THE JOURNAL OF NAVIGATION (2009), **62**, 79–91.
doi:10.1017/S0373463308004992 Printed in the United Kingdom

Planning Emergency Manoeuvres

Rafal Szlapczynski

(*Gdansk University of Technology, Poland*)
(Email: rafal@pg.gda.pl)

The paper addresses the issue of planning emergency manoeuvres and re-planning ship trajectories in case of unpredicted target behaviour. It introduces two methods. The first is responsible for monitoring other ships parameters, estimating the probability of illegal target behaviour and re-planning own trajectory in case of unpredicted events. The second is a visualization tool that enables the navigator to assess collision risk in an encounter situation and choose a collision avoidance manoeuvre if necessary. This tool is based on the Collision Threat Parameters Area display and offers new features: fuzzy sectors of forbidden speed and course values and the possibility to use any given ship domain. Both methods are fast enough to be applied in the real-time decision-support system.

KEY WORDS

1. Navigation. 2. Collision avoidance. 3. Emergency manoeuvres. 4. Course and speed alterations.

1. INTRODUCTION. One might argue that there is a certain contradiction in the paper's title. After all, if an emergency manoeuvre is about to be performed, it probably means that whatever planning there was involved, it has failed and we are in no position to replan – hence the 'emergency' term. Such reasoning, however, relies heavily on the assumption that planning is a long-term activity. And this, considering current computational powers, is no longer true. Contemporary methods of planning collision avoidance manoeuvres and safe ship trajectories can return a trajectory within seconds and re-plan it whenever necessary. Among these methods are indeterminist ones (evolutionary programs which use genetic algorithms [12]), game theory and formal optimisation techniques [6–8], sequence of necessary manoeuvres [3] and various combinations of the abovementioned including a method proposed by the author [11]. In general, the navigational scenario may develop contrary to the method's expectations – and thus enforce quick re-planning of the trajectory or performing an emergency manoeuvre – due to the following:

- a target is detected too late,
- the error in estimation of a ship's dynamics results in the relative position of a target being different from the expected,
- a prioritised target alters its course or speed unexpectedly,

- a target does not give way to the own ship when it should because:
  - the target ship has not detected the own ship yet,
  - the target ship sees the own ship but does not react yet due to the *TCPA* value being too large,
  - the target ship does not intend to give-way due to the fact that it does not consider the situation dangerous (possibly a larger safe distance parameter or ship domain of different shape or size is used),
  - the target ship consciously disregards COLREGS.

Since automatic radar plotting aid (ARPA) systems are able to monitor the relative parameters of targets and AIS systems supply the precise data on targets, the number of occurrences of the first two of the four abovementioned cases is continuously decreasing. The last two cases however are still valid (and will probably remain so) and thus must be handled by contemporary collision avoidance systems. The paper addresses this issue by presenting two methods of dealing with unexpected target behaviour. They are both based on the domain-oriented approach to collision avoidance previously presented by the author in [10] and [11]. The basic assumption of this domain-oriented approach has been replacing DCPA with a new measure: the approach factor f_{min} [10]. Approach factor f_{min} has been defined as the scale factor of the largest domain-shaped area that is predicted to remain free of other ships throughout the whole encounter situation. Consequently, the time remaining to reaching the f_{min} value has been denoted by t_{min}. The first method presented in the paper estimates the probability of illegal target behaviour and re-plans the trajectory when necessary. The second one is constituted by a computational technique and a display directly supporting emergency manoeuvres. The rest of the paper is organized as follows: the two methods are described in Sections 2 and 3 respectively and the conclusions are presented in Section 4.

2. HANDLING UNPREDICTED EVENTS.

The most complex case to handle is that of a target not giving way to the own ship. According to the COLREGS rules [1] the own ship should not initiate the manoeuvre unless it is certain that the target is not going to give way. If the own ship has justified doubts about the target intentions it should signal the target to make it clarify its behaviour. Only when the target's unwillingness to give way has been confirmed, has the own ship the right to initiate a collision avoidance manoeuvre itself.

2.1. *Estimating the probability of illegal target behaviour*.

Whenever the own ship should be given way by the target, it is periodically monitored by the system to determine whether the target ship has initiated the manoeuvre. If the target has altered its course sufficiently, the own ship may keep its course. However, if the target has not initiated the manoeuvre, the system computes the probability that the target will not do so before the critical time T_C. Initially the own ship has no reason to expect illegal behaviour from the target, nor has it a reason to expect the target to initiate the manoeuvre before the own ship would do so in the reverse case. It is assumed here that the probability that the target will take an appropriate action diminishes linearly as the time t_{min} moves gradually from the optimal time T_{Opt} towards the critical time T_C:

$$P(target\_appropriate\_action) = min\left(\frac{t_{min} - T_C}{T_{Opt} - T_C}, 1\right) \quad (1)$$

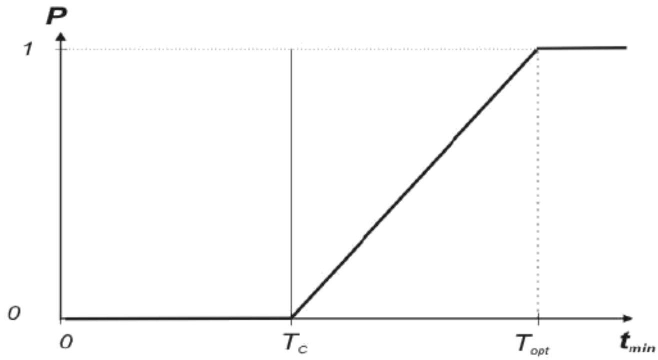

Figure 1. The approximation of the probability of the target's appropriate action.

where:

T_C time remaining to reach f_{min}, when the collision can be avoided by a 60-degree course alteration manoeuvre (the critical time for performing the manoeuvre),

T_{Opt} time remaining to reach f_{min}, when the collision can be avoided by a 15-degree course alteration manoeuvre (the optimal time for performing the manoeuvre).

Equation (1) is illustrated in Figure 1.

The probability that the target ship will not start a collision avoidance manoeuvre before the own ship is forced to do so for safety reasons is simply the probability of the opposite event and thus it may be approximated by formula (2):

$$P(target\_illegal\_behaviour) = 1 - min\left(\frac{t_{min} - T_C}{T_{Opt} - T_C}, 1\right). \tag{2}$$

When the approximated probability of the target's illegal behaviour exceeds a pre-defined threshold value (for example 0·5), the own ship should signal the target ship so as to make its intentions clear. If the target alters its course sufficiently in response to the signal, the own ship may safely keep its course. Otherwise the own ship is justified to start the manoeuvre itself. The safe course alteration and alteration time are then determined. However, the system has to consider the fact that the target ship may still start a collision avoidance action at the very last moment. Therefore, only course alterations to starboard (even though this might mean crossing ahead of the target) may be taken into account and thus the safe course alteration will be the minimum necessary alteration to the starboard, which guarantees safe passing of the target.

2.2. *Re-planning a safe trajectory for a multi target encounter including handling unpredicted events.* The method has to take into account multiple targets that should give way to the own ship as well as the possibility that prioritised targets may change their courses. It is done in the following way:

1. Once a safe trajectory has been determined, all ships within range of the ARPA and AIS systems are continuously monitored. The parameters of the non-prioritised targets are checked and those whose courses collide with the own course are inserted into the non-prioritised colliding targets list.

https://doi.org/10.1017/S0373463308004992 Published online by Cambridge University Press

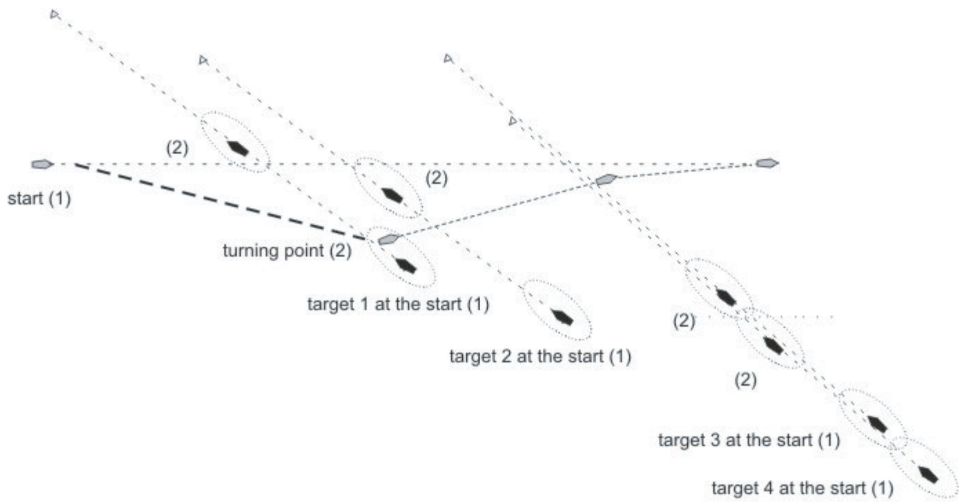

Figure 2. Realization of the determined trajectory (gray icon – own ship, black icons – target ships).

2. For each of the potentially colliding non-prioritised ships a probability of illegal behaviour is periodically computed according to formula (2). When this probability exceeds a configured threshold value, the target is asked (signalled) to give way. If it alters its course sufficiently there is no need to modify the previously determined trajectory. Otherwise the target is inserted into an additional list of unpredictable targets.
3. If any of the prioritised targets changes its course in a way that threatens the own ship, it is also inserted into the list of unpredictable targets.
4. If any new targets have been added to the unpredictable targets list, the procedure of planning safe trajectory is repeated. The procedure is also repeated if the previously planned trajectory is not safe due to any other reason (for example – error in estimation). All unpredictable targets are given way by the own ship, no matter whether they are prioritised ships or not. The difference is that only course alterations to starboard are possible for avoiding collisions with the non-prioritised targets (as opposed to normal situations when manoeuvres to starboard are favoured but manoeuvres to port are also allowed).

The re-planning procedure means basically planning a new trajectory for the updated own ship's and targets' parameters. The detailed algorithm performing this has been presented by the author in [11]. An example of re-planning a trajectory is shown in Figure 2 where the own ship is following a predetermined trajectory. It has safely passed targets 1 and 2 and has set its course to cross safely abeam of targets 3 and 4. However, when the own ship is half the way towards the next turning point, target 3 suddenly changes its course from 310·5° to 333·5°. This results in the fact that the already determined trajectory has to be re-determined for the current positions, courses and speeds of all the ships involved. The change of the situation is shown

https://doi.org/10.1017/S0373463308004992 Published online by Cambridge University Press

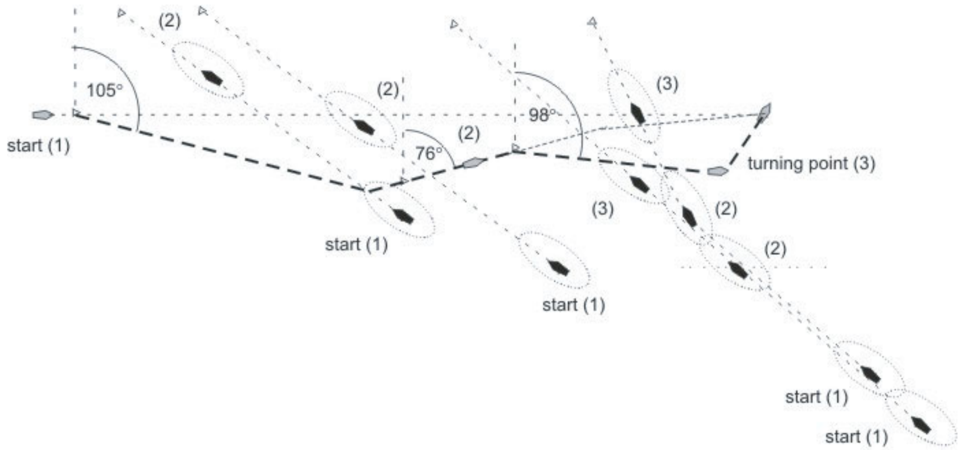

Figure 3. One of the targets alters its course.

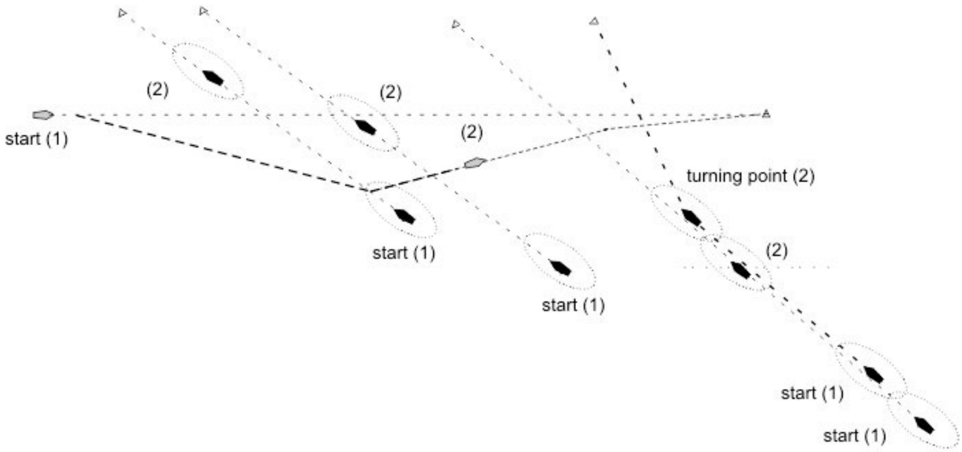

Figure 4. The re-determined trajectory.

in Figure 3. The trajectory is re-determined and the new trajectory is shown in Figure 4.

2.3. *Problems with handling unpredicted target's manoeuvres and re-planning the trajectory*. The case of a target's unpredicted manoeuvre is theoretically simpler than the case of unlawful behaviour, because the own ship can immediately react to the target's action and the assessment of the target's intentions is not necessary. Unfortunately, it can take as much as 3 minutes (according to IMO A.823(19) Resolution [4]) for ARPA systems to deliver precise values of target's predicted motions, after the target has altered its course or speed. This means that the own ship might be left with very little time for collision-avoidance action, if the target has performed a potentially dangerous manoeuvre in the own ship's proximity. Although the system might be capable of re-planning the own trajectory within seconds, the navigator cannot be expected to follow the re-determined trajectory without having it examined first. And examining the complete new trajectory (a sequence of

https://doi.org/10.1017/S0373463308004992 Published online by Cambridge University Press

manoeuvres) thoroughly may be impossible due to not having enough time. Therefore, apart from re-planning the whole trajectory, it is crucial to provide the navigator with a tool helping to assess quickly the current situation and choose an avoiding-collision manoeuvre with the closest targets. Such a tool is proposed in the next section. Its purpose is to visualize possible collision-avoidance manoeuvres in both cases of unpredicted target behaviour and thus to enable the navigator to plan the manoeuvres more effectively.

3. VISUALIZING EMERGENCY MANOEUVRES.

Traditional displays used in collision-avoidance systems were based on the relative Cartesian coordinate system, with the own ship in the centre and X and Y coordinates denoting the relative positions of targets. Their functionality was limited to showing all targets within a certain range and indicating the targets that were considered to be dangerous on the basis of computations performed by the system. Some of them additionally visualized Predicted Areas of Danger (PAD) and the resulting necessary course alterations. What these displays failed to visualize was the nature of collision risk: the colliding combinations of courses and speeds of the own ship and the dangerous targets. Visualizing these forbidden combinations of course and speed (instead of course only) has been introduced by Lenart as a part of Collision Threat Parameters Area (CTPA) method in [5]. However, the display according to Lenart naturally assumes using a pre-defined safe distance D_S as a main safety parameter and $DCPA$ as a collision risk measure. Therefore it cannot be used for precise visualization of the necessary manoeuvres when domains other then circle-shaped are assumed. The author of the paper has combined the following ideas: double coordinate system used in CTPA, a fuzzy ship domain [9] and approach factor f_{min}. The result is a new visualization method called Fuzzy Collision Threat Parameters Area (FCTPA). It is based on the CTPA method and extends it so as to handle any given domain, including fuzzy domains.

3.1. *Collision Threat Parameters Area* (*CTPA*). In [5] a collision threat is defined as a target ship for which the following condition holds:

$$DCPA < D_S \tag{3}$$

The method uses a double Cartesian coordinate system where the horizontal axis represents both the X coordinate of position and V_X coordinate of speed and the vertical axis represents both the Y coordinate of position and V_Y coordinate of speed. The relation between the position and speed coordinates is as follows:

$$\begin{aligned} x &= V_x * \tau, \\ y &= V_y * \tau, \end{aligned} \tag{4}$$

where τ is a fixed time value, for example 12 minutes. The CTPA for a single target ship is defined as an area in the abovementioned system of coordinates that fulfils the following conditions:

- placing the tip of the own speed vector V within this area would result in violating the safe distance D_S between the ships,
- placing the tip of the own speed vector V outside this area would result in keeping the safe distance D_S between the ships.

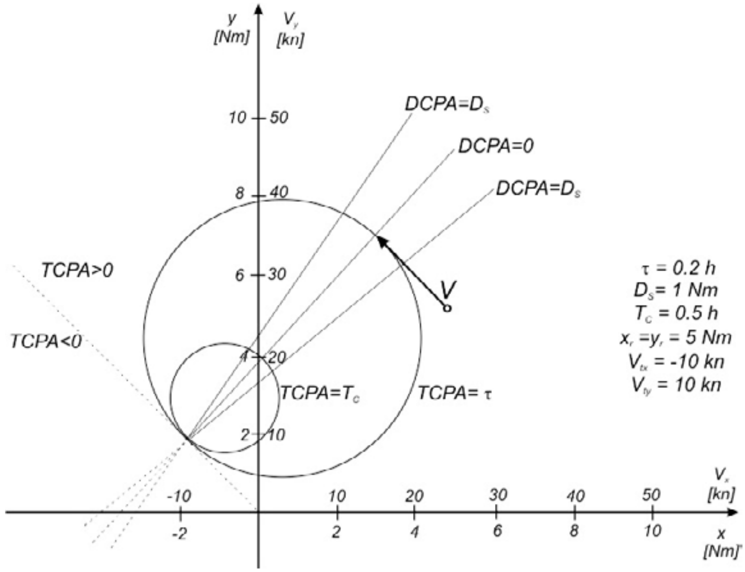

Figure 5. The CTPA method.

The CTPA for a group of target ships is defined as a superposition of the Collision Threat Areas obtained for each of the targets separately. The formula for the two straight lines determining the boundaries of the CTPA for a given single target is as follows:

$$\begin{aligned} y &= a_1 x - b_1 \tau \\ y &= a_2 x - b_2 \tau \end{aligned}, \tag{5}$$

where the coefficients are given by the formulas:

$$\begin{aligned} a_1 &= \frac{x_r y_r + D_S \sqrt{x_r^{\,2} + y_r^{\,2} - D_S^{\,2}}}{x_r^{\,2} - D_S^2}, \\ a_2 &= \frac{x_r y_r - D_S \sqrt{x_r^{\,2} + y_r^{\,2} - D_S^{\,2}}}{x_r^{\,2} - D_S^{\,2}}, \end{aligned} \tag{6}$$

$$\begin{aligned} b_1 &= a_1 V_{tx} - V_{ty}, \\ b_2 &= a_2 V_{tx} - V_{ty}, \end{aligned} \tag{7}$$

where:

x_r, y_r – coordinates of the relative position of the target ship,
V_{tx}, V_{ty} – coordinates of the true speed of the target ship.

In practice CTPA is only this part of the determined area, where the condition $TCPA > 0$ holds, since only future collision threats are of interest. Also, in case of a multiple target encounter, the manoeuvres for which the safe distance D_S would be violated after a time longer than the critical time ($DCPA < D_S$, $TCPA > T_S$) may be

https://doi.org/10.1017/S0373463308004992 Published online by Cambridge University Press

Table 1. The positions, courses and speeds of the own ship and the target ships at the start time.

	Speed [knots]	**Course** [degrees]	**Position coordinates at the start time** x [Nm]	y [Nm]	**The decision time [min.]**
Own ship	15	0	0	0	3
Target 1	8	90	4	−0·5	
Target 2	10	0	−6	5	
Target 3	15	79	−6	3	

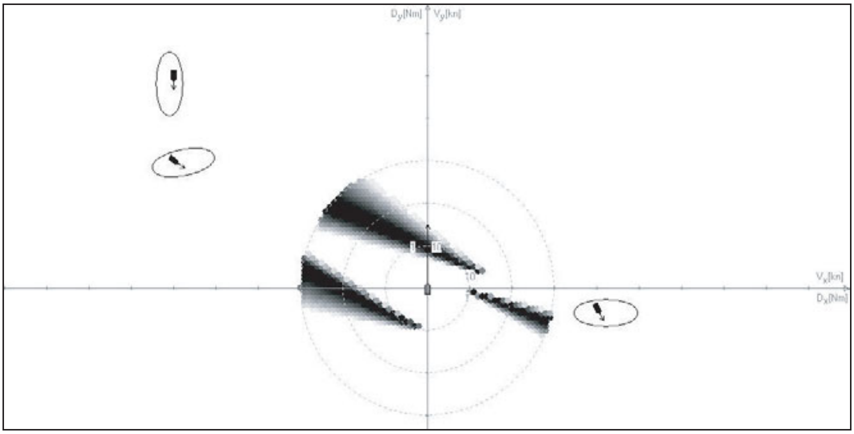

Figure 6. The FCTPA for the given scenario for the start time ($t = 0$ min.).

allowed, if there is no possibility of avoiding all targets with just one manoeuvre. This means that the tip of the own speed vector may be conditionally placed within this part of the CTPA, for which $TCPA > T_S$. When applied to the graphical display, the CTPA method enables the operator to choose manually a safe own speed vector in a very easy way – it is enough to choose a point outside the CTPA and read its speed coordinates. The method is summarized by Figure 5.

3.2. *Fuzzy Collision Threat Parameters Area* (*FCTPA*). In this section a proposed visualization tool, the Fuzzy Collision Threat Parameters Area (FCTPA), is presented. It is based on the same concept of the forbidden area in the double Cartesian coordinate system, but instead of determining the area analytically for a fixed D_S value, it is determined numerically for a given ship domain.

For every combination of the own course and speed the resulting f_{min} value is computed. The algorithms used to compute the f_{min} value for given courses, positions and speeds of the own ship and target ships have been presented in detail in [10]. Depending on the value obtained, a point in the double Cartesian coordinate system representing a particular combination of the own speed and course is assigned a colour in the following way:

- for $f_{min} < 0·5$ (critical domain violation): black
- for $0·5 \leqslant f_{min} < 1$ (domain violation): gradually changing to dark grey
- for $1 \leqslant f_{min} < 2$ (close encounter): gradually changing to light grey
- for $f_{min} > 2$ (safe passing): white

https://doi.org/10.1017/S0373463308004992 Published online by Cambridge University Press

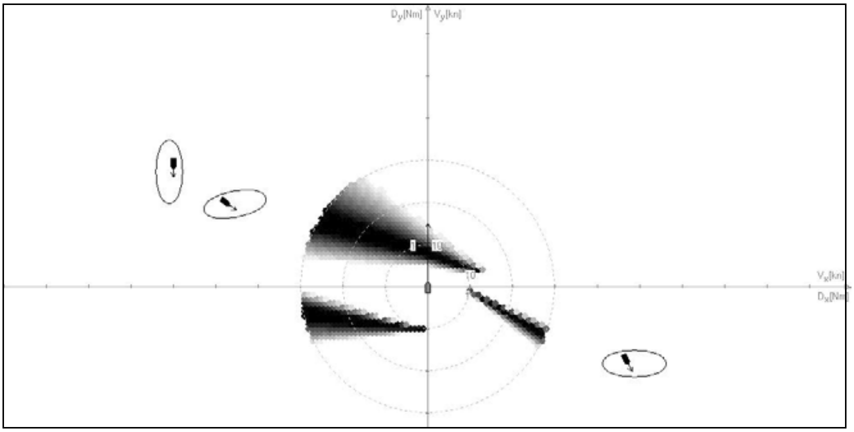

Figure 7. The FCTPA for the given scenario for the time $t=5$ min.

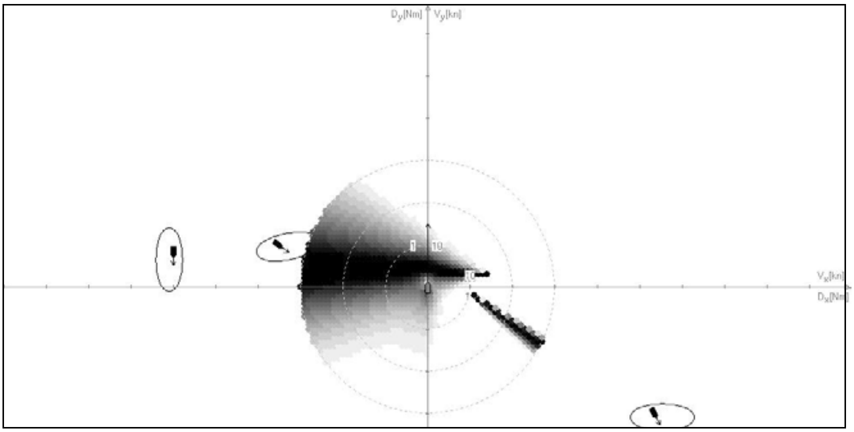

Figure 8. The FCTPA for the start time of the given scenario for the time $t=10$ min.

Whenever the arrow indicating the end of the own speed vector appears on the dark grey or black background a collision avoidance manoeuvre should be performed. The closest white or light grey point on the display represents a safe combination of the own speed and course. An exemplary situation is presented here. The data for the scenario is given in Table 1. The domain according to Coldwell [2] is used for all targets. In Figures 6–11 the relative positions, relative courses and relative speeds of targets as well as the resulting FCTPA are shown. In Figure 6 the arrow indicating the end of the own speed vector is on the light grey area, which means a close but relatively safe encounter with target 3 (no domain violation). In Figure 7 the situation is still safe but the forbidden region has enlarged significantly due to the own ship approaching the target 3. The forbidden region is continuously increasing which is shown in Figure 8. In Figure 9 the forbidden region has changed because the own ship is currently passing target 3. Once the own ship has passed the target 3, the forbidden region decreases rapidly, which is illustrated by Figure 10.

https://doi.org/10.1017/S0373463308004992 Published online by Cambridge University Press

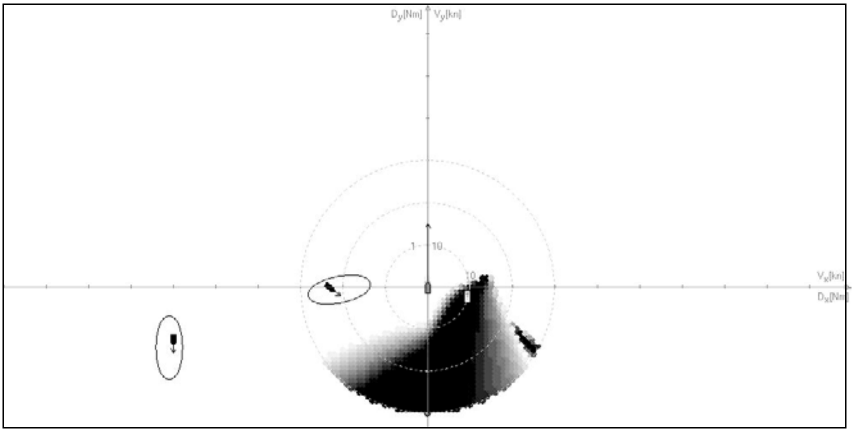

Figure 9. The FCTPA for the given scenario for the time $t=15$ min.

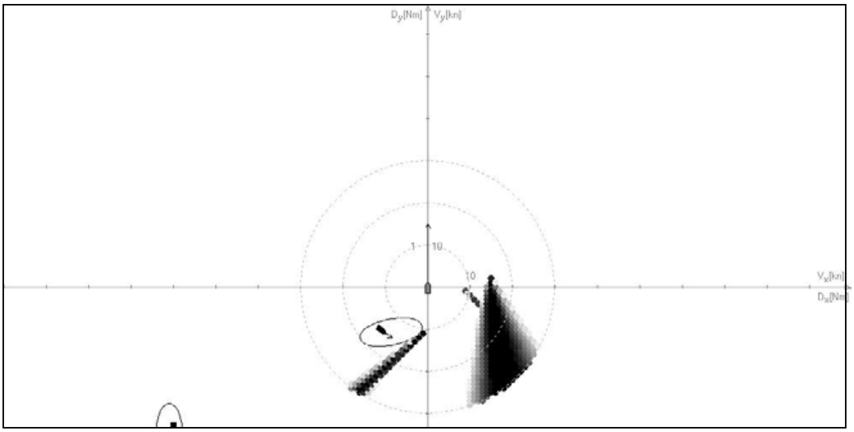

Figure 10. The FCTPA for the given scenario for the time $t=20$ min.

3.3. *An exemplary scenario of the emergency manoeuvre.* In this subsection the situation involving an emergency manoeuvre is presented. It is assumed here that the start data for this scenario is the same as for the situation above, however after 12 minutes from the start, when the closest target is about 3 nautical miles from the own ship it alters its course unexpectedly in such a way that the own ship is forced to perform the emergency manoeuvre. The input data for this scenario is given in Table 2. Figure 11 depicts the situation before target 3 altered its course by 21 degrees and Figure 12 – after target 3 altered its course by 21 degrees.

In Figure 12 the end of the arrow indicating the own speed vector is in the dark grey area, which means that there is a significant collision risk (possible domain violation). It might be concluded from Figure 12 that to avoid the collision, the own ship should take one of the following actions within a 3-minute decision time:

- alter its course to starboard by approximately 75 degrees,

https://doi.org/10.1017/S0373463308004992 Published online by Cambridge University Press

Table 2. The positions, courses and speeds of the ships after target 3 has altered its course.

	Speed [knots]	Course [degrees]	Position coordinates at the start time		The decision time [min.]
			x [Nm]	*y* [Nm]	
Own ship	15	0	0	0	3
Target 1	8	90	5·6	−0·5	
Target 2	10	0	−6	0	
Target 3	15	58	−3·1	0·6	

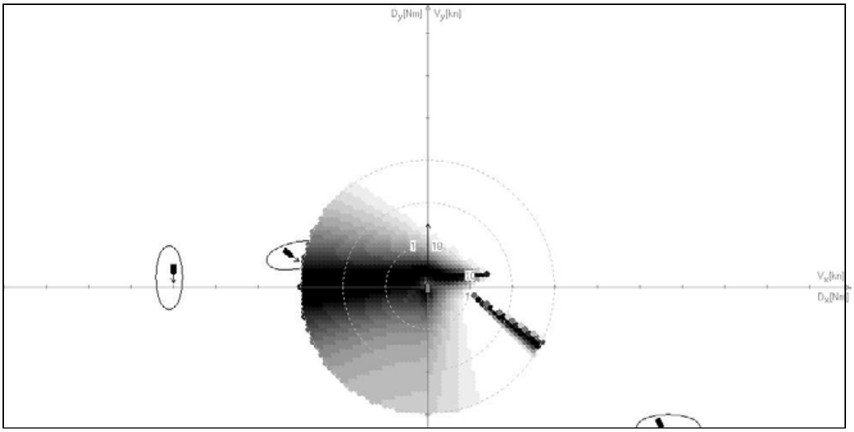

Figure 11. The FCTPA for the given scenario for the time $t = 11$ min. (before target 3 has altered its course)

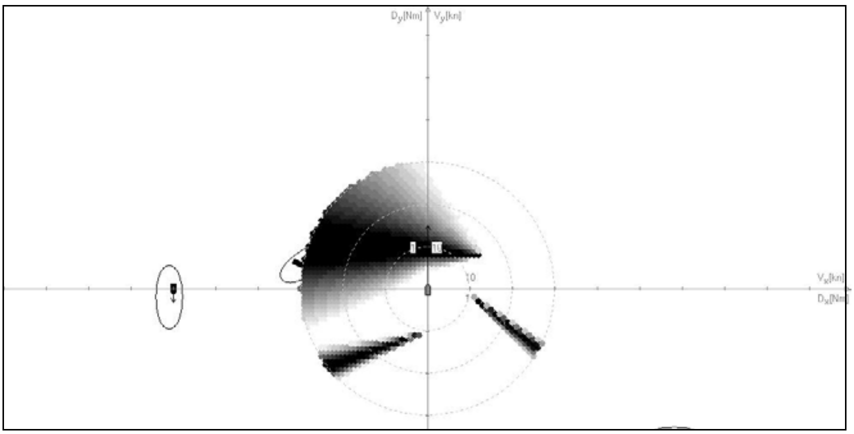

Figure 12. The FCTPA for the given scenario for the time $t = 12$ min. (after target 3 has altered its course)

- reduce its speed from 15 to 5 knots,
- alter both its course and speed, for example reduce the speed from 15 to 8 knots and alter its course by approximately 60 degrees to starboard.

https://doi.org/10.1017/S0373463308004992 Published online by Cambridge University Press

It is worth noting that in the critical situation, that is when no perfectly safe combination of course and speed would be available, the navigator could still choose immediately the optimal (relatively safe) manoeuvre by selecting the course and speed combination corresponding to the lightest possible point in the display.

4. SUMMARY AND CONCLUSIONS.

The paper covers the issue of dealing with two cases of unpredicted target behaviour: unpredicted and potentially dangerous manoeuvres and lack of manoeuvres, when they would be expected. Two complementary methods have been introduced. The first of them is responsible for monitoring the navigational situation, estimating the probability of an unlawful target action (not giving way) and re-planning the trajectory when necessary. Although this method is fast enough to re-plan the trajectory in real time, the navigator may not always have enough time to analyse the proposed solution. This is why the second tool – a new display – is proposed in the paper. The new display is based on the CTPA method but brings two improvements: fuzzy sectors of forbidden speed and course values and the possibility to use any given ship domain. The display enables the navigator to assess an encounter situation and plan a collision avoidance manoeuvre if necessary. It is especially useful for planning emergency manoeuvres because it enables the navigator to choose a combination of course and speed alteration manoeuvre quickly, without performing any additional computations.

ACKNOWLEDGEMENT

The author would like to thank Prof. A. S. Lenart, whose CTPA method has inspired the author's research.

REFERENCES

[1]. Cockroft A.N., Lameijer J.N.F. (1993). *A Guide to Collision Avoidance Rules*. Fourth Edition, An Imprint of Butterworth-Heinemann Ltd.

[2]. Coldwell T.G. (1982). Marine Traffic Behaviour in restricted Waters. *The Journal of Navigation*, **36**. 431–444.

[3]. Davis P.V., Dove M.J., Stockel C.T. (1982). A Computer Simulation of multi-Ship Encounters. *The Journal of Navigation*, **35**. 347–352.

[4]. International Maritime Organization (1995). Resolution A.823(19).

[5]. Lenart A.S. (1982). Collision threat parameters for a new radar display and plot technique. *The Journal of Navigation*, **36**, 404–410.

[6]. Lisowski J. (2001). Determining the Optimal Ship Trajectory in Collision Situation. *Proceedings of the IX International Scientific and Technical Conference on Marine Traffic Engineering*, 192–201, AM, Szczecin.

[7]. Lisowski J. (2001). Game control methods in navigator decision support system. *Archives of Transport*, vol. 17, issue 3–4, Warszawa.

[8]. Lisowski J. (2005). Dynamic games methods in navigator decision support system for safety navigation. *Proceedings of the European Safety and Reliability Conference* vol. 2, p 1285–1292.

[9]. Pietrzykowski Z. (2001). Ship Fuzzy Domain on a Straight Section of a Fairway – Comparative Study. *The IX International Scientific and Technical Conference on Maritime Traffic Engineering*, Szczecin.

[10]. Szlapczynski R. (2006) A unified measure of collision risk derived from the concept of a ship domain, *The Journal of Navigation*, **59**, 477–490.

[11]. Szlapczynski R. (2008) A new method of planning collision avoidance manoeuvres for Multi target encounter situations, *The Journal of Navigation*, **61**, 307–321.
[12]. Smierzchalski R. (2001) Moving Object in Evolutionary Manoeuvre of Collision Avoidance at Sea. *Proceedings of the IX International Scientific and Technical Conference on Maritime Traffic Engineering*. 309–316. AM, Szczecin.