scenarios, guiding evasive actions, and reducing the freedom of solutions. However, certain other parts of the legal instrument to guide vessels in collision avoidance are completely neglected. On top of this, issues identified as introducing vagueness difficult to be handled by machines are disregarded to an even greater extent. It remains therefore a challenge to achieve the final goal of autonomous collision avoidance at sea. Some other challenges are as follows: understanding entire COLREGs instead of the selected Rules only; implementation of well-justified solutions to vague issues such as good seamanship; and resolving the challenging aspects of CAMs themselves such as uncertainties related to the ship dynamics and environmental disturbances.

Regardless of the approach taken, it can take years to change the worldwide legal system and the stakeholders who noticed the disruptive potential of autonomous shipping technology would not wait such a long time. Nowadays, it appears that for every problem solved (at least in relation to collision avoidance of autonomous ships) a few new ones arise. As an intermediate solution, it is recommended that any advancements in the field should be carried out in close cooperation between industrial, scientific, and hands-on stakeholders. Above all, a comprehensive and holistic approach shall be taken to design collision algorithms incorporating all COLREG Rules. An alternative solution might be to develop artificial intelligence capable of not only involving all the Rules, but also comprehending machine-vague aspects of navigating the sea and allowing/supporting human–machine interactions.

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