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Review

Collaborative collision avoidance for Maritime Autonomous Surface Ships: A review

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ABSTRACT

Collision avoidance algorithms for autonomous ships are frequently proposed, but very few studies consider the interaction and information exchange between ships, and if they do, this is usually limited to only between autonomous ships with the use of the Automatic Identification System. However, through projects addressing the International Maritime Organization's e-navigation concept, new communication technologies are being proposed and developed for conventional vessels in the maritime domain. Importantly, vessel-to-vessel route exchange has been explored for conventional ships with seafarers on board. Consequently, it is reasonable to assume that these tools can help facilitate collaborative collision avoidance algorithms that leverage communication and information exchange to a greater extent than current collision avoidance algorithms. This paper distinguishes itself from previous reviews on maritime collision avoidance algorithms by considering and highlighting the importance of collaboration between the involved vessels. We identified gaps ranging from assumptions on communication capabilities and considerations related to non-cooperative actors to cybersecurity concerns. Drawing upon lessons learned from previous studies, we then suggested how to address these gaps by taking advantage of e-navigation concepts and technologies. Finally, we provided a high-level outline of a collaborative collision avoidance protocol. As such, this is the first comprehensive review on this important, emerging topic.

1. Introduction

By volume, global shipping currently exceeds 80 percent of world merchandise trade (UN, 2020). Embracing technological advances, the shipping sector is increasingly preparing for the deployment of maritime autonomous surface ships (MASS). These developments have been further motivated by the vulnerabilities in global supply chains becoming evident during the 2019 pandemic, with labor shortages and extensive lockdowns disrupting international trade. Already a billion-dollar industry, the autonomous ships market is expected to achieve significant growth in the coming years (Jadhav and Mutreja, 2020). In addition to reducing costs and making global supply chains robust against labor shortages and external shocks, MASSs may enhance offshore safety by eliminating accidents caused by human error and eliminating the need for human operators in harsh sea environments (de Vos et al., 2021), although others have argued that the extent to which this is the case is more uncertain (Wróbel et al., 2017). Furthermore, it is believed that the introduction of MASS may lead to a reduction of greenhouse gas emissions and improved port efficiency through slow-steaming and improved route planning (Porathe et al., 2015b).

Enabling increased automation in maritime shipping has been an ongoing effort for several years, with the International Maritime Organization (IMO) guiding the development of MASS through collaboration with regulators, industry, and researchers (IMO, 2021). The IMO has defined four degrees of autonomy, as seen in Fig. 1. In the first two degrees, seafarers are on board the ship with varying degrees of automation. In degree three autonomy, the MASS is controlled from another location, e.g., a shore control center or another vessel, without seafarers on board, while in degree four autonomy, the MASS can operate and solve complex problems autonomously without human monitoring (IMO, 2021). However, significant challenges remain before MASSs are ready for fully autonomous operations. One of these important challenges lies in developing secure collision avoidance systems capable of safely navigating waters with other autonomous and conventional vessels present while complying with the rules of the road

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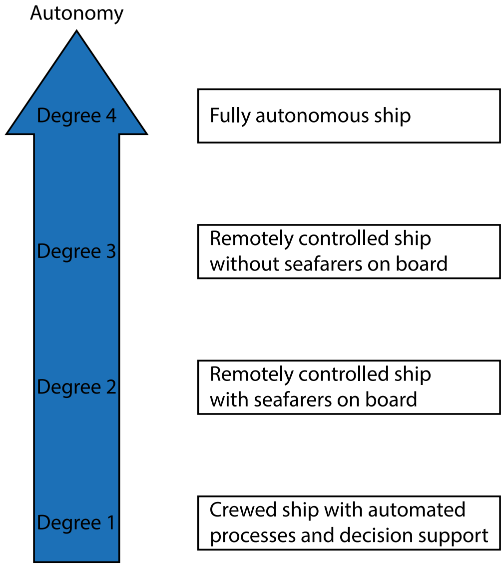

Fig. 1. The degrees of autonomy according to a recent regulatory scoping exercise by the International Maritime Organization (IMO, 2021).

at sea, the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs).

As shown by Vagale et al. (2021), the development of collision avoidance algorithms that are, at least partially, COLREGs-compliant has been on-going for several years. Recently, Woerner (2016) made great contributions by addressing the importance of complying with COLREGs while exhibiting human-like behavior and also considering non-compliant actors. Johansen et al. (2016) used mathematical interpretations of COLREGs rules to formulate the problem of obtaining a protocol-compliant collision-free trajectory in the context of Model Predictive Control (MPC). Field demonstrations of MPC-based collision avoidance algorithms were later demonstrated by Eriksen et al. (2019) and Kufoalor et al. (2020). However, as pointed out by Burmeister and Constapel (2021), most of the proposed algorithms assume access to more or less perfect information. Furthermore, information obtained through communication beyond the Automatic Identification System (AIS) is rarely leveraged.

The observation that collision avoidance algorithms in the maritime domain have been confined to self-contained algorithms, with little emphasis on collaboration and data exchange, is in stark contrast to collision avoidance algorithms developed for ground and air vehicles. In fact, for aerial vehicles, vehicle-to-vehicle (V2V) communication has been identified as crucial for collision avoidance purposes (Chakrabarty et al., 2019). As such, an important question that should be addressed is whether increased use of communication, and the addition of collaborative elements, may enhance collision avoidance algorithms for ocean-going ships.

1.1. Contributions

To address this topic, we start by reviewing the role of communication between conventional ships today and investigate how information exchange is used for collision avoidance purposes. Furthermore, we review current and future technologies that can facilitate the collaboration of vessels. In particular, we look at concepts developed through e-navigation projects, which demonstrate a growing interest in using information exchange between conventional ships. We proceed by carefully investigating and finding gaps in previously proposed collaborative collision avoidance algorithms in the maritime domain. In particular, we consider important cybersecurity aspects that have not previously been addressed by collaborative algorithms in the maritime domain. We also consider the role of shore centers and discuss to what extent collaborative collision avoidance algorithms should use a centralized or decentralized approach. Finally, we draft an outline of what a future collaborative collision avoidance algorithm may look like. As such, this paper distinguishes itself from previous reviews, e.g. (Chen et al., 2020), on maritime collision avoidance algorithms by considering and highlighting the importance of collaboration between the involved vessels and is the first comprehensive review on the topic.

Table 1
Systematic literature review protocol.

Subject	Description
Database	Web of Science
Search strategy	(“collision avoidance” OR “path planning” OR navigation) AND (cooperation OR collaboration OR coordination OR intention OR negotiation) AND (autonomous OR ship OR vessel OR unmanned OR marine)
Exclusion criteria	Air, Ground, Underwater, Space, Formation, Biology/Medicine
Publication type	Journal and conference papers
Time interval	2000 - January 2022

1.2. Research methodology

The scope of the article contains maritime communication technologies, e-navigation projects, and collision avoidance studies that can facilitate the collaboration of vessels. The articles related to communication technologies and e-navigation projects are identified from the authors’ previous readings. For collaborative collision avoidance algorithms, a systematic literature review is conducted. Table 1 defines the review protocol of our study. We excluded multiple ship formation studies and focused on collaborative collision avoidance studies containing active information exchange of the vessels. After filtering, we screened the remaining studies by their abstracts and manuscripts if needed. The studies related to e-navigation and communication are categorized as supplementary articles, and collision avoidance algorithms are reviewed further in detail. Additionally, we included some articles which are not in the search results but identified from reference lists. We recorded the systematic literature review process using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Page et al., 2021). The total number of articles and review process is presented in Fig. 2.

1.3. Outline

The remainder of the paper is structured as follows. Section 2 introduces terminology, COLREGs, current and future communication technologies that can contribute to collaboration, and e-navigation projects. In Section 3, we investigate how previous studies have approached collaborative and cooperative collision avoidance in the maritime domain. We proceed by comparing existing maritime collaborative collision avoidance studies in Section 4 in terms of communication architecture, compliance with COLREGs, MASS-conventional ship interaction, the inclusion of non-cooperative ships, assumption of frequent and reliable information exchange in problem-solving, and security problems that may occur during collaborative communication. Then, in Section 5, we provide high-level suggestions for future directions in maritime collaborative collision avoidance. Finally, we summarize the most significant findings in Section 6.

2. Background

The maritime environment is complex and consists of actors communicating over different communication channels, as seen in Fig. 3. Here, the land station might represent a shore control center or Vessel Traffic Services (VTS). Furthermore, aids to navigation (AtoN) stations,

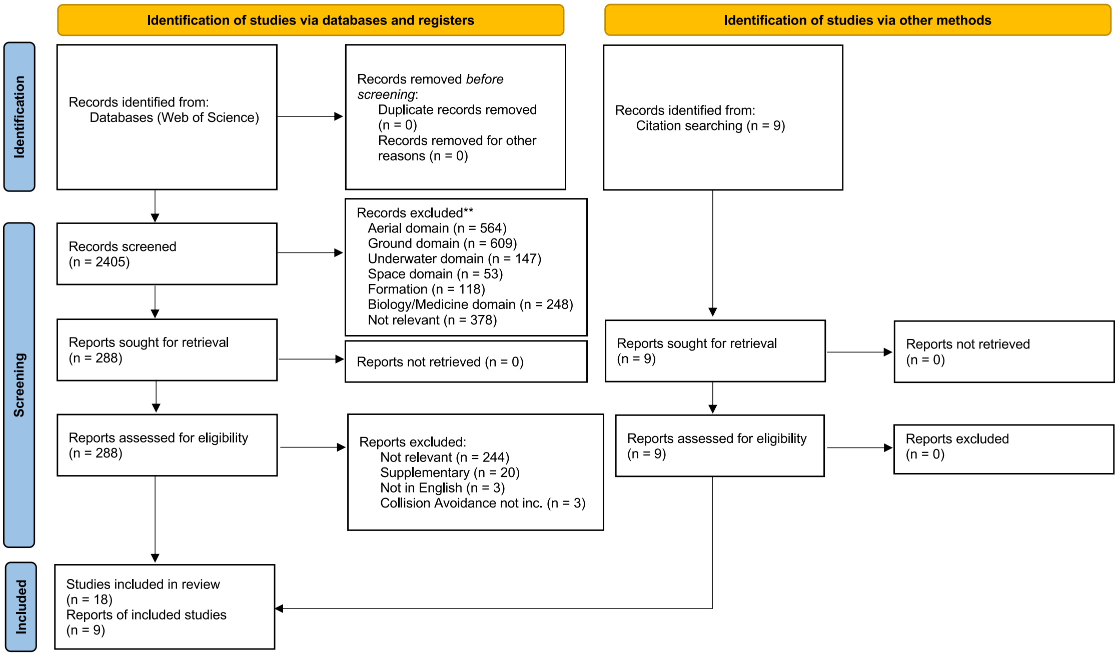

Fig. 2. Systematic literature review of collaborative collision avoidance presented with PRISMA 2020 flow diagram (Page et al., 2021).

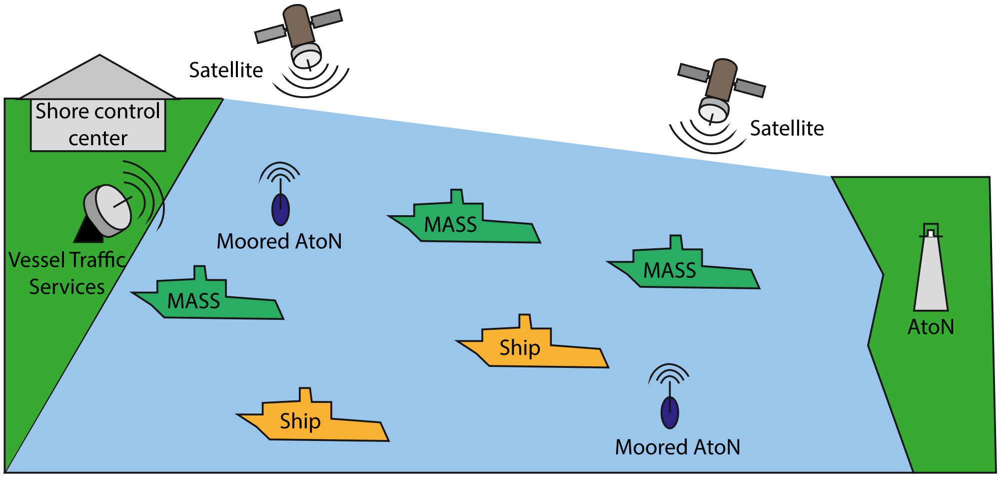

Fig. 3. An overview of relevant actors in the maritime environment, including Maritime Autonomous Surface Ships (MASSs) and Aids to Navigation (AtoN).

which can assist vessels and crews by providing information about local navigational hazards, are included.

While these actors share information, the information, except for that obtained by AIS, is rarely used by collision avoidance algorithms. Instead, collision avoidance algorithms usually limit themselves to local information obtained through onboard sensors such as radar. We are, therefore, interested in whether collision avoidance algorithms can be improved in terms of navigational safety by actively using communication and the information exchanged to a greater extent than today.

2.1. Terminology

The collaboration of MASSs and human operators, both navigators and VTS operators, can be viewed as an example of human–robot collaboration, which is a field that combines robotics, artificial intelligence, cognitive sciences, and psychology. We observe that the terms *collaboration, cooperation, coordination, intention exchange,* and *trajectory negotiation* are used interchangeably in previous studies. Therefore, we believe it will be helpful to reach a common terminology once the meanings of the terms have been clarified.

Hord (1981) states that the main difference between collaboration and cooperation is that collaboration maintains a clear, shared goal for all agents, whereas, in cooperation, the ultimate goal can be different for each agent. Consequently, when agents are cooperating, the activities of the agents are agreed upon and coordinated, but the agents may have different objectives. When agents collaborate, the activities of the agents are agreed upon and coordinated with a common goal in mind. In this context, the sharing of intent and negotiation of trajectories can be perceived as tools that help facilitate coordination for cooperation and collaboration.

With these definitions in mind, the term ‘cooperation’ can be used to describe the interaction between ships in a collision avoidance scenario if we define the individual goal of each ship as reaching its next waypoint. However, a more common problem description used in collision avoidance is that of producing velocity vectors resulting in collision-free trajectories, a goal shared by all agents. Consequently, we find that the term ‘collaboration’ is more suitable when describing these collision avoidance algorithms.

2.2. COLREGs

The rules of the road at sea are determined by the COLREGs, defined by the IMO (1972). Consisting of 38 rules, the goal of the COLREGs is to prevent collisions at sea. Importantly, the COLREGs rules are vague, and intentionally formulated such that experienced mariners can leverage their experience and situational awareness to make sound judgments. This makes the COLREGs very different from air traffic rules and the rules of the road.

With MASSs gaining traction in commercial shipping and public transportation, the development of collision avoidance algorithms has gained increased attention. We can sort collision avoidance algorithms into two categories; those who do consider COLREGs and those who do not. Somewhat surprisingly, there is still significant research on algorithms belonging to the second category, possibly because the extent to which COLREGs apply to MASS has been unclear. However, in a recent scoping exercise, the IMO addressed this question by stating that *'COLREG, in its current form, should still be the reference point and should retain as much of its current content as possible'* (IMO, 2021). Regarding algorithms that belong to the first category, these are often only designed to comply with parts of COLREGs, e.g., rules 13–17. An important reason for only considering this subset of rules is that these are the rules that are somewhat easier to interpret mathematically. Still, the vagueness of the rules poses a significant challenge, and a joint interpretation is likely required to make different collision avoidance algorithms compatible with one another.

However, even if joint interpretations of COLREGs are found, concerns remain about the co-existence of conventional ships and MASSs. For example, according to a study by Rutledal et al. (2020), the behavior of vessels at a Norwegian ferry crossing differed from COLREGs in a significant portion of the encounters. Such deviations are permitted, for example, under COLREGs rule 2. While the vessels involved likely would have exhibited different behavior if they had no means to communicate, large vessels often take for granted that smaller vessels will give way, even if they have the right to stand on according to COLREGs. Consequently, if a MASS does not predict such 'common sense maneuvers', dangerous situations could occur. To address this problem, Porathe (2020) suggested more extensive communication in addition to a traffic separation scheme called *moving havens*, inspired by the coordination of friendly submarines during military exercises. Nevertheless, others, such as Relling (2020), argue that total self-governance of MASSs is neither achievable nor desirable and should, therefore, not be the objective.

2.3. VHF and AIS communication

Today, VHF radio and AIS facilitate information exchange between ships and shore centers, e.g., VTS. The shore centers coordinate ships in ports, harbors, straits, or other areas in their responsibility to prevent incidents such as collisions and groundings. For example, a VTS can guide ships over VHF radio by monitoring the sea traffic using radar and AIS and mapping the information on an electronic navigational chart. Additionally, when in doubt of navigation safety outside of a VTS responsibility area, it is common among mariners to call other vessels over VHF radio to ask for their intention or local advice. Unfortunately, verbal communication is prone to misunderstandings caused by language barriers, accents, and cultural differences.[1] Furthermore, high communication traffic in congested waters can affect the radio communication quality. Therefore, mariners also use non-verbal actions to communicate intentions between vessels. An example of a non-verbal action would be an apparent course and speed change compatible with COLREGs. But the action should be visually observable by eyes, radar, Electronic Chart Display and Information System (ECDIS), or AIS to leave no room for doubt about the ship's intention.

The AIS operates in the VHF maritime mobile band and was developed as a tool to help avoid collisions at sea when vessels are out of range of shore centers. According to the International Convention for the Safety of Life at Sea (SOLAS), Chapter V, all commercial vessels over 300 gross tonnages that travel internationally, as well as all passenger vessels, must be equipped with an AIS Class A transponder, while smaller vessels may be equipped with Class B transponders (IMO, 1974). The Class A transponders transmit dynamic data every 2–10 s while underway and every 3 min while at anchor, and static data every 6 min. Conversely, Class B transponders transmit their position whenever the transmission slot is empty (Golaya and Yogeswaran, 2020). Importantly, this may cause Class B transponders not to transmit data in congested waters.

The data transmitted over VHF is used by ships for collision avoidance, by VTS for traffic management, and by coastal authorities to obtain information about the ship and its cargo. Also, it is used to increase situational awareness in emergencies, such as for search and rescue or environmental pollution incidents. While information from AIS can be used by collision avoidance algorithms, it is important to be aware that not all ships are fitted with AIS. Furthermore, the dynamic ship data describing the course, speed, and position come from Global Navigation Satellite System (GNSS) receivers and internal instrumentation, such as gyroscopes, onboard the vessel. This data could be tampered with before being transmitted over AIS. Additionally, static data describing the location of the position-fixing antenna is manually entered into the AIS transponder and could be erroneous and out of date. Finally, voyage-related data describing the ship's draught and route plan are rarely updated. These weaknesses are compounded by the fact that AIS messages are transmitted without integrity checks, meaning the system accepts messages containing transmission errors, or worse, spoofed messages containing false data. For these reasons, collision avoidance algorithms should not solely depend on AIS data but rather use its data transfer feature for collaboration if additional integrity checks are imposed.

2.4. VHF data exchange system

The VHF marine mobile band was initially used for voice communication but has later been revised by the International Telecommunications Union to include designated data transmission channels. Since AIS messages are transmitted over these channels, the extensive use of AIS and increased demand for data transfer have caused congestion in these radio channels in heavily trafficked areas. Combined with the lack of integrity checks, this severely limits the utility of AIS in these regions. As such, the VHF Data Exchange System (VDES) has been developed as an extension of the AIS system.

The new VDES system integrates the AIS system with two other systems called Application Specific Messages (ASM) and VHF Data Exchange (VDE), using separate terrestrial and satellite channels. The ASM channels enable the exchange of standardized messages and are used to lighten the load on the AIS channels, while the VDE channels enable high-speed data transfer of customized services. Furthermore, the VDES system permits additional integrity checks to detect faulty transmissions and forward error correction. The VDES system is expected to be retrofitted on existing vessels and be widely adopted by 2025 (IALA, 2019).

2.5. Broadband networks

Maritime communication systems such as AIS, VDES, Global Maritime Distress Safety System, and Navigational Telex have extended their coverage by MF/HF/VHF frequencies. However, these systems

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[1] These dangers have been highlighted in several court rulings, such as *The "Maloja II"* [1993] 1 Lloyd's Rep. 48, page 52, *The Aleksandr Marinesko v Quint Star* [1998] 1 Lloyd's Rep. 265, page 278, and *The Nordlake and The Seaeagle* [2016] 1 Lloyd's Rep 656, paragraph 76.

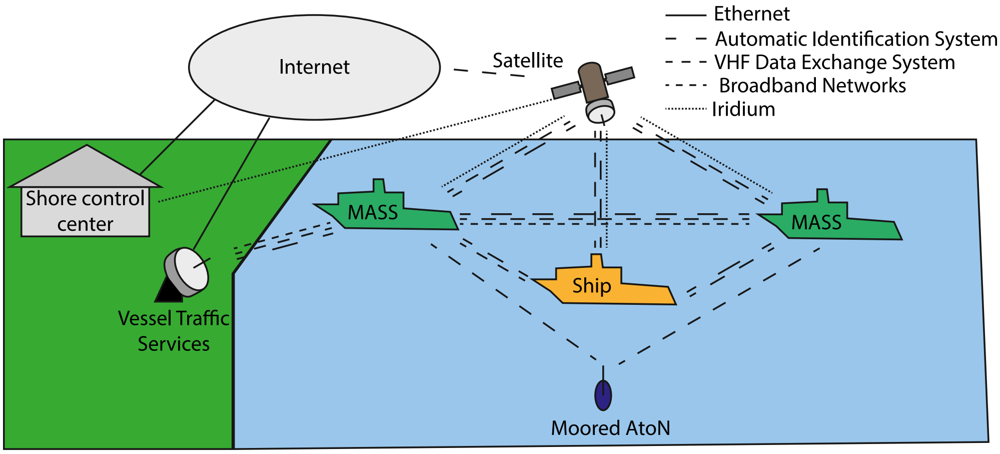

Fig. 4. Communication technologies that can be leveraged for collaborative collision avoidance purposes.

have limited bandwidth. If satellite-based solutions are used, they can provide global coverage, but at the same time, they suffer from high latency and high costs. As such, recent studies are investigating how to use high-speed, broadband terrestrial mobile networks, e.g., 4G and 5G, for coastal maritime applications. Some of the technologies explored are WiFi, WiMax, and Long-Term Evolution (LTE), and the studies are focused on 2.4 GHz, 5.2/5.8 GHz, and 5G mmWave frequency bands for the maritime wireless channels.

The Republic of Korea works on the LTE-Maritime Project to provide data rates of over 10 Mbps, with a coverage of 100 km from the base stations, which are placed on mountains for increased an line of sight (Jo and Shim, 2019). Similar to LTE, WiMax (IEEE 802.16j) offers high data rates and wider coverage with the help of multi-hop networks (Choi et al., 2014). Multi-hop networks consist of base stations, relay stations, and mobile stations, which are end-users. The Norwegian Research Council's MAMIME project aimed to collect WiFi measurements at 5 GHz in the field with an autonomous ship, i.e., Kongsberg Seatex AS's Drone I. The test results demonstrated high data rates, between 10–700 Mbps, from a maximum range of 4800 meters (Yang et al., 2018). For applications to transfer more data over longer ranges, Kongsberg's Maritime Broadband Radio provides data rates up to 16,5 Mbps at ranges up to 55 km (Kongsberg, 2021). High-speed, broadband data transfer is needed to control and monitor MASS from shore control centers. Moreover, MASS connectivity can be supported by collaborative usage of satellites, multi-hop networks, mobile broadband technologies, and long-range terrestrial systems. Consequently, broadband network solutions are attractive options for collaborative collision avoidance systems near shore.

2.6. Multimodal connectivity and the maritime connectivity platform

Zolich et al. (2019) gives a comprehensive review of the available communication links at sea, and Fig. 4 illustrates some of the communication links that may be used. With such a wide range of communication links available, maintaining connectivity when switching communication technology is crucial, and we refer to concurrent communication across different communication technologies as *multimodal communication*. For example, vessels taking advantage of high-bandwidth mobile broadband communication in coastal regions should maintain the connection with nearby ships if they switch over to VDES. In a survey on these issues, Höyhtyä and Martio (2020) suggested the use of a *connectivity manager* whose job it is to ensure that data is transmitted over the appropriate communication channels, subject to requirements such as capacity, latency, and service availability.

To establish an infrastructure for secure, multimodal communication at sea, the Maritime Connectivity Platform (MCP) is being developed (Weinert et al., 2018). The MCP is an open-source, decentralized communication framework that connects maritime stakeholders and maritime information services. The MCP includes three main components; the Maritime Identity Registry (MIR), the Maritime Service Registry (MSR), and the Maritime Messaging Service (MMS). The MIR provides secure communication by verifying and enabling authorized stakeholders to reach the services, and authentication of users is done by Public Key Infrastructure (PKI) and Open ID Connect methods. The MSR is a collection of maritime services where stakeholders can register new services to the platform. Finally, the MMS provides the information exchange part of the service by considering the geographical location and available communication links between users. As such, the MCP is a promising communication framework, and governmental authorities and non-profit organizations are taking part in the project. For example, a collaborative collision avoidance algorithm can be registered as a new service for both conventional ships and MASS usage, and the PKI of the MCP can benefit the cybersecurity part of the collaboration.

2.7. E-navigation and route exchange

To bring shipping into the 21st century, the IMO has adopted an *e-navigation strategy plan*. The goal of the plan is to enhance maritime safety, security, and protection of the marine environment while also reducing the administrative burden and increasing the efficiency of maritime trade and transport. The IMO defines e-navigation as "*the harmonized collection, integration, exchange, presentation, and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment*" (IMO, 2018).

An important concept explored through e-navigation projects is that of *route exchange*, first investigated by the Danish Maritime Safety Administration through the EfficienSea project between 2009 and 2012 (EfficienSea, 2011). The idea was that mariners could create and broadcast waypoints to coordinate their intentions as an alternative to verbal VHF communication. These ideas were expanded upon by Porathe and Brödje (2015a), who proposed the use of two concepts called tactical and strategic route exchange. A tactical route exchange consists of a limited number of waypoints, while a strategic route exchange contains all waypoints of the voyage plan. The idea is that strategic route exchange should be limited to ship-to-shore exchange with authorities, e.g., traffic coordination centers, for business and security reasons, while tactical route exchange can be used for ship-to-ship and ship-to-shore exchange for navigational safety and collision avoidance purposes. The successor of the EfficienSea project, EfficienSea 2, ran between 2015 and 2018, intending to test VDES and MCP concepts.

The MONALISA 1.0 project tested route exchange concepts on bridge simulators and in the Baltic Sea between 2010–2013 and developed the RTZ route exchange format (Porathe et al., 2014a,b). The

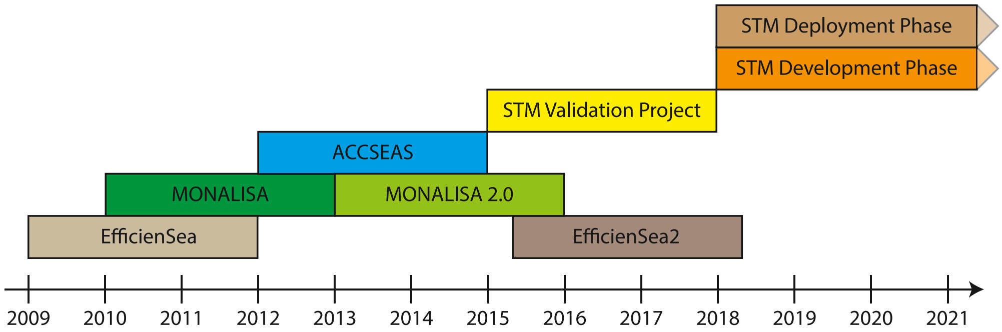

Fig. 5. A timeline of e-navigation projects.

RTZ route exchange format was developed further in the successor, the MONALISA 2.0 project (STM, 2015). The resulting format was then formally standardized as the S-421 route exchange format by the International Electrotechnical Commission (IEC) in IEC 61174 (IEC, 2015) and later IEC 63173-1 (IEC, 2021). These route exchange files consist of three main components where the first part contains general information of the route, the second part contains route geometry, e.g., waypoints, legs, turn radius, revision, etc., and the third part contains a schedule for waypoints and legs.

During the ACCSEAS project, which ran from 2012 and 2015, e-navigation concepts were tested in a test-bed in the North Sea region. Through bridge simulations where a route exchange concept was integrated with the ECDIS, it was found that simultaneously displaying the ship's real position and overlapping, exchanged routes were confusing for the operators. Therefore, to decrease the confusion, a feature that enables or disables the planned route is suggested (Billeso, 2015). Also, considering the possible confusion and user interface problems, the route exchange is not suggested to be used in close-range scenarios by Porathe et al. (2015b).

The Sea Traffic Management (STM) project suggests using route exchange as a strategical tool to support the decision-making of safe trajectories rather than using it in close encounters. Bridge simulation tests (STM, 2019b) showed that mariners were more likely to breach COLREGs when routes were exchanged. It is stated that multiple, overlaid routes would confuse the mariners, and it would be hard to use route exchange in close-range scenarios. Additionally, STM defined requirements for route exchange (STM, 2019a).

A timeline of relevant e-navigation projects is shown in Fig. 5. While the e-navigation projects did not treat collaborative collision avoidance specifically, many of the concepts and ideas developed through the projects are useful tools that can help facilitate collaborative collision avoidance.

3. Collaborative collision avoidance in maritime applications

We proceed by investigating how previous studies have approached collaborative collision avoidance in the maritime domain. As we will see, the main distinction in the classification of collaborative collision avoidance algorithms is the communication architecture used. The communication architecture of collaborative multi-agents can be set up in two ways; centralized or decentralized. Both approaches have advantages as well as disadvantages. In centralized approaches, a central processing unit or master unit is assigned to solve the collision avoidance problem for all the collaborating ships. The master unit can be a shore station, for example, VTS, or an off-shore agent. All the information should be transmitted to the master unit to create a complete situational awareness. If the master unit has full access to information about each agent, then such centralized approaches can find globally optimal solutions. However, centralized approaches are vulnerable to situations where the master unit is missing information or unable to communicate with some agents. In decentralized approaches, each agent shares information with others and then solves the collision avoidance problem locally by using the information currently available to each agent. While this approach may not lead to a globally optimal solution, it is more robust to asynchronous information states and communication problems.

3.1. Decentralized approaches

Although collaborative collision avoidance has not been studied as heavily as self-contained collision avoidance algorithms, some researchers have stressed the importance of interaction between ships. For example, Hu et al. (2006) and Qinyou et al. (2006) pointed out the lack of interaction features between ships in existing collision avoidance algorithms and proposed a decentralized two-ship negotiation protocol in the open sea for COLREGs-compliant give-way and stand-on responsibilities. The proposed protocol, i.e., the Collision-Avoidance Negotiation Framework (CANFO), is initiated by the give-way ship or the one that first detects the collision risk, and the contribution of this study is that the negotiation intention is proportional to the ship's gross tonnage. If the stand-on ship is smaller, the give-way vessel can be more willing to propose alternative trajectories. Hu et al. (2008) improved the negotiation protocol further by integrating the planned routes of both ships into the negotiation. However, since these studies only consider interactions between two compliant agents, the practical usefulness of the proposed protocol is unclear.

Liu et al. (2007) implemented a Multiple Agent System (MAS) model for ship collision avoidance by using the Beliefs Desires and Intentions (BDI) framework to simulate human knowledge and reasoning for the ships and VTS. Sailing-related static and dynamic ship data and practical collision avoidance rules correspond to beliefs, goals such as stand-on, give-way, emergent avoidance, and minimizing risk correspond to desires, and functions or sets of actions to achieve a goal correspond to intentions. Using this concept, ten types of messages, e.g., inform, request, advice, accept, and reject, can be sent to facilitate communication between ships over AIS. Later, Liu et al. (2008a,b) designed decentralized, centralized, and negotiation-based collision avoidance algorithms for multiple vessel encounter scenarios. In the first algorithm, each ship calculates its route without collaboration. In the second algorithm, a delegated leader calculates collision-free routes. Finally, in the third algorithm, the negotiation process is initiated by a ship and runs until all ships agree to the negotiated solution. While the work is noteworthy, the performance of the negotiation procedure is unknown because they do not show complicated scenarios.

Online evaluation of the risk of collision is an important feature to help determine when and with whom to initiate collaboration and collision avoidance actions. However, in multi-ship scenarios, merely determining that a risk of collision exists is not sufficient. Instead, the collision risk must be quantized such that target ships can be sorted according to risk values. Kim et al. (2014) proposed a fuzzy theory-based approach for calculating collision risk by including Distance to the Closest Point of Approach (DCPA), Time to the Closest Point of

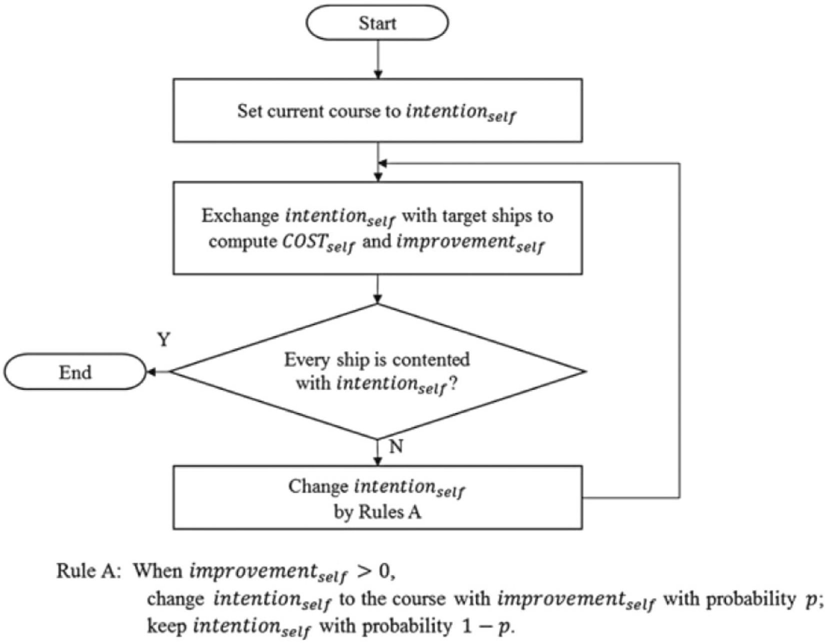

Fig. 6. The Distributed Stochastic Search Algorithm protocol where Rule A represents stochastic course change.
Source: Image courtesy of Kim et al. (2017).

Approach (TCPA), and change in relative bearing. In the proposed Distributed Local Search Algorithm (DLSA), each ship calculates its proposed course and its contribution to reducing the collision risk. The ship with the most significant contribution changes its course. The exchange of intentions and course changes continue until the ships reach their goal destinations. Kim et al. (2015) later developed the Distributed Tabu Search Algorithm (DTSA) to improve the efficiency of DLSA and eliminate quasi-local minimum states, i.e., the inability to generate a course change even though there is a risk of collision. In quasi-local minimum states, the DTSA forces ships to choose a new route. However, it was realized that both DLSA and DTSA required frequent messaging between ships before converging to a steady state. To reduce message traffic, Kim et al. (2017) proposed the Distributed Stochastic Search Algorithm (DSSA) presented in Fig. 6. Simultaneous stochastic course changes often lead to faster convergence to a solution and naturally eliminate the occurrence of quasi-local minimum states. The author conducted further simulations of the DSSA algorithm with multiple vessels and reported the importance of the parameters, i.e., safety domain and detection range, on the collision avoidance performance (Kim, 2019). The aspects of DLSA, DTSA, DSSA that may be improved can be listed as considering speed changes and investigating how to reach a solution where non-cooperative and conventional ships are present.

Hornauer and Hahn (2013) included non-cooperative ships in their collaborative collision avoidance algorithm by using a probabilistic approach. Mean course and speed values of non-cooperative ships were calculated from historical AIS data and used to predict optimal trajectories of negotiating vessels. Nash Bargaining and distributed optimization methods were used to calculate optimal trajectories. In their following study, the A* algorithm was used in the creation of new trajectories during the negotiation, and Nash Bargaining was used to converge to the decentralized solution (Hornauer et al., 2015).

Li et al. (2019a) proposed a distributed coordination mechanism for many-to-many ship encounters that guarantees an optimal solution. The dynamic collision risk calculation based on the ship maneuvering model and the communication cost analysis are the main contributions of their method. The method uses rudder angle and steering time to differentiate different ship maneuvering models and uses these parameters with Distributed Constraint Optimization (DCOP), Synchronous Branch and Bound (SyncBB), Dynamic Programming Optimization Protocol (DPOP), and Asynchronous Forward Bounding (AFM) to find the optimum and compare the methods. The protocol used in their proposed algorithm is shown in Fig. 7.

Zhang et al. (2015) proposed a real-time, distributed anti-collision decision support algorithm for multiple vessel situations under COLREGs requirements. Each vessel decides its anti-collision action, i.e., course or speed change, and broadcasts its intentions. The method consists of decision-making schemes for give-way and stand-on responsibilities based on CPA calculations and crossing angles. The authors indicated that course alterations are more beneficial if the crossing angle is large, and speed alterations should be considered if the angle is small. The method is limited to starboard course alterations and speed reductions, and the broadcasted intention message contains course, speed, and period to be applied. The method was simulated with four ships, and the study revealed that in situations with multiple vessels, violation of COLREGs created more difficult scenarios to solve for the vessels.

Zheng et al. (2015) proposed a cooperative distributed collision avoidance algorithm based on the Alternating Direction Method of Multipliers (ADMM) in the Model Predictive Control (MPC) framework. The goal of the approach is to solve local collision avoidance problems and attain overall safety by iterative communication and optimization between multiple MASSs. A crossing scenario of two MASSs is simulated in the study. After successive iterations, vessels adjust their trajectories, i.e. one vessel slows down, to maintain a safe distance from each other. Later, a fast ADMM approach is proposed by the authors for faster convergence and reduced computation time, to achieve a real-time system (Zheng et al., 2016). The approach was simulated with five vessels and showed considerable improvement in convergence and computation with a reduced number of iterations. The main drawback of the studies is that COLREGs-compliant maneuvers are not considered.

Ferranti et al. (2018) proposed a decentralized approach for multiple robot trajectory planning based on Nonlinear Model Predictive Control (NMPC) theory. The authors simulated three MASSs in a canal intersection scenario. Each vessel solves a local NMPC problem to minimize a cost function and communicates with the others to agree on collision-free trajectories. Deviations from the planned trajectory, and reductions in speed, are penalized in the local cost function. The

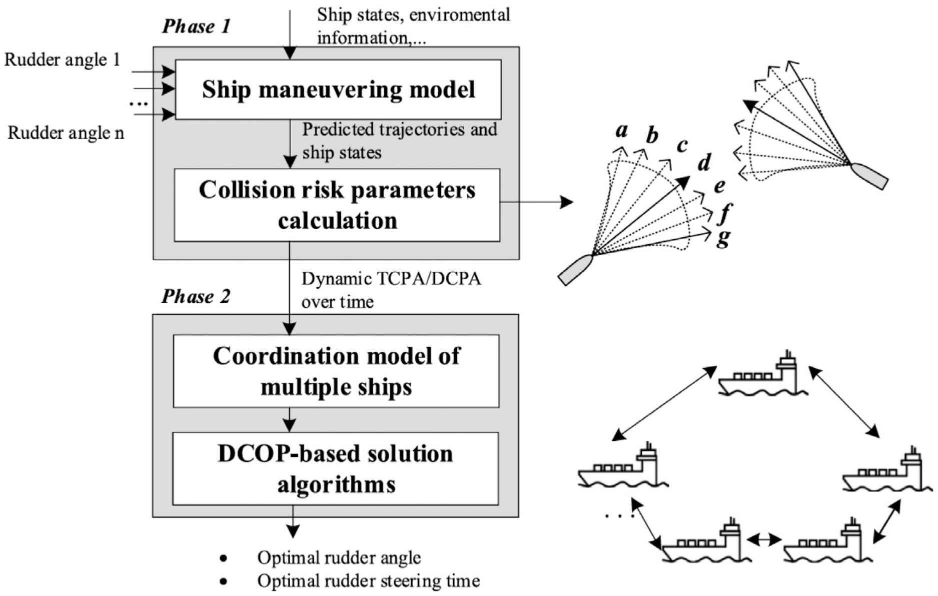

Fig. 7. A distributed coordination mechanism protocol for many-to-many ship encounters.
Source: Image courtesy of Li et al. (2019a).

optimization problems are solved in parallel by vessels with a modified ADMM suitable for nonconvex optimization. However, the method does not take COLREGs and non-cooperative actors into account.

Denker and Hahn (2016) proposed the Maritime Traffic Alert and Collision Avoidance System (MTCAS) in 2016 and ran the MTCAS project through 2018. The MTCAS is inspired by the Traffic Alert and Collision Avoidance System (TCAS), used for collision avoidance on aircraft (FAA, 2011). The TCAS system envelops each aircraft in a protected volume with three regions, a caution area, a warning area, and a collision area. The system may then produce two types of audio messages to the pilot, a Traffic Advisory (TA) and a Resolution Advisory (RA). If an aircraft is found inside the caution area, a TA is issued, warning of its presence. If an aircraft is found inside the warning area, an RA is issued, and an evasive maneuver is suggested. An RA message mandates the pilot to take prompt action according to the RA, whereas the pilot is not obliged to follow a TA message. The MTCAS system was designed as a tool to help the Officer on Watch (OOW) by providing more accurate predictions of Closest Point of Approach (CPA), an alarm system, methods to resolve critical situations, and a framework for cooperative maneuver negotiation. The MTCAS system uses a concept called escalation states to assess the risk of collision at any given time, and the system consists of five states; Clear State, Recommendation State, Danger State, Last Minute Maneuver (LMM) State, and Collision State. The state is determined based on the time and distance until Critical Ship Pose (CSP), an extension of the classical CPA. When determined to be in a Danger State, the system initiates a cooperative negotiation for evasive maneuvers between the vessels involved inspired by the protocol proposed by Kim et al. (2017). If found to be in an LMM State, the system issues an alarm and suggests a collision-avoidance maneuver. As such, MTCAS resembles the TCAS system with RAs in many ways. The CSP seeks to enhance the traditional CPA measure by also accounting for measurement uncertainties, no-go areas, and pose at CPA. The authors then claim that the suggested system produces fewer unnecessary alarms. When a vessel is in a Recommendation State, the MTCAS system produces predictions of the most probable behavior of other vessels based on historical data. These predictions are used to create a most probable maritime situation picture, where encounters with other vessels can be classified according to COLREGs as head-on, crossing, and overtaking situations. Finally, the system uses this prediction to predict the most probable resolution of the situation based on historical data. As such, this resolution prediction is not necessarily compliant with COLREGs.

Chen et al. (2018a,b) did not only work on collaborative collision avoidance but also the formation of vessels. The concept of Cooperative Multi-Vessel Systems (CMVSs) consists of multiple cooperative MASSs and aims to solve the Vessel Train Formation (VTF) problem. In the VTF problem, multiple MASSs are formed into a train formation in narrow passageways or corridors, with a constant distance between them. Each MASS uses a decentralized MPC to determine its actions and communicates the plan iteratively among them by using ADMM. Chen et al. (2019) further developed the CMVSs approach by including Cooperative Waterway Intersection Scheduling (CWIS). CWIS is used to plan the actions of each MASS in an intersection. Both works assume frequent and reliable communication between cooperative autonomous ships. While these ideas are related to traffic management in inland waterways, they might be relevant for future traffic management, e.g., in the future North Sea, where heavy traffic will need to be guided through designated corridors in wind farm zones (Porathe et al., 2014b).

Yang et al. (2019) proposed a two-step-smooth-turn cooperative collision avoidance mechanism for multiple MASSs communicating directly through 5G networks. The authors combined the K-Means clustering algorithm with the Genetic Algorithm (GA) to improve the stability and early convergence problem of the GA. The K-Means algorithm helps to find a better initial condition to be used in the GA. And this improves the probability of successful mutations before the GA converges. The generated trajectories are evaluated by their total length, collision risk value, and smoothness. The two-step-smooth-turn method results in generating shorter and smoother trajectories. The method is simulated with two-vessel crossing and multiple vessel meeting scenarios. Although the method generates safe collision avoidance trajectories, COLREGs-compliance and non-cooperative targets are not considered.

Collision-free trajectory planning for multiple vessels can be done either with an optimization sequence or a global optimization method. In the optimization sequence method, vessels calculate safe trajectories in an order determined by the vessel's maneuverability or the collision risk value. In the global optimization method, all the vessels' optimum trajectories are calculated at once. Ni et al. (2020) proposed a multistage sequential decision-making process called Multilayer Coding-Multiple Population Genetic Algorithm (MC-MPGA) for collaborative collision avoidance. The authors quantified encounter situations by segmenting the collision risk index based on DCPA and TCPA values and queued the vessels into groups, i.e., optimization echelons. Echelons use the GA to solve the collision avoidance problems in order. Vessels are assumed to communicate their planned trajectories. The authors simulated the method with three and six-vessel encounters at open water. And the algorithm generated COLREGs-compliant safe trajectories. Implementing static obstacles and considering vessels not following their planned trajectories are the possible improvements declared by the authors.

Huang et al. (2020b) investigated a less focused field, human–machine-interface (HMI), i.e., collaboration and interaction of MASS and human operator. HMI-oriented collision avoidance system (HMI-CAS) can autonomously find optimal collision-free trajectories based on Generalized Velocity Obstacle (GVO) algorithm. But at the same time, human operators can interfere with the decision if the optimal solution is not COLREGs-compliant. With the help of the GVO algorithm, HMI-CAS can present the feasible solution, optimal solution, finite feasible solutions, closed region of feasible solutions, or closed region of dangerous solutions to the operators. In the multiple vessels scenario, MASS solves the collision avoidance problem in a sequence and exchanges their trajectories with the others. The last vessel in the queue is chosen as the ship with the highest priority. Although the authors did not explain the details of the queueing method, the method is promising both for shore control center operations and conventional ship-MASS encounters.

3.2. Centralized approaches

Looking at centralized approaches, Tam and Bucknall (2013) addressed the collaborative collision avoidance problem by proposing a centralized solution where the collision-free trajectories are planned in one system. To solve the collision-free trajectory problem, the ships are ranked by assigning priorities. If the problem is limited to two-ship scenarios, COLREGs' roles define the priorities between ships. If there are multiple ships, the ship priorities are ranked with their turning radius and stopping distance parameters. Higher priority is assigned to ships with a large turning radius and stopping distance, while more maneuverable ships are assigned lower priorities. The ships with lower priorities then fulfill the give-way role. The collision avoidance algorithm finds collision-free trajectories starting with the highest priority ship and iterates through all ships in the order of descending priority. The proposed method is shown in Fig. 8.

Szlapczynska (2015) proposed a high-level procedure for a centralized collaborative collision avoidance algorithm called a maneuver auto-negotiation system. The approach is semi-distributed, in which negotiating ships send their maneuver availability arrays to the leading ship assigned in the area. The assigned leader finds COLREGs-compliant collision-free trajectories for each ship and sends the plans through the communication system. Because the work remains at a procedural level, the performance of the method could not be evaluated.

Kurowski et al. (2019) proposed a central multi-vehicle trajectory generator for multiple MASSs in confined waters. MASSs exchange their navigation states and control commands with a central server through the GALILEOnautic network, an academy-industry joint program. The central trajectory generator calculates and sends collision-free trajectory commands to each vessel. The A* algorithm is used at every iteration, i.e., after data is exchanged, for single vessel trajectory generation, and WORHP, a nonlinear optimization software, is used for finding the optimal trajectories for the vessels. The cost function for the optimization consists of time to destination, energy consumption, and the square distance between the vehicle's desired and final destinations. The authors validated the method through field experiments with two different USVs and a human-operated boat with an AIS.

Li et al. (2019b) approached the collaborative collision avoidance problem from a different perspective. Instead of maximizing safety, they aimed to minimize path time and course alterations in the cost function and proposed a centralized rolling horizon optimization method, as shown in Fig. 9. Compliance with COLREGs was taken into account in the calculation of collision-free course changes. In the rolling horizon optimization method, the optimization problem is solved in each time step with the updated information from the ships. Since the optimization problem is solved in a central processing unit, a globally optimal solution is found. However, in the study, non-cooperative ships were not included in the scenario, and all ships were assumed to be cooperative and have reliable communication capability.

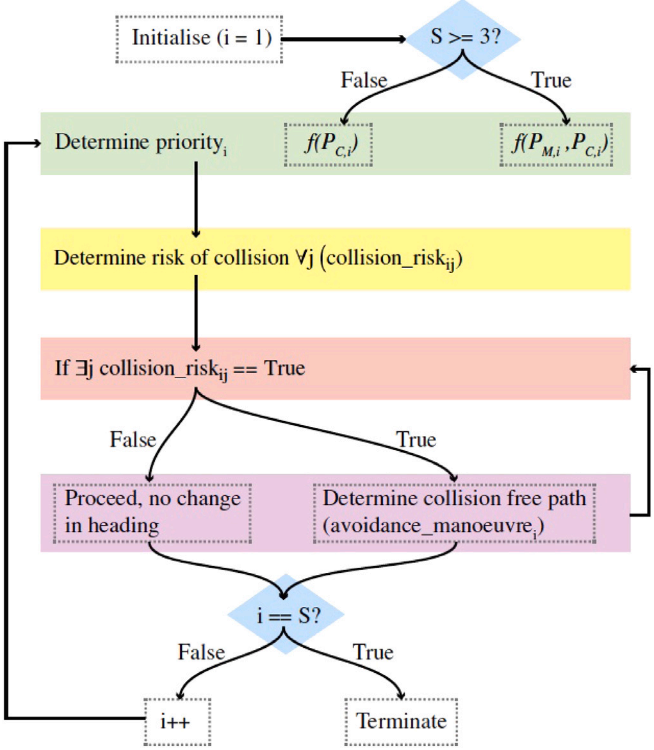

Fig. 8. A deterministic cooperative trajectory planning algorithm protocol where S is the total number of ships in the scenario.
Source: Image courtesy of Tam and Bucknall (2013).

4. Analysis of applications

We proceed by analyzing how collaborative collision avoidance algorithms have been used in the maritime domain, and studies from the maritime domain are compared in Table 2. The studies were evaluated in terms of communication architecture, i.e., centralized or decentralized, compliance with COLREGs, MASS-conventional ship interaction, the inclusion of non-cooperative ships in the scenario, assumption of frequent information exchange in problem-solving, and cybersecurity considerations.

4.1. Centralized and decentralized approaches

Centralized and decentralized approaches constitute the first point of distinction in the classification of collaborative studies. Even though implementing a centralized approach is easier with a master processing unit, the computational cost can be problematic with increasing numbers of agents. Additionally, if one of the agents does not act according to plan, the globally optimal solution is at stake. Decentralized management is robust because the failure of an agent does not affect the globally optimal solution. Moreover, it is scalable because each agent solves the planning problem locally. On the other hand,

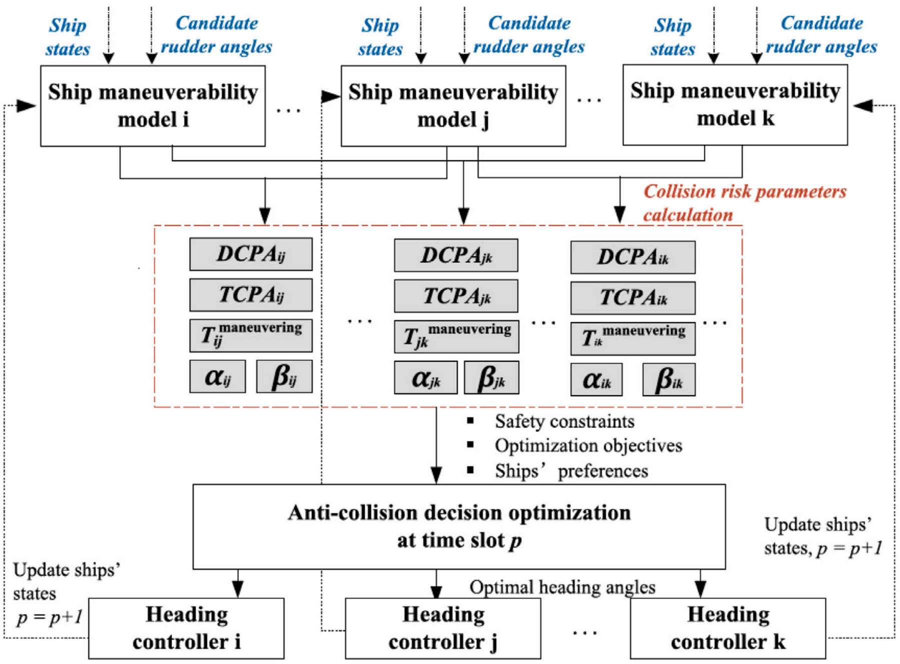

Fig. 9. A centralized rolling horizon optimization protocol.
Source: Image courtesy of Li et al. (2019b).

Table 2
Comparison of collaborative collision avoidance studies in the maritime domain.

Reference	Method name	Centralized	Decentralized	Two ships	Multiple ships	Only between MASSs	Non-cooperative targets	COLREGs considered	Cybersecurity considered
Hu et al. (2006) Qinyou et al. (2006)	CANFO	–	✓	✓	–	✓	–	✓	–
Hu et al. (2008)	Improved CANFO	–	✓	✓	–	✓	–	✓	–
Liu et al. (2007, 2008a,b)	Negotiation-based multi-agent planning	–	✓	–	✓	–	–	✓	–
Tam and Bucknall (2013)	Deterministic cooperative trajectory planning	✓	–	–	✓	✓	–	✓	–
Hornauer and Hahn (2013)	Nash bargaining	–	✓	–	✓	✓	✓	✓	–
Kim et al. (2014)	DLSA	–	✓	–	✓	✓	–	–	–
Hornauer et al. (2015)	Nash bargaining	–	✓	–	✓	✓	✓	✓	–
Kim et al. (2015)	DTSA	–	✓	–	✓	✓	–	–	–
Szlapczynska (2015)	Maneuver auto-negotiation	✓	–	–	✓	–	✓	✓	–
Zhang et al. (2015)	Anti-collision decision making	–	✓	–	✓	✓	–	✓	–
Zheng et al. (2015, 2016)	ADMM	–	✓	–	✓	✓	–	–	–
Denker and Hahn (2016)	MTCAS	–	✓	–	✓	–	✓	✓	–
Kim et al. (2017), Kim (2019)	DSSA	–	✓	–	✓	✓	–	✓	–
Ferranti et al. (2018)	NMPC and ADMM	–	✓	–	✓	✓	–	–	–
Chen et al. (2018a)	CMVSs	–	✓	–	✓	✓	–	–	–
Chen et al. (2019)	CMVs, CWIS	–	✓	–	✓	✓	–	–	–
Li et al. (2019a)	DCOP/DPOP/SyncBB/AFM	–	✓	–	✓	✓	–	–	–
Li et al. (2019b)	Rolling horizon optimization	✓	–	–	✓	✓	–	✓	–
Kurowski et al. (2019)	Multi-vehicle GNC	✓	–	–	✓	✓	✓	–	–
Yang et al. (2019)	K-Means and GA	–	✓	–	✓	✓	–	–	–
Ni et al. (2020)	MC-MPGA	–	✓	–	✓	✓	–	✓	–
Huang et al. (2020b)	HMI-CAS with GVO	–	✓	–	✓	✓	–	✓	–

the decentralized method may not reach a globally optimal solution because it focuses on locally optimal solutions that may not use full information.

We find that decentralized approaches are predominantly applied in both maritime and aerial collaborative collision avoidance studies. Interestingly, maritime traffic management today is also decentralized in which each ship is responsible for itself, and VTS does not have a central authority to order ships' actions. The responsibilities of the VTS are defined in IMOs Guidelines for Vessel Traffic Services (IMO, 1997). In the guideline, IMO state "*When the VTS is authorized to issue instructions to vessels, these instructions should be result-oriented only, leaving the details of execution, such as course to be steered or engine maneuvers to be executed, to the master or pilot on board the vessel. Care should be taken that VTS operations do not encroach upon the master's responsibility for safe navigation, or disturb the traditional relationship between master and pilot*" (IMO, 1997, p. 7). However, VTS operators can still face legal consequences following an accident if VTS does not fulfill its responsibilities.

Building fully decentralized collaboration between ships can also cause problems. Vessels in the VTS area can negotiate routes and come to an agreement, but there may be unknown inputs that they do not consider. For example, an approaching large vessel with limited maneuverability, or a local, strong current, may make the plan difficult to follow. If the route negotiation is built around a centralized approach, the VTS would have to override the master's or pilot's duties and face legal consequences in an accident. As the responsibility of autonomous vessels' actions in the event of an accident is still unclear, giving VTS the responsibility to directly control an autonomous vessel's route should be considered carefully.

Finally, as a third approach, Van Westrenen and Praetorius (2014) suggested a polycentric control. The authors argued that a decentralized management style should be used in low-density traffic, and a VTS-oriented centralized management style should be used in high-density traffic areas. A more authoritative VTS can decide which ship's plan should be accepted after an evaluation. But with this approach, all the participating ships in the scenario need to be able to make plans and exchange information.

4.2. Compliance with COLREGs

A large number of COLREGs-compliant collision avoidance algorithms have been proposed so far. However, when we examine studies claiming to be COLREGS-compliant, we find that the majority of the algorithms are concentrated on rules 13 to 17, possibly with the addition of other rules, e.g., Rule 8. This begs the question: Which rules must a collision avoidance algorithm cover to be 'COLREGs-compliant'? Although answering this question is out of the scope of this study, we find that two rules that are important for collaborative collision avoidance algorithms are not included in most studies. Firstly, Rule 2, i.e., responsibility contains two articles:

- (a) *Nothing in these Rules shall exonerate any vessel, or the owner, master or crew thereof, from the consequences of any neglect to comply with these Rules or of the neglect of any precautions which may be required by the ordinary practice of seamen, or by the special circumstances of the case.*
- (b) *In construing and complying with these Rules due regard shall be had to all dangers of navigation and collision and to any special circumstances, including the limitations of the vessels involved, which may make a departure from these Rules necessary to avoid immediate danger.*

As such, this rule states that to prevent a possible accident, the seafarers should use all available means, knowledge, competence, i.e., ordinary practice of seamanship, and if necessary, act contrary to other COLREGs rules. Cockroft and Lameijer (2004) pointed out some examples for ordinary practice of seamanship, e.g., a power-driven ship should be clear from an anchored ship, ships should consider the effects of shallow water, and tides on their maneuverability. But it is clear that this rule can be interpreted differently from one situation to another and it is hard to quantify the rule in computer algorithms (Porathe, 2019). The present setup of the COLREGs prevents researchers from designing algorithms compliant with Rule 2, but at least some supervisory control mechanism can be included to cover examples as in Cockroft and Lameijer (2004). Additionally, collision avoidance algorithms should be designed to consider maneuvers non-compliant with the other COLREGs rules to fulfill the requirements of the second article. Next, we have Rule 18, i.e., responsibilities between vessels. Rule 18 presents the right-of-way hierarchy between ships and takes into account the restrictions on maneuverability resulting from operations they perform, except for narrow channel, traffic separation scheme navigation, and overtaking scenarios. For example, a MASS in a stand-on position per Rule 15, i.e., crossing situations, must fulfill give-way responsibility per Rule 18 when it encounters a ship with a restricted ability to maneuver. Without collaboratively sharing operational information between ships, MASSs must have an advanced image processing system to classify visual navigational signals and lights to take this rule into account.

4.3. Interaction between MASSs and conventional ships

We find that the route exchange methods proposed in the e-navigation projects are applied only between conventional ships. However, in collaborative collision avoidance studies, the coordination for the collision-free trajectory is studied only for autonomous ships, and conventional ships are rarely considered. But these ships are likely to coexist in future maritime traffic. Therefore, combining route exchange and collaborative collision avoidance might help integrate autonomous and conventional ships and enhance maritime traffic safety.

4.4. Non-cooperative ships

Narrow channels and coastal waters form regions with heavy maritime traffic. In these regions, SOLAS-compliant vessels passing through the traffic line, ferries that enter the traffic line from time to time, and recreational small sea vehicles, fishing boats, and kayaks can be found together. Small marine vehicles used for recreational purposes will not be included in the collaboration process since do not have navigational aids such as VHF radio or AIS. Additionally, ships with communication devices may not be consciously involved in the collaboration process. We refer to these actors as non-cooperative targets. Non-cooperative targets need to be taken into account in collaborative planning.

4.5. Frequent communication and data exchange

In most collaborative collision avoidance studies, it is assumed that there is frequent data exchange between ships both during the trajectory planning and the realization of the plan. With the help of frequent data exchange, MASSs can update their trajectory plans according to emerging situations. However, frequent information sharing might not be possible in the collaboration process, which can include conventional ships. For example, OOWs may not pay attention to a collaborative process and skip periodic updates, not sharing their plans while commanding the ship. Furthermore, frequent communication may be disrupted by cyber–physical attacks or by congestion in high-density traffic regions. A possible solution is to consider using the collaboration activity only for the planning of collision-free trajectories. However, using the collaboration activity only in the planning phase means that reactive collision avoidance algorithms will have to be used when ships deviate from the agreed plan.

4.6. Safety and security considerations

The safety of the proposed collaborative collision avoidance algorithms is rarely properly discussed, and as seen from Table 2, the security aspect is not discussed at all. The main safety concern of the proposed algorithms consists, for example, of evaluating and comparing metrics such as the distance between vessels at CPA. However, we argue that there are significantly more important safety considerations related to the proposed algorithms than these metrics. For example, most of the algorithms assume continuous communication and synchronous information states between all of the involved actors. Virtually all algorithms only consider MASSs and do not consider what effect the presence of conventional, manned vessels will have on the proposed schemes. Moreover, most of the algorithms do not even consider how non-cooperative ships, which are almost certainly going to be present in the vicinity of MASSs at some point, are handled.

We find that the early algorithms often depended on strong assumptions. For example, Hu et al. (2006) did not consider the impact of communication faults on the proposed route negotiation method. In several algorithms, such as those proposed by Li et al. (2019b), where optimization algorithms are used to find optimal trajectories, reliable transmission and consistent situational awareness of all vessels involved are required. However, these are problematic assumptions. Wireless communication at sea is inherently unreliable and is affected by packet loss caused by, e.g., interference and fading. Additionally, actors may be unaware of the presence of others, some may not take part in the collaborative scheme, and some might intentionally transmit false data. Unreliable data transmission and asynchronous states between vessels are considered by Li et al. (2019a), yet the existence of vessels that do not partake in the collaborative scheme is not considered, nor is the possibility of malicious actors. A malicious actor may seek to transmit false data to the other actors to produce a pre-determined outcome, such as the most optimal trajectory for own ship considering fuel costs or time, possibly at the expense of the safety of other vessels. In any event, we find that the safety of collaborative collision avoidance algorithms is closely intertwined with the security of the communication technology used, which is not addressed by any of the studies.

Cybersecurity challenges in inter-vehicular communications over automotive ad-hoc networks were investigated by El-Rewini et al. (2020), and the V2V communication threats considered encompass various types of manipulation and spoofing attacks. Since automotive applications are considered, real-time requirements are important. The recommendation by El-Rewini et al. (2020) is to use a PKI and digital signatures to detect spoofed messages and hold vehicles accountable for transmission of false information with the goal of manipulating the behavior of other vehicles, e.g., to clear a path for own vehicle.

Caprolu et al. (2020) reviews the cybersecurity of vessels, but vessel-to-vessel communication is limited to AIS. Among the concerns listed are spoofing, hijacking, data manipulation, and denial of service attacks, and the authors argue that these weaknesses can be addressed by application-layer frameworks. While manipulation and spoofing attacks can be handled similarly to automotive vehicular communications, jamming attacks are a significant threat at sea and hard to prevent when communication is done over radio. Consequently, from a safety-critical point of view, predictable and reliable operation in the absence of reliable communication should be an inherent feature of collaborative collision avoidance algorithms.

5. Suggestions for collaborative collision avoidance protocols

We proceed by describing how collaborative collision avoidance algorithms can help address the topics described and mechanisms that should be present for future algorithms to be secure in practical applications.

5.1. Centralized and decentralized approaches

Considering the current maritime traffic management and VTS responsibilities, we believe that collaborative collision avoidance algorithms should take a decentralized approach. Notice that an important benefit of centralized approaches, i.e., globally optimal solutions, might not be the most important aspect of collaborative collision avoidance algorithms. Instead, we believe that priority should be given to safety, robustness to non-compliance, and communication failure. Therefore, rather than giving VTS the power to evaluate the big picture and prioritize ships, we think the VTS could serve as an advisor in the collaborative scheme. As such, the VTS could provide local navigation information, e.g., regarding site-specific restrictions or traffic patterns, that can be incorporated into the ships' collaborative planning. Ships start the collaboration protocol in a decentralized approach, and the VTS can suggest an approval, rejection, or include additional considerations to the route exchange process. The number of collaborating ships could be restricted according to collision risk index values, geographic positions, and speeds to fulfill computational requirements and reduce complexity. Clustering algorithms can be used to segment ships into collaborative groups.

5.2. Compliance with COLREGs

For advanced MASS collision avoidance algorithms, in addition to compliance with COLREGs rules 13–17, it is very important to consider Rule 2, i.e., responsibility, and Rule 18, i.e., responsibilities between vessels. The most effective way to include rules 2 and 18 in algorithms will be to provide interaction between ships. For this reason, in collaborative collision avoidance protocols, it is necessary to share the intentions of the ships and the types of operations that restrict the maneuvering capability via the route exchange method.

5.3. Interaction between MASS and conventional ships

For autonomous ships to navigate safely in the same maritime traffic area as conventional ships, the OOWs on conventional ships and VTS operators should also be included in the collaborative activities. In this way, the uncertainty of future target ship trajectories can be reduced. Additionally, ships can request and approve trajectories directly with other ships that may be non-compliant with COLREGs to increase temporal and spatial efficiency, two key metrics stressed by Woerner (2016). Furthermore, autonomous ships should interact with AtoN devices in the future maritime traffic area, such as buoys and lighthouses. For this reason, it would be beneficial to add AtoN devices to the collaboration and data exchange protocol for future studies.

5.4. Non-cooperative ships

Collaborative plans made without considering non-cooperative vessels are easily disrupted since non-cooperative vessels do not necessarily communicate their intentions and route plans, and future trajectories need to be predicted based on current positions and velocities. In the case of small leisure vessels, there will likely be no communication. Therefore, radar, LiDAR, and optical sensors should be used for situational awareness to track these targets. A constant velocity model or historical AIS data can then be used to predict the future trajectories of non-cooperative ships.

5.5. Frequent communication and data exchange

Collision-free routes ensuring safe navigation can be created collaboratively using data exchange between the ships. However, if conventional ships are included in the collaborative activity, the human operators commanding the ship could forget, or neglect, to share their intentions by constantly updating digital plans. Furthermore, vehicles with whom there has been an agreement might deviate from the planned routes. Therefore, the trajectories of other vessels must be monitored to detect such deviations. If deviations are detected, the vessels can initiate a new route negotiation effort. However, if a vehicle gets too close, reactive collision avoidance should instead be used.

5.6. Safety and security considerations

Future communication at sea is bound to be inherently multimodal. While using cryptography to establish secure communication is a necessity for collaborative collision avoidance algorithms and commercial deployment of autonomous ships, it is also important that the added security mechanisms do not become a safety liability. Importantly, the ability to verify the integrity and origin of a received message is critical, yet this does not mean that messages whose origin cannot be authenticated should automatically be dismissed.

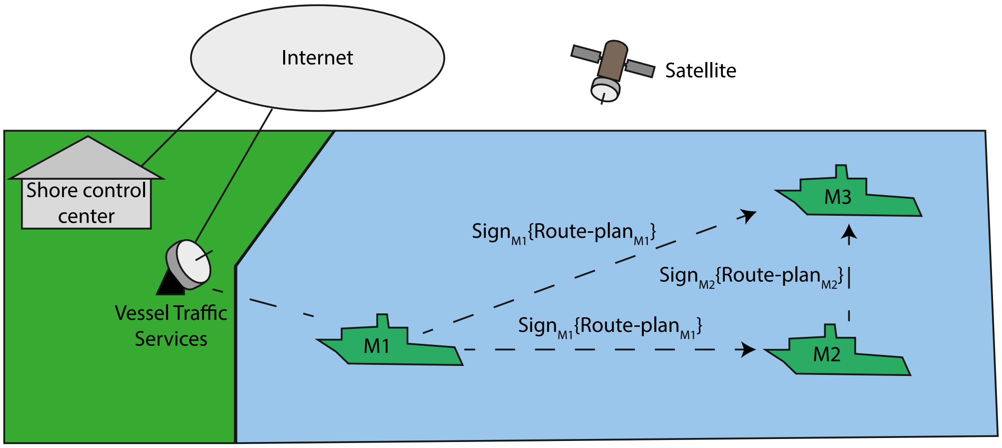

Fig. 10. Secure transmission of messages using digital signatures, assuming a public key infrastructure is available.

We concur with El-Rewini et al. (2020) and believe that non-repudiation of origin is essential since all actors should not be assumed to be trusted entities. By using digital signatures as part of a collaborative collision avoidance protocol, as shown in Fig. 10, the risk of accepting spoofed messages or messages with compromised integrity is negligible. Additionally, each vessel can be held accountable for the information it conveys to other ships in the event of an accident. Furthermore, non-repudiation of receipt could also be incorporated if requirements are placed on the reception equipment, such that the logged data is resistant to tampering. By imposing non-repudiation of receipt, an actor cannot reject having received a message it, in fact, has received, thus helping to resolve responsibility and accountability in the event of an accident. In any event, a PKI should be established for the former requirement.

Notably, the establishment of a PKI for maritime applications may provide additional benefits. For example, there has been an increase in cyber–physical attacks targeting GNSS navigation. Since the GNSS signals are very weak, they are vulnerable to jamming attacks, and because the signals are entirely public, they are vulnerable to spoofing and manipulation attacks. While security mechanisms have been developed for GNSS systems, advanced attacks conducted by nation-states intelligence agencies may have the capability to bypass these mechanisms. These considerations motivate the addition of local, redundant navigation solutions. For example, AtoN devices and local shore stations, such as digital lighthouses, can broadcast their position if GNSS is lost, e.g., due to malfunction or jamming attacks. Consequently, the vessel can estimate its absolute position if it knows its position relative to the shore station, e.g., using bearing and range from radar. The vessel can also re-broadcast these messages to increase the range, thus forming a collaborative navigation scheme. Furthermore, such a navigation scheme can help detect GNSS spoofing attacks by checking for inconsistencies between the estimated position obtained from the local navigation system and the received GNSS signals. In fact, such a scheme is also beneficial from a safety point of view, as ships gain additional navigation redundancy in case GNSS equipment fails for any reason. An illustration of the concept is shown in Fig. 11.

As discussed in Section 2, the MCP is planning to establish a PKI for the maritime domain. Therefore, it is natural to argue that collaborative collision avoidance algorithms should take advantage of this infrastructure in the future. Still, how messages with invalid or missing digital signatures are to be handled remains an open question; it might well be that a vessel with good intent actively participates in a collaborative collision avoidance scheme without having a valid public–private key pair in the PKI. Consequently, treating all such vessels as non-compliant actors is likely not feasible from a safety perspective. In fact, since certification revocation at sea may be slow (Bour et al., 2021), ships whose certificate has been revoked may well participate in information exchange and route negotiation without the other vessels being aware of the revocation.

5.7. Proposed protocol for collaborative collision avoidance

We summarize the gaps we have identified and our recommendations for future algorithms in Table 3. We believe that MASSs should interact and share information with other MASSs, conventional ships, shore stations, and AtoN devices to enhance navigational safety, and collaborative collision avoidance algorithms should take advantage of the information obtained through route exchange methods. By actively using this information, the uncertainty of future trajectories of target vessels is reduced, which should result in better predictions. Additionally, vessels should be capable of requesting and approving trajectories directly with other vessels to increase temporal and spatial efficiency. The assumption is that the collaborating ships can share local route plans, i.e., waypoints and maneuvering limitations defined in COLREGs Rule 18, e.g., engaged in fishing, not under command, restricted maneuverability, etc., by using any of the available communication systems. Here, the combined use of AIS, VDES, and mobile broadband networks over the MCP framework would contribute to increased connectivity. Additionally, the PKI of the MCP can contribute to addressing important cybersecurity threats.

We propose a high-level architecture of a two-stage, decentralized collaborative collision avoidance protocol. In the first stage, the participating cooperative ships negotiate to agree upon a collision-free trajectory plan. Reactive collision avoidance algorithm is used to avoid non-cooperative ships and others that do not act according to the plan. In this way, OOWs on conventional ships are included in the planning phase, and frequent communication is not required throughout the execution phase. A high-level description of the proposed collaborative collision avoidance algorithm is shown in Fig. 12. It should be noted that the trajectory planning algorithm for each stage should generate COLREGs-compliant trajectories considering at least head-on, crossing, overtaken and overtaking rules. But at the same time, the reactive algorithm should also consider non-compliant maneuvers to prevent collision and comply with COLREGs Rule 2.

The MASS should constantly track nearby vessels and calculate collision risk index values. If the collision risk index for a target ship is above a pre-defined threshold value and there is enough time for planning, an invitation to collaborate is sent to the corresponding ship and the neighbors. The neighbor ships in the collaboration activity can be decided with a predetermined range value or with the help of a clustering algorithm. The value of the collision risk index could be computed using a weighted function of the TCPA and DCPA, as proposed by Huang et al. (2020a).

The invitation to collaborate and corresponding replies consist of the initial route exchange messages. A collaborating vessel should maintain each ship's next couple of waypoints, operation type according to the COLREGs Rule 18, and the collision risk index values calculated for its targets. After the route exchange messages are transmitted

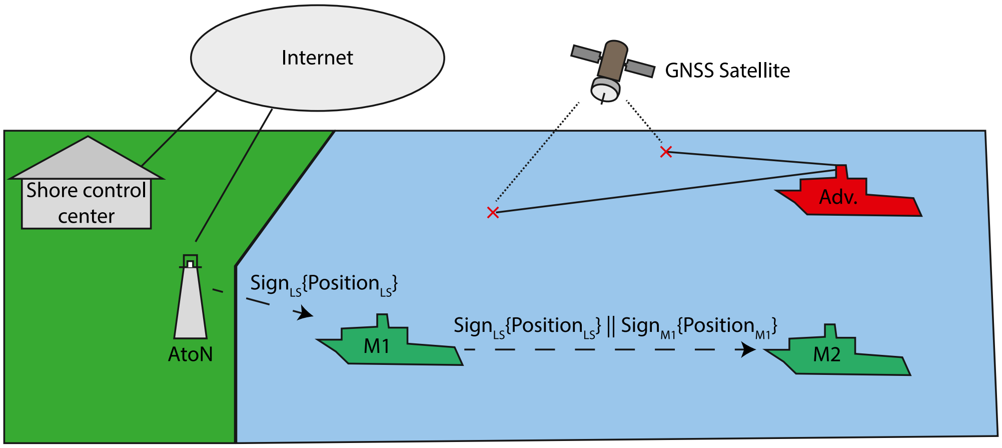

Fig. 11. Leveraging a public key infrastructure to establish secure local navigation when Global Navigation Satellite Systems (GNSS) are unavailable, for example, because an adversary is jamming the GNSS signals.

Table 3
Gaps and suggestions for collaborative collision avoidance applications.

Related topics	Limitations and gaps	Recommendations
Centralized or decentralized architecture	Centralized communication and problem-solving are easier to implement and can find globally optimal solutions but are computationally expensive with an increasing number of ships. On the other hand, decentralized approaches are robust to changes, scalable, and similar to today's maritime traffic management. However, decentralized approaches might result in locally optimal solutions and can miss the global optimum.	We believe decentralized collaboration should be considered between ships, and VTS operators should act with an advisory or referee position. To limit complexity and the number of collaborating ships, clustering algorithms based on parameters such as risk assessment, position, and speed, can be used.
Compliance with COLREGs	MASS collision avoidance algorithms usually consider COLREGs rules 13 to 17. But Rule 2, i.e., Responsibility, and Rule 18, i.e., responsibilities between vessels that shape the right-of-way hierarchy according to operation types and their effect on the maneuverability, are not studied widely. However, these rules are crucial for navigational safety and should be considered by collision avoidance algorithms.	We believe that collaborative collision avoidance algorithms can consider these rules to a greater extent by leveraging shared information. For example, intentions of the ships, e.g., waypoints and the types of operations that restrict maneuvering capabilities, e.g., not under command, restricted in ability to maneuver, fishing, sailing, constrained by draught, etc., are relevant.
Interaction of MASSs and conventional ships	E-navigation and route exchange projects considered only the collaboration between conventional ships, and collaborative collision avoidance studies only considered the collaboration between MASSs. However, MASS and conventional ships are likely to coexist in the maritime traffic of the future.	We argue that OOWs on conventional ships and VTS operators should be included in collaborative collision avoidance protocols. Additionally, we believe that data exchange with AtoN devices should be considered to enhance the navigational safety of MASSs.
Handling non-cooperative ships	Since small vessels do not have a VHF radio or AIS, these cannot participate in collaborative activities. Furthermore, other vessels with these systems may show non-cooperative behavior from time to time.	Since non-cooperative vessels will be present in maritime traffic, we stress the importance of considering the presence of such actors in collaborative collision avoidance algorithms. For example, the future trajectories of these actors can be predicted using constant velocity models or historical AIS data.
Frequent communication and reliable data exchange	Collaborative collision avoidance studies conducted thus far have assumed frequent and reliable communication and data exchange between ships, both during the trajectory planning and execution. However, this might not be possible for OOWs on conventional ships while commanding their ships. Furthermore, communication might fail because of cybersecurity breaches or congestion of the communication channels.	With conventional ships included in the collaborative process, we believe that the frequency of communication should be constrained, and collaborative collision avoidance protocols should only be used during the planning phase. During execution, it should be checked whether there is enough time for a new collaboration activity, and a new collaboration should only be initiated if there is sufficient time. Consequently, we argue that MASSs should also be equipped with a reliable reactive collision avoidance algorithm that can be used if there is not sufficient time to negotiate collaborative maneuvers.
Security considerations	Current collaborative collision avoidance algorithms do not consider the presence of malicious actors and are therefore vulnerable to a range of cyber–physical attacks, such as jamming and spoofing attacks.	We stress that for collaborative collision avoidance algorithms to be secure, they must have a default mode of operation in case communication is lost. Furthermore, using public–private keys and a PKI, digital signatures should be used for non-repudiation of origin and data origin authenticity.

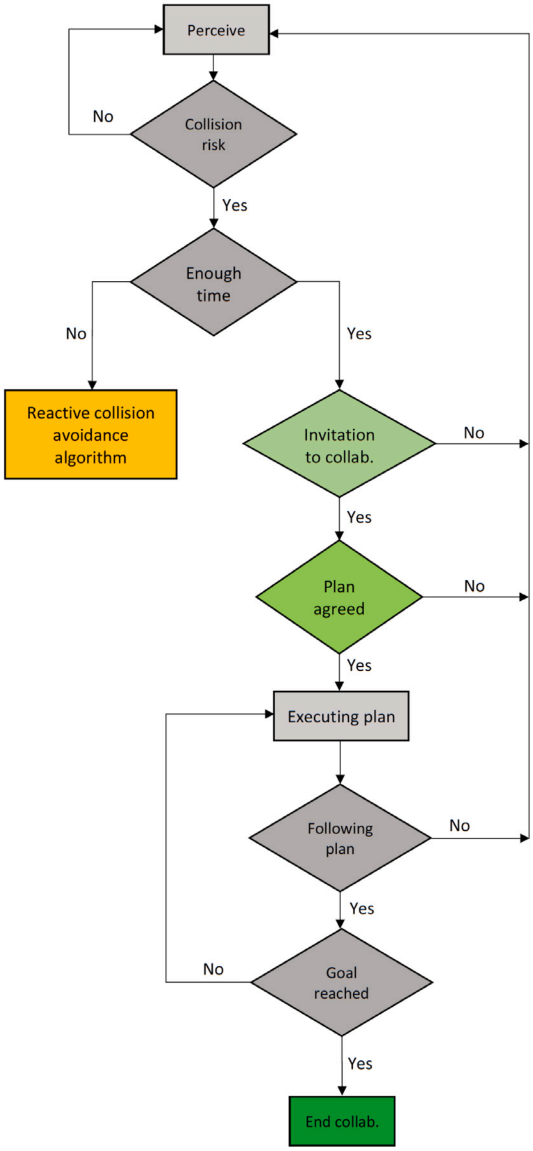

Fig. 12. A high level description of a collaborative collision avoidance algorithm.

to all ships participating in the collaboration, stand-on & give-way responsibilities will be updated according to the maneuvering constraints of the ships. In addition, it will be determined which ship will plan its collision-free trajectory in which order by considering the collision risk indexes between all ships. The give-way vessel with the highest collision risk index value plans the first collision-free trajectory and broadcasts the plan with the safety value of the trajectory. If necessary, the stand-on vessel updates its plan and broadcasts it. The second give-way vessel with the highest collision risk index value calculates and broadcasts its proposed trajectory and safety value. This iteration continues until all ships are covered and safety values converge below a pre-defined threshold value. The execution phase of the plan starts after this step.

A re-negotiation of the plan can be initiated at any time, as long as there is sufficient time to find an agreement. However, if there is not sufficient time to find an agreement, each vessel should switch to reactive collision avoidance maneuvers. Non-cooperative ships should be handled by using predictions of their future trajectories based on the constant velocity model or historical AIS data. Digital signatures should accompany all messages that are transmitted for non-repudiation of origin and to authenticate the origin of the message. The physical medium through which the messages are transmitted may vary depending on availability. However, transitions between different communication technologies should not disrupt current negotiations. For this purpose, the MCP could be used. The collaboration ends once the ship reaches its final waypoint, or the distance to the other ship exceeds a pre-defined threshold.

6. Conclusion

With the use of autonomous shipping technology in practice, MASS and conventional ships will coexist in maritime traffic. Current collision avoidance algorithms are usually self-contained and rarely take advantage of information exchange other than AIS. While collaborative collision avoidance algorithms have been proposed previously, they are usually formulated as optimization problems seeking to find globally optimal solutions considering temporal and spatial constraints. But these methods usually assume reliable communication, which is a very strong assumption. Furthermore, malicious actors seeking to interrupt or manipulate the collaborative effort are not considered. Therefore, in this study, we investigate how current and future technologies and concepts can be used to facilitate collaboration. For example, VDES, which is expected to replace AIS in the future, and mobile broadband networks, which can be used in coastal regions, can offer communication solutions for route exchange and collaboration activities together with the MCP infrastructure. Additionally, the PKI brought forward by the MCP can be used to address cybersecurity concerns by allowing non-repudiation of origin and data origin authenticity.

When examining collaborative collision avoidance algorithms from the maritime domain, we found systematic weaknesses related to the assumed communication capabilities, compliance with COLREGs, the interaction of MASSs and conventional ships, the handling of non-cooperative ships, and cybersecurity considerations. As a result, we have drawn upon lessons learned from the previous studies and outlined a high-level, decentralized collaborative collision avoidance algorithm. We argue that the traditional responsibilities assumed by ships and VTS services should be preserved but also highlight that shore stations and the VTS can assume an important advisory role for both MASSs and conventional ships in the future. We believe route exchange and collaborative collision avoidance methods will not only improve the MASS's navigational safety but also these methods can be used by conventional ships. The proposed method can be implemented in both autonomous and conventional ships' integrated navigation systems. This way verbal communication-related misunderstandings can be prevented while the decision-making process of the OOW can improve with the negotiated collision-free trajectories. In our future studies, the goal is to use the lessons learned throughout this review and design a collaborative collision avoidance algorithm along the lines of the high-level description. The proposed algorithm should then be tested and validated through simulations and field tests.

CRediT authorship contribution statement

Melih Akdağ: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Petter Solnør:** Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Tor Arne Johansen:** Conceptualization, Supervision, Resources, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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