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# OPTIMAL PLANNING OF THE ROUTE AND VESSELS DIVERGENCE TAKING INTO ACCOUNT THE INTERESTS OF ALL PARTICIPANTS IN THE OPERATION

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**Introduction.** The theoretical bases of route planning and divergence with ships are considered in the researches, taking into account the interests of all participants of the operation. Yes, there are $n$ target functionalities for the $n$ participants of the operation and the route must be laid in such a way that all target functionalities reach the extreme. The condition of route planning and divergence taking into account the interests of all participants in the operation was found, according to which the optimal solution should not impair any of the solutions for other vessels, i.e components of the target vector - functional are independent and their states should not affect each other. This solution is known as the Pareto test or as an effective Jeffrion solution. It is shown that the problem of route planning is convenient to solve in the field of risks, and as an integrator of the target vector - functional to take the risk vector of own vessel and targets. In this case, the resulting condition of route planning and divergence means that when planning a route and divergence, the distance between vessels should not exceed the specified risk of collision, i. e the ellipse of specified risk of one vessel should not cross the ellipse of specified risk of another vessel. This formulation of the problem is advantageous in terms of forecasting the actions of their own vessel and goals, as in this case the optimum is reached by each of the participants in the operation and, assuming the convexity of integrants, we practically assume the reasonableness of the operator.

**Relevance of research**. Existing methods of route planning and divergence [1-26] are based on the hypothesis of "absolute safety", however, collisions occur and "absolutely safe" trajectory is not always safe. This is primarily due to the negative impact of the human factor on management processes. Therefore, the development of methods, algorithmic and software of automatic control modules in automated systems that will reduce the impact of the human factor in solving problems of route planning and divergence, is an urgent scientific and technical problem.

**Problem statement**. The task of optimal plotting of the course first of all requires the determination of the criterion of optimality or the function of the goal. It becomes necessary to plot the trajectory of the vessel $S(x)$ in such a way as to avoid possible collisions, loss of cargo and other complications. This need is formulated as minimization of the risk $C$ on the trajectory of the vessel. Obstacles to navigation are expressed by constraints such as the equalities $\varphi_i(\mathbf{x}) = 0,\ i = \overline{1..m}$ and inequalities $\varphi_i(\mathbf{x}) < 0,\ i = \overline{m..n}$, that is, we obtain the Lagrange task.

$$\begin{gathered} \mathbf{x}^* \to \min C(S(\mathbf{x})), \\ \varphi_i(\mathbf{x}) = 0,\ i = \overline{1..m}, \\ \varphi_i(\mathbf{x}) < 0,\ i = \overline{m..n}. \end{gathered} \tag{1}$$

**Material and method.** The well-known technique for solving this problem involves the formation of the Lagrange function $L(x,\lambda)$, the gradient of which on $x^*$ vanishes

$$L(x,\lambda) = \lambda_0 S(x) - \lambda_1 \varphi_1(x) - \lambda_2 \varphi_2(x), \quad gradL = 0, \to \begin{gathered} \frac{\partial L}{dx} = 0, \\ \frac{\partial L}{\partial \lambda_1} = 0, \\ \lambda_2 \varphi_2(x) = 0. \end{gathered} \tag{2}$$

Condition (2), known as the Kuhnna-Tucker theorem, defines the optimum point as a point stationary in the coordinate when constraints such as equality are satisfied and the goal function is insensitive to constraints such as inequality. In this simple but important problem, let us trace the meaning of the Lagrange multipliers $\lambda$

$$gradL(x,\boldsymbol{\lambda}) = 0 \to \frac{\partial S}{\partial x} = \lambda \frac{\partial \varphi}{\partial x} \quad \to \quad \lambda = \frac{\partial S}{\partial \varphi}. \tag{3}$$

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Thus, expression (3) illustrates an important fact - the Lagrange multiplier is the sensitivity of the goal function to constraints. Condition (3) plays an important role in the problem of constructing an optimal route. The considered divergence problem differs from the standard one in that it seeks the optimal solution to the divergence problem for all ships. Thus, for n participants in the operation, there are n goal functions and a route laid in such a way that all goal functions reach their optimum

$$\left.\begin{matrix} x^* \rightarrow \min \; S_1(x) \\ x^* \rightarrow \min \; S_2(x) \\ \vdots \\ x^* \rightarrow \min \; S_n(x) \end{matrix}\right\} \quad \rightarrow \quad \mathrm{s}(x) = \begin{bmatrix} S_1(x) \\ S_2(x) \\ \vdots \\ S_n(x) \end{bmatrix}. \tag{4}$$

For the simplest optimization problem, the vector of function s is set to the problem $x^* \to \min(s)$, then

$$\left.\begin{array}{l} x^* \to \min\ S_1(x) \\ x^* \to \min\ S_2(x) \\ \quad\vdots \\ x^* \to \min\ S_n(x) \end{array}\right\} \quad \to \quad \left.\begin{array}{l} \dfrac{dS_1(x)}{dx} = 0 \\ \dfrac{dS_2(x)}{dx} = 0 \\ \quad\vdots \\ \dfrac{dS_n(x)}{dx} = 0 \end{array}\right\}. \tag{5}$$

Condition (5) is satisfied only if the extremum point for all components of the goal function vector coincides; therefore, in the ε neighborhood of the point $x^*$, the components of the goal function vector are indistinguishable and the problem is degenerate. As a consequence, there are restrictions on the values of the components of the target vector at the extremum point

$$\begin{array}{l} \left.\begin{array}{l} x^* \to \min\ S_1(x) \\ x^* \to \min\ S_2(x) \\ \quad\vdots \\ x^* \to \min\ S_n(x) \end{array}\right\}; \\ \left.\begin{array}{l} S_1(x) - a_1 = 0 \\ S_2(x) - a_2 = 0 \\ \quad\vdots \\ S_n(x) - a_n = 0 \end{array}\right\}. \end{array} \tag{6}$$

Then we obtain the optimality condition (3) in the form

$$\frac{d\mathbf{s}}{dx} = \begin{pmatrix} \lambda_{11} & \cdots & \lambda_{1n} \\ . & . & . \\ \lambda_{n1} & \cdots & \lambda_{nn} \end{pmatrix} \frac{d(\mathbf{s}-\mathbf{a})}{dx}. \tag{7}$$

Solution of the problem - the matrix of Lagrange multipliers must be unit. Indeed, equation (7) has a solution only for the unit matrix $\Lambda$

$$\mathbf{a} = const \rightarrow \frac{d(\mathbf{s}-\mathbf{a})}{dx} = \frac{d\mathbf{s}}{dx} \rightarrow \frac{d\mathbf{s}}{dx} = \begin{pmatrix} 1 & \cdots & 0 \\ . & . & . \\ 0 & \cdots & 1 \end{pmatrix} \frac{d\mathbf{s}}{dx}. \tag{8}$$

Taking into account the meaning of Lagrange multipliers (3), we can write down the optimality condition in problem (4)

$$\begin{gathered} \frac{\partial S_i}{\partial S_j} = 0; \qquad i = \overline{1,n}; \quad j = \overline{1,n}; \quad i \neq j; \\ i \neq j \rightarrow \frac{\partial S_i}{\partial S_i} = 1. \end{gathered} \tag{9}$$

From condition (9) it follows that the optimal solution should not worsen any of the solutions, that is, the components of the goal vector are independent and their states do not affect each other. This result is known as the Pareto criterion or as the effective Jeffrion solution.

Algorithm modeling: Modeling was carried out in MATLAB environment and on the Navi Trainer 5000 navigation simulator. Knowing the conditions for the optimal solution of the discrepancy problem, we can consider the algorithm for plotting a course for the automatic control system (ACS). Since the ACS system is a link of the artificial intelligence of an autonomous vessel and eliminates the risks of the "human" factor, the machine moves the vessel into the risk field. Figure 1. shows a diagram of the construction of the risk field.

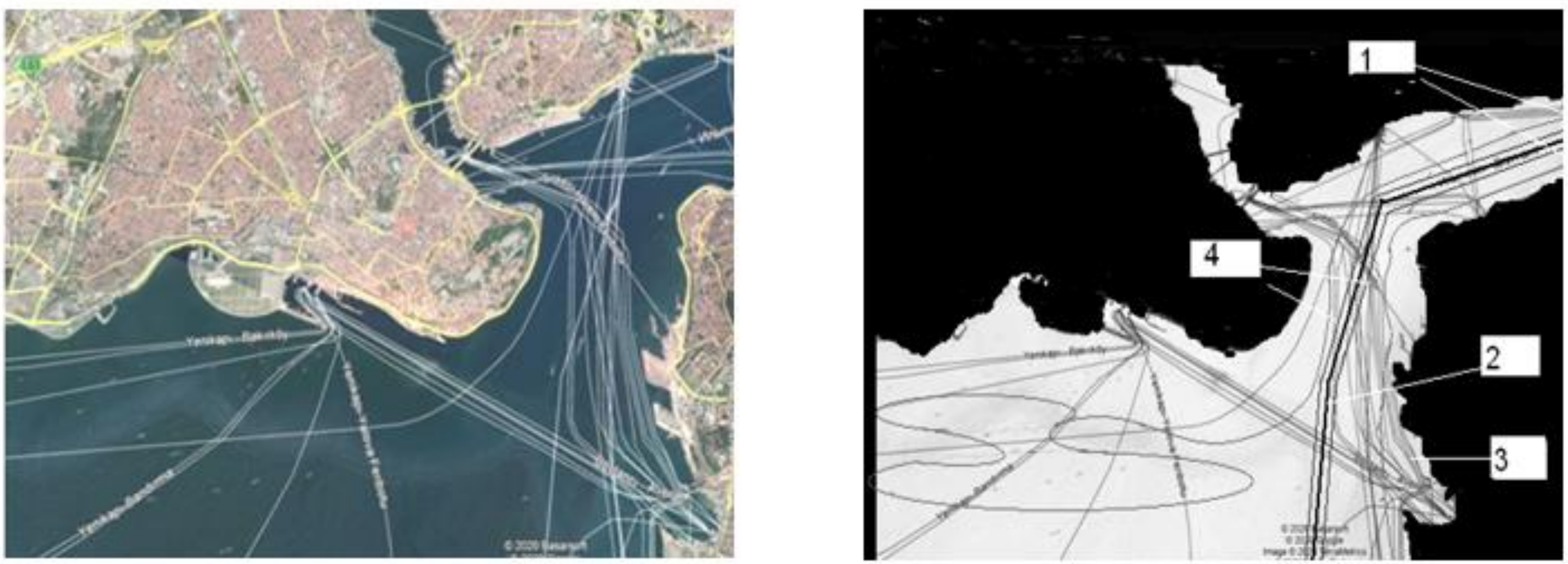



Figure 1 - Scheme for constructing the risk field.

Critical risk (position 1) defines the unacceptable positions, and the acceptable risk (position 2), defines the areas with acceptable but undesirable positions and the field of specified risks (position 3) defines the area of the trace, position 4. The route itself is carried out for reasons of minimum costs when passing the route. In reality, there are standard solutions (algorithms) for laying a route for a route. However, the automatic system must have a criterion that determines the freedom of decision, otherwise the discrepancy problem requires the participation of a person who evaluates the risk of the decision made. Thus, the risk field ensures the “reasonableness” of the ACS action. The route has been set, the schedules have been agreed upon, but a risk field is needed to make a decision. The task of building a risk field at the modern level of Internet technologies is not difficult. A collection of electronic navigation charts (ENC) as well as hydro meteorological information of navigation areas is loaded into the network, you just need to highlight the risk level lines. Here is the question about the companies that sell electronic cards (TRANSAS, C-MAP, NOAA).

The second step in solving the route optimization problem is taking into account the environment at the current time. This is done by analyzing the schedules of the movement of ships, radar and optical fields, determining the coordinates of oncoming ships and their maneuvers. This operation can also be obtained by exchanging information with other vessels containing, in addition to standard data, the maximum risk and variance along the axes of risk distribution. To this information, you can add the ship's coordinates, speed, heading and maneuver. This simple message facilitates the task of diverging ships. While this is not the case, we will consider the radar assessment of the situation to be consistent.

Now you can perform the next step - forecasting the development of the operation. At this stage, the trajectory of own ship is adjusted, taking into account the possible risks of entry into the risk area of other ships, Fig. 2.

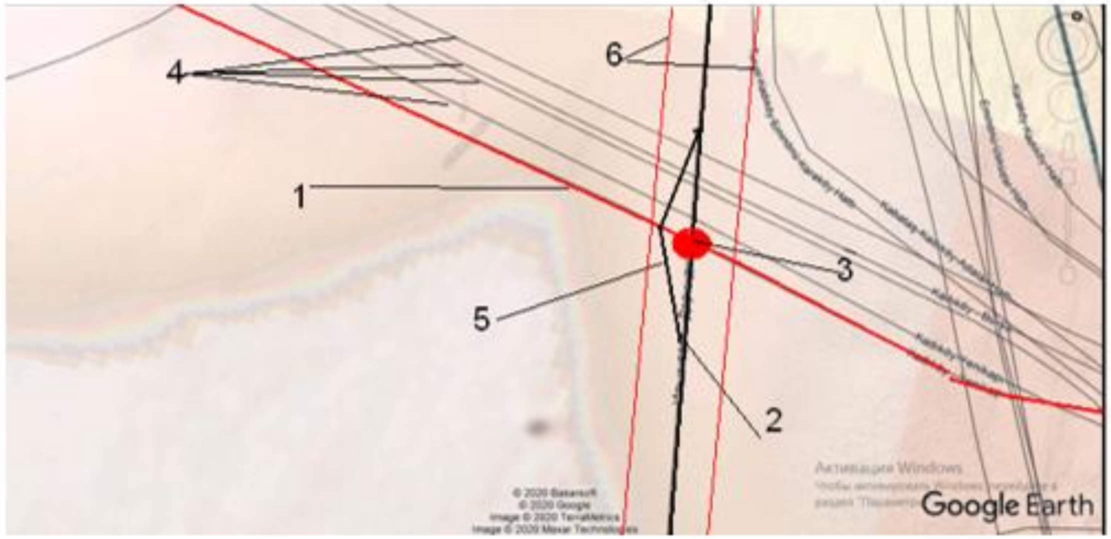



Figure 2 - Correction of your own course based on the results of the forecast of the development of the situation

For the selected trajectory 2, from the intersecting trajectories of other vessels 4, critical trajectories 1 are determined. When a critical trajectory is detected, a divergence maneuver 5 can be planned within the field of permissible risks 6. At the same time, the intersections of the trajectories are not critical if at the moment of crossing the distance between the vessels does not violate the zones of the given risk. The course correction is influenced only by critical trajectories, this is the standard plotting of the course with a restriction on exiting the risk corridor 6.

This operation of the course correction is current, which guarantees control over the situation. However, in spite of the optimality of the performed corrections, situations are possible when it is necessary to quickly carry out the operations of diverging vessels. In this case, either the problem of sliding along the line of equal risk of the target vessel is solved, or, in the case of movement between the vessels, a discrepancy in the minimum of the risk gradient is performed. In both cases, the course is plotted taking into account the preservation of the area of the given risk. Situations are possible when the risk increases. For example, when mooring or bunkering a vessel on the move, the risk increases, which is inevitable in the essence of the operation, and here the speed regime changes, in contrast to the divergence in the open sea, where a change in the vessel's speed is undesirable.

Figure 3 shows the optimal control algorithm in the general navigation problem. This algorithm consists of:

- block 1 for setting goals, in which the points and times of the beginning and end of the movement are determined;
- block 2 of the formation of the risk field, which uses the risk base and data from satellite navigation and electronic cartography;
- block 3 plotting the course according to the criterion of minimum costs. This operation does not require operator participation, as there are clear criteria and limitations;
- block 4 search for critical trajectories;
- block 5 of elimination of critical trajectories;
- block 6 for comparison of risks. If risks are found that are higher than acceptable, go to block 7;
- block 7 of correction of trajectories and graphs of their movement. If the risks are less than permissible, go to block 8 for the analysis of the situation and then to block 9 for checking the criticality;
- block 8 of the analysis of the situation, which uses the information of the radar and other radio navigation equipment;
- block 9 for checking the criticality based on the data of block 8 and visual data;
- block 10 for comparison of risks. If the risk does not exceed the permissible, go to block 13 for performing the maneuver. Otherwise, go to block 11 for analyzing the situation. If the number of vessels with a critical trajectory is one, then go to block 12 to diverge by sliding along the lines of a given risk. If the number of vessels is more than one, then go to block 14 of the gradient divergence. The second part of the algorithm (blocks 8-15) is executed continuously until the end point of the route. The principal difference of the considered algorithm is its optimality in terms of the risk criterion and compatibility with use for autonomous ships.

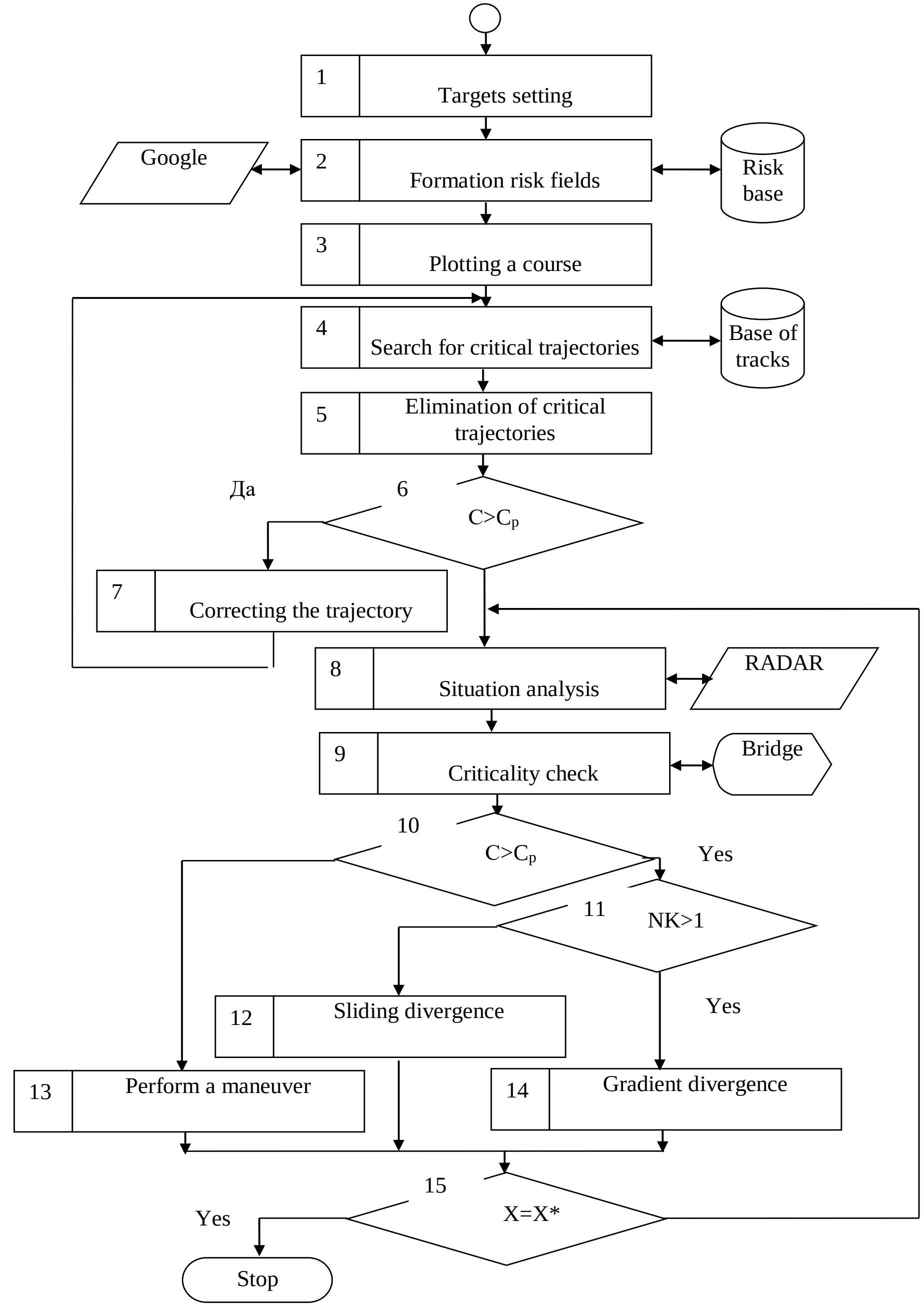
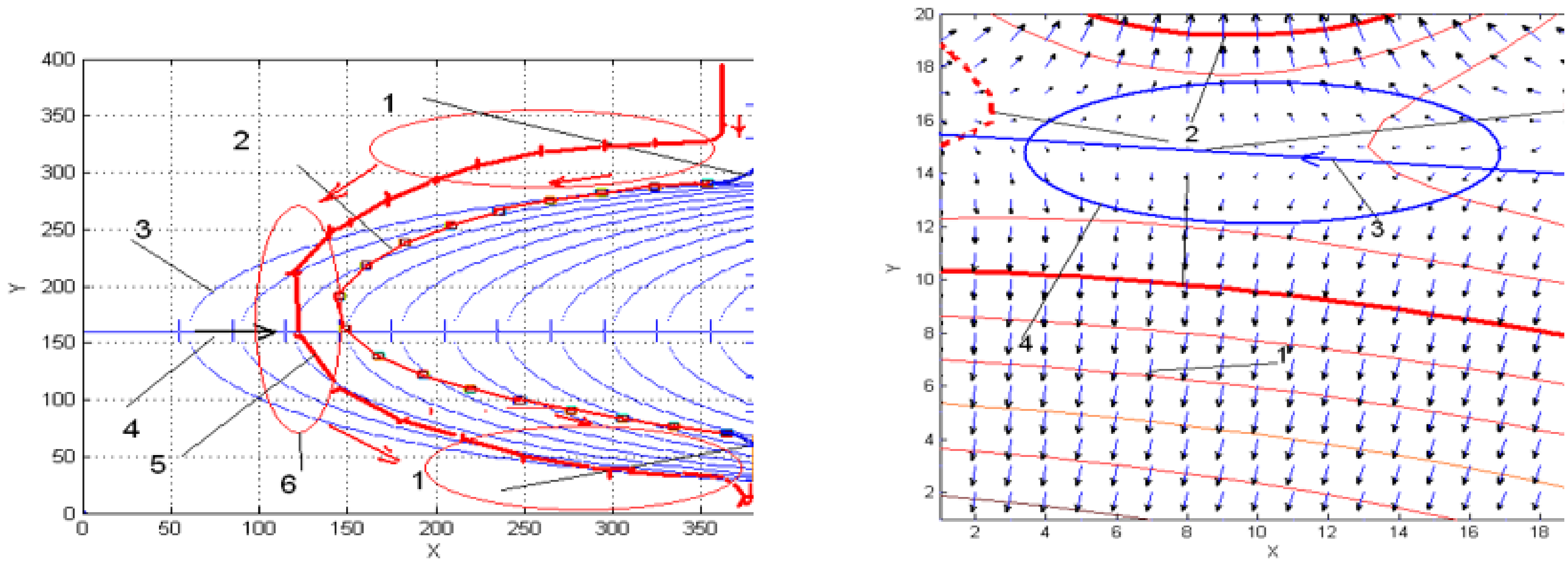



Figure 3 - Algorithm of optimal control in the general problem of navigation

In fig. 4 shows the results of mathematical modeling of the processes of divergence of ships. In fig. 5a shows the divergence trajectory 5 with one vessel, built for the case of no intersection of the zones of the given risk 3, 6. In this case, the sliding trajectory 2 is repeated with an offset to the minor axis of the self-risk ellipse.




a) b)

Figure 4 - Results of mathematical modeling of ship divergence processes.

In fig. 4b shows the results of mathematical modeling of divergence processes with several vessels. In this situation, the intersection of the lines of the given risks 2 and 4 is possible. To ensure the optimal divergence, in this case, the movement is organized along the minimum of the gradient.

**Conclusions:**

• the problem of optimal route planning and divergence of vessels in the field of risks is considered, taking into account the interests of all participants in the operation;

• obtained conditions that take into account the interests of all participants in the operation, which can be used as a constraint in the task of planning the optimal route and differences;

• developed a method, algorithmic and software for planning the optimal route and optimal divergence with ships in the field of risk;

• efficiency and effectiveness of the developed method, algorithmic and software are checked by mathematical modeling in the MATLAB environment and on the navigation simulator NAVI TRAINER 5000;

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