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Procee, Stephan; Borst, Clark; van Paassen, Rene; Mulder, Max

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4 authors:

Stephan Procee
NHL University of Applied Sciences

Clark Borst
Delft University of Technology

Marinus M. Van Paassen
Delft University of Technology

Max Mulder
Delft University of Technology

Using Augmented Reality to Improve Collision Avoidance and Resolution

Stephan Procee, Clark Borst, René van Paassen, Max Mulder

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Abstract

Based on the Cognitive Work Analysis, described in a previous paper, an Ecological Interface is designed and built for the Augmented Reality application at Willem Barentsz. Incorporated, a.o., is the concept of Velocity Obstacles. This innovative way to visualize the *problem space* and *solution space,* provides the navigator with real time information about the possible combinations of course and speed that avoid intrusion into an other ship's protected zone. Hence, it is anticipated that this will result in better Situation Awareness, leading to less close encounters, a.k.a. near misses, and fewer collisions.

Introduction

The subject of Collision Avoidance (CA) has been much described and debated over the past decades. In the Royal Institute of Navigation's Journal of Navigation (JoN) alone, over 500 articles covering CA have been published since the 1950's. This illustrates both the importance and the complexity of the matter.

From the earliest article covering CA published in the JoN onward, Le Page [1949], many valuable viewpoints, strategies, detection methods have been described. Every introduction of shipboard technology, e.g., RADAR, AIS and ECDIS, and each introduction of regulatory, e.g., Vessel Traffic Service (VTS) and Traffic Separation Schemes (TSS) gave reason to adapt new methods or extend existing ones. CheeKuang Tam et al. [2009] provided a comprehensive review of existing strategies. In this paper we don't intend to introduce a new or adapted strategy on CA, but to illustrate how Augmented Reality (AR) might help in visualizing relevant elements of a CA method. The selected CA method in this paper, targets on visualizing so called *velocity obstacles*. These velocity obstacles can be seen as combinations of the own ship's heading and speed that will lead to the intrusion of someone else's Ship Domain (SD). The latter method was first introduced for use in marine navigation by Degré and Lefèvre [1981] and elaborated on later by various authors, e.g, Egil Pedersen et al. [2003] and Rafal Szlapczynski [2008].

The concept of AR is also not new, however, an interface design providing visual cues to assist the watch officer (WO) in his complex task of safe navigation has not yet been published. In Procee et al. [2017], the design principles of such an interface are described. A first instance of this interface has been materialized lately. This paper describes the presumed functionalities and the motivation for these, based on both theoretical underpinnings of the design method and the background of the first author in marine navigation.

Ecological Interface Design and Abstraction Hierarchy

Situation Awareness

There have been more than a few definitions of Situation Awareness (SA) developed over the past. In their review, Breton and Rousseau [2003] classify 26 definitions and methods to measure SA. In this paper the definition of SA is based on that of Endsley and Jones [2012], p.13-29. According to their definition, SA can be broken down into three levels. The interface design, explained in this paper, addresses these three levels of SA.

The first step in achieving SA, i.e., Level 1, deals with the perception of elements in the environment. This means that the visual objects around the Own Ship (OS) must be seen and recognized, and their status or behavior with regard to the OS must be understood. The intuitive thought about AR, namely that just by adding a synthetic marker at the same visual location as the element will help in achieving SA, is misleading. It might even have detrimental effects when, e.g., 'perceiving the marker' is interpreted as 'perceiving the element'. In this paper the focus lies on CA, which in this case is narrowed down to entities underway on the sea surface, i.e., ships.

The second step in achieving SA, i.e., Level 2, deals with comprehending the situation. This means that in the case of CA the WO must get an understanding of the *meaning* of a target with its course and speed and position relative to the OS. By providing a meaningful cue, e.g., the direction of change in bearing, it is expected that the WO is helped in understanding whether a target will pass astern or ahead, or even does not pass astern or ahead at all. The latter being an indication of a close encounter in the future.

The third step. Level 3, covers understanding the projection of the future status. In the case of CA this means that the WO must have an understanding about the predicted closest distance, Closest Point of Approach, CPA, and the time it takes to reach this closest point of approach i.e., time to CPA, TCPA. It is expected that the WO can be supported in understanding the future status by, e.g., showing the target's velocity obstacle in the AR interface.

Abstraction Hierarchy

Burns and Hajdukiewicz [2004](p.16-17) motivate the purpose of developing an Abstraction Hierarchy (AH). In the case of CA, the conventional work domain model, i.e., measures to detect collision danger is provided by several sources, e.g., International Maritime Organization IMO [1972], Petty [2004] or International Chamber of Shipping ICS [2016]. This model relies primarily on detection of a target, visually or by RADAR, and determining the change in bearing of that target. The underlying line of reasoning is that when a target's visual bearing is not changing, risk of collision exists. When RADAR is used for CA, the underlying principle remains the same.

The introduction of the Automated Identification System (AIS), however, implies complications with respect to CA. Firstly, the bearing to the object is determined by calculation instead of direct observation. Secondly, the data on which this calculation is based was in the first place provided by the target itself. Since AIS does not provide in an integrity monitoring mechanism, additional information is needed to solve this integrity issue. This might be solved, e.g., by visual augmented reconnaissance, i.e., co-location of the synthetic marker on top of the target. Despite these complications and the relative lack of debate about it, Stitt [2004], AIS has gained broad support for providing another tool for CA, Tijardovic [2009]. Hua-Zhi Hsu et al. [2009], show through simulator experiments that the use of AIS is beneficial to the

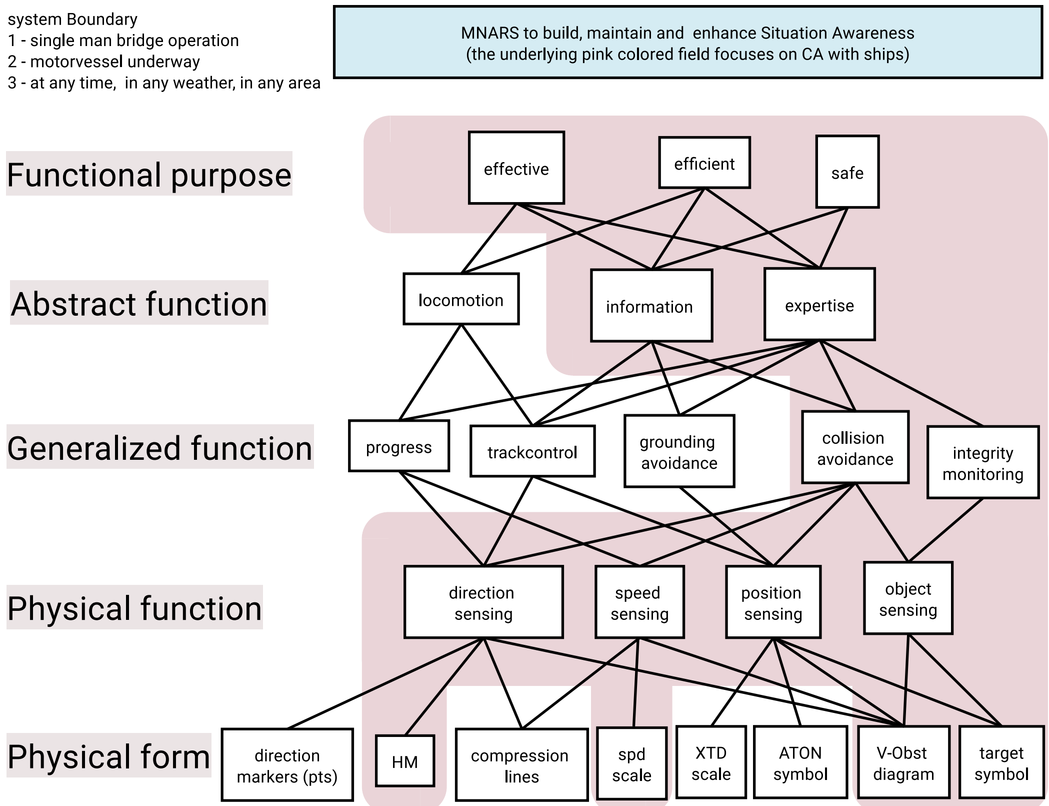

Figure 1: Abstraction Hierarchy Situation Awareness through AR interface.

effectiveness of target detection and avoidance. This justifies the adoption of AIS derived information in the proposed AR interface.

The Abstraction Hierarchy (AH) in Fig. 1 shows five levels of abstraction that define the relation between the *purpose* of the processes, i.e., the top level, and the *physical form*, i.e., the level closest to the worker. This AH shows the process of building, maintaining and enhancing SA within the system boundary of an individually operating WO, working on a motor vessel that is underway in any area and in any kind of weather and at any time of the day.

Here, the top level purpose of navigation is defined as, we have to work *effective*, i.e., goal-driven exploitation of the ship as economical system, we have to work *efficient*, i.e., maximizing output at minimal cost of operation, and we have to work *safe* in order to preserve the value of human, environmental and material assets. The way we do that is by getting underway, *locomotion*, i.e., moving assets from one place to another, thus adding value to it. While locomotion in the absolute sense is thus related to efficiency and production, locomotion relative to (possibly moving) obstacles is key to collision avoidance. Also we do that by providing and using *information*, e.g., ,routeing orders, nautical publications. The third way to do that is by bringing in *expertise*, i.e., the heuristics that have been developed to get the work done, in other words, to reach the purpose.

The Generalized function level shows the ways to realize these abstract functions. If we restrict this to CA, which in Fig.1 is emphasized by the pink colored area, we can define two functions to reach our purpose of effective, efficient and safe, namely, collision avoidance and integrity monitoring. Integrity monitoring, e.g., checking whether the broadcast position of a target aligns with the observed position relative to the OS, is done by the physical function *object sensing*. Collision avoidance is realized by the four physical functions shown in Fig.1, i.e., we need information about both the OS and the target's *speed* and *direction* in order to determine whether danger for collision exists as well as both the OS's and target's *position* relative to each other.

The information which is produced by these physical functions is displayed to support the user in his purpose, i.e., the task of safe, efficient and effective sailing. This *Physical form* layer is the base on which the AR interface is built. Figure 2 shows a first prototype of an AR interface for CA. In the prototype the real world can be seen, e.g., parts of the bridge console, the ships bow and sea space, together with augmentation, like target symbols, heading marker and direction markers for every whole degree. The augmentation is shown on top of the real world, hence, it may be regarded as head-up display, as opposed to a head-down display, e.g., RADAR.

Restricted to CA, the user needs heading information, which is shown through the Heading Marker (HM) combined with the figure for the actual Gyro course, see item **A** in Fig.2.

The user needs also speed information, this is shown in two ways, by a vertical scale, see item **B** in Fig.2 and indirectly by the length of the OS vector in the shown diagram, item **C**. Items **D**, **E** and **F** represent targets. The meaning of the target symbol is shown by its shape and its color. The motivation for the use of target symbols is given in the next subsection. The fourth,

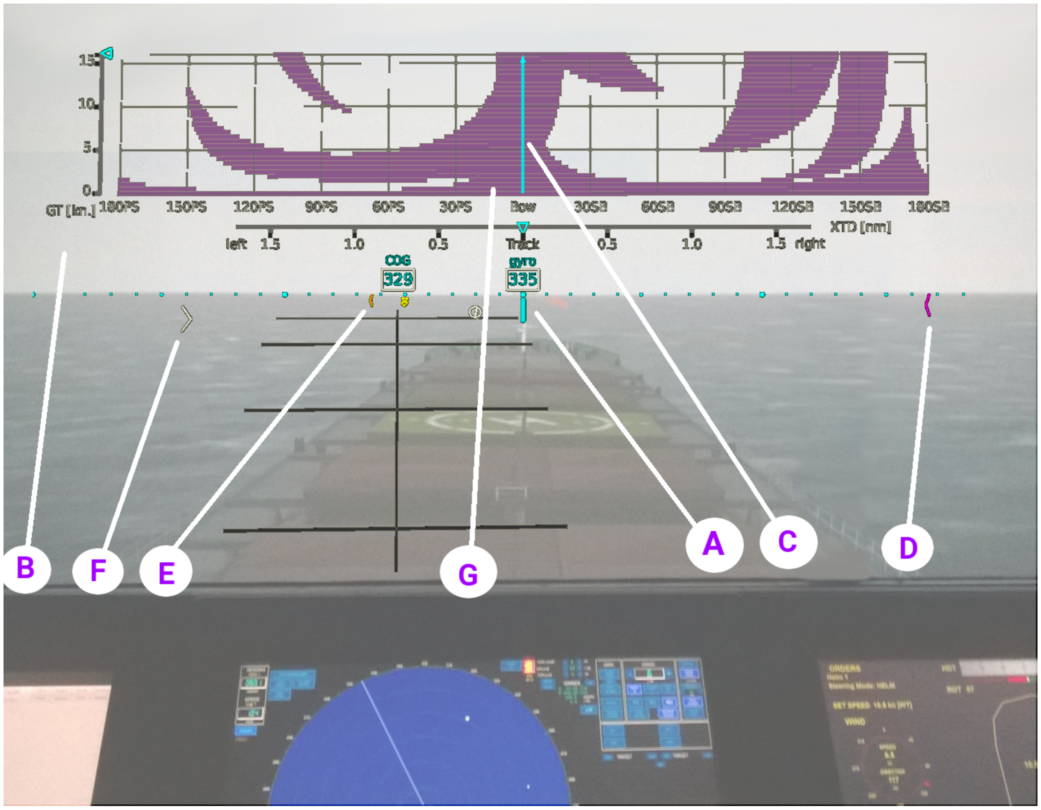

Figure 2: Example of AR interface in a simulation scenario.

CA related, information source, is the Velocity Obstacles diagram. This is shown as item **G** in Fig.2. This diagram shows combinations of OS's speed and heading (a.k.a. Gyro course) which will, when no actions are undertaken, sooner or later result in the intrusion of the OS in the target's SD, and is thus a reflection of the relative velocities with respect to the surrounding moving objects

Ecological Interface Design

Van Paassen et al. [2018] a.o., introduce the fairly recent development, i.e., approximately 25 years, of Ecological Interface Design (EID) in various work domains. For the specific domain of *locomotion* an overview of 13 EID designs is presented. Whereas the majority of these focus on aviation, Ostendorp et al. [2015] give a detailed suggestion for marine piloting. Other suggested sources for EID can be found in, e.g., Burns and Hajdukiewicz [2004], Bennett and Flach [2011]

Within the work domain boundary mentioned in the previous section on AH, i.e., a single WO on the motorvessel's bridge, underway in any weather, at any time and in any area, EID materializes in a number of elements. The overarching EID's framework, to visualize the *ecology*, is related to these elements that are incorporated in the AR interface.

Apart from the elements related to CA, which are described in the previous and, more detailed, in the following section, there are, e.g., a framework of compression lines, symbols for ATON and a cross-track distance (XTD) scale to visualize ecology.

The compression lines are constantly moving underneath towards the observer, thus giving the impression of OS's movement relative to the ground. When OS drifts, i.e., due to wind, or is set from its course due to, e.g., the tidal stream, the moving pattern of compression lines provide an immediate cue. Perceiving this cue requires skill based behavior, e.g., with low cognitive demand.

ATON function as (real) markers of fairways and dangers, hence, they are an inherent part of the ecology. The reason to incorporate ATON symbols in the AR interface is to augment the ecology. The function of ATON is given by their color, their shape and in some cases, their topmark. These cues, i.e., color and shape, are used for the internationally adopted chart symbols and are also used for the symbols in the AR interface. Hence, perceiving these cues, requires rule-based behavior Rasmussen [1983], however, because these symbols are already part of the WO's body of knowledge, it is expected that the mental burden related to perceiving them is low.

The XTD scale shows OS's position relative to the intended track. It is therefore an implicit indication of OS's affordance. The allowable deviation from the track can be taken into account by the WO, or the borders of the validated path , i.e., the width of the track that is checked for dangerous features, can be shown in the XTD. In both cases the allowable space, or affordance, is inherently shown.

Symbol design

The design of a meaningful target symbol for use in an AR interface is a process that has not yet ended. However, in order to reach a first prototype, a number of assumptions have been made. The first assumption is that every target within visual range must be shown by at least a marginal visual cue in order to confirm the integrity of the AR system. Motivation for this can be found in Rasmussen [1983]'s theory of SRK based behavior, namely, when, e.g., a distant target is seen by the observer without the inherent confirmation by the system, i.e., by showing a synthetic visual cue, the observer will utilize problem solving skills, i.e., knowledge-based behavior, in order to verify the system's integrity. An algorithm that balances between the two extremes of a minimum necessary user's computational need in order to perceive, i.e., the conventional perceptual psychologist's approach, and the preferable absence of user's computational need, i.e., the Gibsonian view in order to perceive, see Bennett and Flach [2011] (p.83), is yet to be developed.

A second assumption is that the WO is primarily interested in the relative change in bearing of the detected target. This is because formal training uses this method to detect risk of collision. Observing consecutive visual bearings, e.g., by using compass and azimuth device, is the conventional way to do that. When RADAR is used, consecutive bearings by Electronic Bearing Line (EBL) can be observed as well. The introduction of the Automated RADAR Plotting Aid (ARPA) provides a derived relative vector of the target. The direction of this vector is an indication for collision danger when it points towards the OS. In all three cases it takes time, usually about 3 minutes, to ascertain a reliable outcome. This reliability is restricted to the target's and OS's unaltered course and speed. Each change in course and speed of either target or OS, results in unreliable ARPA data again for approximately the next 3 minutes.

Utilizing AIS, the received target's position, course and speed, results, almost instantaneous, in a derived relative vector, CPA and TCPA. From this it can be inferred what the change in bearing of the detected target will be. This information is shown in the AR interface by two types of symbol shape. The shape, either ' $<$ ' or ' $>$ ', is chosen for its unambiguous simplicity. Relative to the OS, the target will move either to right or to left. In case the change in relative bearing is insufficient, i.e., leading to a critical CPA, the symbol is neither left nor right, hence, ' | '. As said, the effectiveness and user acceptance of this prototype must be validated by empirical experimentation.

The third assumption is that experienced WOs apply an intuitive threshold in TCPA to get alarmed by a detected potential intruder into the OS's SD. Westrenen and Ellerbroek [2017] motivate that a projected intrusion within a time range of 450 seconds is considered as conflicting. This definition is aimed at analyzing the frequency of near misses. However, their paper also mentions that consulted training experts deem a time range of 600 seconds as acceptable. Another perspective to this, is that TCPA can be considered as 'escape time', in which case several factors, e.g., the maneuvering characteristic of both ships, will influence the time range or TCPA to define a critical situation. A globally agreed value on TCPA alarm limit does not exist, in practice the WO uses his personal heuristic or the value prescribed by his most senior colleague, usually the captain.

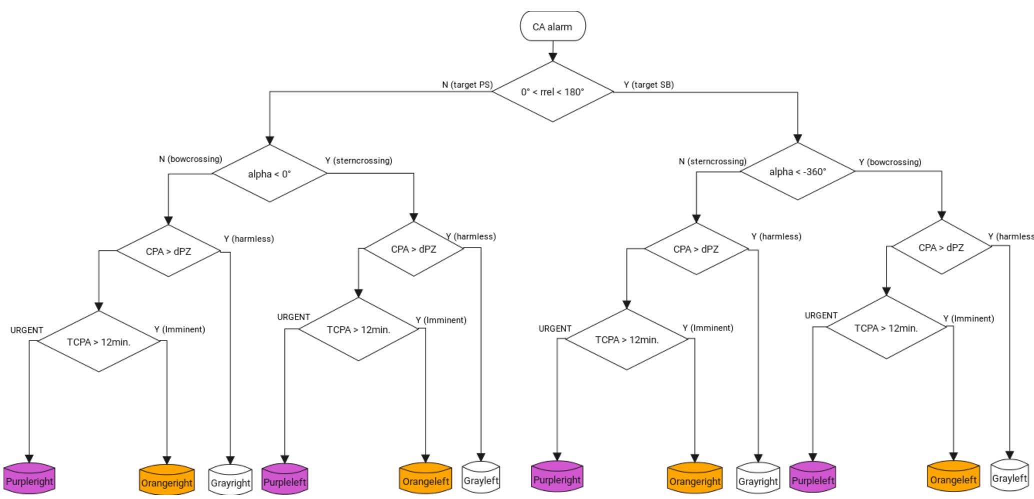

Figure 3: Decision diagram for symbolization of targets.

The AR interface that is discussed here, uses three levels of alarm based on calculated TCPA and CPA, see Fig.3. If the target is crossing either OS's bow or its stern and stays out of the OS's SD, i.e., has a CPA larger than the dimension of OS's SD (shown in Fig.3 as dPZ), the symbol is neutrally colored, gray. If the target is predicted to enter OS's SD within an arbitrarily defined time limit (TCPA) of 12 minutes, the symbol will be colored magenta. Else, the danger is considered imminent , i.e., the target has a critical CPA but there's time to escape, which results in the color orange, meaning it's neither neutral nor dangerous. As said, the value for the TCPA alarm limit depends on several factors and is not globally defined or agreed upon. Hence, the threshold for alarming must be adjustable by the WO in order to function as an effective alarm.

Velocity Obstacles

The principle functioning of Velocity Obstacles (VO) is well described by a variety of sources, e.g., Degré and Lefèvre [1981], Ellerbroek [2013]. Whether the concept of VO was first introduced in shipping or in aviation is irrelevant, the importance is that it has landed on more solid ground now, partly due the introduction of an innovative AR interface as discussed here, partly because of the research into novel ways to support aviators in free flight and Air Traffic Controllers in their controlled airspace.

Usually the proposed way of visualizing the conflict zone is by augmenting an existing display, e.g., RADAR, with an overlay showing the maneuvering envelope and the projected conflict space. The expected acceptance and effectiveness of such a combination lies in the experience that the user already has with the existing display, e.g., RADAR.

Experienced marine RADAR observers are able to generate situation awareness based on the projection of RADAR target returns on a display, which is usually about 50 cm in diameter and covers a range between three and twelve nautical miles. This RADAR picture presents the observer a scaled orthogonal view on the world around the OS. However, when this orthogonal view is projected in perspective, i.e., used in a Head Mounted Display (HMD) for AR, the perception of distance and direction relative to OS changes dramatically. For this reason the projection of the conflict space versus the solution space can hardly be done in perspective. Therefore an alternative is created in the Conflict Space Diagram (CSD). Degré and Lefèvre [1981] (p. 299, Fig.3-4) suggest already a first instance of CSD showing a T-shaped marker projecting vertically a critical speed interval at the present course, and horizontally, a critical course at the present speed. It is not clear whether this CSD was materialized.

An adoption of the T-shaped marker is the proposed CSD used in the AR interface (see Fig.2 item **G**). The horizontal axis comprises of all possible headings relative to the present HM, i.e., Gyrocourse. This means that the affordance, i.e., the allowable option to change heading, either to Starboard or to Port, is shown to the WO. The vertical axis comprises the speed envelope, meaning the affordance in changing speed from the maximum of 16 knots in this example, as shown in Fig.2, to zero. The OS vector, Fig.2 **C**, which is visually aligned with the bow, shows the present speed by its length. From the orthogonal projected conflict zone defined in polar coordinates, i.e., bearing and range, the ACZ is transferred to Cartesian coordinates and shown in the CSD. When the need arises to alter course and/or speed in order to avoid intrusion in the target's SD, the shown solution space indicates possible combinations that can be chosen by the WO.

It is expected, that adding the display of conflict zones from natural and cultural elements, e.g., shoals and ATON, as well as adding the visualized overarching purpose, i.e., to arrive at the destination, safely, timely and using the planned means, will provide an interface that is rich in visual cues. The latter is a requisite for Recognition Primed Decision making (RPD), a principle first introduced by Klein [1998] which seems very suited to modeling the decision making process of the WO. Fine tuning the AR interface in order to support RPD will be covered in a later paper.

Still under development is the user's need to relate the actual target's position with the associated conflict space in the CSD in order to avoid utilizing problem solving skills by the user. The urgent need to support the user in that, is convincingly demonstrated by the shown example, Fig.2, based on a complex situation with nine targets around. Borst et al. [2017] have resolved this issue for an orthogonal (RADAR) presentation in the air traffic control domain.

Another, still unresolved, issue is that the user needs to know how much time is left before actual intrusion into the target's SD takes place. In some, complex, cases for example, it can be necessary to use one target's ACZ for a limited time in order to solve a more urgent conflict with another target. The visualization of this affordance is not yet incorporated. It is suggested that an ordering of color, limited to, e.g., four steps, can be used to express the time to intrusion. This will present a ACZ colored with a single hue, which is subdivided into, e.g., four sections which are ordered by using increasing values of that single hue. In this suggestion, the visual variable hue represents a meaning, i.e., it's a ACZ. Because there is no difference in the meaning of one ACZ to another, hue is not changed from one ACZ to another.

Ship's Domain, Protected Zone

Throughout this paper we will use the term Ship's Domain (SD) as equivalent to the term Protected Zone (PZ), the former having a broader use in marine navigation. In order to discriminate between important or dangerous targets displayed in the AR interface, the SD or ship's domain needs to be defined. The general idea is that targets are not allowed to intrude in the OS's SD. Potential intruders in the SD need to be timely located in order to take evasive measures if necessary. Different from air traffic, where the SD, is defined as a circular area of five nautical mile radius around the airplane, the dimension of the SD of a ship is not globally defined. Many studies have been done in this field, as will be briefly discussed here.

Although the concept of SD is not broadly known among seafarers, almost all seafarers work with the criterion of a predetermined minimum distance (CPA). The latter can be regarded as a circular shaped SD. However, from the observation of traffic, as well as from interviews with seafarers, in reality the SD might have a more complex shape and a different dimension compared to the CPA limit in use.

Fujii and Tanaka [1971] introduced the concept of Ship Domain with the aim of defining the maximum capacity of Japanese fairways. They inferred a relation between the dimension of the SD and the length of the ship, or gross tonnage, on the basis of RADAR-observed traffic in the Tokyo Bay. Fujii and Tanaka suggested the SD to be of an elliptical shape around the own ship. Goodwin [1975] refined the concept of SD with the aim of marine traffic engineering and traffic control. She derived the dimension of the domain from statistical analysis of both simulator observations and observed traffic in the Thames Estuary. Goodwin suggests three sectors around the own ship, each with a radius depending on sea area, traffic density and ship's size, i.e., length over all and Gross Tonnage.

Pietrzykowski and Magaj [2017] analyzed the apparent SD around vessels sailing in the traffic separation scheme (TSS) Bornholmsgat (Baltic Sea) on the basis of AIS data. They also suggest an elliptical shaped domain with dimension independent of ship size in the so called 'precautionary area'. However, when sailing in open sea they found a considerable different dimension of the ship domain. Also, high traffic density in the traffic lane was observed to reduce the length of the domain while the width of the domain remained the same.

Since the early and much cited papers of Fujii, Tanake and Goodwin, many studies and methods to determine the dimension of the SD have been published. Zec [1995], Goodwin and Kemp [1977], Curtis et al. [1987], Lamb [1983, 1989], Goodwin and Kemp [1980], Marcjan et al. [2013], Ning Wang et al. [2009], Goerlandt et al. [2012], Goodwin et al. [1983], Goodwin [1978, 1975] Up to the introduction and global implementation of AIS in 2004 these methods were based on RADAR observations or simulator assessments. Heading information of a vessel cannot be obtained from RADAR observation thus forces a generalized approach by counting the number of targets per OS's sector or introducing noise by using the observed course over ground (COG). By using the AIS incorporated target's heading information this noise can be eliminated to a certain extent, some noise will remain due to the uncertain quality of the provided heading, e.g., corrected for speed and latitude error, or not.

As Fujii and Tanaka stated: *"The boundary of effective domain is more of a psychological barrier than of a stone wall"*. From this it can be inferred that with the progress of time, the 'intuitive' ship's domain might have changed as result of new generations of navigators that have started working at sea, helpful navigational instruments like GPS, AIS and ECDIS have been introduced and economic pressure has increased, which often resulted in a reduction in crew size.

Therefore, a feasible, realistic and acceptable ship domain can only be determined through the analysis of contemporary traffic patterns. Analyzing the traffic density in the so called 'hot-spots' of shipping, gives a clear indication about the apparent acceptable margins of CPA in use today. Pietrzykowski and Magaj [2017] suggested a minor axis of about 500m. and a major axis of about 2,700m. based on one week observation of AIS data in the precautionary area of the TSS Bornholmsgat.

Raw AIS data, received from the Willem Barentsz location at Terschelling, enables the analysis of high density data, i.e., unfiltered and not downsampled data. Data were logged during an arbitrarily chosen period of one week and the data window was limited to the greater area around the Vlieland Junction. (see Fig.4) The Vlieland Junction area, where two traffic flows cross, is generally considered to be a hot-spot, i.e., a high-risk area. This is partly due to the high daily average of passing ships (see table.1), but also due to the lack of VTS assistance outside territorial waters, and lastly due to a relatively large number of vessels crossing the traffic lanes because of the

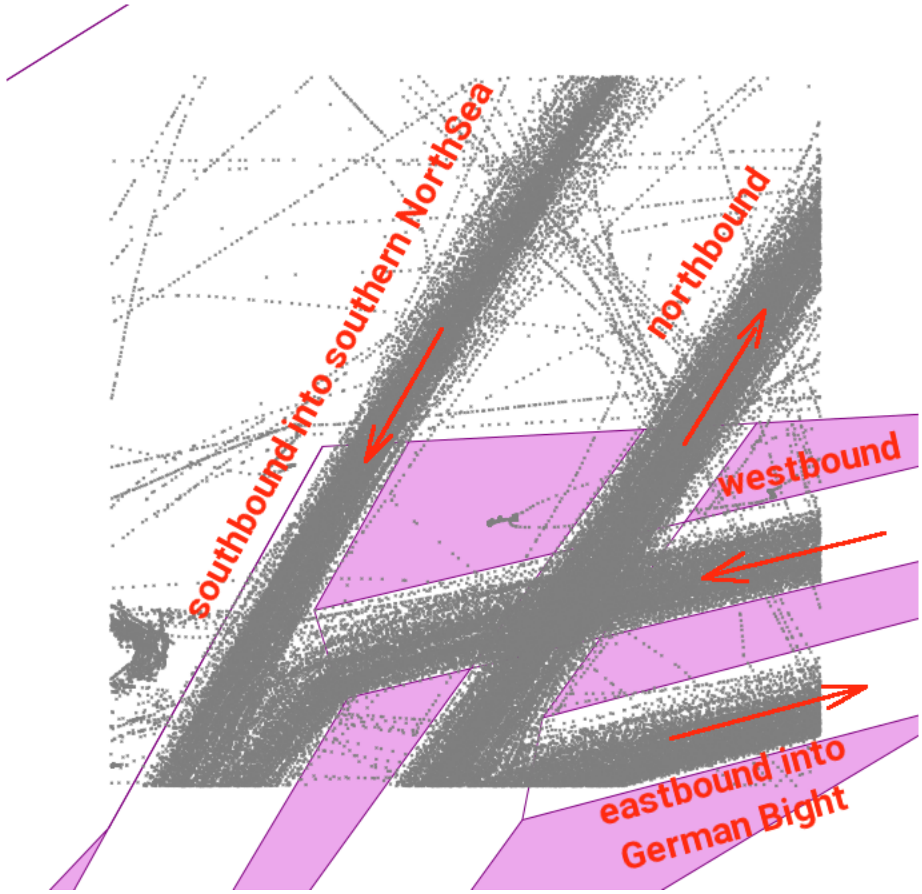

Figure 4: AIS positions of traffic in the Vlieland Junction area.

location of the busy fishing port of Harlingen, which is situated south east of the Vlieland Junction area.

During the week from September 2-nd to September 9-th in 2016, 805 unique ships passed the area. For any discrete moment of time, e.g., a whole minute, the traffic situation was analyzed and the distance and relative bearing from any vessel to the nearest target was calculated. This resulted in about 70,600 targets in every direction relative to any own ship. These were limited to an arbitrarily chosen distance of 12,000m. (±6½nm.) for reasons of computing efficiency and practicability. From this a selection (distance <2,000m.) is depicted in a polar plot (see Fig.5) in order to visualize the apparent SD.

Westbound from German bight	39
Eastbound into German Bight	39
Southbound into Southern NorthSea	24
Northbound from Southern NorthSea	31

Table 1: Daily average number of passing ships (any size).

Together with the relative bearing and distance of all relevant targets, an ellipse is plotted as suggestion for the apparent SD.

A number of observations can be made from this plot. Firstly, the suggestion made by Fujii and Tanaka [1971] that the shape of the SD is an ellipse centered around the own ship still holds. Secondly, the dimension of the ellipse appears to be larger than what Fujii and Tanaka [1971] suggested, both width and length appear to be roughly similar to the dimension that Pietrzykowski and Magaj [2017] suggested. Thirdly, the dimension of the apparent SD seems to be about 500m. on either side, and about 1000m. as well ahead as astern. Fourthly, a towed barge carrying it's own AIS station had passed the area during the week of observation, this is represented by the two isolated clouds of dots at about 400m. from the OS, both dead ahead and astern respectively. The explanation for the large, i.e., ±200m., variation in distance between tow and tug is not clear either the length of the towing line is changed shortly before making the entry in the precautionary area, or noise has entered due to down sampling to whole minute intervals. This has not been investigated further.

Former nautical cadets, Bijkerk [2017], Bos [2016], Hurkmans [2017], interviewed about thirty captains and officers on board during their final internship. From these interviews a variety of views on the intuitive SD emerged. However, the general picture of the SD, also referred to as Safety Zone, is comprised of sectors instead of an ellipse, which conforms to Goodwin [1975]'s approach. The dimension of these sectors is found to vary in detail, ±0.2nm., but the general view is that targets are unwanted in a bow sector of 1¼nm. (±2.3km.) and a stern sector of ½nm. (0.9km.) irrespective of ship's type and length. From these interviews it became clear that, despite that a SD has not been defined globally, nor at company- or ship's scale, the individual WO intuitively uses an area around his ship in which he doesn't want any

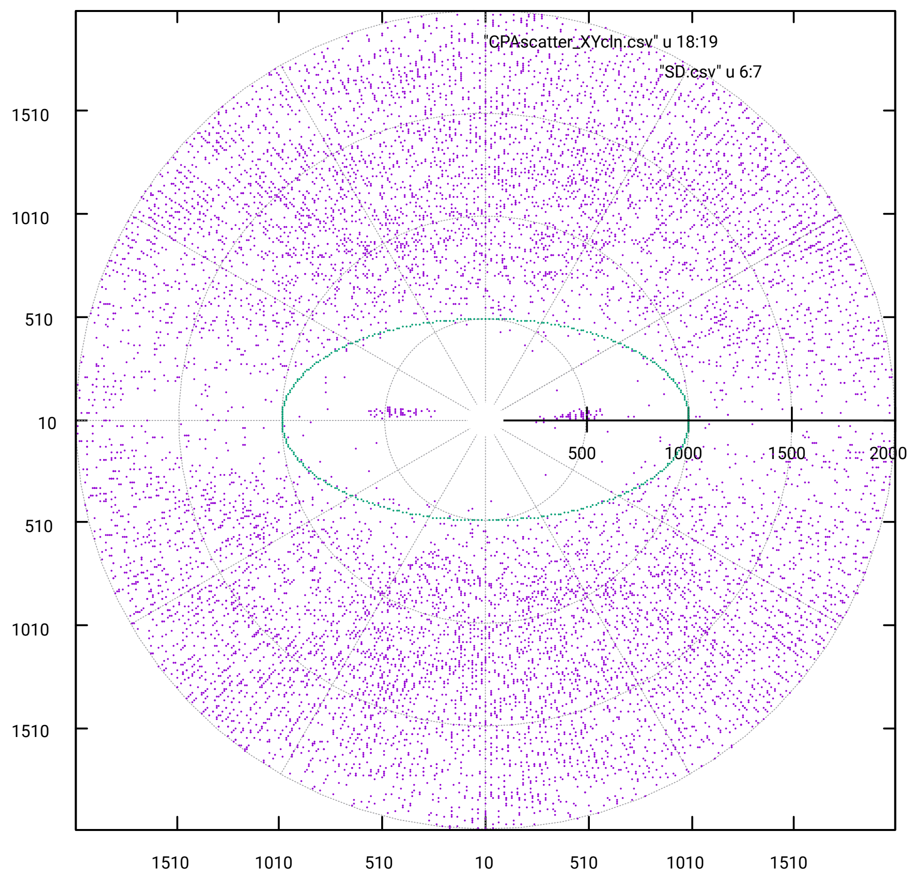

Figure 5: Relative bearing and distance to all targets.

targets. It also became clear that the dimension of this area depends on many variables, but it is larger at the bow than at the stern. This is remarkable in view of the widely used minimum CPA criterion, which would result in a circular shaped SD.

Kant et al. [2017] analyzed 73 simulator runs consisting of head-on situations on starboard bow in order to establish the distance at which the OS's WO reacts with a course change. From their observations they found that subjects, with experience varying from student to licensed mariner, responded on average at a passing distance of less than 0.6nm. (±1.1km) at their starboard side. This remarkably larger distance, as compared to the SD dimension found from the former mentioned analyses in the precautionary area of Bornholmsgat and Vlieland Junction, respectively, might be explained by the open sea situation. This simulated scenario consisted of two ships in an unrestricted sea space.

Pietrzykowski and Magaj [2017] found that the dimension of the SD varies from area to area. They found that the length of the SD inside the precautionary area was about half the length of the SD in traffic lanes.

The explanation for the relatively small width, as compared to length, can be found by the area under examination. Half the number of analyzed ships in the wider Vlieland Junction area do not cross the precautionary area, instead they follow the traffic lane into the German Bight or enter the southern North Sea from the north. These ships do frequently overtake each other in the relatively narrow traffic lanes. Because overtaking is generally considered to be a safe manoeuvre, several small CPA situations are observed. This generates a bias towards a smaller width in the observed SD.

Conclusion

The aim of this research into the dimension of the SD was not to establish in great many detail the definition and varying dimensions and dependencies of this domain, but to derive a realistic criterion for discriminating potentially dangerous targets from the rest. This is needed in order to generate acceptable, effective alarms in the AR interface.

From the aforementioned analyses it appears that the SD seems to be elliptical shaped, about twice as long as it is wide, sometimes symmetrical around the OS, sometimes shifted towards the bow of OS. The circular shaped SD is neither mentioned nor observed. Hence, in perspective of its intended use and without claiming to generate the complete and globally valid model for the SD, the basics of SD for use in the AR interface can be derived from this analyses.

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