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 autonomous ships that interact with conventional ships, as the crew on other ships can and will exert unexpected behaviour that cannot be easily modelled. This paper will discuss the problem of situational assessment and prediction of other ship's actions, for autonomous ships that need to interact with conventional ships. It will provide a simple classification of root causes for the problem and will propose some possible ways to reduce or solve this problem.

Keywords: *Autonomous Ship, Safety, Manned-unmanned interaction, MASS, Autonomy*

1. INTRODUCTION

In general, there is much debate on what an autonomous and/or uncrewed ship is (Rødseth, Faivre et al. 2020), but 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 automation is in full control during autonomous operation. Maritime Autonomous Surface Ships (MASS) is the International Maritime Organization (IMOS's) proposed name for autonomous ships.

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. The required quality of the prediction will depend on how close the two ships are to each other and the margin that each ship has for safe and corrective manoeuvres, including the possibility that something unexpected happens. In close encounters and restricted waters, this can be a challenging requirement. Likewise, the crew on a conventional ship may also have problems with understanding an autonomous ship's intention and plans. A main challenge in both cases is the asymmetric access to information on the two ships: how each ship understands its environment and what plans each ship have. 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, but this will require changes in collision regulations or other international regulatory instruments.

Section 3 will discuss the problem of situational assessment and prediction making, both for autonomous and conventional ships, and will provide a simple classification of root causes of problems. The information asymmetry is a core problem, and section 4 will discuss if this at all can be solved with today's technical solutions. Section 5 will discuss some other possible ways to reduce or solve the problem, e.g. by introducing more restrictions on what ships can do, or to improve the quality of information by increasing communication between ships as well as to shore based information sources. Section 6 will provide a summary of conclusions and findings.

The paper will focus on the general problems of situational assessment and prediction making and will not investigate cyber security issues. However, several of the solutions listed in Section 5 will require digital communication in safety related functions, and the integrity and authentication of the data will be essential (Rødseth, Frøystad et al. 2020).

2. DEFINING THE SCENARIO

2.1 Ship interaction reference scenario

This section will present a simple and generalized example of one autonomous ship and one conventional ship that interacts. The example could be extended to a more complex scenario, e.g. with more than one ship of each type, but for the discussions in this paper, it is convenient to simplify it as in Figure 1.

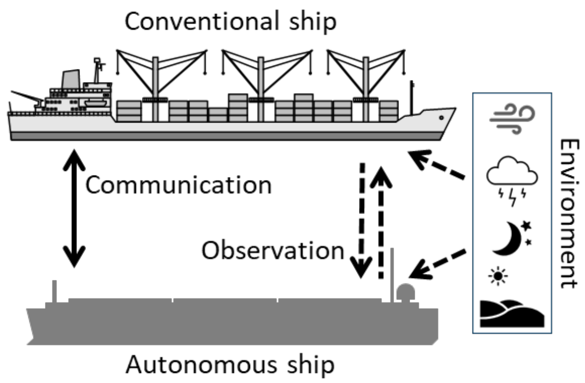

Figure 1. A simplified two-ship scenario.

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, e.g. over 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 considered as communication. However, the position report says little about future intentions and should normally be looked at as observation. One can also argue that the observation of very specific manoeuvres by the other ships is a form of communication and should be classified as such. However, this does not detract from the generality of the two classes.

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.

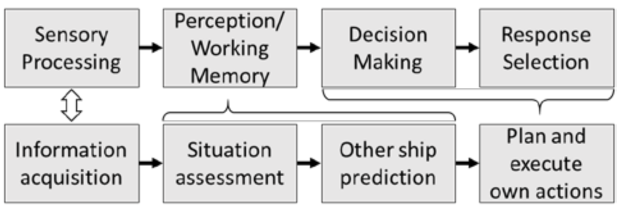

Figure 2. A simple four-stage model for decision making. Top shows Parasuraman et al. (2000).

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

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.

3. DEFINING THE PROBLEM

3.1 Alignment of decision processes

In general, the interaction process can be illustrated as in Figure 3 where the two ships are represented by the decision-making process from Figure 2. The outcome is at the far right, and an incident can happen if one ship's situation assessment or prediction of the other ship's intention differs too much from what the other ship assumes and actually does.

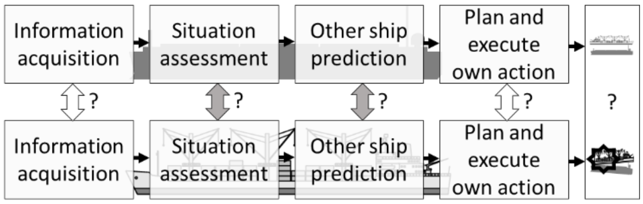

Figure 3. Interaction between conventional and autonomous ship

Thus, the main prerequisite for safe interaction is that the two stages in the individual ships' assessment and prediction process are "aligned" as is illustrated by the filled arrows. 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.

There may also be errors or inconsistencies in accessible information or in the decision-making stages. The information acquisition will normally be specific to each ship as the sensor suite is likely to be different, and each ship will have a different geographical viewpoint for its sensors, where not all objects are equally visible for both ships. Likewise, different objectives for each ship may also cause different actions to be made in the final stage. Thus, there may also be a need for coordination of these stages in the decision process as indicated by non-filled arrows.

The most relevant high-level hazards are illustrated in a "hazard relationship" diagram in Figure 4. This diagram corresponds to the decision-making process from Figure 2 but focuses on what can go wrong. The problems are represented by the basic hazards to the left and diagram. Or/And functions link hazards to intermediate stages and final outcomes. These are graphically the same as in a fault tree. The arguably most difficult to avoid hazards are

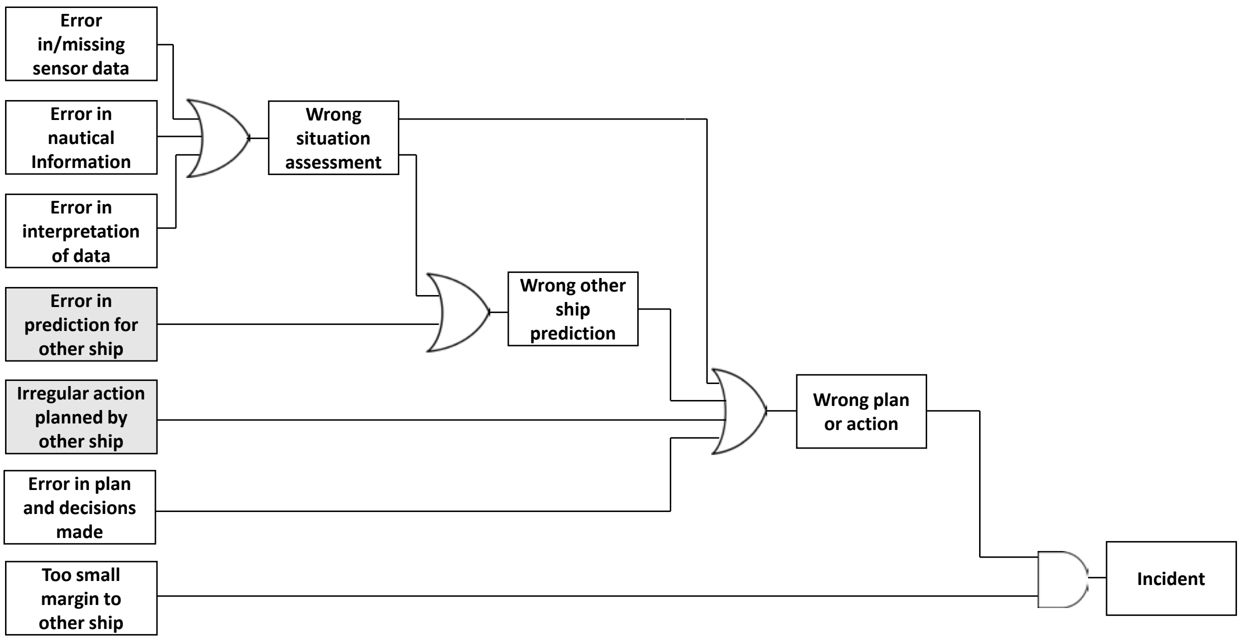

Figure 4. Hazard relationship diagram showing possible outcomes for one ship.

those that involve other ship predictions and actions. These are shaded. The basic hazards are:

Error in or missing sensor data: This means that the system is not getting all the relevant information about the environment. This can be related to technical problems, poor performance of sensors or having a restricted view on the surrounding environment.

Error in nautical information: Not getting correct information from e.g. nautical publications, pilots or VTS. This may be due to errors in the information retrieved or communication system problems.

Error in interpretation of data: This is a human or algorithmic failure to get a consistent and objective understanding of the observed or known surroundings. This may also be caused by different priorities for different types of observations, e.g. if a small floating object is considered hazardous or not. This will be elaborated on in section 3.2.

Error in prediction for other ship: Given a consistent observation of other ship, there may be algorithmic or human deficiencies in what the human or the automation believes the other ship will do. It is also in many cases impossible to do a high confidence prediction, e.g. due to complexity of situation. This will be elaborated on in section 3.3.

Irregular action planned by other ship: This represents actions by the other ship that could not have been predicted. This is the result of the outcome “wrong plan or action” for the other ship.

Error in plan or decision mode: Given that one has access to correct information about the other ship and the general situation, there may still be problems with decision making, e.g. because the operator gets too short time to react or due to irrational behaviour on the part of the human decision maker or automation system. This will be elaborated on in section 3.4.

Finally, there is a risk that own ship has a *too small margin to other ship*. This can be seen as a risk reduction measure, i.e. a minimum distance set by the system to ensure that expected uncertainties in decision making, resulting from other hazards, still ensures that own ship can avoid an incident. If this margin is too large, it may cause inefficiency in sailing the ship or managing the overall traffic, particularly in congested or constricted waters. Thus, it should be made as small as possible, without causing a danger of collisions.

3.2 Errors 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. The different geographic viewpoints the ships have will 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.

2. Any differences in estimations of object positions, directions or speed will change the situation picture between the two ships.

3. 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.

3.3 Errors 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. It is possible to make a wrong interpretation of the ship's past action and by that infer the wrong future actions. A simple example is that large ships change course and speed very slowly and if there is an incorrect estimate of rate of turn, the future deviation from current heading will be under- or overestimated.

2. COLREG is in several cases open to interpretation (Porathe 2019), and this will cause problems in predicting the other ship's response to more complex scenarios.

3. Some ships may also act in ways that may look contrary to COLREG rules, e.g. due to restrictions in draught or manoeuvrability, and this is also difficult to predict when these constraints are not known.

4. 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 et al. 2019).

3.4 Errors 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. The other ship may select another action than own ship assumes.

2. A human operator may also make a wrong action, e.g. due to inattention or problems with the human-machine interface.

3. Technical problems may cause the wrong action to be executed.

The above are some situations that have been found relevant, but the purpose of this paper is not to provide a complete analysis of all possible hazards.

4. BARRIERS ON OWN SHIP ALONE

The basic and composite hazards discussed in the previous section force the question of whether it is realistic to expect the realization of fully autonomous ships, relying solely on own ship's analysis of the situation and corresponding predictions. The hazard relationship diagram in Figure 4 indicates that there are uncertainties particularly in the prediction level of the decision model that may be impossible to overcome in a sufficiently safe manner unless external remedial measures are applied.

There is currently a massive investigation into new situation assessment and prediction methods, e.g. based on various forms of artificial intelligence. This applies to all types of autonomous vehicles, but perhaps most commonly to autonomous cars. However, there is also here doubt if it ever will be possible to provide proof that they are sufficiently safe (Kalra & Paddock 2016).

A fully autonomous ship would also have to implement many preventive and mitigative barriers, should the automation system ever be capable of avoiding all incidents on its own. This would significantly add on to the system complexity and cost, and would probably need to rely on a technology suite that is not available at the present time.

Another, and probably more viable option is to “relax” the need for new technology by providing the automation system with assistance from humans, either staying onboard or residing at a remote-control centre (RCC). If the automation system can detect that it soon will be operating outside its own capability bounds, then requests for intervention can be sent to the human operator, so that the most difficult cases of situation assessment and predictions are done by humans instead. This has some important implications for the overall operational envelope of the system that will not be discussed further in this paper, see Rødseth et al. (2021).

5. AVOIDING THE PROBLEM

The hazards discussed in section 3 can to some degree be avoided by applying various remedial measures outside own ship. This section will briefly discuss some of these measures.

Vessel traffic management (VTM): VTM can be seen as an extended Vessel Traffic Services (VTS) that can give some instructions to ships, 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.

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. However, crossing ships will still be a problem.

Recommended routes: Another help to provide 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 2021). One could also imagine a TSS type regulation to make these mandatory in certain cases.

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, Faivre et al. 2020), the concept of a local sensor system (LSS) was defined as a component of the autonomous ship system.

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 2019).

Autonomous COLREG: With new technology for reporting autonomous navigation to other ships (see previous), 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.

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.”

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 2019). The uncertainty zone can overcome both the hazards related to not knowing the other ships intentions as well as incorrect situational awareness. This will require communication between the ships, and a specification for the message format can been made, based on the S-421 route exchange specification (Hagaseth 2020). This requires that all relevant ships have equipment to receive and display the information.

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 2021). The concept is interesting and has been well received by many users but has some shortcomings: A) Any change in route after departure will be problematic, unless dynamically updated to all parties. B) 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.

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 to 20 minutes 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 at all times have plans for the near future and can reliably transmit these plans to other ships and RCCs. The transmission can use VDES and the S-421 route exchange specification (IEC 2021). This requires that all relevant ships have equipment to receive and display or process the information.

Remote Control Centre (RCC): This involves assisting the automation system on own ship with additional assessment and prediction capabilities from humans. This means that the ship is not fully autonomous, and that the operators can reside either on ship or on shore. This option was discussed in section 4 but is repeated here to add this item to the comparison table below.

Table 1 gives a summary of the different proposed measures with the name of the measure in the left-most column. Column two indicates how much positive impact the measure can provide, from some (+) to much (+++). Column three and four indicates if it requires procedural changes (Yes or No) or new technology (Yes or No) for conventional ships. The final column indicates if the measure requires new regulations (Yes or No).

This classification is only indicative and gives an overview of the relationship between the proposed measures.

Notes as superscript numbers in the left-most column are related to the parentheses in the table. They are explained after the table.

Table 1. List of measures and possible impact

Measure	Impact	Proc	Tech	Reg
Vessel traffic management	+++	Y	N	Y
Traffic separation schemes [1]	+/++	N	N	(Y)
Recommended or mandatory routes [1]	+/++	Y	N	(Y)
Land based sensors [2]	+/++	(N)	(N)	N
Signal autonomy [3]	+	Y	(Y)	N
Autonomous COLREG [3]	++	Y	(Y)	Y
New COLREG for all [3]	+++	Y	(Y)	Y
Uncertainty zone [4]	+	Y	Y	N
Strategic route exchange	+	Y	N	N
Broadcast intention [4]	+++	Y	Y	Y
Remote Control Centre	++	N	N	N

Note 1: This may require changes in regulations, dependent of how strong the incitements for following the routing information should be.

Note 2: Land based sensors may be used by autonomous ship alone or by all ships. In the latter case, one would require both new procedures and new technology, also for conventional ships.

Note 3: These measures would require that the autonomous ship has a method to identify itself as autonomous. This may require new technology if implemented by AIS or other types of communication systems.

Note 4: 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. Thus, no note 3 attached to this measure.

6. CONCLUSIONS

This paper has discussed the problem related to operating autonomous ships together with ordinary crewed ships. The main conclusions are:

1. The main problem is arguably to understand what the other ship is likely to do next and then to plan own actions according to that. This may not be possible when relying on own ship capabilities alone.

2. 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).

3. The best longer-term solution may be to improve the information exchange between the ships. This should, if possible be complemented by changes in COLREG.

4. Without improvements in communication and regulations it may not be possible to fully deal with the problem of mixed traffic operations. In the general case, one may still require a human to intervene when the situation gets too complex.

7. ACKNOWLEDMENTS

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