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Graphical Tools to Facilitate the Selection of Manoeuvres to Avoid Collision

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ABSTRACT: Graphical tools have been proposed to facilitate the selection, evaluation, and correction of anti-collision actions in situations with moving and stationary obstacles, assuming that such situations are not extreme or ordinary with sailing vessels and that the target movement parameters are constant or their upcoming change is known. The choice of evasive combined Z-manoeuvre (both course and speed change at one point and return to the original values of these parameters at another point) and one combined action (both course and speed alteration at the selected point) were considered. The graphical tools developed contain diagrams, showing eight zones of actions, and special marks of targets at the moment of their closest approach to the own ship. In view of the COLREG and good seamanship, these zones were arranged in order of application priority. The results of the enumeration of a representative discrete set of possible manoeuvre variants were used to construct the diagrams.

1 INTRODUCTION

Due to the increase in the number, size, and speed of ships, the problem of collision avoidance is becoming more complicated. Despite the measures taken, including development of Collision Avoidance Support System (CASS), this problem is urgent. One of the ways to solve this problem is to improve information support for decisions, including the development of recommendations for and mapping the zones of acceptable values of manoeuvre parameters, and a number of other elements. Such mapping makes it easier for the operator to evaluate the system's recommendations to avoid collision and to correct them.

In the paper [10], indicators of dangerous course and velocity areas are presented to determine effective actions in one of onboard CASS. In the Visualization-based CASS [9], evasive manoeuvres are selected according to the diagram of own ship velocity vectors, safe for targets passing. This method is called Velocity Obstacle (VO) [2]. The paper [8] highlights an algorithm that allows, using the VO method, to find COLREG-compliant manoeuvres. The creation of visual aids is also envisaged in addition to the definition of recommendations by the methods 'Artificial Potential Field' [5], 'Dynamic Window' [1], 'Model Predictive Control' [7], and others [3, 6, 12, 13]. In the paper [13], the search for the optimal evasive manoeuvre in terms of sailing time loss is based on the enumeration method, and tables are proposed that make it easier for the operator to evaluate and correct the found option. The complexes of graphic elements to facilitate the adoption of anti-collision decisions developed still have drawbacks, and the question of their improvement is urgent.

The objective of the paper is to develop graphical tools to facilitate the selection, evaluation and correction of combined Z-manoeuvre (CZM) and one combined action (OCA) in situation with moving and stationary obstacles, assuming that such situation is not extreme, the target movement parameters are constant or their upcoming change is known.

The following abbreviations are used: OS - own ship; TS - target ship; CPA - closest point of approach; DCPA - distance at CPA; TCPA - time to CPA; GWV – give-way vessel; SOV – stand-on vessel; XTD - cross track distance. For DCPA, TCPA and XTD the symbols δ, τ and η are also used in the text. Own ship was given the number '0', and the targets were numbered from 1 to *n*. The number of the most dangerous (main) target was denoted by μ, and the targets with numbers j and μ were marked by TS_J and TS_μ. The same indices were used for the characteristics of these ships. The initial course, speed of own ship and TS_J were respectively marked K_0, V_0 and K_J, V_J. The own ship course and speed on the evasion section were denoted by K_U, V_U. The Rules referenced in the text are part of COLREG.

2 CONSIDARATION OF REQUIREMENTS FOR EVASIVE ACTIONS

Collision avoidance actions include course or/and speed changes. The anti-collision manoeuvre was defined as a sequence of actions with sections of movement between them with the constant course and speed. This manoeuvre contains evasion actions (evasive manoeuvre) and actions to back to the passage plan (comeback manoeuvre). According to Rule 8, the first actions must be substantial, i.e., sufficiently large and short in time. The use of slow course and/or speed changes, even by a sufficient amount, to avoid collision is not reasonable. Such actions may be interpreted as successive small alterations which should be avoided (Rule 8).

When solving problems of collision avoidance, a situational approach is used, in which the choice of measures is determined depending on the current situation. The used classification of the situations, influencing the conduct of two vessels (with the exception of sailing ones) in normal and restricted visibility, is presented in Fig. 1.

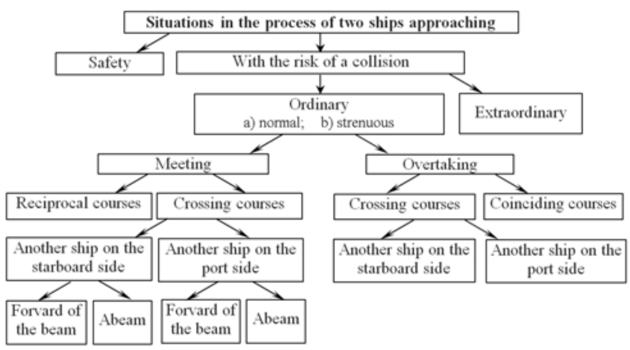

Figure 1. Situations of two ships nearing

Normal situations refer to the vessel approaching phase, in which actions are carried out at the ample time. In strenuous and in extraordinary situations, the vessel, respectively, may or must refuse the conduct prescribed for her. Strenuous situations are those in which give-way vessel is late in evading actions. Situations are extreme when the own ship is so close to the target that a collision can be avoided only by maximum strong manoeuvre of one ship or actions of both vessels. Extreme situations, as well as ordinary situations with two sailing vessels, are not considered below.

In a pair of ships nearing with risk of collision the give-way vessel was defined:
- under Rules 14 and 15, for power-driven vessels in sight of each other in meeting situations (see Figure 1);
- under Rule 18, for ships of different navigational status in sight of each other in meeting situations;
- under Rule 13, for power-driven vessels and ships of different navigational status in sight of each other in overtaking situations;
- under Rule 19, in restricted visibility where both ships take evasive actions.

It is preferable, if circumstances of case admit, to avoid a collision by employing manoeuvres involving a few actions. These manoeuvres include the proposed here manoeuvre containing:
- evading a collision with combined Z-manoeuvre by shifting to parallel original track line, on which movement is safe;
- passing along this line by the target that was dangerous;
- typical comeback manoeuvres.

The typical comeback manoeuvres were considered (Fig. 2):
4. incoming at the active route leg under the selected angle (Q_C);
5. going to the active waypoint (WP);
6. Following to the intersection of course line with the next leg of the route.

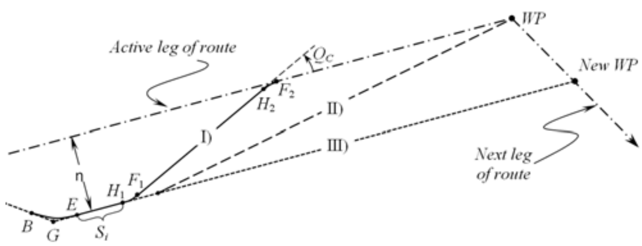

Figure 2. Typical comeback manoeuvres: *B*, *E* - the beginning and the end points of the second action in the evasion manoeuvre; η - lateral deviation from the active route leg; S_i - distance from the evasive manoeuvre end to the comeback manoeuvre start; H_1, F_1 and H_2, F_2 - the start and end points of the first and second actions in the first type comeback manoeuvre

When the direction to turn on the next route leg coincides with the side of evasion, the third type of comeback is preferable. If such sides are opposite, the second manoeuvre is best. If necessary the first manoeuvre applies.

Combined Z-manoeuvre includes two actions [14]: the first is both course and speed change at a selected point, the second - returning to the original values of these parameters at another point. Particular cases of combined Z-manoeuvre are Z-manoeuvre, including a course alteration at one point and a return to its original value at a second point, and a manoeuvre containing a speed change at one point and a return to its previous value at another point. Additionally, the paper considered the choice of one combined action (both course and speed alteration at the selected point). Partial cases of one combined action are the alteration in course or velocity only. Combined Z-manoeuvre and one combined action together with their parameters below are denoted by CZM(*S*,*W*,*Q*,*U*), OCA(*S*,*W*,*Q*), where *S* is the distance from own ship to the beginning of the manoeuvre at the time of its calculation; *W* is speed change; *Q* is angle of turn; *U* is length of the straight segment of the evasion.

The Rules 13-19 regulate the conduct of two ships approaching at risk of collision in waters free of fixed and moving obstacles. These conditions and decisions prescribed for them (turn side, actions, manoeuvres) are called standard below. Under standard conditions, in normal visibility, a give-way vessel usually tries without changing speed to minimize the loss of sailing time and avoid crossing the course of stand-on vessel on the bow. The action that stand-on vessel may take in strenuous situations is selected to ensure safety both when the other ship performs the actions directed by the Rules, and in their absence. In view of the above, for standard conditions, normal visibility, for power-driven vessels and vessels with different navigational status, standard side of turn to avoid collision was determined:

– in situations of meeting on reciprocal courses, the standard action of give-way vessel is the turn to starboard;
– in both meeting and overtaking situations with ships on crossing courses, the standard action of give-way vessel is turn toward the stand-on vessel;
– in overtaking situations of ships on coinciding courses, the standard action of give-way vessel is change course to port, if she is to the left of the overtaken vessel's track, and to starboard, when she is to the right of or on that line;
– in strenuous meeting situations with ships on crossing courses, when stand-on vessel may perform evading manoeuvre, the standard action of that vessel is turn to the side that coincides in name with the standard side of turn for the give-way vessel;
– in strenuous overtaking situations with ships on crossing courses, when stand-on vessel may perform evading manoeuvre, the standard action of that vessel is turn to the side, opposite name to the standard side of turn for the give-way vessel.

It was considered that the turn index (σ) is equal to one (σ=1) when changing course to the standard side, σ=-1 when turning to the opposite direction, and σ=0 if altering speed only.

For waters constricted by ships, the action is determined in relation to the most dangerous of them, and is selected as safe with respect to all stationary and moving obstacles. In normal visibility, the statements for actions in standard conditions apply for constricted waters also, when circumstances permit. For other cases, alternatives to the standard options are used. When the main engine of own ship is ready for manoeuvre, turning to the standard side, altering speed, and turning to the standard side with speed change are the preferred actions over turning to the opposite side without or with speed change. In most cases, the second actions are used when there are no options of preferred actions. Evading actions in constricted waters are generally accompanied by crossing the course of one or the other target on the bow. Such variant is more dangerous than passing on the stern. Therefore, the accepted by GWV distance of crossing the target course on the bow should be greater than on the stern.

For restricted visibility, the standard side of turn to keep clear is established by Rule 19. The basis of such prescription is the requirement, that ships must assist each other to avoid collision. Fulfilling this requirement helps to quickly increase the distance between ships. Rule 19 does not establish the standard evasive turn side in a situation such as when the other vessel, in normal visibility, is being overtaken. Based on the ‘assistance’ requirement, in this case, a vessel that is abaft the beam of another ship should change course to the opposite side of another ship location.

It is now required (MSC.192(79), IEC 62388) in on-board collision avoidance systems to detect ships at risk and select evasive manoeuvres using pre-determined DCPA and TCPA limits (denoted $\hat{\delta}$ and $\hat{\tau}$), which must be consistent with sailing conditions. In addition to $\hat{\delta}$, the minimum acceptable ($\check{\delta}$) under the given conditions DCPA was used. The main factors influencing such restrictions are the following [11, 14]:

– type of navigation area and the density of traffic in it (the constriction of the water area by fixed and moving obstacles);
– features (size, manoeuvreability, speed) of own ship and target;
– errors in determining the parameters of target position and movement.

Here are the main types of navigation areas usually distinguished depending on the distance (ρ) in nautical miles to navigational obstacles:

– open sea ($\rho \geq 50$);
– coastal waters ($50 > \rho \geq 5$);
– constricted waters ($\rho < 5$).

When considering limits of target danger, we can distinguish:

– generalized limits ($\hat{\delta}_G$, $\hat{\tau}_G$), which did not take into account own ship and targets features and refer to ordinary medium tonnage vessels;
– limits ($\hat{\delta}_O$, $\hat{\tau}_O$) specified with regard to the own ship characteristics for ordinary medium-tonnage targets;
– limits ($\hat{\delta}_j$, $\hat{\tau}_j$) calculated considering the features of own ship and target.

To determine generalized limits, their dependence on the degree of tightness of the water area can be used. These limits for the main types of navigation areas are usually recommended for use on seagoing vessels. One such recommendation is: $\hat{\delta}_G$ =20 cb, $\hat{\tau}_G$=30 min for open sea; $\hat{\delta}_G$ =15 cb, $\hat{\tau}_G$=25 min for coastal waters; $\hat{\delta}_G$ =10 cb, $\hat{\tau}_G$=20 min for constricted waters. The minimum acceptable DCPA value for the open sea is usually considered to be 10 cb, and for constricted waters - 5 cb [11]. It should be noted that the above limits for coastal and constricted waters correspond to the average of distances to navigational obstacles in these areas.

When studying the problem of collision avoidance, $\hat{\delta}$ is often used in a broader sense than the limit of targets DCPA. This threshold is considered an argument for calculating the boundaries of one shape or another of target domain of danger. The variant where $\hat{\delta}$ is the limit of DCPA is a particular case of this interpretation. Circular domain of danger with the centre in the target mass centre and radius equal to $\hat{\delta}$ corresponds to this particular variant. In navigation practice such domains are used in the predominant majority of cases. A circular domain shifted relative to the target in the direction of its motion can be applied so that the acceptable crossing distance of target course would be greater fore than aft. More complex domains shapes are proposed to take into account factors not considered by circular domains. The domain form is usually taken the same for all targets. When the features of the targets are taken into account, their domain sizes will be different.

TCPA limit defines when Rules 13-19 come into force. The distance between own ship and main target, which corresponds to such start, was limited to $\breve{D}$ =1,1· $\hat{\delta}$ from below and $\hat{D}$ =8· $\hat{\delta}$ from above. If appropriate $\hat{\tau}$ this distance was smaller than $\breve{D}$ or greater than $\hat{D}$ the $\hat{\tau}$ value was corrected:

$$\text{IF } (\hat{\tau} \cdot v_{\mu 0} < \breve{D}) \text{ THEN } \hat{\tau} = \breve{D} / v_{\mu 0}; \tag{1}$$

$$\text{IF } (\hat{\tau} \cdot v_{\mu 0} > \hat{D}) \text{ THEN } \hat{\tau} = \hat{D} / v_{\mu 0}; \tag{2}$$

where $v_{\mu 0}$ is the main target speed relative to the own ship.

Taking into account $\hat{\tau}$ and the length (L_{OS}) of the own ship, the points (B_τ, E_τ) of the start and end of the Rules 13-19 action were determined on the own ship path line. The distances from the own ship's position, at the moment of the closest approach with the main target, to the points B_τ and E_τ were calculated using the following expressions

$$\Delta_B = V_0 \cdot \hat{\tau}\,; \;\; \Delta_E = 5 \cdot L_{OS}\,. \tag{3}$$

The parameter S of manoeuvre was obtained as S=Y_S-Y, where Y_S and Y are the distances from point E_τ to the own ship position at the moment of task solution and to the manoeuvre start point. In the $B_\tau E_\tau$ interval two stages were distinguished: of give-way vessel in ample time action, and of possible stand-on vessel action. The boundary of these stages was considered by default to be the middle of the $B_\tau E_\tau$ interval.

In the process of collision avoidance, the own ship should remain controllable and be able to accelerate the course and speed alteration. In order for the action to be fast enough and not impair the ship's controllability, it was assumed that:

– turns are made with a radius (R_Z) average for the own ship;
– the speed is reduced by applying the mode 'slow astern' or 'dead slow astern', and should not be less than the dead slow ahead;
– engine power to increase speed to a given value V_Z is greater, if possible, than the power to move at this speed, so action time will not be too long.

To define large enough changes in course and/or speed, the β index was used

$$\beta = |Q| / \hat{q} + |W| / \hat{w} \tag{4}$$

where $\hat{w}$, $\hat{q}$ are the limits of sufficiently large changes in speed and course.

Usually it was recommended that $\hat{q}$ be taken as 30°. The minimum acceptable value of Q is most commonly considered to be $\breve{q}$ =15° [15]. One of the recommendations for the lower limits of sufficiently large and acceptable values of W when avoiding collision by speed reduction is $\hat{w}$=V_0/3 and $\breve{w}$ =0,2V_0. The boundary $\hat{\beta}$ of sufficient values of β is equal to one, i.e. the action is large enough when β⩾1. To find the minimum acceptable value of β, the expression $\breve{\beta} = (\breve{q} / \hat{q} + \breve{w} / \hat{w}) / 2$ was used:

To prevent collisions with navigational obstacles, a safety lane was defined by limits ($\breve{\eta}$, $\hat{\eta}$) of own ship safe lateral deviations from track line to the port and starboard. The boundaries of lane cut off water areas dangerous in depths for the own ship and prohibited for navigation regions.

3 OFFERED GRAPHICAL TOOLS

Below for simplicity, the domains of danger are assumed to be unbiased, circular, and equal in size for all targets. Proposed graphical aids to facilitate the selection of anti-collision manoeuvres include diagrams, showing the zones of acceptable actions, and special marks of targets at the moment of their closest approach to the own ship. When developing these tools, in the area of the acceptable manoeuvre variants, the basic and alternative sets were distinguished. The first set contains the manoeuvres satisfying the requirements for evasive actions. The alternative sets included acceptable manoeuvres not meeting this requirements for magnitude ($\breve{\beta} \le \beta \le \hat{\beta}$) and/or evasion side (σ=-1) and/or safety ($\breve{\delta} \le \delta_m \le \hat{\delta}$), where δ_m is the minimum value among DCPA of targets in the own ship path. When (β<$\breve{\beta}$) or ($\delta_m < \breve{\delta}$) or (η<$\breve{\eta}$) or (η>$\hat{\eta}$), the manoeuvre was considered unacceptable. The basic variants of the combined Z-manoeuvre and one combined action were denoted as CZM{0} and OCA{0}. In the designation of the alternative manoeuvre option, the parameters, whose values do not meet the requirements, are given in curly brackets, e.g., CZM{δ, β}. For own ship with engines ready for manoeuvre, table 1 shows in order of application's priority the combined Z-manoeuvre zones Z_h, where h is the priority index (h=1, 2, …, 9), and the colors we have chosen to represent them. The same colors are used for one combined action sets. In general, the manoeuvre must be selected in the zone with the highest priority.

Table 1. Sets of acceptable manoeuvres

Zone	Manoeuvre type	Area color
Z_1	CZM{0}	light green
Z_2	CZM{β}	green
Z_3	CZM{δ}	dark yellow
Z_4	CZM{δ,β}	yellow
Z_5	CZM{6}	light gray
Z_6	CZM{6,β}	gray
Z_7	CZM{6,δ}	light violet
Z_8	CZM{6,δ,β}	light blue
Z_9	Unacceptable	dark red

The basis of obtaining data for the diagrams was the method of enumerating a representative discrete set of possible manoeuvre variants. A finite discrete set is considered representative, when it replaces the infinite continuous set with sufficient completeness for the task at hand. Before obtaining data for the diagrams, the lower $\left(\breve{S},\breve{W},\breve{Q},\breve{U}\right)$ and upper $\left(\hat{S},\hat{W},\hat{Q},\hat{U}\right)$ boundaries of the possible values of the manoeuvre parameters, and the limits ($\breve{\eta}$, $\hat{\eta}$) of OS safe deviations from the route line to the port and to the starboard, are set. When enumerating for each manoeuvre option the values δ_m, β, η, *h*, dT for combined Z-manoeuvre, W_S for one combined action are determined, where dT is the loss of sailing time, $W_S=V_0 - V_U\cdot\cos Q$. The enumeration method is inferior in time to the accelerated search procedures for optimal anti-collision manoeuvres [8, 10]. But enumeration allows obtaining the necessary characteristics of each of the possible manoeuvre variants, and to define in the form of representative subsets the areas of sufficient, acceptable and unacceptable such options, taking into account various factors. In this respect, the approach applied has an advantage over finding such areas by calculating their borders using analytical geometry methods [2]. The dynamics of own ship when enumerating was taken into account in a simplified manner. The trajectory of the turns with the average for own ship radius (R_Z) was represented by a set of a straight-line segment and an arc of a circle with this radius. The length of the straight-line segment was equal to $l=\kappa\cdot L_{OS}$, where κ – is the coefficient considering the ship's initial turning ability. The change in *V* during braking and acceleration was represented by the expressions

$$W = a_1t + a_2t^2\,,\;\; W = b_1t + b_2t^2\,; \tag{5}$$

where *t* is the process time.

The coefficients of these expressions were found using the stopping and acceleration data, given in the own ship manoeuvreing booklet, and the mathematical model of the ship dynamics in the form of an interconnected system of nonlinear differential equations. If to use speed change with a given acceleration, then expressions for predicting *W* will be the simplest. When calculating the trajectories of turn with speed change, these processes were considered independent.

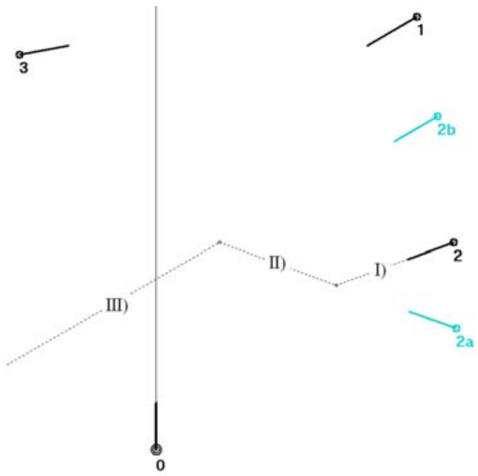

Figure 3. Example of virtual targets formation

With the help of AIS, ships are able to transmit elements of their routes. The change in motion data, provided by the targets can be accounted for in a number of ways. We reduced this problem to the task with unchanged parameters of targets motion by entering additional virtual targets. Fig. 3 shows an example of input virtual targets 2a, 2b for target 2, with a known trajectory of movement. The positions of targets 2a, 2b, as well as real target, correspond to the moment of the problem-solving start. By setting TCPA limits, the trajectory section 'I)' was assigned to target 2, and the trajectory sections 'II)' and 'III)' – were assigned to targets 2a, 2b, respectively.

Diagrams with one and two coordinates (for example, *S* and *Q*, *W*) are presented as S-diagram and QW-diagram. When working with diagrams to obtain combined Z-manoeuvre and one combined action, the cursor in the top priority area is placed to the point that determines the preferred, in the operator's opinion, values of the manoeuvre parameters. Symbols of the values selected by the cursor are given below with the index *Z*. Diagrams for choosing combined Z-manoeuvre are the following:

– WS- and QU-diagrams, when the main engine is in manoeuvreing mode;
– S- and QU-diagrams, when main engine is not ready to manoeuvre (W_Z=0).

The WS-diagram cell has the colour of the zone (see Table 1) of the top priority combined Z-manoeuvre variant among its possible variants, values of *S* and *W* parameters of which are this cell coordinates. The colour of S-diagram cell is determined similarly. WS-diagram, or S-diagram, is used by the operator to set suitable S_Z, W_Z values, or only S_Z (W_Z=0), to obtain the QU-diagram corresponding to these values, and to determine among possible manoeuvre variants, with the S_Z and W_Z values of *S* and *W* parameters, or only S_Z value of parameter *S*, the values of *Q*, *U* parameters of the optimal variant:

– for Z_1, Z_5 - with minimum loss of sailing time;
– for Z_2, Z_6 - with the maximum of β value;
– for Z_3, Z_4, Z_7, Z_8 - with the maximum value of the minimum distance between the own ship and targets on the own ship trajectory.

The QU-diagram cell has the colour of the zone of the combined Z-manoeuvre variant, the values of *S*, *W*, *Q*, *U* parameters of which are S_Z, W_Z and coordinates of this cell. By selecting a point on the QU-diagram with the cursor, it is possible to correct the combined Z-manoeuvre variant obtained by the computer using the WS- or S-diagram.

If one combined action is found when the main engine is in manoeuvreing mode, the S-diagram and the QW-diagram are used. If the main engine is not ready to manoeuvre, the QS-diagram is applied. The S-diagram cell has the colour of the zone of the top-priority one combined action variant among its possible variants, the value of the *S* parameter of which is the coordinate of this cell. This diagram serves to set S_Z with the cursor, to receive the QW-diagram corresponding to this value, and to determine among possible manoeuvre variants, with value S_Z of parameter *S*, values of *Q*, *W* parameters of optimum variant. For zones Z_1, Z_5 the one combined action variant with the minimum value W_S is searched for. For other zones the optimality criteria are similar to those used in the selection of combined Z-manoeuvre. The cell of QW-diagram has the colour of the zone of one combined action variant, the values of *S*, *Q*, *U* parameters of which are S_Z and coordinates of this cell. The one combined action variant found by S-diagram can be corrected by QW-diagram, setting on it with the cursor a point with suitable coordinates. Note that usage in maritime navigation the QW-diagram in polar coordinates was proposed by E. Pedersen, and is covered in his works, in particular, in [2].

QS-diagram cell has the color of the zone of the one combined action variant, the *S*, *Q* parameters values of which are the coordinates of this cell. The selection of anti-collision manoeuvres with the help of diagrams is presented in Section 4.

When finding diagrams to select the comeback manoeuvre, the enumeration method is also applied. The manoeuvre of the first type (see Fig. 2) is searched by the S_C-diagram for the set angle of approach to the route, and by the S_CQ_C-diagram when the range of this angle values is given. To select the manoeuvre of the second type the S_C-diagram is used. In the name of the diagrams Q_C is the angle of approach to the active segment of the route, and S_C is

- the distance from the end of combined Z-manoeuvre to the beginning of the comeback manoeuvre, if this manoeuvre is searched before the end of combined Z-manoeuvre,
- the distance from the own ship location at the time of the comeback manoeuvre calculation to its start, if this manoeuvre is selected after the completion of combined Z-manoeuvre.

In order to assess the quality of selected manoeuvres visually, it is proposed, along the own ship trajectory, planned to keep clear, to use special CPA marks of targets at the moment of their closest approach to the own ship. This mark contains:

- the predicted positions of own ship and target at the time of their closest approach;
- the base segment of δ length, beginning at the predicted target location and pointing to the predicted own ship place;
- the short segment pointing to the current target location.

From CPA mark it is easy to estimate the value of the shortest distance between the own ship and target, fore or aft the own ship will cross the target course. CPA marks were determined by numerical prediction in accelerated time of future ship positions in 1 s increments. Rule 8 requires that the effectiveness of the action taken to avoid collision with another vessel shall be carefully checked until this vessel is finally past and clear. Therefore, in the process of the anti-collision manoeuvre execution, it is expedient at a short time interval (2 min, for example) to find, taking into account the information obtained, the future minimum distances between own ship and targets on the own ship path for timely detection of adverse changes in the situation.

4 VALIDATION OF PROPOSED METHOD

The proposed method of manoeuvre selection was validated with the help of a program developed in Delphi programming language. In this program, the quantity of targets was limited to 20. Various simulated encountered situations were resolved in this program, confirming that the research goal was achieved. In the solved tasks, the computer time to obtain all the diagrams data did not exceed 4 seconds. One such task is described below, in which the own ship and 9 targets are power-driven vessels. Own ship and targets data are shown in Tables 2 and 3, where *B* and *D* are the target bearing and distance. Target TS_1 is the most dangerous vessel, which the own ship must give way.

Table 2. Own ship data

L m	*K* dg	*V* kn	R_Z cb	κ -	a_1 cb/min²	a_2 cb/min³	b_1 cb/min2	b_2 cb/min³
220	345	17,1	3,5	1,0	-0,93	0,073	0,89	-0,78

Table 3. Targets data

TS	1	2	3	4	5	6	7	8	9
B, dg	36	51	69	326	325	101	27	332	331
D, cb	71,0	73,1	39,3	30,0	43,3	38,8	105,7	83,7	144,7
K, dg	258	260	267	88	197	346	194	132	133
V, kn	19,1	16,9	17,3	21,2	8,6	9,7	7,2	9,0	7,2

The used constraints are presented in Table 4, in which *p* is the general notation of the parameter, regardless of its type.

Table 4. Parameter limits

Para-meter	*S* cb	*W* kn	*Q* dg	*U* cb	η cb	δ cb	τ min	w kn	q dg
$\breve{p}$	0	-12	-90	0	-30	5	-	2,0	16
$\hat{p}$	50	0	90	70	30	7	15	4,0	30

The enumeration step for *S* and *U* was 1 cb, for *W* - 1 kn, and for *Q* - 2 dg. The information presentation form is shown in Fig. 4, where:

- chart field;
- indicator of distances between waypoints of the combined Z-manoeuvre;
- button to memorize the marked supposed change of the target motion parameters;
- indicator of the basic data of the selected manoeuvre (CZM or OCA);

– indicator of the basic data of manoeuvre (CZM or OCA), corresponding to the cursor coordinates on the QU-diagram or QW-diagram;
– QU-diagram or QW-diagram;
– indicator of the basic data of manoeuvre (CZM or OCA), corresponding to the cursor position on the WS-diagram or S-diagram;
– WS diagram or S-diagram;
– switch for the type of manoeuvre to be defined (CZM or OCA);
– ON/OFF switch of the information presentation mode, when moving the cursor in the diagram field.

If the component ON/OFF is in OFF position, the indicator 5 (or 7) shows the manoeuvre data relevant to the cursor coordinates on diagram. In the ON position, in addition to the data in indicator 7, the following elements, corresponding cursor coordinates on WS-diagram or S-diagram, are displayed:
– QU-diagram or QW-diagram;
– own ship evasive path and CPA target marks on the navigation chart.

If the cursor moves along the field of QU-diagram or QW-diagram, in addition to the data on the indicator 5, the own ship evasive path and CPA marks, responding to the cursor position, are displayed on the navigation chart.

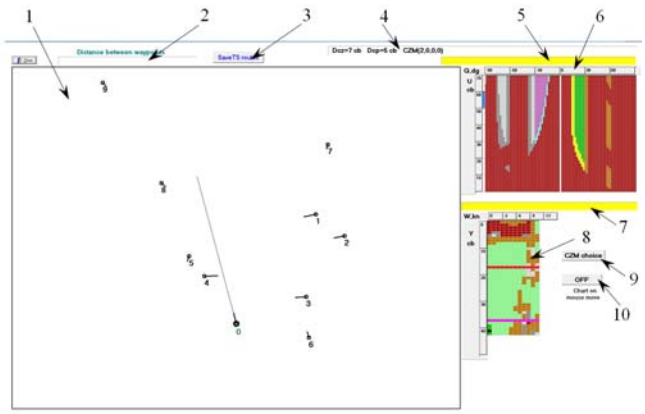

Figure 4. Information presentation form

The diagrams show all Z_h zones of manoeuvres. It is possible to represent from one to eight of these zones, as well as only the zone with the top priority.

The selection of combined Z-manoeuvre by the cursor on the WS-diagram is explained in Fig. 5, which shows with a change of proportions the components of the presentation form: data indicators, part of the chart field, WS-diagram with the position of the cursor on it, QU-diagram, switches for the type of manoeuvres to be defined and the overlay mode. In this figure:
1. indicator of the selected combined Z-manoeuvre;
2. manoeuvre lane boundaries;
3. trajectory of the selected manoeuvre;
4. CPA marks;
5. point on the QU-diagram, marking coordinates of the optimal manoeuvre corresponding to the position of the cursor on the WS-diagram.
6. indicator of combined Z-manoeuvre data selectable on WS-diagram;
7. edge of give-way vessel manoeuvres started at ample time;
8. the beginning of COLREG requirements accounting;
9. line, corresponding to own ship current position;
10. lower bound of the diagram, responding to the OS position at the time of the diagrams receiving;
11. own ship position at that time on chart.

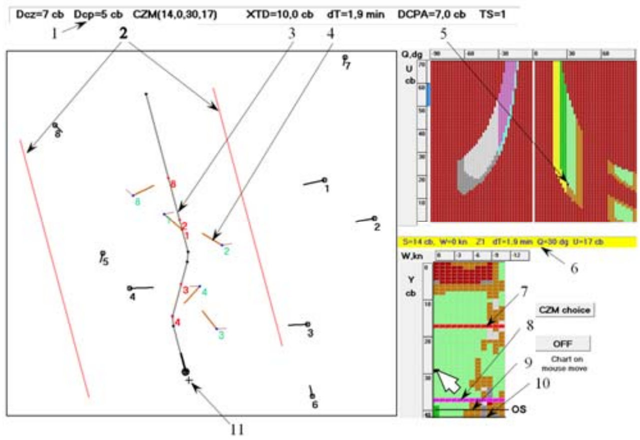

Figure 5. To the combined Z-manoeuvre choice on the WS-diagram

As the cursor moves along the WS-diagram field, the values of its parameters *S* and *W* corresponding to the chosen combined Z-manoeuvre variant, the designation of the highest-priority zone, the value of the optimality criterion for this zone, and the parameters *Q* and *U* of the optimal manoeuvre are displayed above WS-diagram. When clicking on a cell, it is coloured black. The coordinates of such cell are labelled as S_Z, W_Z. The appearance of the QU-diagram corresponds to S_Z, W_Z. The black dot on this diagram marks the coordinates of the optimal manoeuvre. The basic data of the selected combined Z-manoeuvre is given on the indicator. Own ship on the electronic chart is supplemented by trajectory of the chosen manoeuvre and by CPA marks of targets if necessary (Fig. 5). The indicator shows: the values of $\hat{\delta}$ and δ (Dcz, Dcp), optimal *Q* and *U* of combined Z-manoeuvre parameters ($S=S_Z$, $W=W_Z$), the cross-track distance, the loss of sailing time (dT), the minimum value of DCPA and the target number with this value. The CPA mark is shown when δ_j is less than specified value (20 cb in the example). The *Q* and *U* parameters of the combined Z-manoeuvre obtained from the WS-diagram can be corrected by pointing their new values on the QU-diagram with the cursor (Fig. 6).

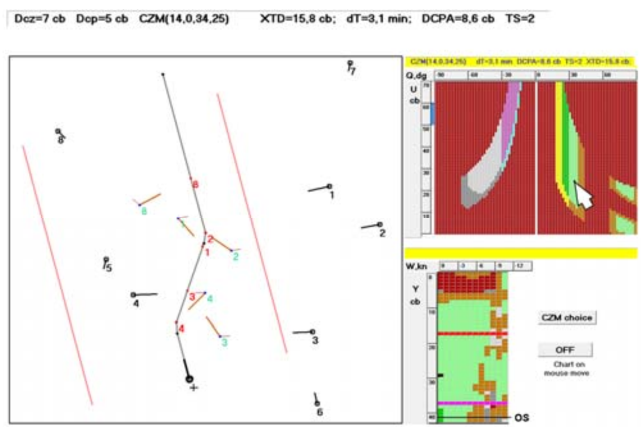

Figure 6. To the selection of combined Z-manoeuvre on the QU-diagram

The operation with S-diagram and QW-diagram for one combined action choice (Fig. 7 and Fig. 8) is similar to the work with the diagrams for combined Z-manoeuvre selection.

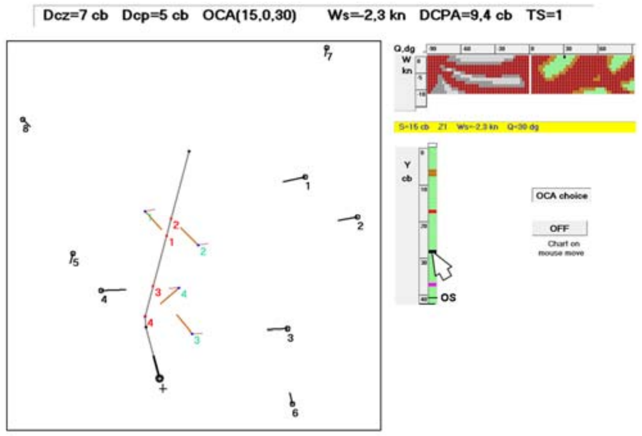

Figure 7. To the one combined action choice on the S-diagram

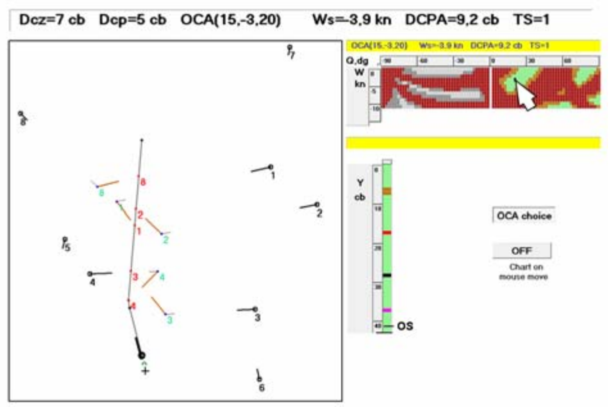

Figure 8. To the one combined action selection on the QW-diagram

When main engine is not ready to manoeuvre, finding combined Z-manoeuvre is similar to choice on the WS-diagram and QU-diagram, but in this case the first diagram has one column (W=0). To determine the one combined action in this case, the QS-diagram is applied (Fig. 9).

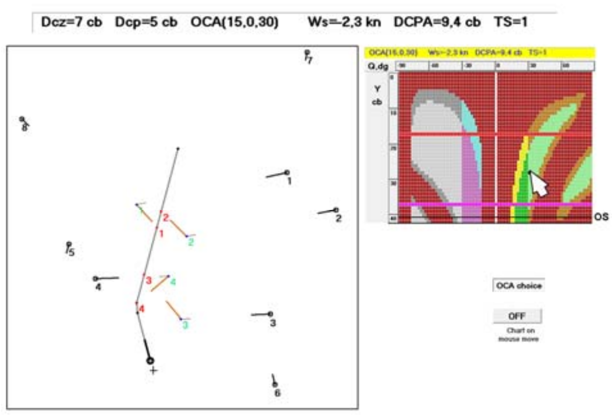

Figure 9. Selecting the one combined action using the QS-diagram

It is possible to check how the safety of own ship manoeuvre can be affected by a potential change in the target motion parameters. To do this, the needed target is highlighted in the chart field with the cursor, and its trajectory is supplemented with one or two segments. After that the computer, in 1-second increments, determines the future distances between the own ship and that target. The closest of these distances is defined and the CPA mark is shown on the chart. By this mark the impact of the target action on the safety of the selected own ship manoeuvre can be evaluated. Digitally, shortest distance between own ship and target is displayed in the upper left corner of the chart. If it is greater than $\hat{\delta}$, the colour of the symbols is black, if it is less than $\breve{\delta}$, the colour is red, if the distance value is between these boundaries, the color is light brown. The parameters of the created target paths can be memorized by pressing the 'Save TS routes' button. To illustrate the presented procedure, Fig. 10 shows the effect of possible changes in the target TS_2 and target TS_5 motion parameters on the selected combined Z-manoeuvre. The assumed paths of these targets movement are indicated on the chart. The figure shows that changes in the path of TS_2 will result in the collision threat immediately after the end of combined Z-manoeuvre. The possible action of TS_5 is not accompanied by a collision risk.

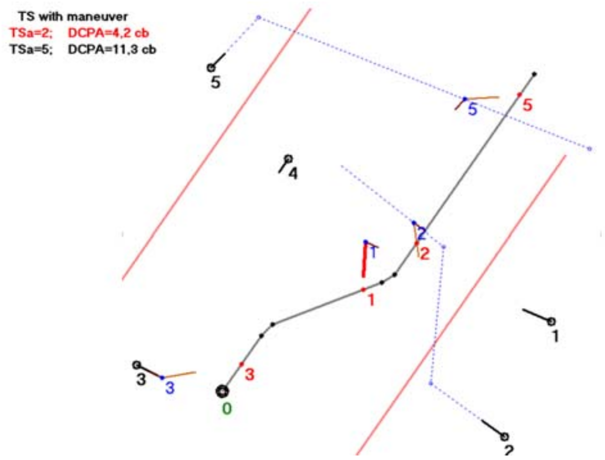

Figure 10. Effect of possible changes in the target motion on the manoeuvre

The developed program also provides the ability to display diagrams for the choice of comeback manoeuvres after combined Z-manoeuvre. As an example, Fig. 11a shows a Q_CS_C-diagram for the selection of the first kind of that manoeuvre in the 10°-60° range of arrival angles to the route active segment. The situation at the time of diagram calculation is shown in Fig. 11b. In this example, own ship is 16.0 cb to the starboard of the route. The values of $\hat{\delta}$ and $\breve{\delta}$ in the example are 5 cb and 3 cb, respectively. Own ship and targets data at the time of the diagram calculation are shown in tables 5 and 6. The comeback trajectory and CPA target marks shown in Fig. 11b corresponds to the cursor position on the diagram (Q_C=30°, S_C=15 cb).

Table 5. Own ship data

L m	K dg	V kn	R_Z cb	κ -
220	345	17,1	3,5	1,0

Table 6. Targets data

TS	1	2	3	4	5
B, dg	53	65	287	12	358
D, cb	19,2	34,9	18,5	55,4	62,2
K, dg	293	302	116	217	122
V, kn	19,1	16,9	14,8	10,1	9,4

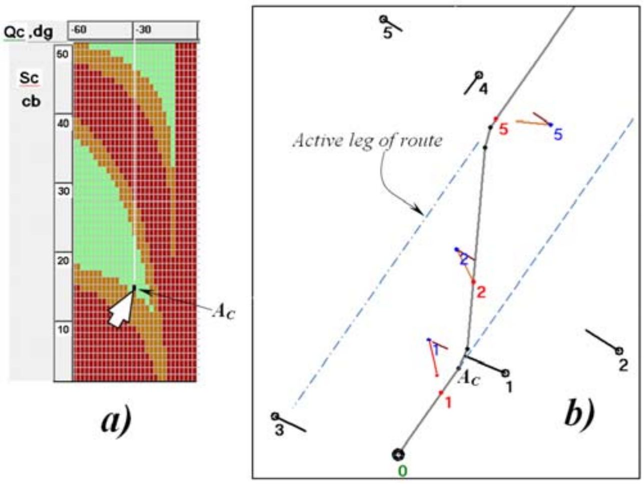

Figure 11. To the comeback manoeuvre choice by QcSc-diagram

5 CONCLUSION

To achieve the research objective, the following was carried out:

– the classification of situations in the process of two vessels approaching was specified, and general provisions for determining actions in free waters under normal visibility were established;
– the areas of possible evasion actions were singled out and ordered by priority;
– the possibility of using enumeration of representative discrete set of evasion manoeuvre variants to solve collision avoidance tasks in situations with several targets, was confirmed;
– diagrams were obtained for selecting, in situations with stationary and moving obstacles, an evasive and a typical comeback manoeuvres;
– the procedure has been defined to assess the effect on the manoeuvre safety of known or probable future changes in target movement;
– special CPA marks for visual evaluation of the manoeuvre quality are proposed.

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