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THE ALGORITHM OF SEARCH OF ANTI-COLLISION B-MANOEUVRE IN THE CONFINED WATERS

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Abstract: Tools for collision avoidance are still lacking, and there is a margin for human error. To minimize such errors an algorithm of search by the computer of rational B-manoeuvre for collision preventing in confined waters was developed. It allows advising the OOW on the required action. Offered algorithm is based on the use of predicted area of danger (PAD_B) marks reflecting limitations of targets on motion and B-manoeuvre of own ship. The selection of rational action is executed by sorting out of acceptable variants of B-manoeuvre, taking into account safety, substantiality, done early and sparing of each variant. The offered method simplifies planning of anti-collision strategies. It can be used in marine collision avoidance system (CAS), ECDIS and in navigation simulators.

KEY WORDS: collision avoidance, B-manoeuvre, mark, manoeuvre automatic selection.

1. INTRODUCTION

Anti-collision strategies may include course or/and speed alteration, circulation and shifting to the parallel line of way (B-manoeuvre) [1]. In this study an algorithm for forming of recommendations about own B-manoeuvre for safe passing by other ships is discussed. The design of collisions free trajectory is examined in many literary sources devoted to navigation, for example, in works [2-5]. Quantitative determination of collision risk and assessment of efficiency of measures selectable for safe passing other ships come into question, in particular, in papers [6, 7]. The analysis of the literature sources on ships collision avoidance shows that this problem is studied not completely.

2. BASE PARAMETERS FOR MANOEUVRE CHOICE

At the removal of collision threat experience of navigator is needed, foremost, at assessment of the base parameters determined not clearly by COLREG. They must correspond to the prevailing circumstances and conditions taking into account the size of ship, hers manoeuvring qualities and other features. The aggregate of the adopted factors is named “sailing conditions” below. It is difficult to find mathematical expressions for the determination of base parameters values on the sailing conditions information. In that behalf expert’s assessment are more effective. On a ship such expert is a captain, because he has utmost knowledge and experience in this field of human practice.

We will designate the distance at closest points of approach as DCPA or D and time to closest points of approach as TCPA or T. For specification of the required by COLREG standard anti-collisions measures the captain should set

$D^{\underline{S}}$ - limit of DCPA safe values;

$T^{\underline{S}}$ - limit of TCPA safe values;

$\theta^{\underline{P}}$ - preferable angle of course alteration;

D_A - alert radius;

S_S, S_P - distances between the own ship (OS) way and the parallel lines limiting starboard and port side safety motion and manoeuvres water area.

On base parameters and data of navigation sensors the CAS must define:

- type of OS ship and the target with which there is a collision threat;
- rational values D_R, T_R, θ_R of DCPA, TCPA and angle of course alteration;
- good time interval for anti-collision actions;
- parameters of B-manoeuvre for targets safe passing.

3. DETERMINATION OF THE APPROACH TYPE

Depending on the relative bearing (RB) and foreshortening (FS) of the target it is expedient to select 11 types of dangerous approach of OS and the target, submitted in the table No.1.

Table No.1 – Types of two ship approach.

	Type of approach	**Specification**
1.	Crossing situation, target is on OS starboard forward of the beam	$-112.5 \le FS < -\Delta_1, \quad \Delta_1 < RB \le 67.5$
2.	Crossing situation, target is on OS port forward of the beam	$\Delta_1 < FS \le 112.5, \quad -67.5 \le RB < -\Delta_1$
3.	Crossing situation, target is on OS starboard abeam	$-112.5 \le FS < -\Delta_1, \quad 67.5 < RB \le 112.5$
4.	Crossing situation, target is on OS port abeam	$\Delta_1 < FS \le 112.5, \quad -112.5 \le RB < -67.5$
5.	Overtaking situation, overtaking target is on OS starboard abaft of the beam	$-112.5 \le FS < -\Delta_1, \quad 112.5 < RB \le 180 - \Delta_2$
6.	Overtaking situation, overtaking target is on OS port abaft of the beam	$\Delta_1 < FS \le 112.5, \quad \Delta_2 - 180 \le RB < -112.5$
7.	Overtaking situation, target to be overtaken is on OS starboard forward of the beam	$\Delta_2 - 180 < FS \le -112.5$
8.	Overtaking situation, target to be overtaken is on OS port forward of the beam	$112.5 < FS \le 180 - \Delta_2$
9.	Head-on situation	$ABS(FS) < \Delta_1, \quad ABS(RB) < \Delta_1$
10.	Overtaking situation, target to be overtaken is head-on	$ABS(FS) > 180 - \Delta_2, \quad ABS(RB) < \Delta_2$
11.	Overtaking situation, overtaking target is stern-on.	$ABS(FS) < \Delta_2, \quad ABS(RB) > 180 - \Delta_2$

Mathematical expressions for determination of approach type are given in right part of the table, where

- the digital values are in degrees;
- angles RB/FS on starboard from head of OS/target are positive and on port – negative;
- the value of Δ_1 lies in the interval 6-10 degrees, the interval of Δ_2 values is a little greater.

The demarcation line between the approach types of «abeam» and «forward of the beam» is not expressly certain by COLREG. As abeam is usually adopted directions from the head of the ship in intervals from six to ten rhumbs to starboard and to port ($|RB|=67.5^0 \div 112.5^0$).

4. TUNING OF BASE PARAMETERS

For the prescribed COLREG standard measures a rational D_R safe distance at closest points of approach is $D^{\underline{S}}$. If the circumstances force to give up standard measures, distance D_R will be greater than $D^{\underline{S}}$. For example, for the manoeuvres of "give-way" OS, resulting in crossing ahead of the target or at deviations to the not recommended but permitted by COLREG side, value of D_R is

$$D_R = k_B \cdot D^{\underline{S}}; \qquad D_R = k_Y \cdot D^{\underline{S}}; \tag{1}$$

where $(1.1 < k_B < 1.5)$, $(1.5 < k_Y < 3.0)$.

For the turns to the port, that are forbidden by COLREG, it is possible to take $D_R = D^{\underline{S}} / \varepsilon$, where ε is a small enough size, for example 0.001. The best values of k_B, k_Y and ε are determined by experts.

The rational value of T_R is $T^{\underline{S}}$ in most cases. However such value is used not always. Choosing the value of $T^{\underline{S}}$ a captain is oriented on "Crossing" and "Head-on" situations mainly. At the ships slow approach, for example at overtaking, such value usually is not rational. There may be cases, when distance to target is shorter $D^{\underline{S}}$ and $T > T^{\underline{S}}$. To avoid such cases the low limit T_M of T_R values is defined

$$T_M = k_T \cdot D^{\underline{S}} / u, \tag{2}$$

where u is OS speed in relation to the target and ($3.0 < k_T < 4.0$).

Value of T_R is as follows

$$\text{IF } T^{\underline{S}} \ge T_M \text{ THEN } T_R = T^S \text{ ELSE } T_R = T_M. \tag{3}$$

When standard anti-collision actions are taken in a good time the value of θ_R is equal to $\theta^{\underline{P}}$. If not recommended but permitted by COLREG alterations of course are used, then $\theta_R = k_{\theta 1} \cdot \theta^{\underline{P}}$, where ($1.0 \le k_{\theta 1} < 1.5$). If "give-way" target failed to take appropriate action and "stand-on" OS is forced to undertake a manoeuvre, then $\theta_R = k_{\theta 2} \cdot \theta^{\underline{P}}$, where ($1.3 \le k_{\theta 1} < 2.0$).

5. CRITERION OF B-MANOEUVRE EFFICIENCY

Below the partial criteria of B-manoeuvre efficiency are degrees p_D, p_θ, p_T, p_E of this actions in accordance with rational for the sailing conditions levels: of safety (D_R), of substantiality (θ_R), of done early (T_R) and of sparing (increasing Δ_S of OS way). The general criterion C_R of B-manoeuvre efficiency below is

$$C_R = \delta(\mathrm{x}) \cdot \frac{w_D \cdot p_D + w_\theta \cdot p_\theta + w_T \cdot p_T + w_E \cdot p_E}{w_D + w_\theta + w_T + w_E},$$

(4)

where w_D, w_θ, w_T, w_E - weights of p_D, p_θ, p_T, p_E;

$$x = p_D \cdot p_T \cdot p_\theta;$$

$$\delta(x) = \begin{cases} 0 & when\ x \le 0 \\ 1 & when\ x > 0 \end{cases}.$$

Partial criteria p_D, p_T, p_θ, p_E are functions:

$$p_D = F_D(D_M); \quad p_T = F_T(T / T_R); \quad p_\theta = F_\theta(\theta); \quad p_E = F_E(\Delta_S);$$

where D_M is the minimum of distances from "give-way" OS to targets and to the border of safe in a navigation relation water area in the process of future implementation of anti-collision plan by OS.

These functions reflect accordance of the obtained at navigation values of D_M, T, θ, Δ_S to the rational values. Types of functions $F_D(D_M)$, $F_T(T / T_R)$, $F_\theta(\theta)$, $F_E(\Delta_S)$ are defined by experts taking into account the requirements of COLREG. For the B-manoeuvre selection the functions submitted on the fig. 1-4 are used.

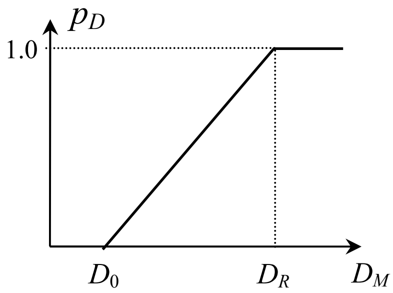

Fig. 1. Selected function $p_D=F_D(D_M)$

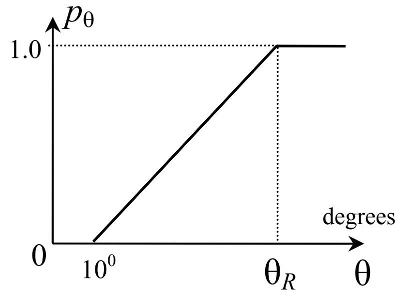

Fig. 2. Selected function $p_\theta=F_\theta(\theta)$

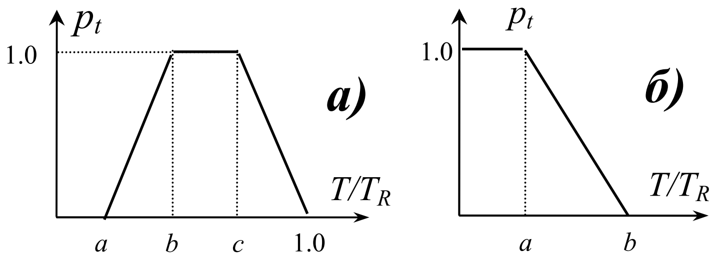

Fig. 3. Selected function $p_T=F_T(T/T_R)$
a) for “give-way” ship; *б*) for “stand-on” ship.

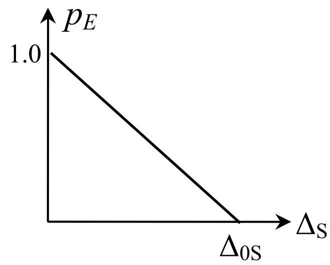

Fig. 4. Selected function
$p_E=F_E(\Delta_S)$

6. ALGORITHM OF AUTOMATIC SELECTION OF B-MANOEUVRE

B-manoeuvre is vessel shift to the parallel line of a way which is carried out under a certain angle θ to the initial line of a way. In a number of sources B-manoeuvre is called as Z-manoeuvre. Three pieces are selected in a B-manoeuvre (fig. 5): segment $0F_1$ between the current position of OS and the first waypoint, segment F_1F of deviation, segment FF_3 of motion after deviation. Last segment length is equal to the distance passable by the OS per time $k_t \cdot T^{\underline{S}}$, where $(1.0 \le k_t < 1.5)$.

A safe in the navigation relation water field for B-manoeuvre searching is set by S_S and S_P values. Selection of rational B-manoeuvre is characterized only in the starboard bar below. The algorithm of B-manoeuvre search in the port bar is similar.

The B-manoeuvre with deviation angle θ is fully determined by base point F. Position of this point is represented in the oblique-angled coordinates system $Z0U$ with an angle θ between axes (see fig. 5). On this figure:

θ - angle of alteration;

Z - distance between the positions of OS and the point F_1;

U - distance between points F_1 and F.

a_ib_i - the mark of limitation of own ship B-manoeuvre by the target *i*.

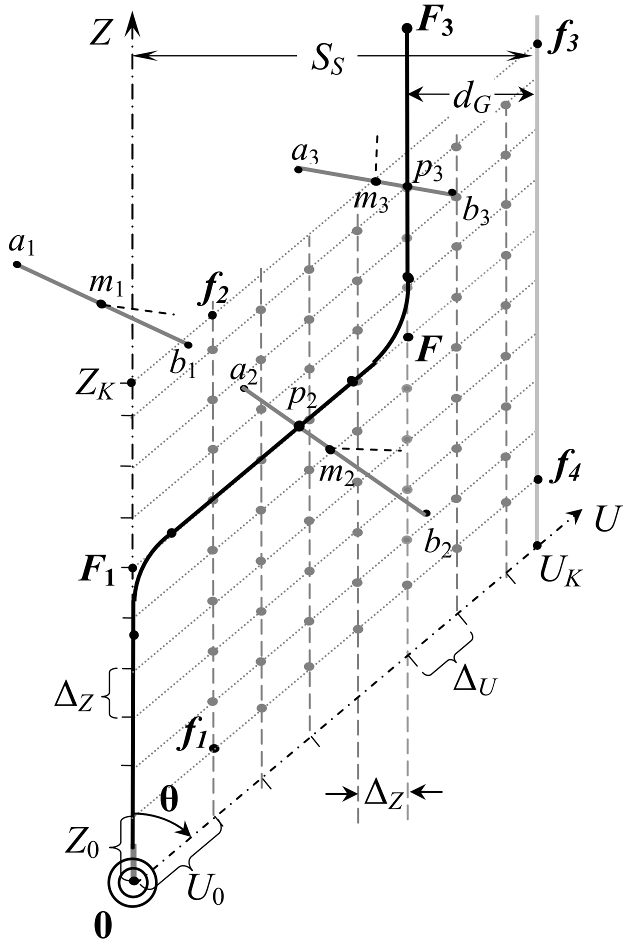

Fig. 5. To the search of rational B-manoeuvre

DCPA of the target *i* is determined on the distance between the centre m_i of PAD$_{Bi}$ mark and point p_i of crossing mark line and the planned path $0F_1FF_3$ [8]. The region of acceptable values of point F coordinates is determined by the scopes of parameters θ, Z, U:

$$\theta_0 \le \theta \le \theta_K, \qquad Z_0 \le Z \le Z_K, \qquad U_0 \le U \le U_K; \tag{5}$$

where scopes Z_0, U_0 depend on the angle θ.

For one θ value the field $f_1 f_2 f_3 f_4$ of acceptable coordinates Z, U of point F is shown on the fig. 5. The θ_0 value exceeds 10 degrees at least because course change at collision avoidance must be substantial. The right limit θ_K is set 150 degrees or less.

The borders Z_0 and Z_K are accepted

$$Z_0 = S_\theta + s_m, \quad Z_K = V \cdot T - s_m,$$

where S_θ - distance between wheel over point and waypoint;

s_m - distance passable by OS per one minute;

V - own ship speed.

B-manoeuvre can be normally executed, when U_0 (see fig. 5) is not shorter than $2 \cdot S_\theta$. The U_K value is

$$U_K = S_S / \sin\theta .$$

The amount of the point F positions is endless in the field $f_1 f_2 f_3 f_4$. For the B-manoeuvre selection this area is represented by a set of the point F positions taken through the certain intervals Δ_θ, Δ_Z, Δ_U of coordinates θ, Z, U:

$$\theta_h = \theta_0 + h \cdot \Delta_\theta , \quad Z_i = Z_0 + i \cdot \Delta_Z , \quad U_j = U_0 + j \cdot \Delta_U , \qquad (6)$$

where $h = 0, 1, 2, \ldots, n_\theta$, $\quad i = 0, 1, 2, \ldots, n_Z$, $\quad j = 0, 1, 2, \ldots, n_U$.

The values n_θ, n_Z, n_U are

$$n_\theta = INT(\frac{\theta_\mathrm{K} - \theta_0}{\Delta_\theta}), \; n_Z = INT(\frac{Z_\mathrm{K} - Z_0}{\Delta_Z}), \; n_U = INT(\frac{U_\mathrm{K} - U_0}{\Delta_U});$$

where the function INT gives whole part of argument.

The point F discrete positions at one θ value are shown on the fig. 5. For finding of rational B-manoeuvre it is possible to apply sorting out of its variants proper to possible positions of point F. Time interval of B-manoeuvre search by this method depends on the sizes Δ_θ, Δ_Z, Δ_U, values θ_K, Z_K, U_K and number of $\mathrm{PAD_B}$ marks in the field $f_1 f_2 f_3 f_4$. One $0F_1FF_3$ of variants of B-manoeuvre trajectory is shown on the fig. 5.

For each of point F position there are D_M, θ, T and Δ_S values. Values T and Δ_S are calculated according to formulas

$$T = (Z_K - Z)/V , \quad \Delta_S = U \cdot (1 - \cos\theta) + \frac{U}{\sin\theta_B}(1 - \cos\theta_B);$$

where θ_B - angle of B-manoeuvre for returning to the initial path.

The criterion C_R of efficiency of B-manoeuvre variant is determined on the formula (4). The effective B-manoeuvre has the C_R value maximal of sorted out variants of this action.

The algorithm of effective B-manoeuvre search is submitted on the fig. 6. At calculations on this algorithm the rectangular system of coordinates $X0Y$ is used. Its axis $0Y$ is directed on the north, and axis $0X$ - on the east.

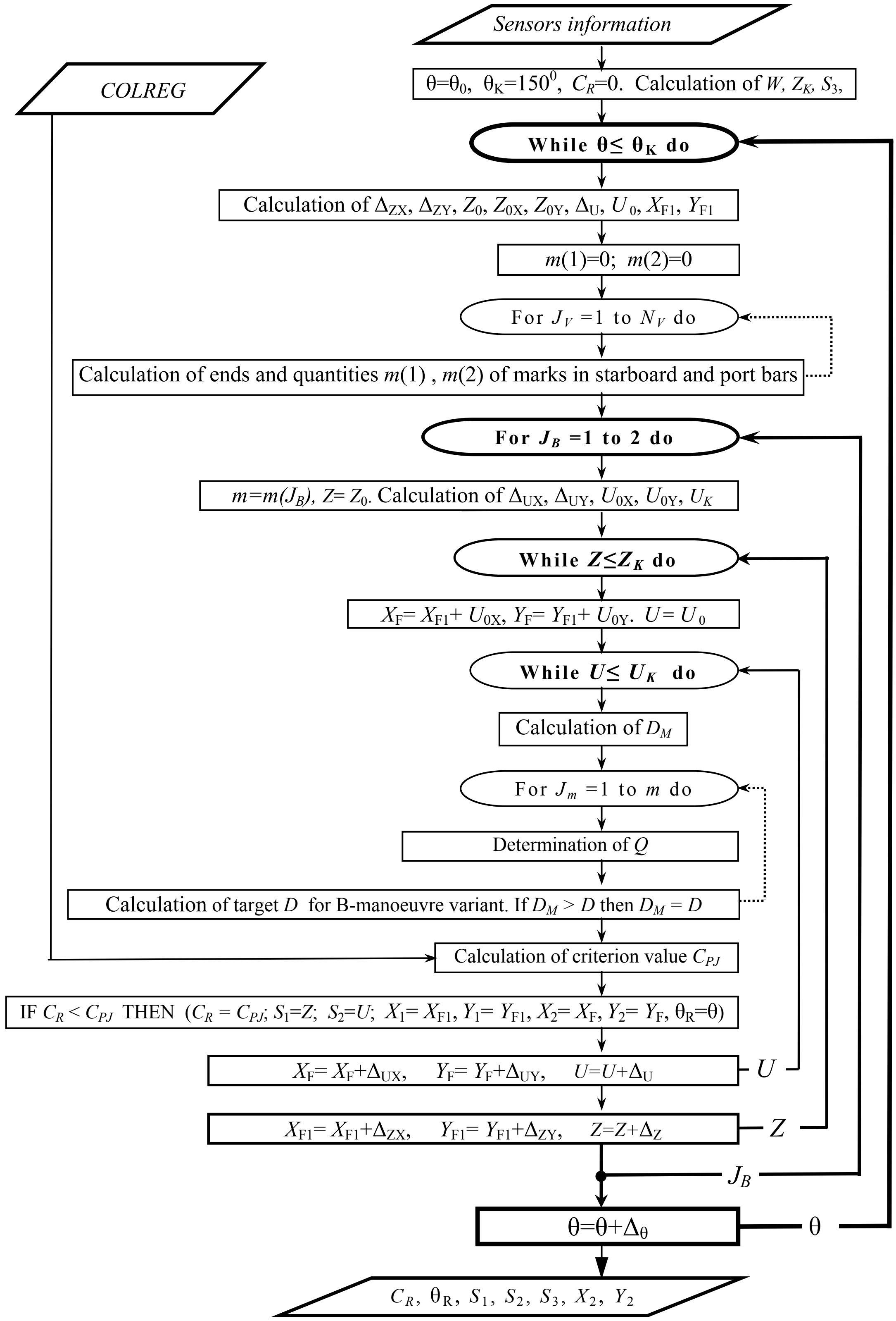

Fig. 6. Algorithm of effective B-manoeuvre search

The following denotations are used in the represented flow-chart of algorithm:

C_R, C_{PJ} - criterion of efficiency and its value proper to one of the sorted out B-manoeuvre variants;

W - approach type of OS and dangerous target;

S_1, S_2, S_3 - length of segments $0F_1$, F_1F, FF_3 of the B-manoeuvre;

Δ_{ZX}, Δ_{ZY}, Z_{0X}, Z_{0Y}, Δ_{UX}, Δ_{UY}, U_{0X}, U_{0Y} - accordingly coordinates of Δ_Z, Z_0, Δ_U, U_0 in the system $X0Y$;

J_B - sign of deviation side (1 – to starboard, 2 – to port);

$m(J_B)$ - amount of PAD_B marks in the starboard or in the port bar;

J_m - number of mark at the sorted out B-manoeuvre variants;

N_V - quantity of the targets;

J_V - number of target at the sorted out B-manoeuvre variants;

Q - sign of most dangerous target course crossing (1 – ahead, 2 – astern);

C_{DV} - course of most dangerous target.

Calculations confirmed the correctness of the algorithm developed. It was certain, that at $\Delta_\theta = 5^0$, $\Delta_Z = 0.05$ NM, $\Delta_U = \Delta_Z / \sin\theta$, $S_S \le 7$ NM, $S_P \le 7$ NM the time expended by a computer on the search of anti-collision B-manoeuvre with a few ships exceeds 5 seconds rarely.

7. SUMMARY

The search of rational anti-collision B-manoeuvre by sorting out acceptable variants of this action allows getting results in the real time. The recommendations produced on this basis facilitate and accelerate of acceptance by the OOW of effective decisions for collisions avoidance and limit the influence of the human subjective factor in navigation. Time interval of rational B-manoeuvre selection exceeds five seconds rarely. Usually such search takes about one second.

For verification of efficiency of the recommended B-manoeuvre it is enough to submit on display the CPA marks [8] for assessment of targets risk after this action. B-manoeuvre can be used for collision avoidance in many cases. But it is necessary to remember that there are situations in which such action is not rational. Therefore in any case OOW must comprehend advices obtained from CAS.

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