УДК 656.61.052 DOI: 10.31653/2306-5761.31.2021.08-21

COLLISION AVOIDANCE PLANNING WITH A SITUATIONAL APPROACH TO DETERMINE THE TYPE OF ACTIONS

ПЛАНУВАННЯ РОЗХОДЖЕННЯ З ЗАЛУЧЕННЯМ СИТУАЦІЙНОГО ПІДХОДУ ДО ВИЗНАЧЕННЯ ВИДУ ДІЙ

L. Vagushchenko, *DSc, professor*, **A. Vagushchenko,** *PhD, associate professor*, **A. Aleksishin,** *PhD, associate professor*

Л. Л. Вагущенко, *д.т.н., профессор*, **О. Л. Вагущенко,** *к.т.н., доцент*, **А. В. Алексішин,** *к.т.н., доцент*

National University "Odessa Maritime Academy", Ukraine

Национальный университет «Одесская морская академия», Украина

ABSTRACT

It is proposed to form strategies to avoid collision by using combined Z-maneuvers and their particular cases. To be with due regarding to COLREGs, limitations and situational approach were used to identify timely, safe and adequate situations, decisive ships' passing maneuvers. The type of encounter situation was determined depending on the visibility conditions, the geometry of approaching own ship and hazardous target, and navigation status of these vessels. Acceptable on distance of targets passing combined Z-maneuvers with their particular cases were found by using two composed semi-ellipses domains and circular domains of hazard, the center of which is shifted from the target mass point towards the bow. In the measures allowed by the COLREGs for resolving different types of encounter situations, the three kinds of actions were distinguished according to the degree of their adequacy to the situation: basic, backup, and non-recommended actions.

To comply with the COLREGs, enumerating method was applied to search for optimal strategy to avoid collision and return to the initial course and speed. At each step of the enumeration, it is determined that the current option of the maneuver belongs to one of the selected sets of acceptable variants of the maneuver. Among the current number of variants of this set, according to the selected criterion the best one has been found. Also, at each step of enumeration, the loss of sailing time due to deviation from the route and other characteristics are determined for the current variant of maneuver. After the end of the enumeration, according to the selected criterion the best maneuver variant on the set of required substantial variants is considered optimal for collision avoidance. If this set is empty, the optimal variant for collision avoidance is the best option on the set of lower degree of adequacy to the situation. The criteria and limitations for determining the best option for different sets are not the same. A numerical method for determining the set of the acceptable start of the maneuver for returning to the active route leg after the completion of combined Z-maneuver has been also developed. When solving the problem, the dynamics of the own vessel was taken into account in a simplified manner, and it was assumed that the parameters of the movement of targets would be unchanged. The authenticity of this method has been checked by means of simulation modeling of ships' passing.

The results of the analysis of the set of acceptable variants of the strategy, obtained during the enumeration, were memorized. Having based on these results it became possible to build the diagram, which facilitates for the operator the choice of actions in the dialogue mode with the system.

Key words: collision avoidance, combined Z-manoeuver, compliance with COLREGs, enumerative method.

РЕФЕРАТ

Пропонується утворювати антиколізійні стратегії з комбінованих Z-маневрів, включаючи їхні окремі випадки. Для врахування вимог МППСС використовувалися обмеження і ситуаційний підхід для виділення завчасних, безпечних, адекватних ситуації, рішучих маневрів розходження. Вид колізійної ситуації визначався в залежності від умов видимості, геометрії зближення власного судна і небезпечної цілі, навігаційних статусів цих суден. Допустимі по відстані розходження варіанти стратегій знаходилися за допомогою пов'язаних з центрами мас цілей областей небезпеки: зміщеного кругового домену та складеного з двох пів-еліпсів домену. У заходах, що допускаються МППСС у колізійних ситуаціях, за ступенем їх адекватності ситуації виділялися основні, резервні і нерекомендовані дії.

Для пошуку відповідного МППСС ефективного маневру для ухилення від зіткнення і повернення до початкових значень курсу і швидкості використовувався метод перебору. На кожному кроці перебору визначалася втрата ходового часу через ухилення від маршруту прямування та інші характеристики поточного варіанту маневру, а також належність цього варіанту до одної з виділених за ступенем адекватності ситуації множини. Після закінчення перебору найкращий за обраним критерієм на множині рекомендованих суттевих заходів варіант маневру вважався оптимальним для розходження. Коли ця безліч виявлялося порожней, оптимальний для уникнення зіткнення варіант знаходився на множині варіантів з нижчім ступенем адекватності ситуації. Критерії і обмеження для визначення найкращого варіанту на різних множинах бралися неоднаковими. Також був розроблений алгоритм чисельного визначення множини допустимих початків маневру для приходу на маршрут слідування до порту призначення після завершення комбінованого Z-маневру. Динаміка власного судна при плануванні маневрів враховувалася спрощено. Достовірність запропонованого методу перевірялася шляхом імітаційного моделювання процесів розходження суден.

Результати аналізу отриманої при переборі множині допустимих варіантів антиколізійної стратегії запам'ятовувалися. На їх основі була отримана діаграма, що істотно полегшує оператору вибір дій для розходження в режимі діалогу з системою.

Ключові слова: попередження зіткнень, комбінований Z-маневр, відповідність МППСС, метод перебору.

Introduction

The problem of ships' safe passing has remained relevant for many years. The currently available technologies with broad capabilities have allowed domestic and foreign scientists to achieve certain progress in preventing ship collisions. Methods based on these technologies have been developed for predicting situations, assessing collision risk, selecting appropriate COLREGs and the observance of good seamanship anti-collision strategies taking into account the vessels dynamics. Due to the fact that local legislation may be applied in certain water areas, this fact was also taken into account in a number of works. It should also be noted that new challenges are emerging in the development process. One of them is the creation of methods and systems for resolving collision situations for unmanned vessels. A number of issues of improving the effectiveness of collision avoidance support systems for manned sea vessels also remain unresolved. Many research teams continue to work on the solution of these problems.

Analysis of literature data and problem statement

The basic methods for preventing collisions with target-ship (TS) are analyzed in the article [1]. Among the investigations presented in recent years on this theme, we have noted the following. The paper [2] provides an overview of procedures for ships' motion predicting, for detecting the risk of close-quarters situations, and for avoiding collisions. The strengths and weaknesses of the analyzed algorithms and the possibility of their application on autonomous ships are discussed. In the publication [3] attention is drawn to new methods of finding oriented to modern digital technologies anti-collision strategies, which have the prospect of being applied on unmanned vessels. The document [4] reports on the developed anti-collision procedure for an unmanned vessel based on a modified Artificial Potential Fields method. In the article [5], for solving collision problem, it is proposed to use an improved distributed stochastic search algorithm, which allows defining changes in course and speed to avoid collisions. The publication [6] presents the sea trials results for an autonomous surface vehicle equipped with a collision avoidance system based on a model predictive control. The results of trials showed that this approach allows to find the corresponding COLREGs solutions in complicated situations close to the decisions of experienced navigators. The article [7] is dedicated to the study of the human role in the collision avoidance operations of autonomous sea surface vessels. A hierarchical analysis of tasks and a cognitive model for their categorization are presented. A review of the domains of danger to be used for solving collision avoidance problem, is represented in paper [8]. The survey [9] describes ship domains when developing numerical procedures for calculating collision risk. The study [10] is dedicated to assessing the influence of the water area available for maneuvering on the shape and size of the ships' domains of danger. Simplified models of ship dynamics, which allow in real time to search for effective actions among their possible options, are given in the publication [11]. The work [12] offers the literature review on the current state of collision avoidance systems at sea, and the extent to which COLREGs is taken into account in various situations, both when ships are in sight of each other and in the restricted visibility. The article [13] presents COLREGs formalizing method to be implied in decision support systems for navigators, and autonomous ship control systems in the future. In the publication [14], the Rapidly Exploring Random Tree algorithm was applied to obtain COLREGs-compatible collision avoidance trajectories. The solution of the anti-collision problem is closely connected with the increase of efficiency of on-board integrated Track and speed planning and control system. One way to increase the effectiveness of this system is to use Track and Speed control systems, which are able to adopt and execute the action plan without direct operator participation. The article [15] presents intelligent control system of ship motion in encounter situations. Despite the fact that much has already been done to successfully resolve collision situations at sea, this problem remains open and urgent.

The purpose and tasks of the research

The objective of the work is to choose a rational strategy to avoid collisions with several vessels, and the procedure for its stage-by-stage finding in situations that are not extreme. To achieve this goal we have determined:

- limitations and criteria for defining COLREGs compliant actions;
- the type of strategy and the algorithm for its calculation;
- diagram to select a strategy in the dialogue mode with the system.

Limitations and criteria for defining COLREGs compliant actions

It was assumed that encounter situations are not extraordinary, own ship (OS) is under command, dangerous target is not sailing vessel when own ship is such one, the positions of ships are characterized by the coordinates of their mass centers. OS was assigned the number 0. Targets were numbered from 1 to n. Target j was denoted by TS_j. The number of the dangerous target, and if there are several, then the number of the most dangerous one was designated m. Due to the severe consequences of collisions, the aim is to provide the highest level of safety when solving encounter situations. However, if in the open sea it is possible to get round TS at a distance of 3 NM, then in confined waters this is impossible, and targets have to be passed at shorter distances. In other words, under specific conditions it is possible to ensure only an achievable level of safety. The greater the distance the vessels need to pass, the more time this operation takes, and, accordingly, the earlier the COLREGs must be applied, and the maneuver initiated.

In order to decrease space for maneuvering due to navigation obstacles and traffic intensity, four types of water areas were distinguished: open sea, coastal waters, confined waters I, and confined waters II. For these types of areas, accepted by default, values were set up as follows: r_w for parameter that determines the size of the target domain of danger (TDD) and threshold of acceptable values of DCPA (distance at closest point of approach), $\hat{\tau}$ for limit of acceptable values of TCPA (time to closest point of approach), and $\hat{R}$ for radius of the alertness zone for warnings about the appearance of targets.

The start of COLREGs accounting was determined by distance ($\hat{D}_m$) between OS and TS$_m$. The procedure for $\hat{D}_m$ obtaining looks like

$$(\text{IF } v_{0m}\hat{\tau} > \hat{R} \text{ THEN } \hat{D}_m := \hat{R}) \text{ ELSE } (\text{IF } v_{0m}\hat{\tau} < 1{,}5\hat{\rho}_m \text{ THEN } \hat{D}_m := 1{,}5\hat{\rho}_m) \text{ ELSE } (\hat{D}_m := v_{0m}\hat{\tau});$$

where: $\hat{\rho}_m$ denotes the distance from the boundary of TDD$_m$ to TS$_m$ in k_{om} direction, k_{om} and v_{om}- indicate OS course and speed relative to TS$_m$.

According to COLREGs, any action to avoid collision shall, if the circumstances of the case admit, be made in ample time, substantial, acceptable on distance of passing targets, navigationally safe, with due regard to the observance of good seamanship (adequate to the situation), doesn't result in a risk of close-quarters situation with other ships, readily apparent to another vessel. If there is sufficient sea-room, alteration of course alone may be the most effective action to avoid a close-quarters situation provided that it is made in good time, is substantial and does not result in risk of collision. A succession of small alterations of course and/or speed should be avoided.

To provide the conformity of the COLREGs to computer-based collision avoidance strategies, various approaches were applied, in particular, such as those presented in publications [12-14]. This issue was resolved taking into account the experience accumulated by the navigators, reflected in the comments to the COLREGs.

To determine the time of initiation of anti-collision actions, the OS positions of expected start of COLREGs accounting and of close proximity with TS$_m$ were found. In the interval between these positions, three stages were distinguished while OS approaching to TS$_m$:

1. Made in good time measures;
2. Possible actions when the first stage is missed (delayed actions);
3. Urgent actions.

For large and average give-way vessels (GWV) the best place to initiate a maneuver is accordingly the beginning and the center of the first interval. For a stand-on vessel (SOV), in case of inactivity of GWV, this place is the center of the second interval. For actions in the first and second stages, compliance with rule 8 and the corresponding provisions from rules 13-19 was provided. Usually, strong maneuvers (full astern, all starboard/port) are not required at these stages. It is important in the avoiding process to maintain the maneuverability of own ship, so that if the situation begins to develop in an undesirable or dangerous direction, she would be able to improve it. Therefore, turns are usually done with an average for ship radius. In these cases turn rate can be increased if necessary. Due to the deterioration of the vessel's turn ability with decreasing velocity, the speed to avoid collision is usually reduced only to a certain limit, at which the ship remains controllable. It is also considered that when the vessel is moving forward, the work of the propeller in reverse reduces the efficiency of the rudder, and when using the full astern mode the vessel may become uncontrollable. To make this action fast and not to deteriorate the turn ability of the vessel greatly, the speed is reduced by using the mode 'slow astern' or 'dead slow astern'.

When choosing a maneuver at the third stage (extreme situation), Rule 2 is to be followed. The COLREGs don't define the type of action for these cases. Any measure is possible that results in the avoidance of an immediate danger. The very fact of such a situation indicates a serious violation of the COLREGs by both ships, or errors in the actions selected to avoid collision of one of them. As already mentioned, extreme situations are not covered in this paper.

Action to avoid collision must be substantial, if the circumstances of the case admit, and fast enough. It was considered that performance would be provided. The significance of the change of course and/or speed was determined using the expression

$$\varsigma = |\theta|/\hat{\theta} + |W|/\hat{W} \geq 1;$$

where θ, W and $\hat{\theta}$, $\hat{W}$ are changes of course, speed, and the limits of substantial values.

Acceptable on distance of passing targets variants of maneuvers were found using TDD. Close-quarters situation will occur when the OS course relative to TS_j passes through TDD_j. TS_j was considered to be dangerous for the OS when

$$\delta_j < \hat{\delta}_j \text{ and } \tau_j > 0 \text{ and } D_j < \hat{D}_j.$$

Here: δ_j, τ_j - indicate DCPA and TCPA of target TS_j; $\hat{\delta}_j$ - denotes threshold of safe δ_j values; D_j is the distance between OS and TS_j. Let us denote by the symbols K_0, V_0, L_0, B_0 and K_J, V_J, L_J, B_J course, speed, length, width of OS and TS_j. We also use the notation k_{oj}, v_{oj}, α for OS course and speed relative to TS_j, and difference $(k_{oj} - K_j)$.

A circular domain with a center shifted by a third of the radius from the TS center of mass towards the bow (Fig. 1) was used for the open sea, coastal navigation and rather wide passages. For other waters composed of two semi-ellipses TDD was applied. Within the radius of the first domain components (r_w, Δ_L) were distinguished, taking into account the peculiarities of the navigation region and the size of ships:

$$r_j = r_w + \Delta_L;$$

where $\Delta_L = 0{,}5(L_0 + L_J)$. The formulas for $\hat{\delta}_j$, $\hat{\rho}_j$ computation were obtained from describing the boundary of this domain function, derivative of this function, and the MJ line equation in the ξζ system (see Fig. 1)

$$\zeta = (r_j^2 - \xi^2)^{1/2} + \sigma; \quad \zeta' = c_\delta = -\xi(r_j^2 - \xi^2)^{-1/2}; \quad \zeta = c_\delta \xi;$$

where σ - indicates offset of the domain center from the center of mass of TS_j.

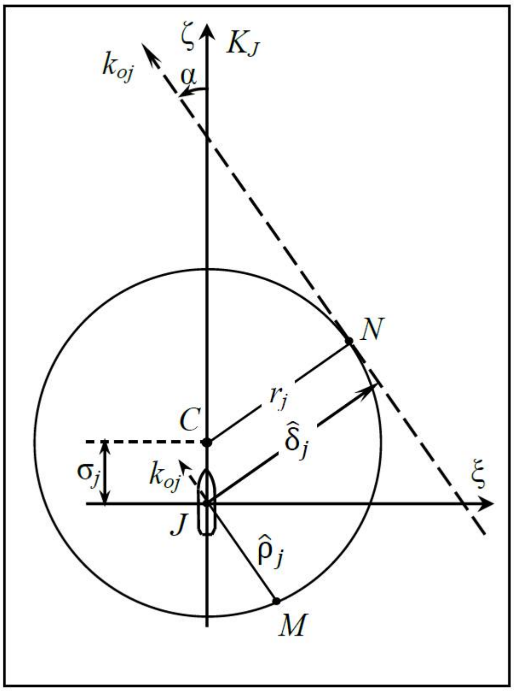

Figure 1. Circular domain with a shifted center

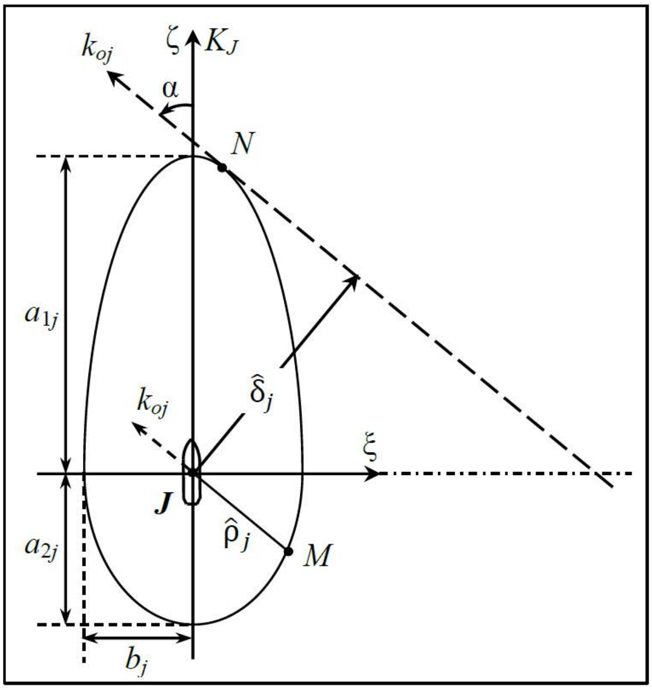

Figure 2. Composed of two semi-ellipses domain

Considering that $c_\delta = \tan(\pi - \alpha)$, the ξ_N coordinate of point N was determined from the expression of derivative. Then from the first equation, the ζ_N coordinate of this point was found. The $\hat{\delta}_j$ value was calculated as the distance from TS_j to the tangent, passing through point N. When solving the first and third equations together, the ξ_M, ζ_M coordinates of the point *M* were found. These values were used to compute the $\hat{\rho}_j$ value.

The parameters of the composite domain (Fig. 2) were found by the formulas:

$$a_{1j} = c_1 r_w + \Delta_L; \qquad a_{2j} = r_w + \Delta_L; \qquad b_j = r_w + \Delta_B;$$

where $\Delta_B = 0{,}5(B_0 + B_j)$, c_1 is the coefficient which is equal to 3.

To define the procedures of $\hat{\delta}_j$ and $\hat{\rho}_j$ values computation, the describing the ellipse function, a derivative of this function, and the *MJ* line equation were considered:

$$\zeta = \frac{a}{b}(b^2 - \xi^2)^{1/2}; \qquad \zeta' = c_\delta = -\frac{a}{b}\xi(b^2 - \xi^2)^{-1/2}; \qquad \zeta = c_\delta \xi .$$

The principle of $\hat{\delta}_j$, $\hat{\rho}_j$ values' definition with the help of these expressions is the same as for the circular domain with a shifted center.

In the confined waters OS should adhere to a certain corridor that is safe to navigate. Collision avoidance in these regions must be accompanied by the opportunity to stop the deviation from the route within this corridor without close-quarters situation.

Conformity to the observance of good seamanship can be interpreted as the consistency of the measures applied to the actions taken by experienced navigators in similar situations in the past. To establish such a conformity in Collision Avoidance System (CAS), firstly, it is necessary to distinguish the types of encounter situations and permitted actions for their resolution by the COLREGs. These actions are: turn starboard, turn port, decreasing speed, increasing speed, turn starboard with speed reduction, turn starboard with speed increase, turn port with decreasing speed, turn port with increasing speed.

The type of encounter situation was determined in relation to TS_m without consideration other targets and navigation obstacles. We took into account the visibility conditions (1 - normal, 2 - restricted), the kind of OS and TS_m approach (the selected kinds are given in Table 1), and navigation statuses of vessels (Table 2) for 01-05 variants of vessels' approach in sight of each other. For other cases, the status of the ships did not affect the choice of actions. For 01-05 variants of ships' approach in normal visibility, situations were distinguished in which the statuses of the vessels are the same (EE), the code of status of the first vessel is greater than the code of status of the second one (HL), and the code of status of the first ship is less than the code of status of the second one (LH). The case in which OS and TS_m are sailing vessels has been considered separately. The type of encounter situation was represented by five symbols. The first one characterizes the visibility, the second and third signs indicate the kind of approach, the fourth with the fifth symbols denote OS and TS_m navigation statuses (or the result EE, HL, LH of their comparison) when statuses influence decision making. For situations in which the decision does not depend on the statuses of the ships, the fourth and fifth symbols are zeros.

Table 1. Kinds of OS-to-TS_m approaches

Code	Kind of approach
01	TS_m is head-on of OS, reciprocal or nearly reciprocal courses
02	TS_m is on the starboard side forward of the beam of OS, OS is not abaft the beam of TS_m, crossing courses
03	TS_m is on the port side forward of the beam of OS, OS is not abaft the beam of TS_m, crossing courses
04	TS_m is on the starboard side abeam of OS, crossing courses
05	TS_m is on the port side abeam of OS, crossing courses
06	OS is on the port side abaft the beam of TS_m, crossing courses
07	OS is on the starboard side abaft the beam of TS_m, crossing courses
08	OS is stern-on of TS_m, coinciding or nearly coinciding courses
09	TS_m is on the port side abaft the beam of OS, crossing courses
10	TS_m is on the starboard side abaft the beam of OS, crossing courses
11	TS_m is stern-on of OS, coinciding or nearly coinciding courses

Table 2. Navigation status of ships

Code	Status	Code	Status
1	not under command	4	engaged in fishing
2	restricted in their ability to manoeuvre	5	sailing
3	constrained by her draught	6	power-driven

In the interpretation of the COLREGs on different situations, the actions required and non-recommended, but permitted by these rules, are distinguished. The first actions are divided into basic ones, which should be applied first, if the circumstances of the case admit, and backup ones for cases when the basic type of actions does not lead to a solution of the problem. According to the degree of adequacy of the situation, the basic, reserve and non-recommended actions will be referred to the operations of the first, second and third rank, respectively. It should be noted that navigational obstacles and other targets in the sailing area complicate the encounter situation, and the only possible action to solve the problem can be the third rank actions. A preliminary version of the ranking of actions for different encounter situations is given in table. 3.

The speed increase to avoid collisions in these situations is not considered.

Table 3. The rank of the OS actions to avoid collision

Type of situation	OS	Stage	Rank 1	Rank 2	Rank 3
101EE, 101HL	GWV	1 or 2	$\theta>0$ and $W=0$	-	$\theta>0$ and $W<0$
102EE, 102HL,104EE, 104HL	GWV	1 or 2	$\theta>0$ and $W=0$	$\theta\geq0$ and $W<0$	$\theta<0$ and $W\leq0$
103HL, 105HL	GWV	1 or 2	$\theta<0$ and $W=0$	$\theta\leq0$ and $W<0$	$\theta>0$ and $W\leq0$
10600	GWV	1 or 2	$\theta>0$ and $W=0$	$\theta>0$ and $W<0$	$\theta<0$ and $W\leq0$
10700	GWV	1 or 2	$\theta<0$ and $W=0$	$\theta<0$ and $W<0$	$\theta>0$ and $W\leq0$
10800	GWV	1 or 2	$\lvert\theta\rvert>0$ and $W=0$	-	$\lvert\theta\rvert>0$ and $W<0$
101LH, 103EE, 103LH, 105EE, 105LH, 102LH, 104LH, 10900, 11000, 11100	SOV	1	$\theta=0$ and $W=0$	-	-
103EE, 103LH, 105EE, 105LH	SOV	2	$\theta>0$ and $W=0$	$\theta>0$ and $W<0$	$\theta\leq0$ and $W\leq0$
102LH, 104LH	SOV	2	$\theta<0$ and $W=0$	$\theta<0$ and $W<0$	$\theta\geq0$ and $W\leq0$
10900, 11100	SOV	2	$\theta<0$ and $W=0$	$\theta>0$ and $W=0$	-
11000	SOV	2	$\theta>0$ and $W=0$	$\theta<0$ and $W=0$	-
20100, 20200, 20300, 20500	-	1 or 2	$\theta>0$ and $W=0$	$\theta>0$ and $W<0$	$\theta\leq0$ and $W\leq0$
20400	-	1 or 2	$\theta<0$ and $W=0$	$\theta<0$ and $W<0$	$\theta\geq0$ and $W\leq0$
20600	-	1 or 2	$\theta>0$ and $W=0$	$\theta>0$ and $W<0$	$\theta\leq0$ and $W\leq0$
20700	-	1 or 2	$\theta<0$ and $W=0$	$\theta<0$ and $W<0$	$\theta\geq0$ and $W\leq0$
20800	-	1 or 2	$\lvert\theta\rvert>0$ and $W=0$	-	$\lvert\theta\rvert>0$ and $W<0$
20900, 21000, 21100	-	1	$\theta=0$ and $W=0$	-	-
20900	-	2	$\theta>0$ and $W=0$	-	$\theta<0$ and $W=0$
21000	-	2	$\theta<0$ and $W=0$	-	$\theta>0$ and $W=0$
21100	-	2	$\lvert\theta\rvert>0$ and $W=0$	-	$\lvert\theta\rvert>0$ and $W<0$

The type of strategy and the algorithm for its calculation

To pass the targets at safe distance, it was chosen a strategy formed from combined Z-maneuvers (CZM) and their particular cases. This maneuver [16] consists of two operations: the first one is course alteration together with speed at a certain point and the second one is return to the initial values of these parameters at another point. In particular cases Z-maneuver includes only course alteration or only speed changes. The CZM trajectory and parameters (the distance S_{OA} from the current position OS to the start of maneuver, the changes θ and W of course and speed, the length U of the deviation segment FB) are shown in Fig. 3. Dot G will be referred to as key waypoint. The first CZM operation must comply with the COLREGs. The second operation was considered acceptable (safe) when it did not result in a collision risk, and unacceptable (dangerous) otherwise.

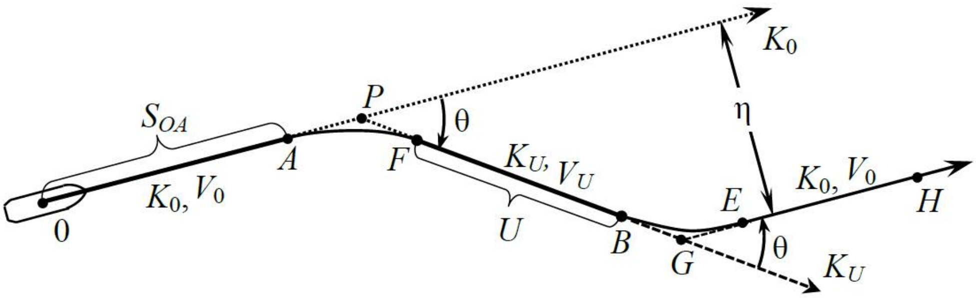

Figure 3. CZM structure:
P, G, Q are waypoints; A, B and F, E are start and end of operations points; K_0, V_0 and K_U, V_U are course, speed of OS before maneuver and on segment FB; η is cross track deviation.

Along with this strategy its stage-by-stage planning was applied. At the beginning the first CZM was determined. Then, while its fulfillment the second block consisted of two operations was found taking into account the revealed changes in the environment. After that, if necessary, the subsequent blocks were obtained in a similar way. When an efficient option of actions is determined at each stage, then the overall strategy will be effective.

Before choosing an adequate ships' passing strategy, the appropriate level of safety for the case should be determined. The threshold of safe DCPA values is usually used as this level index. For a concrete navigation area the captain defines this index and sets into the CAS memory. In the paper the parameter r_w of TDD is the index of achievable level of safety. If value of r_w is too high, then the set of corresponding to COLREGs maneuvers may be empty. Lessening of r_w is accompanied by an increase of the amount of such maneuvers. This technique can be used as an alternative to taking actions that should be avoided.

Effective CZM variant for collision avoidance was found taking into account the COLREGs, navigation restrictions, other vessels, and OS dynamics by using the enumeration method [16]. This method includes the selection of ranges of variation of CZM parameters (S_{OA}, θ, W, U), their discretization, review of all possible variants of maneuver and the choice of the optimal one. At each step of the enumeration, it is determined that the current option of the maneuver belongs to one of the selected sets of acceptable variants of the maneuver (Table 4). Among the current number of variants of this set, according to the selected criterion the best one has been found. Also, at each step of enumeration, the loss of sailing time due to deviation from the route and other characteristics are determined for the current variant of maneuver. After the end of the enumeration, according to the selected criterion the best maneuver variant on the set **Z1** is considered optimal for collision avoidance. In the cases (**Z1**=Ø), (**Z1**=Ø, **Z2**=Ø) and (**Z1**=Ø, **Z2**=Ø, **Z3**=Ø), the optimal variant for collision avoidance is, respectively, the best option on **Z2**, on **Z3** and on **Z4**. The criteria and limitations for determining the best option for different sets are not the same. For example, for **Z1** the objective function may be a minimum loss of sailing time, for **Z2** and **Z4** - a maximum value of index of the substantiality of the action with a minimum speed change, and for **Z3** - a minimum loss of sailing time with TDD_m increased. When solving the problem, the dynamics of the vessel was taken into account in a simplified manner, and it was assumed that the parameters of the movement of targets would be unchanged.

Table 4. The sets of CZM variants allowed by COLREGs

Set	CZM variants
Z1	CZM variants fully meet the requirements
Z2	CZM variants do not meet the requirement of substantiality only
Z3	CZM variants are non-recommended in the situation only
Z4	CZM variants do not meet the requirements of substantiality and are non-recommended in the situation only

When realizing the ships' passing on the deviation segment *FB* (see Fig. 3), it is necessary to control whether a collision threat has appeared, and whether at point *B* the return to K_0 and/or V_0 has become unacceptable. After the realization of CZM, three route return variants may be used (Fig. 4):
I) incoming at the active leg under the selected angle γ;
II) going to the active waypoint (WP);
III) following to the intersection of course line with the next leg of the route.

The second and third variants are, in fact, route corrections.

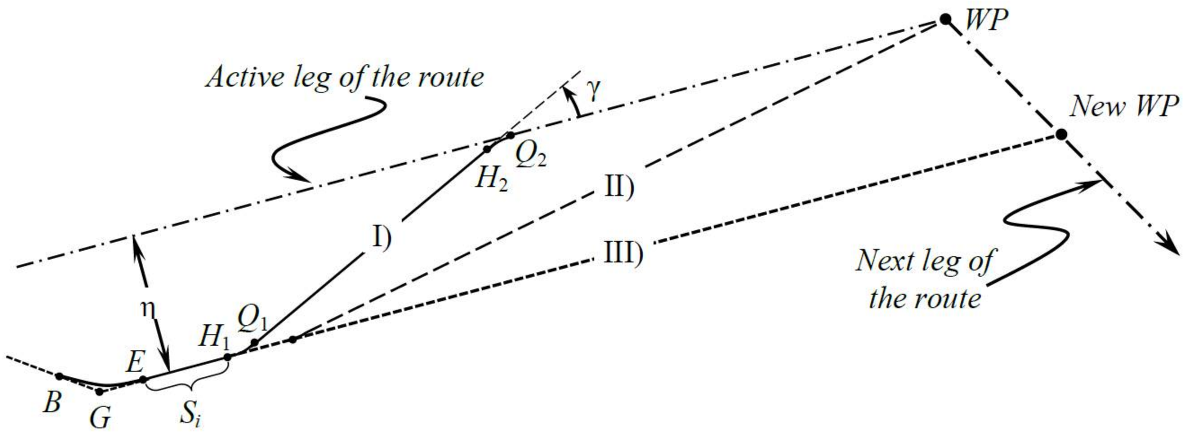

Figure 4. Variants for returning to the route

Flowchart of the algorithm for determining a set (**S**) of distances from the *E* point to the acceptable start of returning to the active route leg is shown in the Fig. 5. In this figure Δ_S is the step of changing of S_i values (1 cb was taken), n_S is the quantity of these values. If the turn on the angle γ with the start in corresponding S_i point in relation to all targets is safe, this variant index Ψ_{1i}=1, otherwise Ψ_{1i}=0. When turning to the active route leg at the point H_2 with the corresponding S_i start point H_1 and Ψ_{1i}=1 is safe with respect to all targets, then this option index Ψ_{2i}=1, otherwise Ψ_{2i}=0.

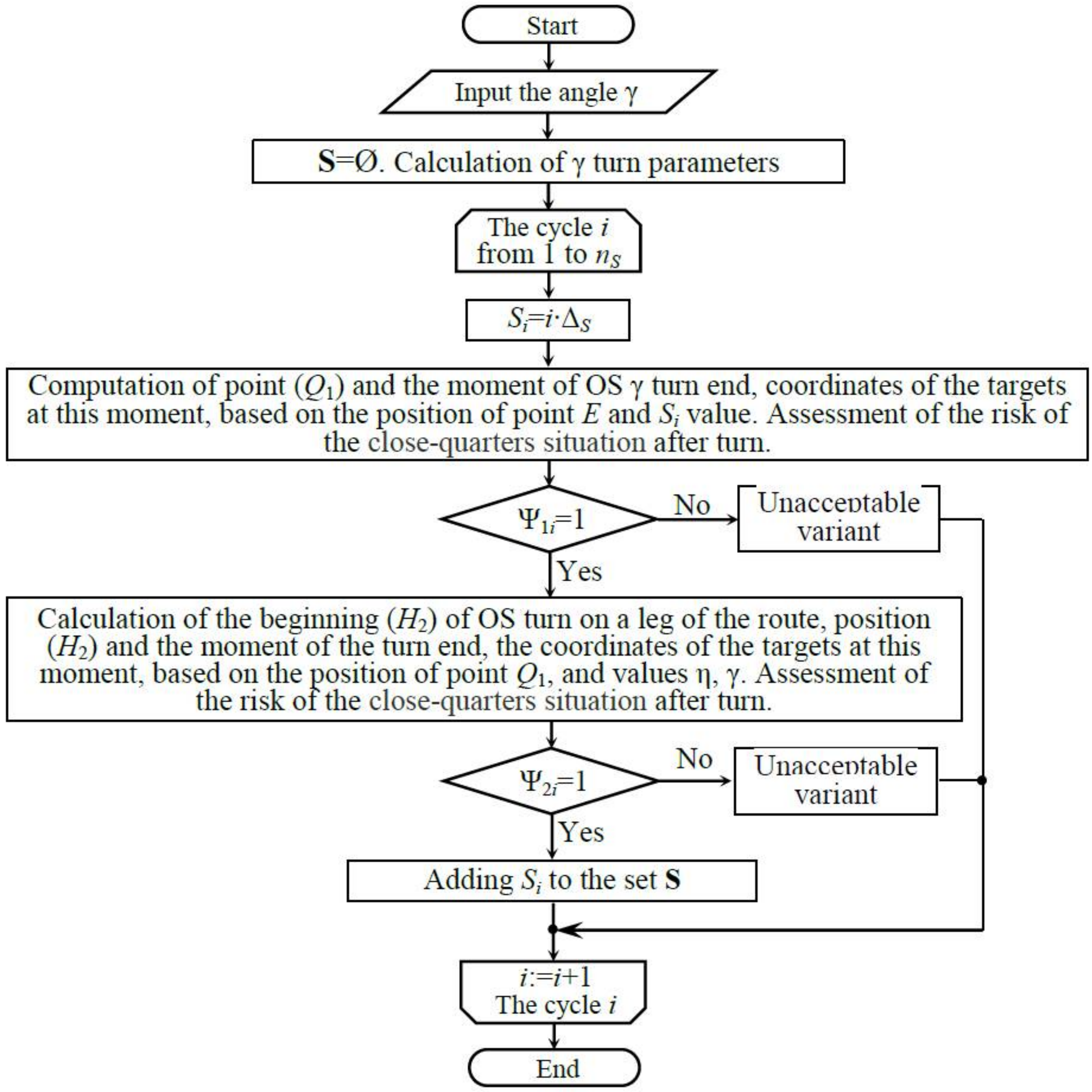

Figure 5. Flowchart of the algorithm for determining the set of distances to the acceptable start of returning to the active route leg

Diagram to select a strategy in the dialogue mode with the system

The application of the enumerating method of possible variants to avoid collision with the analysis of their effectiveness allows to use these results to construct images that facilitate the choice of a maneuver in a dialogue mode with the system. Let's present a combined diagram for choosing CZM with a given start based on the situation with six power-driven vessels in sight of one another. Parameters of these ships relative positions and rapprochement are given in Table 5. In this example: S_{0A}=1,1 NM; $\overleftarrow{\theta}$=-90° and $\overrightarrow{\theta}$=90°, $\overleftarrow{V}$=5 kn and $\overrightarrow{V}$=17 kn, $\overleftarrow{U}$=0 NM and $\overrightarrow{U}$=6 NM are the boundaries of the selected intervals of possible θ, V, U values; $\overleftarrow{\eta}$=-4,0 NM and $\overrightarrow{\eta}$=3,5 NM are scopes of acceptable cross track distances; $\hat{\theta}$=30°, $\widehat{W}$=4 kn and $\hat{\theta}$=40°, $\widehat{W}$=4 kn are the thresholds of substantiality of recommended and not recommended actions. Circular domains with a shifted center and r_w=0.4 NM were used for targets. The dangerous target in this situation is TS_1. To enumerate the possible variants of CZM with a given start, the following steps were used: 2° for θ; 1 knot for V; 0,1 NM for U. The speed increase to resolve the situation is not considered in the example.

Table 5. Parameters of the relative position and movement of ships

No. of ship	*L, m*	K^0	*V,* kn.	Π^0	*D,* NM
0	220	0	17,0	-	-
1	250	237	21,6	30	6,65
2	140	57	16,2	341	4,97
3	175	358	14,4	318	1,60
4	330	241	11,2	38	6,02
5	80	164	16,6	352	11,02

In the diagram, the colors highlight the areas of maneuvers which satisfy certain restrictions in compliance with the COLREGs. The colors for the distinguished areas are given in Table. 6.

Table 6. Colors for the areas highlighted in the diagram

Area	Color	Compliance of CZM variants with the requirements
Z11		The first operation fully complies with the COLREGs, the second one is safe
Z12		The first operation fully complies with the COLREGs, the second one is dangerous
Z21		The first operation is not substantial only, the second one is safe
Z22		The first operation is not substantial only, the second one is dangerous
Z31		The first operation is non-recommended only, the second one is safe
Z32		The first operation is non-recommended only, the second one is dangerous
Z41		The first operation is not substantial and non-recommended only, the second one is safe
Z42		The first operation is not substantial and non-recommended, the second one is dangerous
Z5		The first operation results in close-quarters situation

The lower part of the diagram (Fig. 6) represents the parameters of the allowable velocity vectors for collision avoidance with the start at a given point. When the first operation of all variants of CZM in a certain area satisfies the COLREGs and there is an acceptable second operation for these variants in the safe lane for OS, the color of this area will be light green. If there is no commencement of such operation, then the color of the area will be dark green. Similarly, light and dark colors are determined when the first operation (see Table 5) is not substantial by value, not recommended, not substantial and not recommended.

The upper part of the diagram is intended to select the position of key point of CZM with a given start and speed change. The speed change is set in the first column of the lower part of the diagram (in the example, $W = 0$). For a given turn angle, the key point is determined by the distance (*PG*) from the waypoint *P* (see Fig. 3). CZM with key WP in the light green area fully meet the requirements. If this point is in the dark green area, the second CZM operation will be dangerous. The maneuver can be selected with the cursor in areas of light color only. If a light green area exists, then in it. Otherwise, this choice is made in the yellow zone, in its absence - in the light purple zone, and lastly, in the light blue zone. In the example, it is defined in the light green zone. If necessary, in certain areas of the light zones, one or another characteristic of the maneuver variants can be given. In the diagram, values of the sailing time losses in minutes are shown in the light green area.

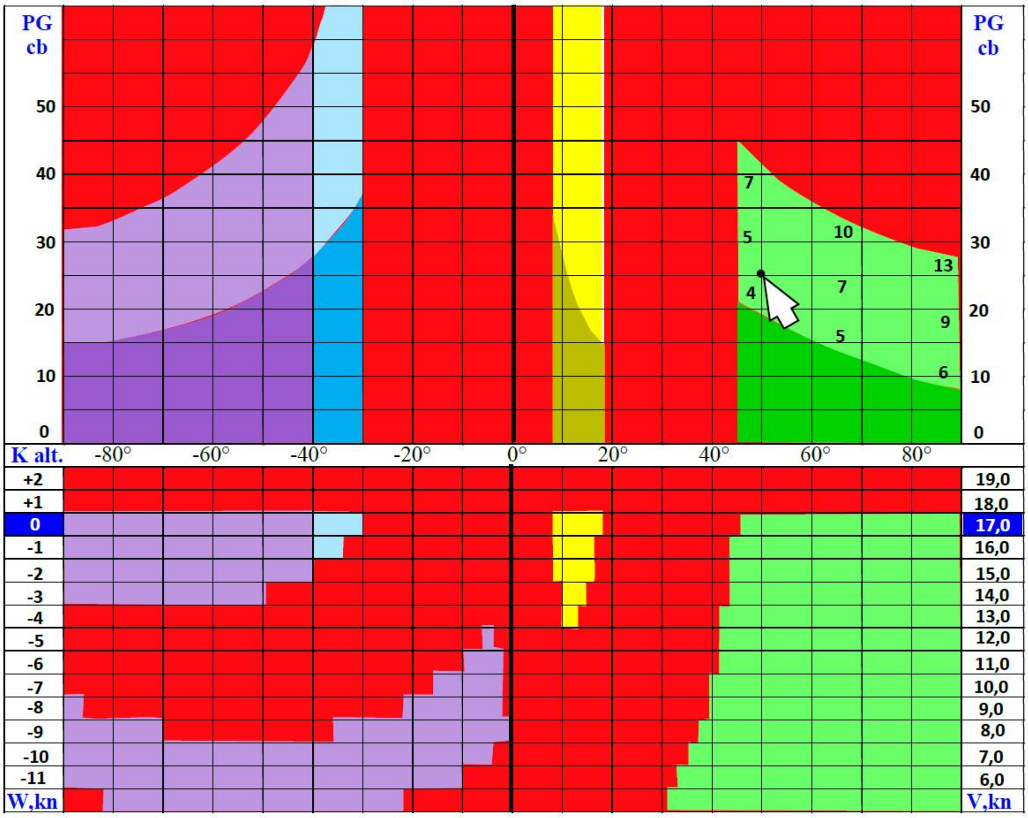

Figure 6. Diagram for choosing a key point of CZM with W=0

In the CAS, this diagram is recommended to be displayed on the periphery of the screen, and the trajectory of the maneuver selected on it - on the electronic navigational chart.

Discussion of the results of the collision avoidance planning with the help of a situational approach to determine the type of action

In order to achieve the goal, the following parameters have been determined: limitations and criteria for COLREGs compliant actions, the type of strategy and the algorithm for its calculation, diagram to select a strategy in the dialogue mode with the system. For solving the first task, an algorithm is proposed, which is based on a compiled table of encounter situations recommended by the COLREGs, and corresponding to these situations, required and not recommended types of actions. This algorithm implements the procedure for determining compliance with the COLREGs, which is usually used in the practice of manual navigation, including in cases where the most effective type of action is hampered by the circumstances and conditions of navigation. The proposed algorithm, in contrast to the procedures existing for such a purpose, makes it possible to recommend actions when the vessels are in sight of each other, but have different navigational status. This is the obvious advantage of the proposed algorithm. DCPA-acceptable strategy variants were found by means of hazard areas around the targets: a shifted circular domain and a composed of two semi-ellipses domain. The first domain, although it has a simple form, fully meets the requirements for resolving encounter situations in the open sea, coastal waters, and fairly wide passages. Its use not requires significant time increase of maneuvers search. The second domain corresponds to confined waters. Ships are considered here not as circular areas with a diameter equal to their length, but as rectangles, one side of which is equal to the length of the ship and the other - to her width.

When solving the second problem, a strategy formed from combined Z-maneuvers and their particular cases was chosen to prevent collision. The following circumstances determine the selection of this strategy. Firstly, in case of avoiding collision in confined waters, it is necessary to remain within the navigational safe lane. It is easy to establish that the least deviation from the route usually occurs when the OS, after avoiding the danger, returns to her initial course. Secondly, the forecast of the OS action has higher errors than the movements without altering course and speed for the same time ahead. If the number of actions in avoiding process increases, then the accuracy of its results prediction deteriorates. In addition, when the OS is moving, any of the ships being tracked may maneuver and new target may appear in the observation area. During the implementation of the avoiding plan the probability of these events increases with the time from the moment of plan adoption. The prediction of a two-step maneuver is still accurate.

To search for a combined maneuver, it is proposed to use the enumeration method, and it is shown that it is effective in solving this task on modern computers. The advantage of this method lies in the possibility of analyzing all possible maneuver options, obtaining their characteristics, which simplifies the use of various optimality criteria corresponding to the circumstances of the case. The characteristics of the maneuver options, in addition to changes in course and speed, include loss of sailing time, lateral deviation from the route, the minimum of the target passing distances, an increase in fuel consumption, etc. The disadvantage of enumerative method is the large number of operations to be performed, which is increasing due to the number of targets in the observation area. This can lead to unacceptable search of maneuver. Therefore, when solving problems, the number of targets was limited and no more than twenty were taken. It should be noted that the need to account for more than 20 targets is extremely rare. The efficiency of the enumeration method also depends on mathematical models for predicting maneuvers. To reflect accurately the movement of the vessel during maneuvers for the simplified model, the mode of their execution should be the same. Note that these models turn out to be quite simple when turns are performed with a given radius, and speed changes - with a given acceleration.

The proposed diagram has the following positive features: in situations with several vessels and navigational obstacles, it allows to choose the appropriate maneuver in compliance with the COLREGs; provides the area of all acceptable maneuver variants within the specified boundaries; upon request, for acceptable options allows to reflect in a numerical form certain characteristics that may be necessary for the officer of the watch when making a decision; does not obstruct the navigational controlled area ahead of own ship.

Simulation testing of collision avoidance processes has shown that the proposed procedures for resolving collision situations are effective.

Summary

The proposed algorithm for computer accounting of COLREGs maneuvering rules reflects the procedure of their accounting in the practice of non-automated navigation. As a result, adjusting the parameters of this algorithm to sailing circumstances and conditions will not cause difficulties for operators in the process of navigation.

The use of the selected avoiding strategy and the developed algorithms to determine its parameters makes it possible to find effective ways for resolving most collision situations, taking into consideration the COLREGs, own ship dynamics and navigation restrictions.

The proposed diagram provides significant help in choosing maneuvers in the dialogue mode with the system.

REFERENCES

1. Tam C., Bucknall R., Greig A., (2009). Review of collision avoidance and path planning methods for ships in close range encounters. The Journal of Navigation, 62 (3): 455-476.

2. Huang Y., Chen, L., Chen P., Negenborn R.R., van Gelder, P.H.A.J.M. (2020). Ship collision avoidance methods: State-of-the-art. Safety Science. 121: 451–473.

3. Fışkın R, Kisi, H, Nasibov E. (2018). A research on techniques, models and methods proposed for ship collisions avoidance path planning problem / The International Journal of Maritime Engineering. 160(A2): 187-206.

4. Naeem W, Henrique S. C., Hu L. (2016). A Reactive COLREGs-Compliant Navigation Strategy for Autonomous Maritime Navigation /10th IFAC Conference on Control Applications in Marine Systems: Trondheim, Norway: 207-213.
5. Hirayama K., Miyake K., Shiota T., Okimoto T. (2019). DSSA+: Distributed Collision Avoidance Algorithm in an Environment where Both Course and Speed Changes are Allowed /TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 13, No. 1: 117-123.
6. Kufoalor D. K. M., Johansen T. A., Brekke E. F., Hepsø A., Trnka K. (2020). Autonomous maritime collision avoidance: Field verification of autonomous surface vehicle behavior in challenging scenarios /Journal of Field Robotics. 37: 387–403.
7. Ramos M.A., Utne I.B., Mosleh A. (2019). Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events /Safety Science. 116: 33–44.
8. Szlapczynski R. & Szlapczynska J. (2017). Review of ship safety domains: Models and applications. Ocean Engineering 145: 277–289.
9. Xu Q., Wang N. (2014). A Survey on Ship Collision Risk Evaluation. / Promet – Traffic & Transportation, Vol. 26, No. 6: 475-486.
10. Wielgosz M. (2017). Ship Domain in Open Sea Areas and Restricted Waters: an Analysis of Influence of the Available Maneuvering Area. /TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 11, No. 1: 99-104.
11. Smolentsev S. V., Isakov D. V. (2019). A simple analytical model of ship movement. Vestnik Gosudarstvennogo universiteta morskogo i rechnogo flota imeni admirala S. O. Makarova 11.1: 7–21.
12. Salous M., Hahn A., Denker C. (2016). COLREGs-Coverage in Collision Avoidance Approaches: Review and Identification of Solutions /12th International Symposium on Integrated Ship's Information Systems & Marine Traffic Engineering Conference. Hamburg: 1-10.
13. Zaccone R., Martelli M., Figari M. (2019). A COLREG-Compliant Ship Collision Avoidance Algorithm. - 18th European Control Conference (ECC). Napoli, Italy: 2530-2535.
14. Chiang H-N. L., Tapia L. (2018). A RRT-based COLREGS-Compliant Motion Planner for Surface Vehicle Navigation / IEEE Robotics and Automation Letters. 3(3): 2024 – 2031.
15. Łebkowski A., Śmierzchalski R., Gierusz W., Dziedzicki K. (2008): Intelligent ship control system. Transnav, the international journal on marine navigation and safety of sea transportation, vol. 2, No. 1: 63-68.
16. Vagushchenko A. A. & Vagushchenko L. L. (2020). Numerical method for selection of maneuvers to avoid collisions with several vessels. Science and Education a New Dimension. Natural and Technical Sciences, VIII (27), Issue 224: 74-80.