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Heuristic Method of Safe Manoeuvre Selection Based on Collision Threat Parameters Areas

J. Szlapczynska
Gdynia Maritime University, Gdynia, Poland

R. Szlapczynski
Gdansk University of Technology, Gdansk, Poland

ABSTRACT: This paper is a continuation of papers dedicated to a radar-based CTPA (Collision Threat Parameters Area) display designed to support safe manoeuvre selection. The display visualizes all the ships in an encounter and presents situational overview from the own ship's point of view. It calculates and displays information on unsafe or unrealistic own ship's course & speed allowing a user to select a safe manoeuvre. So far only the manual selection was possible, thus the paper aims at presenting a heuristic approach towards the manoeuvre selection when using the display.

1 INTRODUCTION

The continuous increase in the density of marine traffic makes it necessary to search for new solutions improving the safety aspect of maritime transportation. These solutions, among others, include various methods and tools dedicated to collision avoidance. They range from optimal ship control (Lisowski 2013, Lisowski 2014) through ship trajectory planning (Lazarowska 2015, Lazarowska 2016) to determining and visualizing safe manoeuvres, which is addressed in the hereby paper.

The long-lasting development of marine radars and associated Automatic Radar Plotting Aid (ARPA) followed by the introduction and mass application of Automatic Identification Systems (AIS) made it easier to make navigational decisions concerning evasive manoeuvres. Integration of those two technologies with Electronic Navigational Charts (ENC) (Weintrit 2009) resulted in a new generation of displays, which can now offer consolidated navigational information on a single screen. A proposal of such a display is presented here. It is based on a Collision Threat Parameters Area (CTPA) technique of presenting ship motion parameters and resulting collision risk graphically. This is supplemented with other information, including risk of grounding and compliance with COLREGS. Finally, the new version of the method presented here utilizes a heuristic manoeuvre selection algorithm to offer an explicit manoeuvre recommendation. Owing to this, navigator's decisions in collision situations can be made easier and faster.

The following sections are organized as follows. In Section 2 a brief history of the research in this field and related literature summary is provided. Section 3 presents an overview of the CTPA-based display and briefly recalls its version given in (Szlapczynski & Szlapczynska, 2017). Then Section 4 describes the newly proposed method of automatic safe manoeuvre selection in the display. Section 5 presents some examples of usage for the updated display. The last Section 6 summarizes and concludes the presented material.

2 LITERATURE OVERVIEW

The first displays designed especially for marine radar applications were available already in 1960s (Birtley 1965). They were restricted though to displaying raw data of targets' velocity vectors only. Almost a decade later two new radar display approaches appeared, namely Potential Points of Collision (PPC) and Predicted Areas of Danger (PAD). In PPC and PAD danger points were marked that if the own ship should steer towards any of these points a collision would occur. The idea of how to build such areas was changing with time. They were initially circles (Riggs 1973), later ellipses (Fleischer et al. 1973), irregular shapes (O'Sullivan 1982, Zhao-lin 1988), polygons (Hakoyama et al. 1996) and curves (Wood et al. 2002). Quite different approach was presented in (Lenart 1983) where a Collision Threat Parameters Area (CTPA) has been defined. For each target CTPA is as an area where the tip of the own velocity vector should not be placed, because it would cause violating the safe distance between the ships. This approach was later continued in Qiao and Pedersen (2004) and Qiao et al. (2006) as cone-shaped Collision Danger Sectors (CDS) and Collision Danger Lines (CDL).

An extended CTPA version presented in (Lenart 1999) has inspired one of the authors of this paper to designing a new display focused on presenting safe manoeuvring possibilities and introducing a ship domain instead of the safe distance (Szlapczynski 2008). Since then the display has been significantly expanded: first in (Szlapczynski & Szlapczynska 2015) its version with good and restricted visibility support, accelerated look-ahead mode and time-based filtering was presented. Then in (Szlapczynski & Szlapczynska 2017) the display was further extended by introducing analytical support for ship domains (which seriously accelerated its performance) and restricted waters support (via uploading and presenting information about shoal waters and land obstacles). Since so far the display had no method for safe manoeuvre selection, this paper aims at filling this gap.

3 AN OVERVIEW OF CTPA-BASED TARGET INFORMATION DISPLAY

The CTPA-based radar display offers a situational view from the own-ship (OS) standpoint. It assumes that for all the target ships (TSs) in range of the display their current course and speed is known. The OS is located in the centre of the display with her bow up (however, her true course doesn't have to be North-oriented, it is merely a visualization assumption). The Cartesian coordinate system, with OS located in its origin, presents points as ship position (x, y, in Nm) and ship speed (V_x, V_y, in kn) coupled by τ value as given below:

$$x = V_x * \tau, \quad y = V_y * \tau, \tag{1}$$

where τ is a constant value of time (in hours), utilized to calibrate the display. The range of available ship speed values is set constant in the display, thus when increasing the τ value the more distant targets are in view.

In the original method in (Lenart 1983) and (Lenart 1999) the CTPAs were cone-shaped areas, each area assigned to one target in an encounter, with its shape and location dependent on target's relative parameters (position & course) and the configured safe distance. Here, in the display being described, presented in Figure 1, the CTPAs are determined by taking into account elliptically-shaped domain with a ship position offset. It is possible by utilization of a Degree of Domain Violation (DDV), a risk-related parameter introduced in (Szlapczynski & Szlapczynska 2015) as:

$$DDV = \max(1 - f_{\min}, 0) \tag{2}$$

where f_{min} is a scale factor of the largest domain-shaped area (around OS) that is free from the target ships.

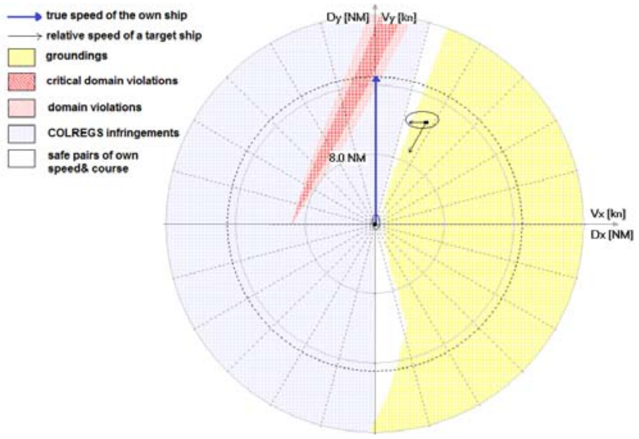

Figure 1. The CTPA-based target information display – a sample view

The display as in Fig.1 offers much more information than just CTPAs. Based on the coloured areas presented in the display's view the user is able to select a safe manoeuvre for the OS. As depicted in the legend of Fig. 1 there are the following colour codes:

- yellow: possible groundings, provided OS speed and course would be kept within a fixed time horizon (configured by the user e.g. for 1 hour),
- red: OS domain violations by any TS in the encounter, determined (for the assumed elliptic domain with OS position offset) by the DDV values in [0.0; 0.5] range (light red) or for serious domain penetration by the TS (possibly leading to a crash) with DDV in [0.5; 1.0] range (dark red),
- light blue: OS speed and course, when kept, resulting in violation of one or more COLREG rules,
- white: safe pairs of OS speed and course.

Another colour coding (dark blue) for maximal and minimal OS speed, previously presented in (Szlapczynski & Szlapczynska 2017), has not been applied in this paper in order to improve its clarity.

Each point in the display can be considered as in the polar coordinate system with OS true speed represented by its radial coordinate and OS course, relative to her true course, represented by its angular coordinate (measured clockwise from the North). In order to investigate current OS status the user should look at the tip of her true speed vector (in blue). Here in Fig. 1 the tip is located in the border between light and dark red areas indicating quite serious domain violation, providing current OS course and speed would be kept. Thus, to avoid collision with the TS, manoeuvring is strongly recommended. To find a safe OS manoeuvre it is enough to move the tip of her true speed (which obviously assumes some OS manoeuvring) to any white point in the display (as white depicts safe OS speed and course). In Fig. 1 there are roughly two possibilities for OS: to turn starboard for 15-18° or to divert her course (turn starboard for 165-180°). The user would probably select the starboard 15° turn with keeping speed, since it's the easiest while technically and economically reasonable manoeuvre, in this case assuring collision avoidance with the TS in the encounter.

The display provides also an additional "accelerated look-ahead" mode in which the user is able to simulate future (for a configured time) encounter situation, assuming that all the ships keep their courses and speeds. This way the user is able to determine after what time past the collision avoidance manoeuvre he is able to safely get back to the original track.

Up to this time it was assumed that the process of safe manoeuvre selection would be manual, as presented in (Szlapczynski 2008), (Szlapczynski & Szlapczynska 2015) and (Szlapczynski & Szlapczynska 2017). However, in order to improve the display and increase safety level of the ships utilizing the solution in future, the authors decided to introduce an automatic safe manoeuvre selection method, described in the next section.

4 PROPOSED SAFE MANOEUVRE SELECTION IN THE DISPLAY

An action of selecting safe manoeuvre in the CTPA-based display is a process of selecting a safe pair of OS speed and course the way that the tip of the OS true speed vector would be placed in the white (safe) display area. In order to automate this action the following policies are applied:

1. selecting a "keep speed" manoeuvre: the length of the true speed vector would not change, only rotation of the vector is possible,
2. selecting a "keep course" manoeuvre: the vector's angular coordinate would not change, but vector length could increase or decrease,
3. selecting a mixed manoeuvre, in which simultaneous true speed vector length and angular coordinate (rotation) changes are required.

Each of the abovementioned policies has slightly different limitations. In the first "keep speed" approach the rotation should be big enough to make the manoeuvre apparent, thus rotations below 15° would not be possible. Obviously, the lesser the rotation above 15°, the better, thus the rotation angle would be minimized in the given range. Moreover, due to COLREGS implications rotations to the right (starboard) will be favoured over rotations to the left (port board) for encounters other than overtaking.

The "keep course" approach assumes that the vector length is amended and the final vector cannot be longer than the maximal and shorter than the minimal possible OS speed (if applied). Similarly to the previous case, the change should be minimized within possible OS speed limits.

The last mixed approach would be applied to situations when no "keep course" or "keep speed" is possible (in cases when white areas are irregular, far from the current OS speed circle and current OS course direction). In such situations it is difficult to determine which manoeuvre is better: is it well-founded to have a bigger rotation and a slight speed change or the opposite. To solve such problems Pareto-optimality technique has been introduced. A similar approach has already been applied to a different navigational problems e.g. in (Szlapczynska 2015).

Pareto-dominance is an underlying element of the Pareto-optimality concept. It is stated that an element A Pareto-dominates another element B if and only if A is no worse than B for all the considered criteria except at least one criterion, for which A has to be better than B. In case of the manoeuvre selection in the mixed approach one manoeuvre dominates another if either it requires a smaller course change and exactly the same speed change or it requires a smaller speed change and exactly the same course change. Thus a manoeuvre of 20° to starboard and increase the speed of 5kn will dominate a manoeuvre of 22° to starboard and 5kn increase, but will not dominate another one of 18° to starboard and 6kn increase. All the search space elements that are not dominated by any other element of the same space are called non-dominated and constitute a set of Pareto-optimal solutions.

The precise rules of dominance used here for selecting a Pareto-optimal set are as follows.

For crossing or head on encounters:

1. A solution, whose course alteration is 15 degrees and speed alteration is 0 knots dominates all solutions whose speed alterations are larger than 0 knots.
2. A solution, whose course alteration is larger than 15 degrees and speed alteration is 0 knots dominates:
   - all solutions of larger course alterations,
   - all solutions of equal course alterations and speed alterations larger than 0 knots.
3. A solution, whose speed alteration is larger than 0 knots dominates all solutions where alteration of one parameter (course or speed) is larger and alteration of the other one is larger or equal.

For overtaking encounters:

1. A solution, whose course alteration is 15 degrees and speed alteration is 0 knots dominates all solutions, whose speed alteration are larger than 0 knots and course alterations are in the same direction.
2. A solution, whose course alteration is larger than 15 degrees and speed alteration is 0 knots dominates:

– all solutions of larger course alterations in the same direction,
– all solutions of equal course alterations in the same direction and speed alterations larger than 0 knots.

3 A solution, whose speed alteration is larger than 0 knots dominates all solutions where:
– alteration of course is in the same direction and
– alteration of one parameter (course or speed) is larger and alteration of the other one is larger or equal.

Following the abovementioned dominance analysis, Pareto set in a discretized manoeuvre space is presented with a resolution of 1 degree and 1 knot. An example of such a Pareto-optimal set is shown in Figure 2, where all non-dominated solutions (Pareto-optimal) are marked as green dots. Optionally, additional rules and a ranking method may be used to further estimate and compare the quality of solutions within a Pareto set.

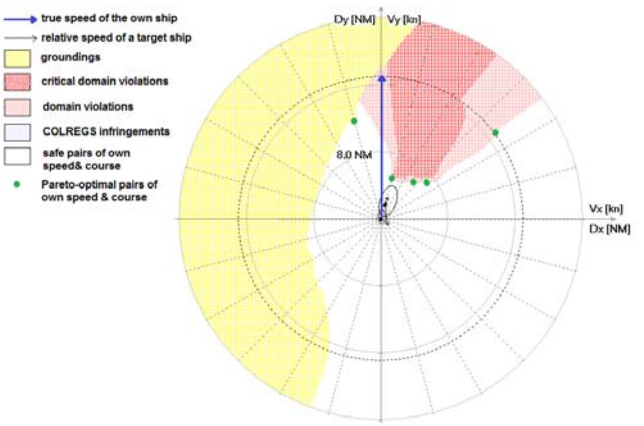

Figure 2. Pareto-optimal solutions for a close quarters overtaking encounter

5 USAGE EXAMPLES

In this section two scenarios – overtaking a target and crossing encounter with a target – are described in detail. In both cases the own ship is approaching two targets and an encounter would lead to a collision in lack of a safe manoeuvre. Both scenarios emphasize how difficult it might be to choose this manoeuvre based on ships' motion parameters only. Fortunately the provided display view makes it easy to choose a safe solution. Additionally the "accelerated look ahead" mode visualizes the consequences of a manoeuvre – future motion parameters of all ships involved in the encounter.

5.1 *Scenario 1 – overtaking*

In this scenario the OS is approaching a target (TS 1) navigating in roughly the same direction, but at a much lower speed. Overtaking is the sole situation where both manoeuvres to port and starboard are compliant with COLREGS. Because of the proximity of landmass on starboard and an additional target on port (TS 2) it may be difficult at first to choose a manoeuvre based on the overview shown in Figure 3. However the situation gets clearer when looking at Figure 4, where the display view is shown with the two non-dominated Pareto-optimal solutions shown as green dots. As can be seen, it is possible to manoeuvre to port by altering own course by 15 degrees. As for manoeuvring to starboard, however, it would require additional speed reduction by at least 4 knots. Also, as shown in Figure 5, 50 minutes after manoeuvring to starboard combined with speed reduction the own ship should plan turning back to port by at least 20 degrees so as to avoid running aground. As opposed to that, in Figure 6 the consequences of manoeuvring to port are more convenient: the own ship can keep the new course for as long as it takes before getting back to the old one.

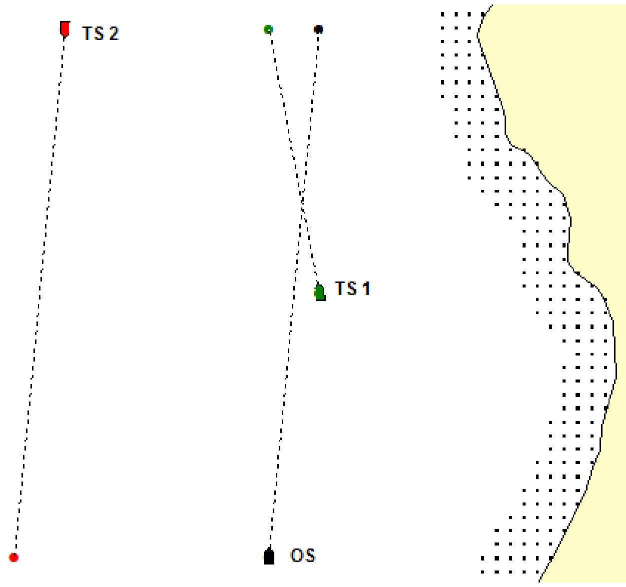

Figure 3. Scenario 1 (overtaking) – overview

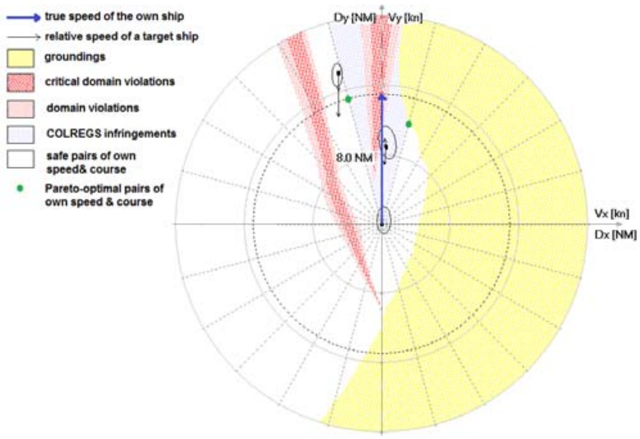

Figure 4. Scenario 1 (overtaking) – display main view

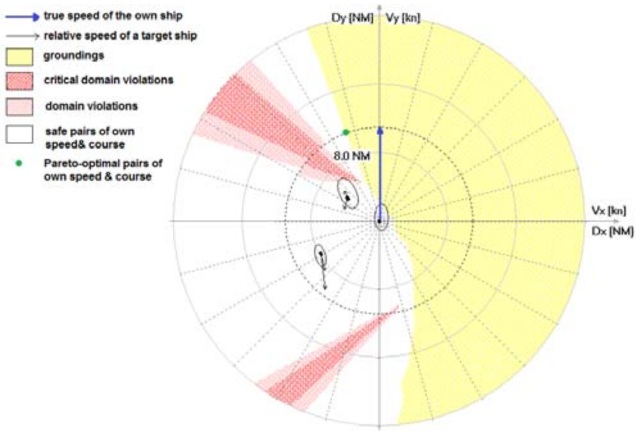

Figure 5. Scenario 1 (overtaking) – "accelerated look ahead" mode – 50 minutes after manoeuvring to starboard by 15 degrees and reducing own speed by 4 knots

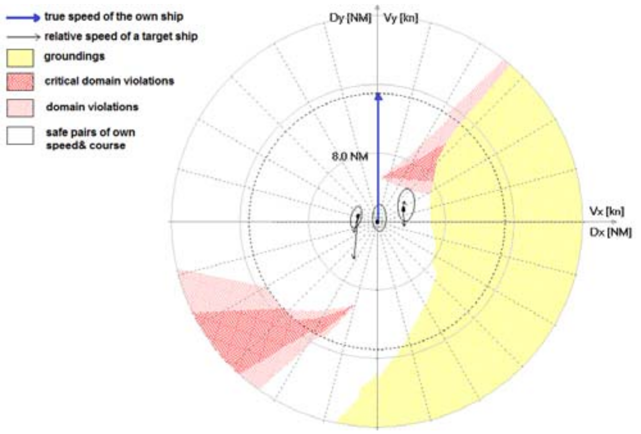

Figure 6. Scenario 1 (overtaking) – "accelerated look ahead" mode – 40 minutes after manoeuvring to port by 15 degrees

5.2 *Scenario2 - crossing*

In this scenario the OS is about to meet two targets on starboard (Figure 7). The encounter with the TS 2 would lead to collision in lack of manoeuvres, so some action of the OS is necessary. Possible manoeuvres of the OS are limited by the landmass on starboard, so it is not sure whether such a turn (compliant with COLREGS) is indeed safe. However, a look at the display main view (Figure 8) indicates that a number of manoeuvres to starboard (marked as green dots) are possible. The OS may either simply turn to starboard by 20 degrees or may combine a slightly lesser course alteration with a minor speed reduction. Of these possibilities, the manoeuvre of course alteration alone is the best solution in terms of execution and economics. Its consequences are shown in Figure 9 as "accelerated look ahead" mode. 32 minutes after manoeuvring to starboard by 20 degrees the own ship is passing astern of the closest target and neither of the ships' domains is violated.

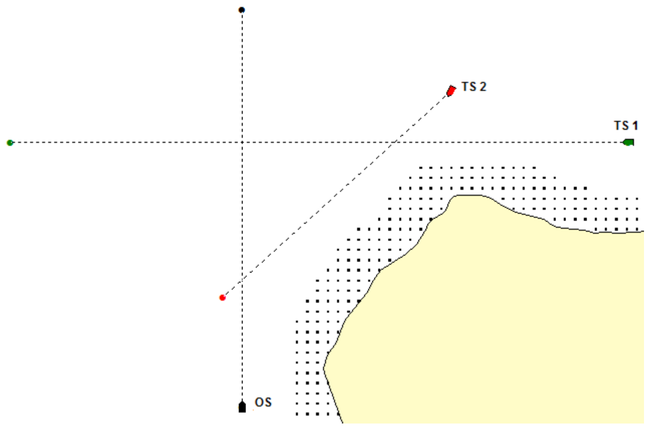

Figure 7. Scenario 2 (crossing) – overview

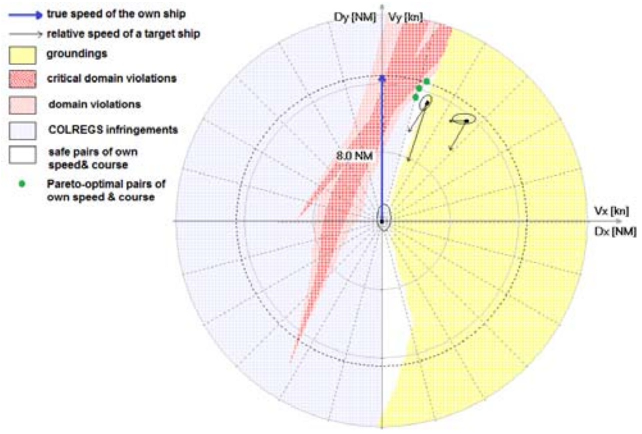

Figure 8. Scenario 2 (crossing) – display main view

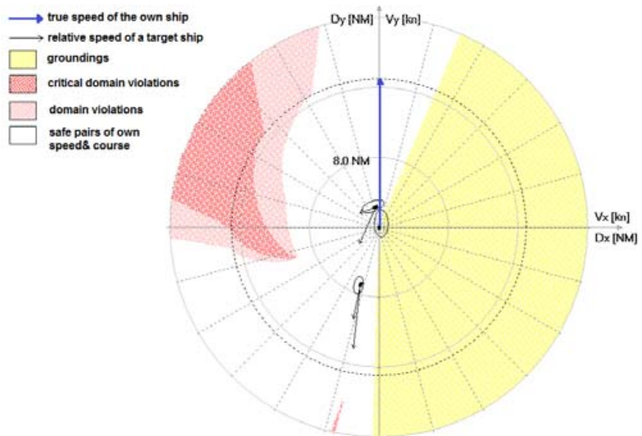

Figure 9. Scenario 2 (crossing) – "accelerated look ahead" mode – 32 minutes after manoeuvring to starboard by 20 degrees

6 SUMMARY

The paper describes an extended version of the previously introduced method of visualizing safe manoeuvres in complex encounter situations. The new element is an algorithm, which utilizes information on all safe manoeuvres and specified criteria to determine a set of Pareto-optimal solutions. Once this set is determined, additional user preferences may be applied to limit the proposed solutions to one or two recommended manoeuvres, which are graphically highlighted in the display. The practical usage of the presented version of the method is illustrated by two examples, where possible manoeuvres and their consequences are analysed. The research on the method is ongoing and the future research will be focused on taking into account rough weather conditions, when possible manoeuvres are seriously limited due to the risk of losing stability.

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