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Resilience in Maritime Transport for the Next Decade †

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Abstract: This vision paper covers the increased complexity of navigational environments and presents an innovative navigation system that can support the human in this task. Shipping in general also requires a mean to support navigators reduce the risk of accidents due to smaller passing distance or a shorter reaction time. An innovative approach called Velocity Obstacles might help the operator to avoid intruding into an object's protected zone by visualizing the problem space in relation to the maneuvering potential of the Own Ship.

Keywords: velocity obstacles; protected zone; transparency; collision avoidance systems

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1. Introduction

Conventional vessel navigation thus far has always made use of the various tools at hand to determine the best navigational solution for an individual vessel. Limited consideration is taken of the entire situation as this is a very complex task to perform. With more computational power available and navigational environments becoming more multifaceted with not only an increasing number of vessels, but also additional obstacles such as wind farms becoming more prominent on navigational routes, a need for improved situational awareness is rising. To optimize the navigational performance of an individual vessel and reduce the navigation risk, a shift of the navigation perspective from an own vessel-centric perspective to a situation-centric perspective, taking into consideration the constraints of all participants, has to take place.

This article advocates for this shift by explaining the problem of stress creation during conventional sailing by guiding the reader through a real scenario of Automatic Identification System (AIS) recordings. It then explains the concept of the Protective Zone around vessels and their use within Velocity Obstacle (VO) diagrams, as a stepwise solution to gain a better visualizing and understanding the consequences of navigational changes in complex navigational situations. To do so, this article provides a step-by-step time-lapse of a real navigational recording from two different vessel perspectives and explains how VO could have helped reduce the navigational risk. It is also addressed how such visualization tools enable transparent monitoring, supporting the integration of automated or autonomous navigational systems.

2. Velocity Obstacles a Novel Approach to Avoiding Danger for Collision

2.1. Analysis of Conduct

The conduct of vessels is regulated by the IMO's COLREG [1]. Due to the absence of external traffic control, i.e., outside Vessel Traffic Service (VTS) areas in a nation's territory, this conduct can be regarded as self-regulated. Based on formal education, training and licensing, the professional mariner behaves responsible and prudent, and applies the rules. Hence, it can be expected that danger for collision is mitigated at all times.

However, individual ships have their individual constraints and each Officer On Watch (OOW) has their individual interpretation of a safe passing distance. The dimension of a Protected Zone (PZ) or a safety limit, like the Distance Closest Point of Approach (dCPA), is neither exchanged nor mutually agreed. This can result in a stressful situation for the stand-on vessel that has to wait for measures from the give-way vessel with a smaller safety limit.

Although some general idea about safe passing distance exists can be analyzed that in reality, this distance shows quite some variation. From observed AIS data during four months in 2021, a selection of 113 encounters in the area east of the F-3 buoy were analyzed. The F-3 buoy functions as a central point in the Belgium–UK bound traffic and the North Sea–English Channel traffic. All of these encounters consisted of two vessels with a dCPA less than three miles, and one of the two, the Northbound vessel, showing an action. (see Figure 1).

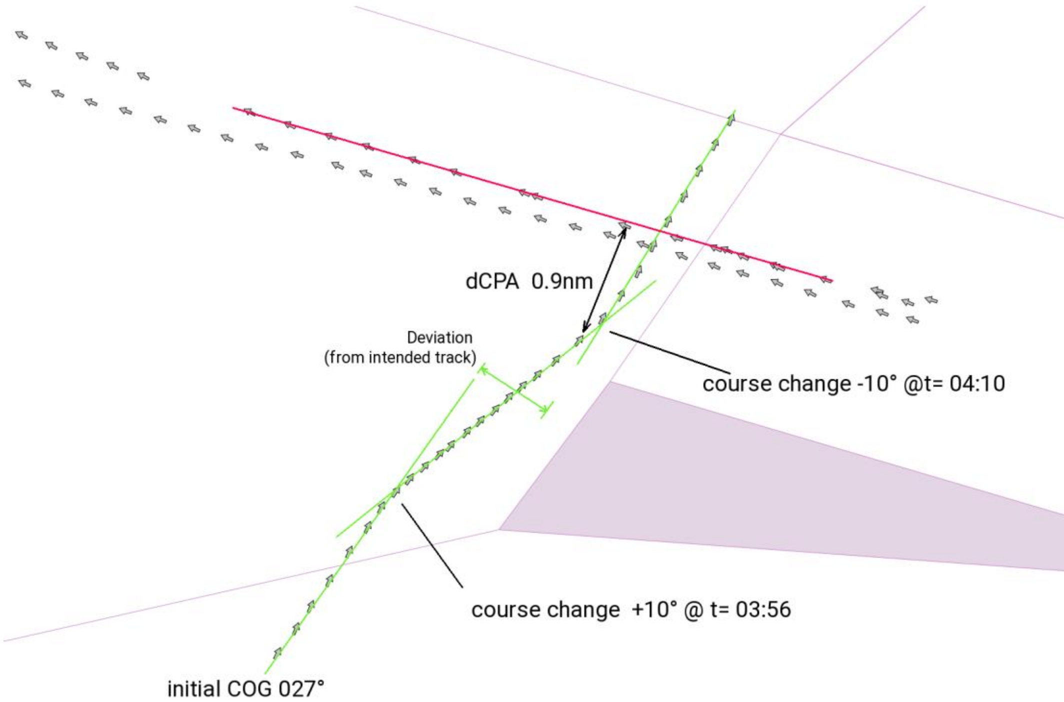

Figure 1. Typical Selected Encounter.

It was found that practically all reacting vessels applied only a course change to starboard. This change varied from 5° to 60° (m = 15°). The resulting safe passing distance (dCPA) varied from a third nautical mile (about 660 m.) to two miles. The amount of course change and the safe passing distance appeared not to be correlated. From this analysis, it might be concluded that neither a common safe passing distance nor a common course change seems to exist. This makes predicting the other vessel's behavior difficult. The assumption that the reaction time, i.e., the time between the moment of course change and the moment of CPA, relates to the amount of course change (e.g., a late reaction requiring a drastic maneuver) could not be proven. This corroborates the hypothesis that a common method to conduct in accordance with the rules does not exist.

2.2. Dimension of PZ

Many studies have been spent on the required protected zone, also referred to as the ship domain. Apart from these theoretical approaches, there actually exists an area around the Own Ship (OS) that inhibits an emotion of uneasiness by the OOW. From research carried out by cadets at sea, it was found that the often intuitive ship domain has a dimension of about one and a half mile in front of OS, half a mile astern of it and one mile abeam. This research was carried out on merchant vessels underway with lengths between 150 and 200 m.

Analyzing traffic based on AIS broadcasts can also determine the area that a ship apparently wants to keep free from other traffic. Several studies, Fujii and Tanaka [2], Goodwin [3], Pietrzykowski and Magaj [4], Procee, Borst, van Paassen, and Mulder [5] a.o., show all slightly different dimensions than the intuitive area based on the cadets' research. They all, however, provide proof of the very existence of an area around the OS that the OOW wants to keep free from dangers.

It might be striking to observe that, in the marine world, collision avoidance as well as the ship's domain is almost uniquely approached from the OS's perspective, meaning, the self-imposed obligation to keep traffic outside OS's own domain. Aviation, on the other hand, uses a uniformly defined horizontal Protected Zone (PZ) of five nautical miles radius around the airplane in which another should not intrude. This different perspective is interesting for marine navigation and might promise a solution for the stressful situation where the stand-on vessel is forced to wait for action of the give-way vessel. In the case that the latter vessel uses a much smaller domain than the stand-on vessel, it might enter, unintentionally, the other's domain and cause great stress for the waiting OOW, potentially resulting in unexpected action or illogical behavior. An example of this can be found in [6].

Ships are, different from airplanes, not highly standardized. Applying a uniformly defined protected zone for shipping might not be feasible due to a lack of acceptance, nor be effective due to the variety of ships and their individual operations. However, if the required PZ of a ship would be shared with the environment directly around the OS, e.g., by a dedicated field in the AIS broadcast, than a novel approach for resolving danger for collision becomes available. This approach visualizes the required PZ of the target with which one is engaged with and predicts whether one is going to intrude into that PZ. In the case that intrusion is imminent, then action is required, if not, then course and speed can be maintained by all vessels involved. The tempting simplicity of this novel approach is that when intrusion can be avoided by e.g., a minor course change long before any engagement can be defined, then the size of the required maneuvers will be minimal, which impacts efficiency, and traffic shows a less chaotic, i.e., more predictable, pattern. Although in this paper it is called a novel approach, a taught strategy at nautical colleges, e.g., in the Netherlands, also refers to taking a preemptive measure, i.e., a minor course change long before the situation starts, to be 'collision avoidance', in order to avoid that situation at all. So, this principle is known and has been effectively used for a long time, while the planning by visualizing the PZ of the other vessel is not. The latter is also known as Velocity Obstacles (VO). In the next paragraph, the method of visualizing is explained based on some realistic examples.

As pointed out in this paragraph, the dissemination of the dimension of one's PZ to vessels that are directly involved in the situation, e.g., within a radius of three to six miles, would provide a number of opportunities. First, it avoids the situation that a vessel with a relatively small PZ unintentionally enters the PZ of a vessel that has a much larger PZ. Because the PZ's dimension of one's own ship is usually not formalized, i.e., intuitively present only, the awareness of a PZ of the target is even less likely. By visualizing the target's PZ and its associated conflict zone it is expected that stressful situations will be reduced because ships can avoid, unintentionally, intruding into the target's PZ. It is expected that this reduced stress level leads to better decision-making. An example of a stressful situation leading to a collision can be found in [6]. Secondly, by visualizing the solution space, the time it takes to decide and reach a resolving action is expected to diminish, hence providing opportunity to increase the quality of decision-making. Based on Wickens, Hollands, Banbury, and Parasuraman [7], their information processing model of decision-making it can be inferred that a repetition of the Diagnosis- > Confirmation- > Selective Attention- > Cue Filtering- > Diagnosis cycle, enhances the quality of the assessment and its subsequent decision-making process. Kahneman's [8] 'slow thinking' refers to a similar process in decision-making.

3. Planning with Velocity Obstacles

Solution Space vs. Problem Space

In their initial paper, Degré and Lefèvre [9] pointed out that predicting the OS's position relative to the target's domain, even based on the simplest form of a circular zone, will provide useful information for OS's OOW. Their visualization differentiates between the 'room to manoeuvre', also known as the solution space and the 'danger zone', which is commonly referred to as the 'problem space'. Visualizing the solution space provides multiple combinations of course and speed that will guarantee a passing distance greater than the critical distance, i.e., the circumference of the target's domain. In particular, when two or more targets are to be dealt with, the prediction of the combined solution space helps to choose an evasive course and speed that solves all problems at the same time. Also, Huang, van Gelder, and Wen [10], and Westrenen & Ellerbroek [11] provide evidence that the method of VO, i.e., visualizing the problem space and solution space, enables the OOW to resolve complicated traffic situations with multiple targets involved.

An example of traffic conduct that is observed during the four months of AIS data collection is shown in Figure 2.

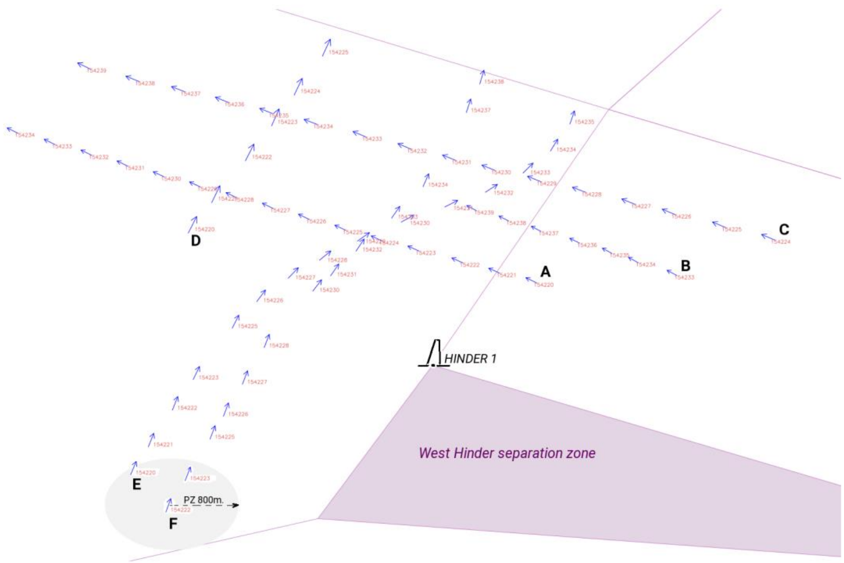

Figure 2. Example Maneuver showing Westbound vessels A, B and C crossing the northbound traffic lane. Vessels D, E and F are Northbound. The shaded circular protected zone (PZ) of 800 m. radius is shown around vessel F.

In the given example, there are six vessels sailing near the exit of the Traffic Separation Scheme (TSS) West Hinder into the Dover Strait TSS. Every AIS broadcast is considered to be a vessel underway, its position is reflected in the position of the arrow (in blue). The direction of the arrow corresponds with the course over ground and the speed over ground is expressed by the length of the arrow. The time interval is limited to one minute, the relative time stamp is shown as number in red with one minute time resolution.

Three vessels, i.e., A, B and C, are leaving the West Hinder TSS on a westerly course, and three vessels, D, E and F, are heading for the North Sea on a northerly course. According to collision regulations, the three ships on the northerly course are to give way when risk for collision is deemed to exist. Apparently, the north bound vessel sailing in the western part of the area, vessel D, did not assess the situation as 'risk for collision'. The other north bound vessel, vessel F, assesses the situation as risky and decides to change course to starboard at about time stamp 154228. The third northbound vessel, vessel E initially time stamped 154220, assessed the situation as such that a drastic course change, i.e., 35°, to starboard was executed, which resulted in a bow crossing of the second northbound vessel. Ultimately both vessels, E and F, passed the three westbound vessels astern. This situation developed in the early morning around half past three GMT. Weather analysis showed there was a declining ridge of high pressure from Scandinavia to the Iberian peninsula. As the wind gradient was weak at the F-3 location, there is no reason to expect much wind. Some disturbances in the southern North Sea and NW Europe hint at vertical movement of the atmosphere, hence, a small chance for low visibility at the surface. This means that it is likely that the ships in this example sailed in sight of each other and the normal rules, i.e., not Rule 19, were applicable.

It is assumed that each of the ships in the given example has a circular protected zone with a tentatively chosen radius of four cables, i.e., ±800 m. This is illustrated as the gray-shaded oval in Figure 2 for vessel F only once. The explanation for the apparent oval shape is the scale difference between the major and minor axis at this latitude in the Mercator projection. Buoys and fairway markers, usually referred to as Aids To Navigation (ATON), can be dedicated to have a protected zone as well. The dimension of this dedicated PZ depends on the navigator because no formal rule applies. In the given example, the Hinder-1 buoy is to be avoided by applying a PZ with a tentatively chosen distance of 185 m., i.e., a tenth of a mile.

A third feature that determines the navigable space is Routing Measures, also known as Traffic Separation Schemes. In this case, the Separation Zone, the light magenta shaded area in Figure 2 is a forbidden area, the northbound vessels are not allowed to enter the exit of the West Hinder TSS, i.e., the traffic lane where the west bound vessels are coming from. This fairway restriction is not shown in the following example.

The developing traffic situation is illustrated in Figures 3 and 4. Each of these Figures shows the same situation albeit from two different perspectives. Figure 3 refers to vessel E which is represented by the pink protected zone. Figure 4 refers to vessel's C perspective. Vessel C is represented by the green oval.

The top half of each row shows the developing situation in the chart, the lower half of the row shows the orthogonal projection of the conflict zones of each target from either, vessel's E perspective (Figure 3), or vessel's C perspective (Figure 4).

At t = 22, vessel E is northbound underway with a speed of 14 knots over ground. It has one northbound vessel, i.e., vessel F with blue shaded PZ, on its starboard quarter. Also, there is a northbound vessel on E's port bow, i.e., vessel D with a yellow shaded PZ, and there is one westbound crossing vessel, i.e., A with the purple PZ. The Hinder-1 buoy is on the northwestern corner of the West Hinder Separation zone (See Figure 2).

From the perspective of vessel E, the Conflict Zones (CZ) of vessel F, vessel A and the Hinder buoy (Hby) are shown (See Figure 3 t = 22 lower half). The CZs are displayed relative to the OS's bow, also known as the Head Up orientation, the red arrow in this diagram indicates the OS's speed and course. From this diagram it becomes clear that vessel E has no conflict with vessel F as long as E keeps its speed. It also is clear that E does not have a conflict with A as long as E does not speed up. There is neither a conflict with the Hinder buoy at this course. Hence there is no need to take action at the present moment (t = 22), and if vessel E should want to change course, it finds potential combinations of course and speed to do so, i.e., without intruding in someone's PZ, in the solution space. The vessels B, C, D are not shown in the diagram for the reason that their CZs are outside the area of interest which in this case is limited to 3 miles.

At t = 24 the CZ of vessel C shows up in the diagram, and from the position of the OS's arrowhead, that is located inside C's CZ it becomes clear that intrusion into C's PZ will happen at some time. At t = 25, vessel E has started to change course to starboard, at t = 27 the effect of this course change becomes noticeable as the OS's arrow head shifts gradually to the border of the CZ. At t = 29, it becomes obvious that vessel E will not intrude into C's PZ because of its course change. The course change was found in the solution space, meaning that no conflict arose as a result of the action to resolve the first conflict.

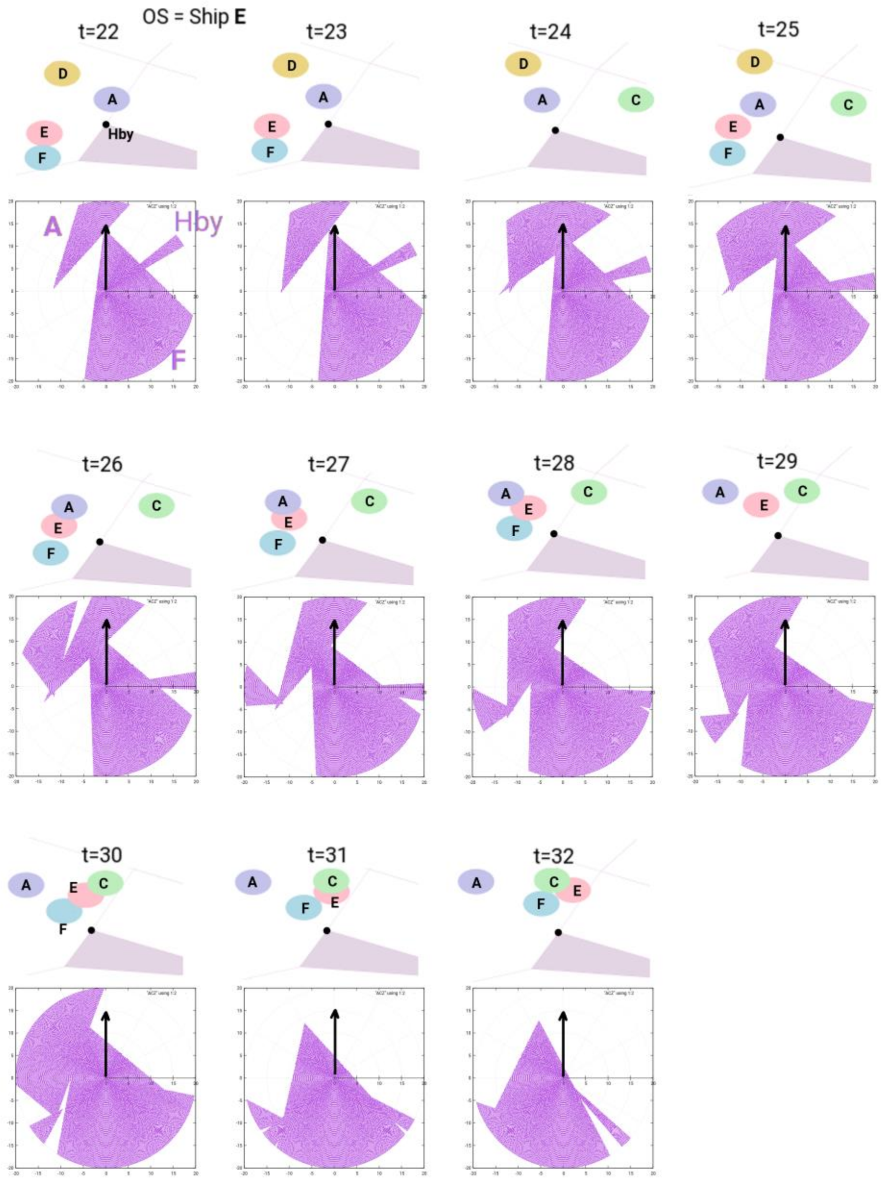

Figure 3. Velocity Obstacles from Vessel E's perspective (vessels B C D are not shown).

The identical situation is presented from the perspective of vessel C in Figure 4. At t = 22, the CZ is shown for vessel D (to starboard of OS) and for vessel E. Also, the CZ of the Hinder buoy (Hby) is shown, to port, originating from OS. From the head of OS's vector (red) it appears that intrusion in the PZ of vessel E is not expected. As the situation develops over time, the CZ of vessel D shifts and increases in dimension. At t = 24, the head of OS's vector is inside the CZ of vessel E, indicating that intrusion in its PZ is expected (in time). At t = 26, a part of the CZ of vessel F appears separate from the overlapping part with E's CZ. It also appears that the head of OS's vector shifts gradually toward the margin of E's CZ indicating that E's course change to starboard (at t = 25) has an effect. The apparent continuation of the effect is illustrated in the subsequent fragments until t = 29, where it can be seen that OS is neither expected to intrude into the PZ of vessel E nor into the PZ of vessel F.

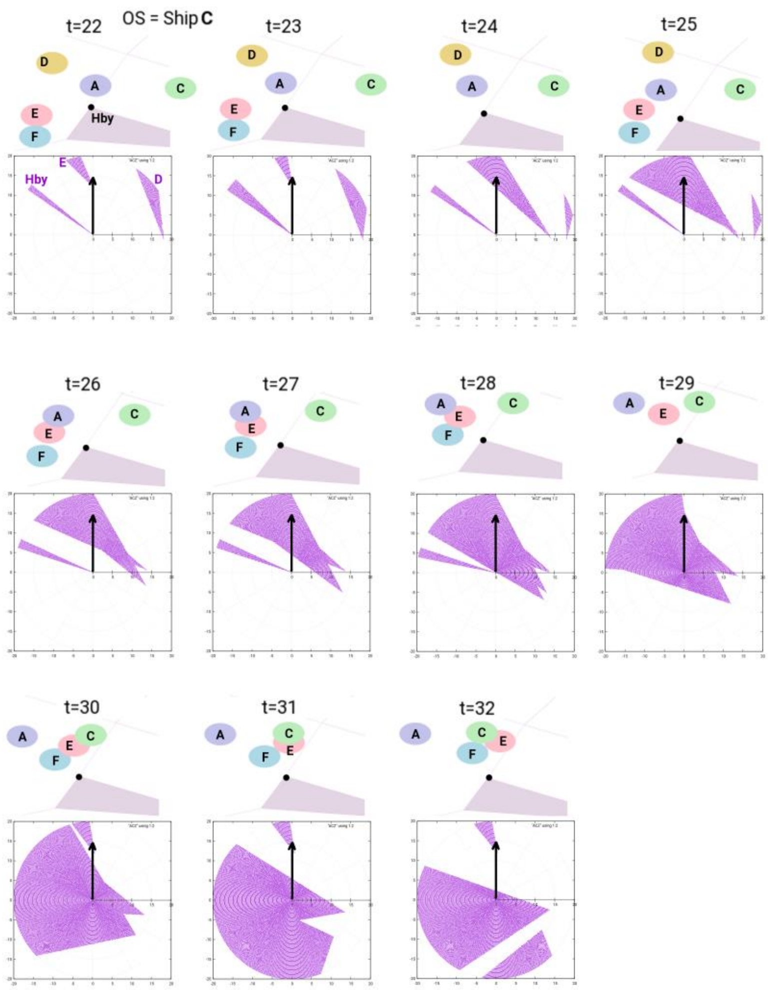

Figure 4. Velocity Obstacles from Vessel C's perspective.

If OS (vessel C) assesses the situation as danger for collision, e.g., at t = 24, it might be tempted to take action. Objectively, OS might be tempted to find any combination of course and speed that will result in a position of OS's vector head outside the presented CZs, i.e., inside the solution space. Changing course, however, might have the greatest effect in a limited time due to the maneuvering potential of vessels. As shown in the fragments, a course change to port is also part of the solution space. However, this would result in a heading towards the target (s) that ship C wants to avoid, hence the preferred change to starboard if such a maneuver is desired by the OOW of ship C. From the viewpoint of ColRegs there would only be reason for vessel C to maneuver when danger for collision is deemed to exist and the give way vessel, i.e., ship E here, is deemed to be unable to avoid the collision on its own.

4. Using the VO in Automated System Settings

The use of tools such as the VO play a key role in conveying trust to automated and future autonomous systems. They enable sufficient interpretation and transparency in the decision-making process of the system. It is vital for the users to judge whether they are willing to trust the system and not simply intervene at every instance where the system does not perform the same way a human operator would. The visual simplification of the situation with the VO is needed to allow effective monitoring, and also enables a faster situational awareness overview when coming from a temporary mind-off navigation task. In an emergency situation, the effective human-to-machine takeover capability forms the foundation to demonstrate safe operation a pre-requisite to regulatory compliance of highly automated or autonomous systems.

The accurate visualization of the collision scenarios surrounding the vessel is reliant on the sensor data available. The merger of different sensors information isn't new, as superimposing radar and AIS on the ECDIS is a common practice on most vessels, however, the processing of this data for the decision-making process of systems is the new aspect in navigation and control systems. The uncertainty of sensors measurements in, for instance, GPS positioning, is commonly accounted for through Kalman filters in control systems. Yet, for situational awareness systems the strengths and weaknesses of different target identification methods AIS, X-/S-/W-band radars, LIDAR or cameras need to be carefully considered for different operating conditions. Not only are the HW components of varying cost levels thereby not making each applicable for all applications, yet even if they are all available, they each have varying update rates and operational envelope/performance which affects their data reliability. For instance, in time-critical situations in busy waters surrounded by vessels, not all vessels have AIS. Also, the 25 rotations per minute for standard marine radar and the target following algorithm translates to an ARPA target in 1–2 min. This is too slow to perform reliable risk assessments based on only this sensor data for the moving targets that surround the vessel. Even though one could interpolate the estimated position based on the data history, there is no certainty that this data of this interpolation is accurate. In these situations, the continuous object detection using machine vision can support. In turn, the machine vision system has limited operational envelopes based on the visibility conditions and is not as accurate when for long-distance target estimations. Thus, based on the type and the movement of the targets the sensor fusion needs to be able to decide which data information is the most trustworthy.

5. Conclusions

This article has provided a concrete example of stress creation in a commonly encountered situation and explained the importance of Protective Zones for not only manual operations, but also as a commonly used principle in autonomous collision avoidance. While the topic of PZ and VO are not new in research and are used in the aerospace industry, they have not yet taken off in the maritime context. The authors believe that the increased technology available, combined with the greater navigational complexity for today's navigational needs shines a new light on the concepts making their benefits more visible and tangible to support the navigational crew in their tasks.

To illustrate this use, a collision avoidance scenario was analyzed from two different vessel's perspective using the aid of VO diagrams to emphasize how such visual support can reduce stress and collision risks and, in the future, become a vital monitoring tool for partially unmanned bridges. To enable such concepts to be realized the authors suggest a technical adaptation to the AIS messaging or any future kind of communication technologies to include Protective Zone dimensions of individual vessels.

It is acknowledged that this proposed solution is not a silver bullet. There are numerous valid weaknesses of the AIS including reliability that are not to be denied. Additionally, as was addressed by other authors (Zhang, Kujala & Wang [12], Rawson & Brito [13]), PZ have their limitations, being influenced by the geographical factors surrounding the vessels as well as the operating mode the vessels are operating in. More limitations will reveal themselves as the application rolls out and becomes common use in the daily navigation, some of which will be addressable with machine learning technologies individualizing the parameters for different navigational participants. Yet, the step of the AIS message adaptation can be the first step in creating a mindset change, and enables advisory systems such as VOs to become more reliable than being based only on the assumption of the technology developers.

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