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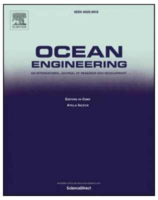

# Improving safety of interactions between conventional and autonomous ships

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ABSTRACT

Automatic controllers work best when the system they control can be sufficiently well modelled. This is a problem for control of autonomous ships in mixed traffic situations where the autonomous ship interacts with conventional ships, as the crew on other ships can and will exert unexpected behaviour that cannot be easily modelled. This paper analyses the problem of information acquisition, situational assessment and how to predict other ship's actions for autonomous ships that need to interact with conventional ships. We identify causes for the interaction problem and classify these into a decision making model. We also identify possible measures to overcome the problems and based on an impact analysis where technical, procedural and regulatory aspects are considered, we discuss and propose some possible ways to reduce or solve this problem. The conclusion is that the most likely and effective short-term solution is to assist the autonomous ships with human operators and the best longer-term solution may be to improve the information exchange between the ships, complemented with changes in COLREGs.

## 1. Introduction

When an autonomous ship needs to interact with a conventional ship, this can only be done safely when the automation system is sufficiently able to assess its environment and predict the conventional ship's next actions (Kim et al., 2022). The required quality of this prediction will depend on several factors. Amongst these are the distance between the two ships and the margin, represented by a safety zone, that each ship has for safe and corrective manoeuvres (Berge et al., 2019). In close encounters and restricted waters, this can be a challenging task, and at higher speeds, and especially for shallow waters, the complexity of interaction manoeuvres may also be affected by ship-to-ship generated wave forces (DeMarco Muscat-Fenech et al., 2022). Likewise, the crew on a conventional ship may also have problems with understanding an autonomous ship's intention and plans (Porathe, 2019a). The main challenge in these cases is the asymmetric access to information on the two ships: how each ship understands its environment and what plans the other ship has. While it is questionable if this asymmetry can be overcome by sensors and information processing alone, there are some other ways that this asymmetry can be reduced or sometimes eliminated. This paper will explore proposed measures to deal with this problem, evaluate their impact, and requirements for implementation.

The IMO Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) (IMO, 1972) provides crew on conventional ships with a set of rules on how to avoid collisions between ships for a set of encountering scenarios together with a set of corresponding requirements to signalling. The COLREGs have been the basis for dealing with interactions with other ships for many years. However, it is at best challenging to implement the COLREGs in automatic decision making systems (Veitch and Alsos, 2022), and any machine implementation of the COLREGs is a factual interpretation that can lead to its own problems. This is also highlighted in the review on anti-collision algorithms in (Akdağ et al., 2022), where it is found that anti-collision algorithms either ignores COLREGs completely, or only implements the parts of COLREGs that can be expressed mathematically. Furthermore, since COLREGs contains qualitative rules, e.g., based on "good seamanship" or and "ordinary practice", they cannot easily be applied by autonomous ships in mixed traffic situations with conventional ships. Thus, common standardised interpretations are needed (Akdağ et al., 2022).

The two terms "good seamanship" and "ordinary practice", written as they are without any specific definition, implies that the crew must make their own judgement on how to assess a situation and take actions

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to avoid collision, and if necessary, also deviate from and possibly breach one or several rules (Porathe, 2019b), which might contribute to escalate the encounter to a more complex one (Zhang et al., 2015). Automatic controllers cannot in general handle this type of ambiguity. How to carry out "good seamanship" and "ordinary practice" is further complicated within the rules by use of other qualitative wording and phrasing such as "early", "substantial", "as soon as", "so close", "best aid" and "if circumstances … admit" which cannot be translated directly to machine-readable code (Porathe, 2019c; Porathe and Rødseth, 2019). Not only does this pose an implementation problem for the automatic controllers in the autonomous ship; the crew and automatic controllers are likely to have deviating interpretations of these terms, which together with practices and customs needs to be better understood before quantifiable and measurable criteria can be adopted (Woerner et al., 2019).

In relation to autonomous ships, IMO states 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), and any new development of rules for interactions between manned and unmanned vessels is considered to be a big challenge for the maritime community (Felski and Zwolak, 2020). There is also an ongoing debate on the need for COLREG changes versus the technical feasibility for systems to comply with COLREGs. Hannaford et al. (2022) concluded that minor amendments to certain terms and definitions are recommended, whereas Wróbel et al. (2022) concludes that the feasibility of collision avoidance methods for autonomous ships is questionable due to the ambiguous character of COLREG, and that all existing collision avoidance methods are at best only partly COLREG-compliant. Thus, autonomous collision avoidance at sea remains a challenge.

The review on human-AI interaction in Veitch and Alsos (2022) acknowledges that conventional and autonomous ships will co-exist, and that new technical solutions are needed for these mixed traffic situations. Some of the major safety challenges and hazards that exist in these mixed traffic situations are problems with interpreting COLREGs, the inability to interpret behaviour or actions of other ships, issues with sensors and failure to identify objects (Bolbot et al., 2021; Kim et al., 2022).

The above problems in implementing automated collision avoidance can to some degree be overcome by more cooperative decision procedures based on communication between the ships. This is already part of COLREG, e.g., by requiring that actions taken to avoid close encounters or collisions should be substantial enough to be understood by other ships as evasive manoeuvres. However, this is a form of "after the fact" communication that cannot be used to determine other future actions. Additional requirements to signalling between the ships are based on a human-to-human communication loop, by visual or audible signals, or by voice communication over VHF. One proposed solution in Felski and Zwolak (2020) is to communicate intentions early and automatically. Although results from modelling of intentions and inclusion of these in simulated collision avoidance scenarios is promising (Liu et al., 2022; Rothmund et al., 2022; Tengesdal et al., 2020), the aforementioned requirements will make it difficult to communicate intentions between the conventional and autonomous ships, particularly in situations requiring fast responses. This will in turn make it difficult to predict each other's manoeuvres and subsequently take proper action to avoid collision.

To summarise, there are two main areas where the COLREGs introduce problems in a mixed traffic situation: (i) use of qualitative words and phrasings leaves a gap where definitions that ensure the same understanding of a situation and required actions, by crew and automation, are missing, and (ii) means for signalling intensions such that both ships can communicate.

The above indicate that mixed traffic situations not only will be subject to regulatory barriers, but procedural and technical barriers as well. Thus, for mixed traffic situations where a conventional crewed ship interacts with an autonomous uncrewed ship, there is a need to solve how both the conventional ship and the autonomous ship can interpret each other's intensions in an unambiguous way, predict the next move and perform actions to avoid collision if necessary.

The novelty of this study includes: (i) a definition of what the basic interaction problem in mixed traffic situations between conventional crewed ships and autonomous uncrewed ships consist of, (ii) an impact assessment of applying today's available technical measures to avoid the interaction problem and (iii) a proposal for likely short term and long term solutions to deal with mixed traffic situations.

Furthermore, we will mostly disregard incidents that also may befall ships that are not involved in interactions with other ships, e.g., adverse weather, machinery failure of loss of structural integrity. The focus is on incidents where the interaction with another ship defines the main causative hazard.

In the following, Section 2 describes the methodological approach of this study together with its limitations and assumptions. Section 3 will discuss the problem of information acquisition, situational assessment, prediction and decision making, both for autonomous and conventional ships, and will provide a classification and description of the problems. The information asymmetry is a core problem, and Section 4 will provide an overview of today's technical solutions that may be used to solve the problem. Section 5 will analyse the impact of applying each individual technical solution, and discuss which solution, or combination of solutions that is considered as the best way forward. Section 6 will provide a summary of conclusions with short term and long term recommendations.

## 2. Methodological approach

This study carries out a systematic assessment of how to overcome the asymmetric information access that occurs in mixed traffic situations where conventional crewed ships interact with autonomous uncrewed ships. To do so, the following methodological approach have been applied.

1. Definition of a basic reference scenario (case description) that allows for identification of involved actors, the main components of the interaction process and the available means to aid in interactions.
2. Definition of the interaction problem based on the four stages of the decision making process of Parasuraman et al. (2000).
3. An analysis of the interaction problem based on each stage of the decision making model.
4. Analysis of available measures, i.e., today's technical solutions and other proposals, from the literature that can be applied to overcome the interaction problems in the reference scenario.
5. Impact assessment and discussion of the measures based on regulatory, technical, and procedural considerations, ending in a recommendation for short and long term proposals.

### 2.1. *Definition of the ship interaction reference scenario*

This section presents a basic and generalized reference scenario example where one autonomous ship and one conventional ship interacts. In general, there is much debate on what autonomous and uncrewed ships are (Rødseth et al., 2021). Maritime Autonomous Surface Ships (MASS) is the name that the International Maritime Organization (IMO) has proposed for autonomous ships, but the abbreviation could also be interpreted as Maritime Autonomous Ship System (Wennersberg et al., 2020). In the following we will use the term autonomous ship for a ship that is operating without human supervision for the duration of the encounter with a conventionally crewed ship. This means that there may be crew onboard the autonomous ship, but also that automation is in full control during the autonomous operation.

The purpose of the reference scenario is to identify the involved actors and means that are available to aid the interaction. For the discussions in this paper, it is convenient to simplify it as in Fig. 1.

The scenario assumes that the ships may need to make evasive manoeuvres and thus, to determine how to physically interact with the other ship. In addition to the physical side, the interactions between the ships will consist of two main components.

1. Observation: This is a "passive" observation of the other ship and, by implication, cannot say anything about future intentions or plans, except what can be inferred from recent history. Observation normally use sensors, such as radar or video, as well as the human outlook on the conventional ship.
2. Communication: This represents intentional information exchanges between ships that can be used to transfer information about status and future intentions by voice radio (e.g., VHF), by visual means (e.g., signal lamp) or by digital means (e.g., VHF Data Exchange System).

Note that an Automatic Identification System (AIS) position report is technically a communication action. In the context of collision avoidance, AIS data is typically used to find near collisions or traffic conflicts to be used as input to create evasive manoeuvres in collision avoidance algorithms (Rong et al., 2022), to create proposals for future trajectories that could help reduce the collision risk (Murray and Perera, 2020) and to create scenarios for simulator verification of collision avoidance algorithms (Pedersen et al., 2020) However, the position report says little about future intentions and should therefore, in this context, be considered an observation. One can also argue that the observation of specific evasive manoeuvres by the other ships is a form of communication and should be classified as such. However, as noted earlier, this type of communication has little or no value in predicting further actions from the other ship and should therefore also be considered as an observation.

### 2.2. A model for decision-making

In this paper we will use a simple four-stage model for how decisions are made, based on the four-stage model used by Parasuraman et al. (2000) Our model is somewhat modified to better isolate problem areas in a decision process involving not one, but two parties. This has led to splitting general perception into situation assessment and other ship prediction. Decision making and response selection have been merged into one stage.

Our model is illustrated in Fig. 2 (bottom) together with the original (top). Our model defines the following stages.

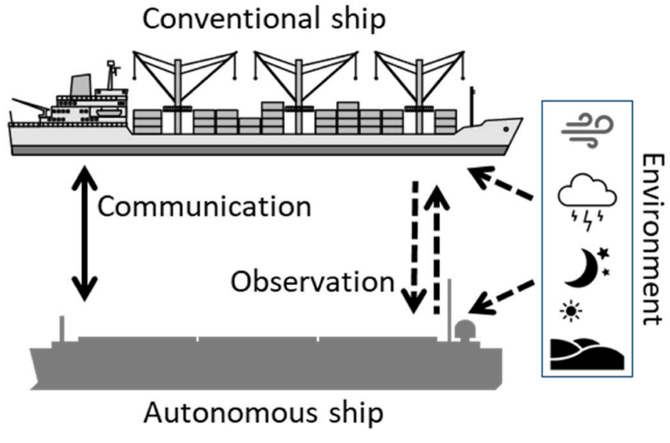

Fig. 1. A simplified two-ship scenario.

1. Information acquisition: Use all available means to acquire information about the situation, including the environment, the other ship, and the current behaviour of the other ship.
2. Situation assessment: Get a good understanding of the situation, including environmental properties such as visibility, wind, currents and waves, geographic constraints, and other ships in the vicinity.
3. Other ship prediction: It is necessary to predict what the other ship will do in the given situation. In many cases this can be based on the general rules of collision avoidance at sea, but in cases where these rules are ambiguous or when for some reason the other ship does not follow them, a sufficiently good prediction will be problematic.
4. Plan and execute own actions: When all information and assessments have been made, it is necessary to plan own actions to ensure a safe forward voyage.

The model indicates a strictly sequential process, but this is not necessarily the case. Particularly for situation assessment and other ship prediction, one will if possible and convenient, try to use additional communication means to get more information. Neither is it really a discrete set of steps. At least for a human, this process is to a certain degree continuous, where each step is processed in parallel with other steps.

### 2.3. Assumptions and limitations

This paper focus on the problems related to mixed traffic situations and the four stages of the decision making model. Although the interaction between larger ships and smaller leisure crafts have also been identified as critical as the combination of event frequency and the potential damage is large (Bolbot et al., 2022), this paper will mainly deal with interactions between commercial ships that are designed and operated according to IMO regulations such as SOLAS (navigational equipment), STCW (training and watchkeeping) and COLREG. However, these regulations may also be applied to smaller crafts.

Note that the definition of the reference scenario in Section 2.1 could be extended to a more complex scenario by including e.g.,.

- Multi-ship traffic scenarios for increased traffic complexity (Kufoalor et al., 2020; Liu et al., 2022).
- Weather conditions: Wind, waves and currents (Burmeister et al., 2015; Ventikos et al., 2018).
- Crew competence and skills (Abilio Ramos et al., 2019).
- Manoeuvring margin between the ships and other infrastructure or shore (Berge et al., 2019; Gil, 2021; Tengesdal et al., 2020).

However, this added complexity will not add any value to the basic definition of the interaction problem in Section 2.1 and the forthcoming discussions of high level causes and possible solutions.

Furthermore, we analyse the asymmetric relationship between the interacting ships for the steps of the decision making model. As such, we focus the analysis on the hazards resulting from the asymmetric information relationship, and not the root causes. There are many other hazards, faults and technical issues that could lead to a collision, but these are thoroughly dealt with in literature on general risk control and collision avoidance of autonomous ships, see e.g., (Basnet et al., 2023; Fan et al., 2022; Lee et al., 2023; Puisa et al., 2018; Utne et al., 2020; Ventikos et al., 2020).

Finally, we do not investigate cyber security issues even though several of the proposed solutions listed in Section 5 requires digital communication for safety related functions, and that the integrity and authentication of the data will be essential (Rødseth et al., 2020).

## 3. Definition of the interaction problem

In general, the interaction process can be illustrated as in Fig. 3 where the two ships are represented by the decision-making process

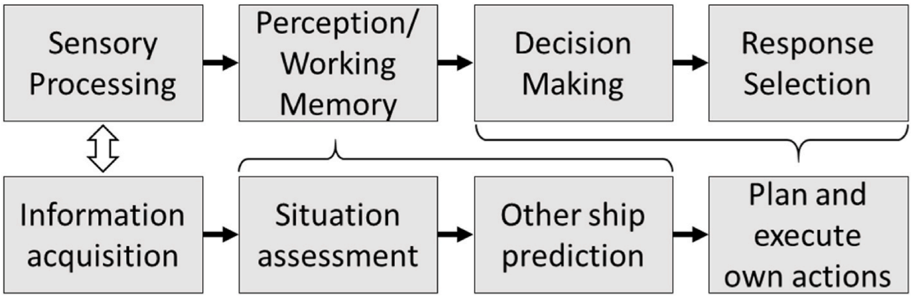

**Fig. 2.** A simple four-stage model for decision making. Top row shows (Parasuraman et al., 2000).

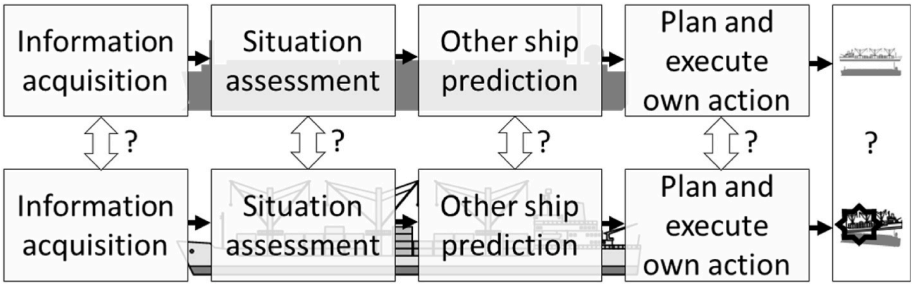

**Fig. 3.** Interaction between conventional and autonomous ships.

from Fig. 2. The outcome is at the far right, and an incident can happen if alignment of the plan and execute own action stage is not aligned between the ships. This in turn requires alignment of the prevailing steps as misalignment will propagate through the steps of the decision making model. Aligned means that the result from each stage is sufficiently close between the two ships to result in similar predictions which in turn leads to safe actions. Any misalignment means that one of the ships has another picture of the situation than the other, and that the final decision made will be based on different assumption.

### 3.1. Detailing the problem

While there are many safety challenges related to autonomous ships in mixed navigational environments (Kim et al., 2022), we focus on the problems that can lead to errors in the information acquisition, situation assessment, other ship prediction, and the planning and execution of actions. In Fig. 4 we have redrawn the decision process and indicated some of the concrete problems that will be investigated in this section. These problems are related to establishing an aligned situational awareness and decision making process on the two interacting ships and does not cover more general problems such as hardware or software errors.

### 3.2. Problems in information acquisition

This stage is related to collecting information from own sensors and other information sources. This stage outputs information about the ship's surroundings to the situation assessment. The main identified issues are.

1. Nautical information, including charts, needs to be constantly updated to ensure safe navigation (Dias et al., 2023). Any differences in nautical information may be a source to differences in how the environment will be assessed.
2. Requirements to sensing equipment for autonomous ships are not yet established by regulations. One step in this direction is found in

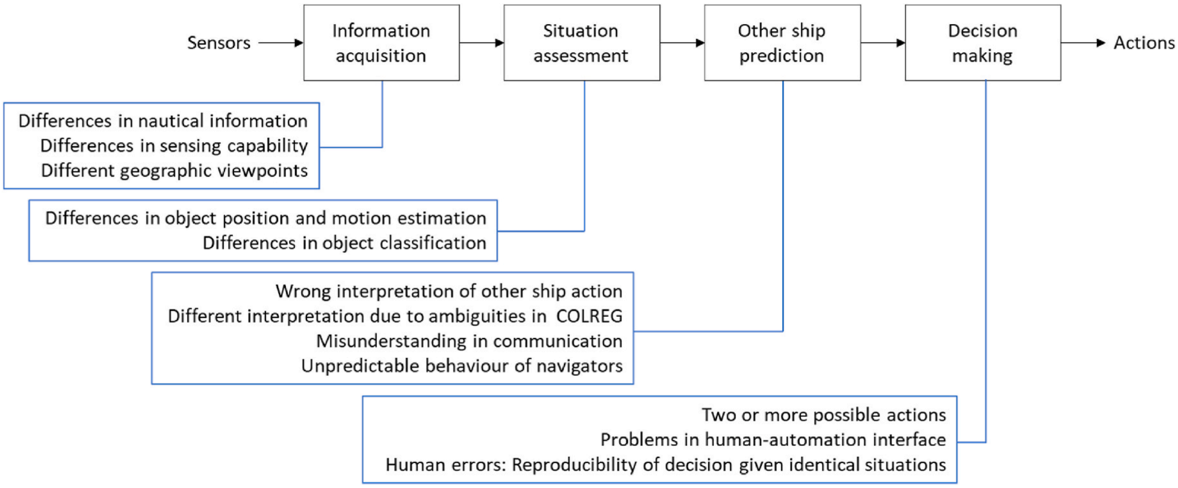

**Fig. 4.** Concrete problems in the decision model.

Thombre et al. (2022), who studies the requirements to situational awareness for autonomous ships by investigating existing rules and regulations, and proposes a set of minimal limits for e.g., sensor range, accuracy, integrity, etc. However, even if such minimal requirements are defined by regulations, equipment could either be designed for the minimal limits or for better performance than the minimal limits, leaving the possibility for differences in performance of different equipment. Furthermore, the conventional ship will likely depend on a combination of sensing equipment and the human senses (e.g., radar and human vision). This obviously creates a difference in the sensing capability between the conventional and autonomous ship. Such differences, e.g., differences in the conditions under which object detection is possible, or differences in the ability to detect small objects, will obviously cause a different situation picture on the two ships.

3. The different geographic viewpoints the ships have will also cause discrepancies. If one obstacle that needs to be avoided is hidden by the ship that will take evasive manoeuvres, this may cause the ship to make wrong assumptions about the other ship. An example of this is radar shadowing, where one ship cannot see an object because it is hidden behind another object that reflects the radar waves instead (Salous et al., 2015).

### 3.3. Problems in situation assessment

The situation assessment stage will build an integrated situation picture, including safe areas for sailing, obstacles that need to be avoided and general environmental conditions, such as waves and wind. Even when sensor information is the same on both ships, there are still problems that can cause differences in how situations are assessed.

1. As discussed in the review in Huang et al. (2020), there are several methods for predicting other vessel or object positions and motions. Furthermore, they also observe that several researchers make simplifications to the prediction models to ease implementation. Differences in methods and prediction models can lead to differences in estimations of object positions, directions, or speed, which may lead to different assessments of the situation picture between the two ships.
2. While object detection and classification on a conventional ship is handled by the human, this is one of the primary objectives for the Situational Awareness System (SAS) of an autonomous ship. Some challenges related to different methods for object detection and classification is discussed in Thombre et al. (2022), and requirements to SAS are proposed. While such requirements could be imposed to ensure common behaviour of different SAS, it is harder to ensure common behaviour of SAS and human based object detection and classification. Differences in how objects are classified, e.g., if it is necessary to avoid the object or not, will create differences in how each ship's possibilities and best actions will be decided.

### 3.4. Problems in predicting other ship

The other ship prediction stage will estimate the most likely action by the other ship, based on the situational picture. Some relevant sources of prediction errors are.

1. One method for predicting the future action of other ships is by using a constant velocity model (Akdağ et al., 2022). Another method for predicting the future behaviour of other ships is by utilizing Machine Learning (ML) techniques and historical AIS data (Murray and Perera, 2022). However, it is possible to make a wrong interpretation of the ship's past action and by that infer the wrong future actions. For constant velocity models a simple example is that an incorrect estimate of e.g., rate of turn, will lead to that the future deviation from current heading will be under- or overestimated. While for ML techniques based on AIS data, the deviations for predicting future behaviour is quite significant (up to 30%) (Murray and Perera, 2022).
2. COLREG is in many cases ambiguous, and this will cause problems in predicting the other ship's response to more complex scenarios (Porathe, 2019c; Porathe and Rødseth, 2019; Wróbel et al., 2022). Some ships may also act in ways that may look contrary to COLREG rules, e.g., due to contradictions in COLREGs for certain situations (Wróbel et al., 2022). An example could be that the *Give way* vessel is subject to restrictions in draught or manoeuvrability and thus is not giving way, which is difficult to predict when these constraints are not known to the autonomous vessel.
3. When receiving voice communication from other ships, which could also be relevant for autonomous ships, it is not uncommon that language problems or other issues like bad sound quality cause misunderstandings. This has already led to collisions (Porathe and Rødseth, 2019).
4. While autonomous ships will always act according to its algorithms, the navigators in the conventional ship is often unpredictable (Felski and Zwolak, 2020).

### 3.5. Problems in plan and decision

Once the situation has been assessed and the other ship's intention is correctly predicted, there are still problems that can occur in the plan and execution stage.

1. There are cases where there is more than one obvious action (two or more actions have a similar level of probability and confidence). The other ship may select another action than own ship assumes (Porathe, 2019b).
2. A human operator may also make a wrong action, e.g., due to inattention or problems with the human-machine interface (Ramos et al., 2018; Veitch and Alsos, 2022).
3. While it is possible to design automation systems that makes the same decision every time it is presented with the same input parameters, there is no way of ensuring such performance by humans, as seen by human errors being a significant source of accidents (Abilio Ramos et al., 2019).

## 4. Proposals to avoid the problems

The interaction problems discussed in Section 3 can to some degree be avoided or dealt with by applying various remedial measures. This section will introduce these measures and point to which problems they can contribute to solve.

**Vessel traffic management (VTM)**: VTM can be seen as an extended Vessel Traffic Services (VTS) that can inform or give some instructions to ships (Aps et al., 2017; Relling et al., 2022), similar to air traffic management. Given that the VTM has the correct picture of the situation, and can instruct both ships, this should significantly reduce problems associated with interactions between manned and autonomous ships as the collision avoidance action selection step will be aligned through coordinated instructions from the VTM.

**Traffic separation schemes (TSS)**: TSS is defined by rule 10 in COLREG (IMO, 1972). TSS can help in keeping different types of traffic separated and will provide a more orderly sailing pattern. One could in principle also add other restrictions to the TSS rules, and e.g., design various types of "multi-lane" systems where autonomous ships get their own routes. Crossing and entry-exit situation will still be a problem. However, as pointed out in Porathe and Rødseth (2019), the traffic complexity within a separation scheme is lower and the requirements to the collision avoidance systems could be relaxed.

**Recommended routes**: Another possibility for providing more deterministic actions is the concept of recommended routes. The Norwegian Coastal Administration has published a number of recommended routes for the coast of Norway (NCA, 2023). One could also imagine a TSS type regulation to make these mandatory in certain cases, where also additional information could be provided to navigators of conventional ships. Recommended routes will assist with simplifying the decision making capabilities of the autonomous ship and have similar impact on collision risk as TSS.

**Land based sensors**: The problem with missing or wrong sensor data can in principle be alleviated by providing additional sensor data to the ships in the area. This could be done between ships directly, from a VTS to the ships or from a dedicated sensor system. In (Rødseth et al., 2021), the concept of a local sensor system (LSS) was defined as a component of the autonomous ship system.

Shore-based radar or video equipment, possibly also with object detection and classification functions, could provide the autonomous ship with better information about the actual situation. However, one could still be in a situation where the conventional ship has another situation picture and makes wrong assumptions about the autonomous ship, as also pointed out in our discussion on different geographic viewpoints in Section 3.2.

**Signalling autonomy**: It will also help conventional ships if they know that another ship sails under autonomous control. This would in theory make it possible to make better qualified assumptions about how the ship will react in different situations. Various forms of signs or light patterns have been suggested (Porathe, 2019c). Signalling autonomy will assist with prediction capabilities of other ships.

**Autonomous COLREG**: With new technology for reporting autonomous navigation to other ships (see Signalling autonomy), one could change COLREG by adding new and simpler rules for how autonomous ships should behave in certain cases. This would be a benefit for autonomous ships as well as conventional ships. Autonomous COLREG would primarily simplify the decision making process in encounter scenarios for autonomous ships, and assist conventional ships with predicting the behaviour of the autonomous ship.

**New COLREG for all**: COLREG is intentionally vague about many situations and quotes “good seamanship” or the “ordinary practice of seamen” as a necessary prerequisite. COLREG may also be difficult to apply in cases where more than two ships are involved in a situation (Benjamin et al., 2006). Thus, one could envisage that COLREG is revised with a view to making rules more “automation friendly” by removing ambiguities (Wróbel et al., 2022). New COLREG for all would primarily simplify the decision making process in encounter scenarios.

**Uncertainty zone**: Another principle is to define a moving safe zone around each ship and transmit this to ships in the vicinity. By avoiding this zone, the other ships will have a guarantee that the ships will not hit each other. This concept has been called an uncertainty zone (Berge et al., 2019) or a moving haven (Porathe, 2019b). The uncertainty zone can overcome both the hazards related to not knowing the other ships intentions as well as incorrect situational awareness. However, they may be problematic in densely trafficked waters where there may not be space enough for sufficiently large uncertainty zones.

**Strategic route exchange**: The Sea Traffic Management project provides a service where planned routes can be sent to a shore-based Ship Traffic Coordination Centre where the provided route is checked against other ship’s intended routes and advice given on possible problems (Porathe et al., 2014). This service is now operated by the Navelink consortium (Navelink, 2023).

**Broadcast intentions**: A variant somewhere between the uncertainty zone and the strategic route exchange is to send the planned route for, e.g., next 10–20 min directly from the ship. This allows other ships to better plan ahead than the uncertainty zone allows, and the route is more likely to be correct than the strategic route. As an autonomous ship is controlled by a computer, the computer will always have plans for the near future and can reliably transmit these plans to other ships and RCCs. The transmission can use VDES (Akdağ et al., 2022) and the S-421 route exchange specification (IEC, 2021). Note that this will make the route exchange a safety critical operation and that means that proper cyber security measures must be implemented.

**Remote Control Centre**: A remote control centre (RCC) can be defined as “a site remote from the ship that can control some or all of the autonomous ship system processes” (ISO, 2022). Introducing a RCC is probably a more viable option to “relax” the need for new onboard ship technology by providing the automation system with assistance from humans, either staying onboard or residing at a remote-control centre (RCC). This means that the ship is not fully autonomous.

## 5. Impact analysis and discussion

This section classifies the proposed measures from Section 4 by assessing their impact, i.e., their ability to solve one or several of the problems listed in Section 3, and the subsequent requirement to changes in procedures, technology, and regulations, resulting from implementing the measure.

A summary of the classification and impact assessment is given in Table 1. Here, the different proposed measures are listed with the name of the measure in the left-most column. Column two indicates how much positive impact the measure can provide in term of solving the problems from Section 3, ranging from low to medium to high. Columns three and four indicate if the implementation of the measure requires procedural changes or new technology for conventional ships. Column five indicates if the procedural changes or the new technology requires regulatory changes for conventional ships.

**Vessel Traffic Management (VTM)** will primarily assist ships with aligning the decision making processes of the two ships involved in the encounter scenario. The drawback is obviously that this would require a new regulatory regime in the relevant areas. It may also mean that the VTM would become liable for any errors it makes and this may cause some issues relative to the responsibilities of the master of the ship. VTMs could also contribute with improved situational assessment. A more active VTM could also be used to, e.g., distribute updated and more complete situation pictures to the involved ships (Relling et al., 2022). As the VTM will normally have access to radars, AIS and CCTV that enables it to have a much better situational awareness than ships in the area. The impact of implementing VTM is evaluated to be *high*.

**Traffic separation schemes (TSS)** and **Recommended** or **mandatory routes** will assist with simplifying the decision making capabilities of the autonomous ship, but not with information acquisition, situation assessment or other ship prediction. Implementation of dedicated separation schemes or routes for autonomous ships may require changes in regulations, depending on how strong the incitements for following the instructions or routing information should be. Any regulatory change that enforces the use of these measures, and by that how much they can be trusted, will increase the measure’s impact from *medium* to *high*.

**Table 1**
List of measures and possible impacts.

| Measure | Impact | Procedures | Technology | Regulation |
|---|---|---|---|---|
| Vessel traffic management | High | Yes | No | Yes |
| Traffic separation schemes | Medium/ High | No | No | No/Yes |
| Recommended or mandatory routes | Medium/ High | Yes | No | No/Yes |
| Land based sensors | Low/ Medium | No | No | No/Yes |
| Signal autonomy | Low | Yes | Yes | No |
| Autonomous COLREG | Medium | Yes | Yes | No |
| New COLREG for all | High | Yes | Yes | Yes |
| Uncertainty zone | Low/ Medium | Yes | Yes | No/Yes |
| Strategic route exchange | Low | Yes | No | No |
| Broadcast intention | High | Yes | Yes | Yes |
| Remote Control Centre | Medium | No | No | No |

**Land based sensors** will primarily assist with information acquisition but could also have some role in situational assessment. Land based sensors may be used by autonomous ships alone or by all ships. In the latter case, one would require both new procedures and new technology, also for conventional ships. The impact of this measure ranges from *low* to *medium* depending on whether conventional ships also would use land-based sensors. The latter will probably require regulatory changes.

**Signalling autonomy** will assist with prediction capabilities of other ships, in particular the ability for conventional and autonomous ships to understand the intention of other autonomous ships. This measure would require that the autonomous ship has a method to identify itself as autonomous (Porathe, 2019c). This may require new technology if implemented by AIS or other types of communication systems. The impact of this measure is assessed to be *low* as it primary serves to improve the understanding of autonomous ship's intention.

**Autonomous COLREGs** will mainly simplify the decision making process in encounter scenarios for autonomous ships. This measure requires the ability to signal autonomy. A drawback with this measure is that if the measure is used to help conventional ships with predicting the behaviour of the autonomous ships, then they need additional technology implementation as well. The impact of this measure is *medium* as it does not improve the autonomous ship capability of predicting the conventional ship behaviour.

**New COLREG for all** ships would simplify the decision making process in encounter scenarios for all ships by removing ambiguities (Wróbel et al., 2022). This would imply that each scenario has one specific outcome in terms of what action each interacting ships shall take. This measure does also require the ability to signal autonomy as discussed above. The impact of this measure is assessed to be *high* as it would be a common basis for collision avoidance principles across ship types. However, it would require regulatory changes for conventional ships.

**Uncertainty zones** will contribute to improved situational assessment and other ship predictions. This measure requires communication between the ships, and that a specification for the message format, e.g., based on the S-421 route exchange specification (Hagaseth and Berge, 2020). This also requires that all relevant ships have equipment to receive and display the information. This would require a suitable communication system to be installed also on conventional ships. It is assumed that this system would also be able to inform conventional ships about autonomy status. Uncertainty zones is considered to have *low* impact as long as it is not mandated by regulation changes. This could increase to *medium* by regulatory adjustments as its usefulness likely would be limited in congested waters.

**Strategic route exchange** will assist the ship with decision making in planning of routes, but not operational execution of collision avoidance scenarios. The concept is interesting and has been well received by many users but has some shortcomings: (i) Any change in route after departure will be problematic, unless dynamically updated to all parties (Porathe et al., 2014). (ii) Non-participating ships, e.g., fishing vessels are not included in the analysis. They may also cause route deviations for participating ships. Thus, it may be better to use route information that is generated directly from the ship during transit. The measure is considered to have *low* impact if used properly in planning of the voyage prior to departure from port.

**Broadcast intentions** will assist with prediction capabilities of other ships. The operational route that is exchanged is more likely to be correct than the strategic route. This measure requires that all relevant ships have equipment to receive and display or process the information, and as specified earlier, VDES and the S-421 route exchange specification can be used for this purpose (Akdağ et al., 2022; IEC, 2021). This would require a suitable communication system to be installed also on conventional ships. It is assumed that this system would also be able to inform conventional ships about autonomy status. The technical feasibility combined with the probable correctness of the broadcasted intentions result in a *high* impact assessment of this measure.

**Remote control centres** will assist ships with situation assessment, prediction, and decision making capabilities from humans, and it can act as a communication hub between an autonomous ship and a conventional ship. By using an RCC the most complex interactions scenarios, e.g., the most difficult cases of situation assessment and predictions are managed by humans instead of the automation system on the ship (Rødseth et al., 2022). Note that this also means that we introduce potential unpredictable behaviour of remote operators, similar to the navigators. This does however have some important implications for the overall operational envelope of the system, i.e., the combined capabilities of the autonomous ship and the remote control centre including human operators, that will not be discussed further in this paper, see Rødseth et al. (2021). The impact of introducing RCCs is considered to be *medium* as they represent a "low threshold" option to realise uncrewed ships where operators still would be in or on the loop to handle complex situations that technology in combination with regulations is not yet ready to manage.

### *5.1. Discussion*

There is currently a massive investigation into new situation assessment and prediction methods, e.g., based on various forms of artificial intelligence (Thombre et al., 2022; Zhang et al., 2021), and collision avoidance for autonomous ships (Akdağ et al., 2022). Meanwhile, COLREGs regulates the interactions between ships at sea, which implies that anti-collision algorithms for autonomous ships must be COLREG compliant. However, Hannaford et al. (2022) concluded that minor amendments to certain terms and definitions of COLREGs are recommended, whereas Wróbel et al. (2022) concludes that the feasibility of collision avoidance methods for autonomous ships is questionable due to the ambiguous character of COLREG, and that all existing collision avoidance methods are at best only partly COLREG-compliant. Thus, autonomous collision avoidance at sea remains a challenge. Furthermore, the problems with the mixed traffic scenario that were detailed in Section 3 requires us to ask whether it is realistic to expect that we can realise fully autonomous ships that rely solely on its own analysis of the situation and corresponding predictions of other ships.

The problems we identified in the situational assessment level of the decision model may be possible to overcome with improved sensor systems or further developments on model verification of ML and AI applications for situational awareness (Murray et al., 2022). The uncertainties we identified in the prediction level of the decision model (i.e. problems with interpretations of COLREGs, wrong interpretation of other ship actions, misunderstanding in communication and unpredictable behaviour of navigators) may be impossible to overcome in a sufficiently safe manner unless external remedial measures are applied: A fully autonomous ship would have to implement many technical barriers should the automation system ever be capable of avoiding all incidents on its own. This would also significantly add onto the ship system complexity and cost, and one would probably need to rely on a technology suite in combination with regulations that is not available at the present time.

So instead of focusing efforts on measures that can be implemented to make autonomous ships fully independent, we should instead look for a combination of viable options that could assist both autonomous and conventional ships with situation assessment and prediction of each other's future actions during their interactions.

In the short term, this points to using Remote Control Centres, as they would not require any changes on a procedural, technical, or regulatory level for conventional crewed ships. Remote operators could communicate with onboard crew to solve those situations that are complex using the principles of today's COLREGS with voice communication over VHF. The operators in the remote control centre could also communicate with VTSs without any changes. It is then up to the stakeholders of the autonomous ship to prove that the ship in combination with the RCC can be navigated and manoeuvred in a sufficiently safe manner by following alternative approval processes based on IMO's "Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments" (IMO, 2013).

If we consider moving towards fully autonomous ships that should be able to manage most interaction scenarios by themselves, then we need to consider measures that would potentially also affect technology and procedures on the conventional ships together with modifications in regulations, and that in general are available in relevant sailing areas. Traffic separation schemes and recommended or mandatory routes helps to constrain the operation in a restricted area and simplify requirements to the technology but does not directly address the problem of improving the situational awareness and prediction of other ships. Land based sensors on the other hand can contribute to improved information acquisition and situational assessments in a restricted area such as a port. Although Vessel Traffic Management is considered to have high impact, this measure is also not available in all areas. The area restriction of these measures makes them less attractive for a long term recommendation as they only will be available in parts of a ships voyage.

The information acquisition issue related to potential inaccuracies in nautical charts (due to the need to keep them up to date) adds on to the issues with strategic route exchange. Strategic route exchange might be a good planning or replanning tool of voyages, but not for operational handling of interaction scenarios. Uncertainty zones on the other hand is ideal for operational handling of interactions as one create a buffer zone for manoeuvring, but this measure only creates a "larger" ship that needs to be avoided and will still require improvements on the capabilities of predicting the intention of other ships to function properly.

In the long term, we need to be able to improve the conventional and autonomous ships' ability to broadcast their intentions by exchanging their short term operational route, which in effect means to improve the communication between the interacting ships. However, this measure alone does not solve the mixed traffic interaction scenario. In addition, the longer term solutions to more fully autonomous operation will likely require changes in regulations. Technically, it would require that conventional ships could automatically identify autonomous ships and vice versa. Updates to regulations could then be made to allow more deterministic approaches to collision avoidance as described in Table 1. In the current setting in IMO this will likely not be even suggested before 2028 when the plan is to enter the mandatory MASS code into force (IMO, 2022). Then it would take some sessions in the IMO Maritime Safety Committee to create and approve the revised regulations, and they may also require a longer implementation period to include all sailing ships in the system. Thus, a time horizon towards 2035 or 2040 may be likely.

We conclude that the best long term solution amongst the identified measures is to leverage available protocol specification on exchange of operational routes to broadcast intentions and this should be complemented with changes in COLREGs.

## 6. Conclusions

To improve the safety of interactions amongst uncrewed autonomous and crewed conventional ships in mixed traffic situations, we need to overcome their asymmetric access to information. In this paper we suggest that the main problem created by the asymmetric access to information is the ship's inability to understand what the other ship is likely to do next and then to plan own actions according to that to avoid a potential collision or a near accident. We argue that it is difficult to create symmetric access, or even improve the asymmetric access to information, if we only rely on ship technology and capabilities due to the expected system complexity, high cost, and a technology suite in combination with regulations that is not available at the present time.

Our analysis shows that measures external to the ships should be used to improve the situation so that the ship's situational assessment match and that their prediction of each other's actions are aligned. The impact assessment of implementing each measure to improve the information asymmetry was based on a classification of the proposed measures with respect to their ability to solve one or several parts of the interaction problems together with an assessment of requirements to changes in procedures and technology, together with subsequent requirements to updates and changes in regulations. We conclude that.

1. The most likely and effective short-term solution is to assist the autonomous ships with human operators, either residing onboard or in a remote control centre (RCC).
2. The best longer-term solution may be to improve the information exchange between the ships by communicating intended actions. This should be complemented by changes in COLREGs.

We also conclude that without improvements in communication and regulations it may not be possible to fully deal with the problem of mixed traffic operations.

## CRediT authorship contribution statement

**Ørnulf Jan Rødseth:** Conceptualization, Investigation, Funding acquisition, Writing – original draft. **Lars Andreas Lien Wennersberg:** Investigation, Project administration, Writing – original draft. **Håvard Nordahl:** Investigation, Writing – original draft.

## 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.

## Data availability

No data was used for the research described in the article.

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