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Simplifying interactions between autonomous and conventional ships with e-Navigation

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Abstract. Ships in autonomous mode will for a long time interact with conventional ships with human decision-makers on the bridge. For safety it will be necessary to simplify this interaction and this paper discusses three areas which will be crucial in this respect: the collision regulations, e-navigation and traffic separation schemes. To be able to code collision avoidance algorithms COLREGS must be quantified. Soft enumerations like "good seamanship" needs to be made machine-readable. At the same time, such attempts threaten to make them less human-readable. On the positive side e-Navigation services like route exchange promises to make ship intentions more transparent and paired with an extended network of Traffic Separation Schemes future interaction between manned ships and ships in autonomous mode can be facilitated.

1. Introduction

It is highly unlikely that we will soon see autonomous ships without a human in the control loop, except in very special applications with low operational complexity. However, for commercial reasons, one will try to avoid that the human must remotely control the ship and being continuously in control of one single ship. The preferred operational scenario will be a control centre where one person can supervise several ships. When needed, this or another person will take control over the ship, to handle situations that are too complicated for the automation systems. This requires that it is necessary to detect that the situation starts to deteriorate early enough to ensure that the human has gained enough situational awareness to safely take control before the consequences of the situation become too severe. This time period is sometimes called "Control Latency" or "Operator Control Latency".

Autonomous ships shall in principle be at least as safe as conventional ships, but for public and societal acceptance, it is probably necessary that they actually are safer. An accident involving an autonomous ship where the public has reason to believe that the accident could have been averted if there were persons in control, can easily cause significant loss in public confidence in and the commercial reputation of the company involved.

This may be particularly difficult with respect to operation of autonomous ships close to manned ships. COLREG provides rules for this, but it also explicitly mentions "good seamanship" and generally relies on that the master or crew of meeting ships understand the autonomous ship's intentions. It can be argued that the solution is to require that the autonomous ship should behave in a similar manner to a manned ship to avoid problems with misinterpreted intentions. However, this may not be the optimal solution for an automation system, and it will also pose some substantial problems in proving that the automation system does this in all conceivable situations.

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A better approach may be to define simplified and unambiguous behaviors, consistent with the principles of COLREG, for autonomous ships that are easy to understand for the crew on conventional ships. Such a version of COLREG would help to keep the Operator Control Latency at a high enough level, even in relatively dense traffic, to operate autonomously for a much higher percentage of the voyage.

We will start this paper by looking at a ship collision in the Dover Strait in 2017. This accident contains many events which generally are attributed to "human error" and we will here point at possible safety improvements that might be the result of the introduction of MASS. But we also share this story to illustrate the challenges in the interaction between ships in autonomous mode and manned vessels.

1.1. The collision between Huayang Endeavour and Seafrontier in the Dover Strait

In the small hours of 1 July 2017, the 225 m long, bulk carrier *Huayang Endeavour* collided with the 183 meters long oil tanker *Seafrontier*. Both under Hong Kong flag but with a Chinese and an Indian bridge crew respectively. The collision took place in the Dover Strait Traffic Separation Scheme (TSS) in the English Channel. *Huayang Endeavour* was underway between Amsterdam and Colombia in ballast, while *Seafrontier* was underway with gasoil from Antwerp to Nigeria.

Seafronter entered the southwest bound TSS lane at the Foxtrot 3 buoy at 2 o'clock in the morning just in front of the two vessels *Marcel* and *Huayang Endeavour* (see Fig. 1).

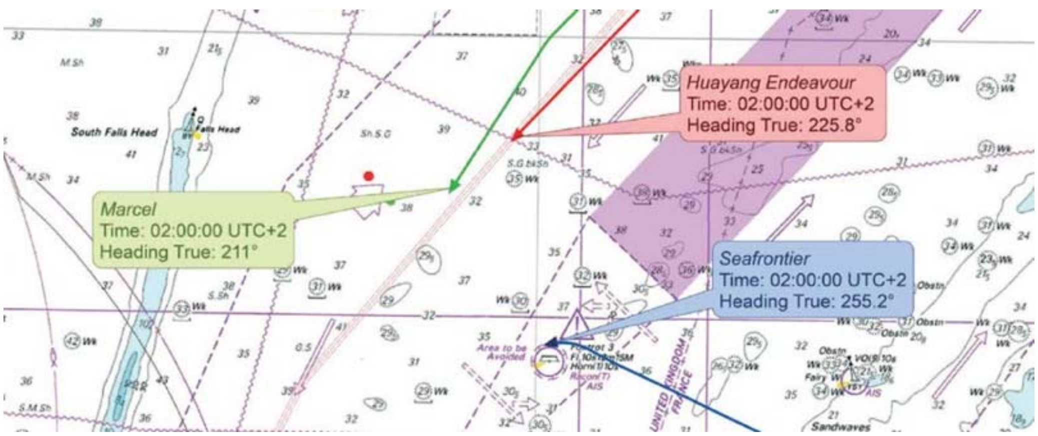

Figure 1. Seafrontier entering the south-west bound traffic lane at the Foxtrot 3 buoy [1].

The ships then continued southwest in the TSS. A little less than an hour later, as the TSS started to converge, *Seafrontier* and *Huayang Endeavour* was closing in on each other. *Seafrontier* 1 nautical mile in front of *Huayang Endeavour* which was slowly catching up. Another smaller cargo ship, the *Donau Express II* was in turn a short distance in front of *Seafrontier* who now slowed down to half ahead to increase the distance to *Donau Express II*. At this time the captain of the *Huayang Endeavour* got worried about the closing distance and asked his watch officer to call *Seafrontier* on the VHF and ask for her intentions. The following is a transcript of the VHF conversation [1].

Time	Station	Message
0253:50	*Huayang Endeavour*	Err *Seafrontier*, *Seafrontier*, *Seafrontier*. Motor vessel *Huayang Endeavour*, *Huayang Endeavour* call me back
0253:58	*Seafrontier*	Station calling *Seafrontier*, go ahead
0254:01	*Huayang Endeavour*	Ah zero six please
0254:03	*Seafrontier*	Zero six
0254:07	*Huayang Endeavour*	Yah, *Seafrontier*, *Seafrontier*. *Huayang Endeavour*, *Huayang Endeavour* call me back

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0254:11	*Seafrontier*	… This is ..go ahead, go ahead
0254:15	*Huayang Endeavour*	Yah, err *Seafrontier*, what is your intention?
0254:20	*Seafrontier*	I should ask you what is your intention, you are overtaking me and not keeping me clear - what is your intention?
0254:29	*Huayang Endeavour*	Yah, I will overtake you on your starboard side, starboard side okay?
0254:34	*Seafrontier*	Alter your course to starboard side, I have a vessel on my port side, I cannot alter so much on my port side. I am giving some few degrees to my port side, I will give you some 4-5 degrees clearance but I cannot alter too much on my port side okay?
0254:53	*Huayang Endeavour*	Yeah, err port overtake is so near, so near. Is very dangerous
0256:02	*Seafrontier*	No, you have to keep me clear because you are overtaking me, you can reduce your speed, do you understand?
0255:26	*Huayang Endeavour*	Yeah okay, thank you thank you

What is not visible in the transcript is the inherent language difficulties for people not talking their native language and the distortion due to the quality of the radio communication. But the content is clear: there is a complete misunderstanding. *Seafrontier* thinking that *Huayang Endeavour* will pass on her starboard side, and *Huayang Endeavour* believing that they have just agreed a passing on the *Seafrontier's* port side. In the final moment before the collision *Seafrontier* decides to make a 360 degree round turn to increase the distance to *Donau Express II* which is now really close on *Seafrontier's* port bow. Believing that *Huayang Endeavour* is passing on his starboard side the captain orders hard port rudder without looking behind him where *Huayang Endeavour* is just about to start passing. Figure 2 shows the situation at the moment of collision.

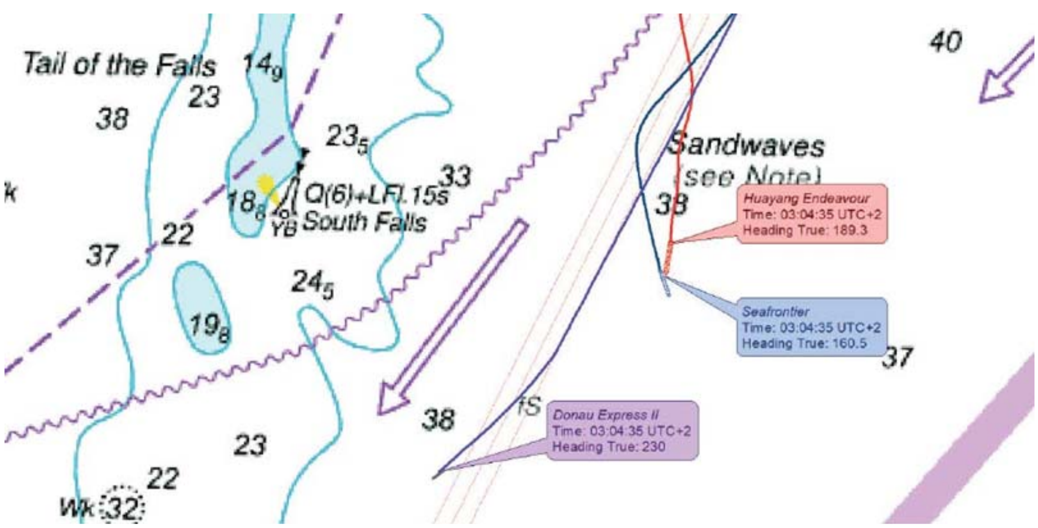

Figure 2. The collision between Huayang Endeavour and Seafronter in the Dover Strait. Seafrontier has just started a 360 degree round turn to port without checking his rear where Huayang Endeavour has just started to overtake.

What we see here is misunderstood intentions. However well planned, with a voyage plan made ahead of time, the actual sailing of a ship is often an improvisation, guessing other vessels intentions and when finally a radio call is made to find out for sure, language barriers causes misunderstandings. The IMO cautions for radio calls and misunderstandings, and there is a saying among officers that "a well run ship is a silent ship". Still communication is crucial to avoid misunderstandings.

Would ships in an autonomous mode make better choices? Presumably. One can assume that an autonomous *Seafrontier* would not have entered the TSS just ahead of *Huayang Endeavour* causing a congested situation. One would assume that she would have slowed down and entered when the traffic had cleared. One would also assume that a group of autonomous ships passing down the TSS would synchronize their speeds and not start overtaking as the TSS was narrowing. One would assume that a group of autonomous ships in close vicinity of each other would shake hands and communicate and coordinate their actions in machine-readable language that was free from misunderstandings. That is what one would assume, *if all stakeholders where autonomous*.

However, we know for sure that for a long time there will be conventional, manned ships in the equation as well. If only one of the ships here is autonomous and the other is manned, the risk is that the situation will be even worse. In the following we will look at some potential risks and suggest some potential solutions.

1.2. Automation can make shipping safer

In the example above, we can see how human shortcomings took part in causing a shipping accident.

Fatigue and attention: It is does not come as a surprise that this accident as well as disproportionate number of maritime accidents occurred during darkness and in the small hours of the night. Humans are day animals and many cognitive and physical functions are reduced during night. The captain onboard *Seafrontier*, was according to the accident investigation affected by not having slept for 18 hours prior to the accident. In these respects, an autonomous system works better, not being affected by deprived vigilance due to human physiological factors.

Misunderstood communication: The VHF radio call between the Chinse 2nd officer onbord *Huayang Endeavour* and the Indian master of *Seafrontier* was misunderstood. When the 2nd officer of *Huayang Endeavour* relayed the content of the radio call to the master in Mandarin he said that *Seafronier* did not want to be overtaken on her starboard side, quite contrary to what the master on *Seafrontier* had said in the radio call. Although human spoken language has a lot of redundancies and the recommendation to use IMO's simplified Standard Maritime Communication Phrases (SMCP) when talking on the VHF, intentions was misunderstood. Automation has a much better chance of making secure communication.

Situation awareness (SA): Possibly due to factors mentioned above, darkness, fatigue, misunderstood communication, the two crews did not have an adequate and shared SA. They did not have a common perception of the environmental elements and events with respect to time or space, nor a common comprehension of their meaning, and a projection of their future status [2]. The gravest mistake was made by *Seafrontier* by not checking for oncoming traffic from behind before commencing the 360-degree port turn. Humans have a limited working memory and these kinds of slips and mistakes are common because only a limited number of hypothesis about a situation can be active at any one time. Automation has much better prerequisites for this type of multi-tasking.

We could continue listing areas where machines are better than humans, but we think the point is made. However, there are other areas where humans are better than machines.

1.3. Automation can make shipping less safe

An important part of the safety work in the maritime domain consists of the type of investigations of accidents and incidents which the narrative above is an example of. The objective is to make sure that barriers against similar accidents in the future are created. Numerous studies point to the large involvement of what is called "human error." However, to prevent repetition, it is vital that barriers are created on a system level. The need for investigations has also led to the availability of good statistics on accidents and incidents, while statistics of "miraculous human recovery" of situations that would otherwise have led to an accident are missing.

Once the autonomous ship eventually enters the stage it is important to acknowledge that for the foreseeable future autonomous ships will coexists with conventional, manned ships. This introduces the problem of human-machine interaction at sea. Imagine that one, or the other, of the two ships in the narration above had been autonomous. How would that have affected the scenario? For instance, when a manned *Huayang Endeavour* would hail an autonomous *Seafrontier* on the VHF, there would eventually be an answer from a Shore Control Centre somewhere in the world. Apart from the operator control latency, this would probable increase the risk of misunderstandings as the remote operator would be even further from the context of the dark night in the English Channel. And the chances are that the remote operator is engaged in other tasks and an answering machine would respond "Please hold the line" for some time while the situation continues to develop.

Preparing for unavoidable encounters between manned ships and ships in autonomous mode, we will here look at some problems and mitigation possibilities: COLREGS, e-navigation and traffic-separated route networks.

2. COLREGS

This section discusses some possible ways to modify COLREGS to make the interaction between conventional ships and MASS more predictable for both. This should increase safety of mixed operations as well as simplify the design of the MASS' sensor and control systems. It is understood that modifications of COLREGS will be met with great reluctance in the international community, but the discussion is important because this may be simplest way to ensure that mixed ship interactions become as safe and efficient as possible. Otherwise, it will be very challenging to specify behavioural criteria and test methods for the MASS' control systems and sensor equipment, due to the multitude of different situations and ways to interpret COLREGS in each.

2.1. Modification of COLREGS for all ships

The first commandment for MASS would be to stay out of trouble by avoiding close quarters situations which would depend on a shared understanding involving other, manned, vessels. However, this will not always be possible so as a final resort MASS needs to be equipped with a robust and transparent collision avoidance behavior based on COLREGS.

The International Maritime Organization (IMO), adopted the latest revision of the International Regulations for Preventing Collisions at Sea (COLREGS) in London in 1972 [3]. The COLREGS is a thin booklet containing 38 rules and some annexes. The collision regulations are, like legal text often is, written in a general manner to be applicable in as many situations as possible. It contains statements saying that the master or crew of a ship must always take "any precautions which may be required by the ordinary practice of seamen, or by the special circumstances of the case" (Rule 2). Instead of specifying the distance in nautical miles when a collision avoidance maneuver needs to be conducted it uses qualitative enumerations such as "early and substantial" (Rule 16). Under Rule 8(a), any action that is taken to avoid a risk of collision shall "if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship".

For a computer programmer translating COLREGS to code these soft enumerations will be troublesome. But the prospects of producing a "quantitative COLREGS" that will be applicable in all situations might be bleak because there are just as much "it depends" in the maritime world as in life in general. This is further discussed in [4 and 5].

It is more likely that the collision avoidance algorithms will need to assess a situation and act to the best of its ability and, if the outcome is bad, that the programmers or software companies, just like any master or watch officer, will need to defend these actions in a court of maritime law.

2.2. Modified COLREGS only for MASS

An alternative to a general modification of COLREGS would be to define, e.g. a special version of COLREGS for autonomous ships. This should be translatable to computer instructions, as discussed above, but one might also consider restricting the rule set so that it is easier for other ships' crew to predict the MASS' response in a given situation and by that giving a much better situational awareness to the other ship's crew as well as making the automatic control systems more predictable, easier to test and easier to approve.

This restricted set would probably give the MASS fewer options in each situation and also make the general operation more conservative in cases that can cause misunderstandings. This would require that conventional ships get a higher responsibility for not creating difficult situations for MASS, e.g. by keeping a longer distance from them. Otherwise, this could create efficiency problems for the MASS and would also open up for certain types of hostile attacks.

To do this, it is important that conventional ships' crew can distinguish an autonomous ship from other ships. This could be done through AIS messages as discussed in the next section.

3. E-navigation

The IMO launched in 2008 the concept of "e-navigation" defined 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." [6].

This exchange of information between ships, and between ships and shore, holds promises of solutions to many of the problems of building a common situation awareness between humans and autonomous systems.

To present day the IMO has suggested a Maritime Service Portfolio containing 16 services [7]. It is likely that in the future the Service Portfolio will be amended with services related to MASS. One such service that has been extensively researched in several EU projects is *route exchange*, which is discussed below, a quicker modification to implement concerns the AIS.

3.1. AIS warning of autonomous ships

Today, all ships in international trade has an Automatic Identification System (AIS) transponder onboard. This sends fast updates of current position, track and speed through a *position message* to other ships in the vicinity and receives similar data from these ships. This is a very efficient complement to the radar to establish a good situational awareness and understanding of other ship's actions. AIS also sends out a *static message* information about, e.g. ship size, type and destination at longer intervals.

The above discussion on COLREGS indicates that it would be very useful to have some means to distinguish an autonomous ship from conventional ships and one obvious possibility is AIS. There are several possibilities that are briefly discussed below [8]. All have the drawback that it will require some changes in existing ships' equipment.

1. It may be possible to define a new position message for MASS. This would give us full freedom in putting the most relevant information in it.
2. One may also add information in the position message, e.g. in spare bits or in existing fields. This could be the best way as it makes minimum modifications to existing systems.
3. Finally, one can also put information into the static message to the same effect. This is less attractive due to the relatively low update rate of this type of message.

AIS message modifications should also be accompanied by similar modifications in the COLREG rules on shapes and lights.

3.2. Route exchange

Route exchange has been researched in several EU projects like the EfficienSea [9, 10], MONALISA [11]; ACCSEAS [12] and the STM validation project [13]. Route exchange is the provision to electronically exchange voyage plans or segments of voyage plans between ships and between ships and shore. Every SOLAS ship (over 500 GT, and all passenger ships, on international water) today must prepare a voyage plan “from birth to birth” before leaving port. Today this voyage plan only resides in the electronic chart system onboard. If this voyage plan could be sent to a central coordination centre it would be theoretically possible to lay all voyage plans on top of each other and see if any two ships at any point in time would be at the same place at the same time. And in such case send out a suggestion of some small speed or course change. Of course, things happen: engines have trouble, wind and waves make a change of speed necessary, things do not go as planned. However, the voyage planes will be continuously updated and could, as ships approach each other, be very precise, given that the intentions in the voyage plan is followed. But this would ask for a change in behavior: ships would need to adhere to their plans and be aware that they are not only transmitting their present position, but also their future intentions. The effects and potential dangers of route exchange has been studied in simulator studies with positive results, see e.g. [14, 15].

3.3. Simplified route exchange

One may also make do with a much more simplified route exchange than the general message discussed in the previous section. As the MASS is controlled by a computer, it will at all times exactly know what its immediate plans are and can send continuous updates of next waypoint, speed and heading, together with its planning horizon, to ships around it. This is a relatively small message that may be sent in one AIS slot (168 bits payload) and by that allow faster updates. This would give conventional ships definitive knowledge of the MASS' next actions.

But awareness of intentions is already today enhanced by the simple mean of *Traffic Separation Schemes*.

4. Traffic separation

In 1967 the IMO approved the first traffic separation scheme (TSS) in the world in the Dover Strait. The intention was to decrease the risk of ship collisions by separating the two traffic streams from the North Sea to the Atlantic and vice versa, just like car traffic on roads are separated. The introduction of the Dover Strait TSS resulted in an immediate decline in the number of collisions and groundings [16].

However, even if the number of TSS has grown since 1967, they are only found in a limited number of congested or narrow areas of the world. In other places ships must avoid collisions based on COLREGS.

In the ACCSEAS project [12] the focus was set on the future ship traffic environment of the North Sea Region. Astonishing plans for future offshore wind farms was discovered in the southern part of the area. In the Germain Blight 10 000 wind turbines is planned to replace the energy today produced by German nuclear plants that is to become decommissioned. The effects to navigable space will be dramatic. Ship traffic will in the future be confined to corridors in areas of wind turbines, which each has an exclusion zone with 500-meter radius [17].

Because of the findings regarding future navigable space, work on route networks for ship traffic started. The main reason was to ensure that water for future ship traffic was reserved. By looking at traffic density maps of the North Sea area it was obvious that shipping today took place in relatively well-defined corridors. This is natural since the closest distance between two points is a straight line, of course taken into consideration obstacles like shallow water, oil platforms, etc. As a result of this work the ACCSEAS project presented a North Sea Region Route Network Topology Model (NSR-RNTM) [17]. Such a route network, if traffic separated, will have the added benefit of de-conflicting ship traffic. It will do so for present day ship traffic, and it will simplify the task of collision avoidance for future ships in autonomous mode.

Let us, as an example, look at the situation around the northern tip of Denmark where most of the traffic in and out of the Baltic Sea passes. The process of creating a route network is illustrated in the figures below. Figure 3 shows a current screen shot from Marin Traffic where the number of AIS symbols of ships are visible. The traffic intensity here would certainly be a challenge for the behavior of any collision avoidance software where an evasive maneuver for one ship might lead to a close quarter situation with another, in a cascading interaction with uncertain outcome.

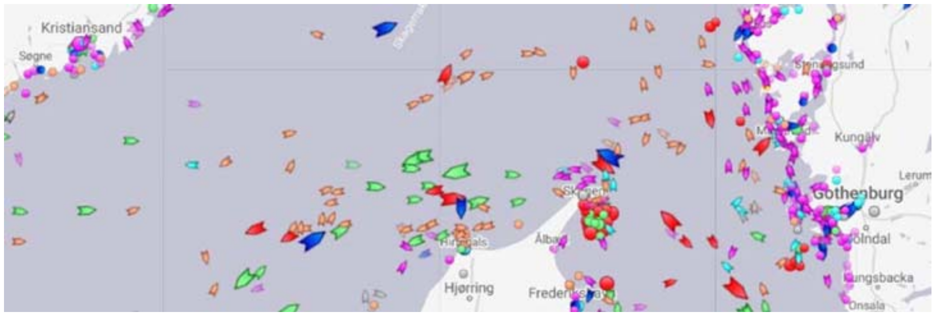

Fig. 3. This screen shot from Marintraffic.com from the 10 June 2019 shows the complex traffic situation around the northern tip of Denmark where most traffic between the North Sea and Sweden, Denmark and the Baltic Sea passes.

Figure 4 shows a traffic density map over the same area for the whole of 2012. This density map was produced during the ACCSEAS project and we can see that there is a good fit with the traffic situation in Figure 3.

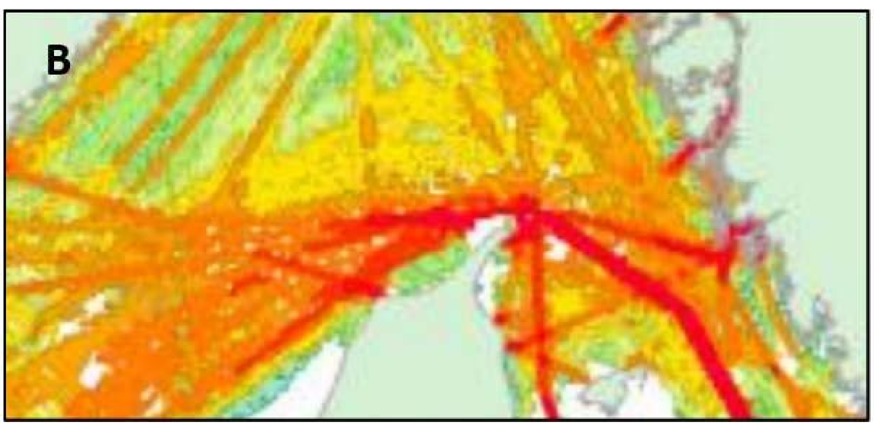

Fig. 4. This is a traffic density map based on the number of AIS equipped ships during the whole of 2012 where red depicts the highest number of ships [18].

In the next figure, Figure 5, the main "track" distinguishable in the density map has been extracted and drawn as red line. This is the first simplified version of the route network purely based on the traffic density map. In the next step, in Figure 6, a rout network topology is suggested. This involves deciding on the number and importance of the different route links. Which routes are the main "motorways", which are the "regional" and "local" roads? This step will of course involve important international and bilateral political decisions and the design in Figure 6 is only an example.

Fig. 5. This map shows all routes that appear to be used by AIS carrying ships over the year 2012 in the depicted area. This is a generalization made from the AIS tracks deduced from the density map in Figure 4 [18].

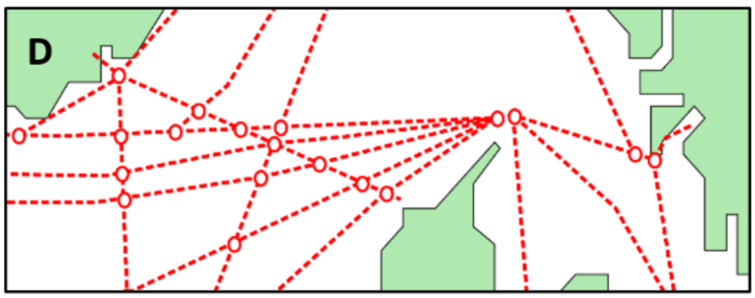

Fig. 6. The final "motorway" route network topology derived in the ACCSEAS project from this exercise [18].

For such a route network to function as a deconflicting measure it should be traffic separated throughout. Present day limited Traffic Separation Schemes has a vulnerable spot at the entrances and endings, something that would be less prominent with separation throughout the length of a voyage. However, also junctions will be a weak point into which attention needs to be put. That is why, outside London, in the Northern Approaches to the Thames Estuary, a ship traffic "roundabout" was created in 2007 to help de-conflicting the traffic in the Sunk precautionary area (see Figure 7),

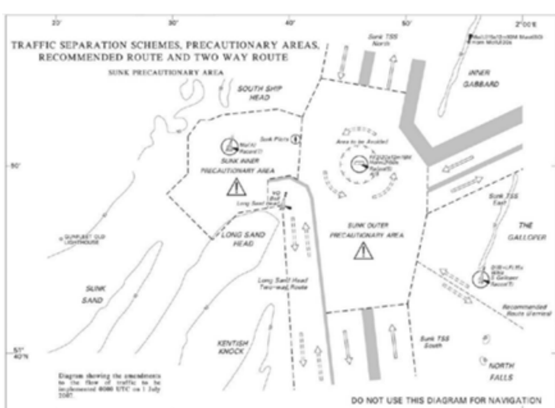

Fig. 7. The Sunk Precautionary Area and the three Traffic Separation Schemes in the Northern Approaches to the Thames Estuary implemented in 2007 [19].

Special care must be taken here when designing such a shipping route network. To increase the effectiveness of the larger "motorways" a multi-lane structure can be introduced when space so allows. This would decrease risk in overtaking situations.

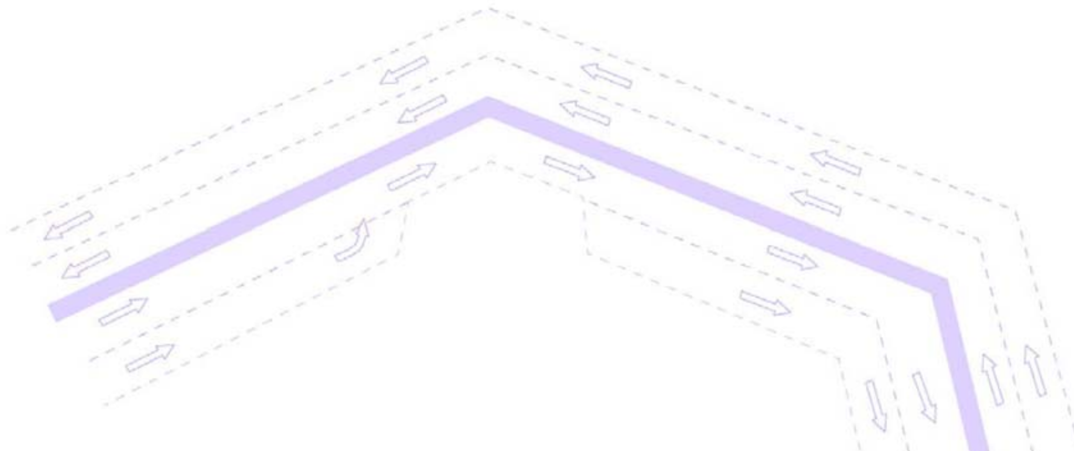

Fig. 8. An illustration of a design for a "motorway" route network topology derived from the exercise above. Illustration by the authors.

The suggestion is a network of traffic separated shipping lanes of different sizes, from multi-lane "motorways (Figure 8) to smaller "regional" and "local" fairways (not shown in the figure). The hypothesis is that implementing such a network of shipping lanes would de-conflict ship traffic not only for the interaction between autonomous and conventional manned ships, but also for the common ship traffic.

5. VTS – shapes and lights

5.1. VTS information to all ships
One should also consider the possibility the VTS has to inform other ships about MASS operations in its area of responsibility. This would obviously make other ships aware of their operations and by that improve situational awareness but would not provide clearer rules for interactions as other methods can provide.

5.2. Extended VTS
One may also consider giving the VTS extended power to guide both MASS and conventional ships to establish safe and efficient interactions between them. This creates a problem for innocent international passage as current conventions do not allow this. It may be possible to do this in conjunction with TSS and in certain national waters, but this is not obvious and may not work very efficiently, unless international conventions and codes are changed.

5.3. Shapes and lights
In the section on e-navigation it was discussed the possibility to code AIS messages to make conventional ships aware of MASS operating in their vicinity. As was mentioned there, a corresponding physical measure is to define new shapes and lights to make MASS stand out from other ships both in daytime and night.

6. Conclusions

We have in this paper discussed some challenges regarding the interaction between ships in autonomous mode (where decision-making and maneuvering is done by computer software) and conventional manned ships. We have discussed three areas which will be important for this interaction:

- COLREGS. Quantification of the rules of the road at sea will be necessary to translate COLREGS into machine-readable format. At the same time the simple human-readable format will be essential for humans and must be kept. The solution must be that programmers of collision avoidance software will have to do their best to translate soft enumerations like "early and substantial" into code using culture and behavior in different shipping areas of the world. If anything goes wrong, they, or their companies, will need to defend the actions of their software in a court of maritime law, just like any captain or bridge officer.
- E-Navigation. Some of the advances in digitalizing and sharing data already available in the maritime community can be used to make intentions transparent, e.g. route exchange. This will benefit the interaction between all ships
- Traffic separation. Traffic Separation Schemes (TSS) have had good safety implications in many parts of the world. By creating a network of traffic separated shipping routes, maybe in the manner illustrated in the ACCSEAS project, the traffic situation will be simplified and the need to use anti-collision algorithms will be lessened. This could benefit the safe interaction not only between autonomous and conventional ships, but to shipping as a whole.

It is clear that modifications of existing international rules and convention will be met with reluctance in the international community, but it is believed that this may be the easiest way to make interactions between conventional ships and MASS safer and more efficient. Thus, this option should be examined carefully. It may also create an intermediate framework for coexistence between MASS and other ships until an IMO regulation for MASS is agreed on. As MASS is expected to start to sail internationally relatively soon, this again should be considered.

Acknowledgements

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