OPTIMIZATION OF DIVERGENCE IN THE FIELD OF RISKS

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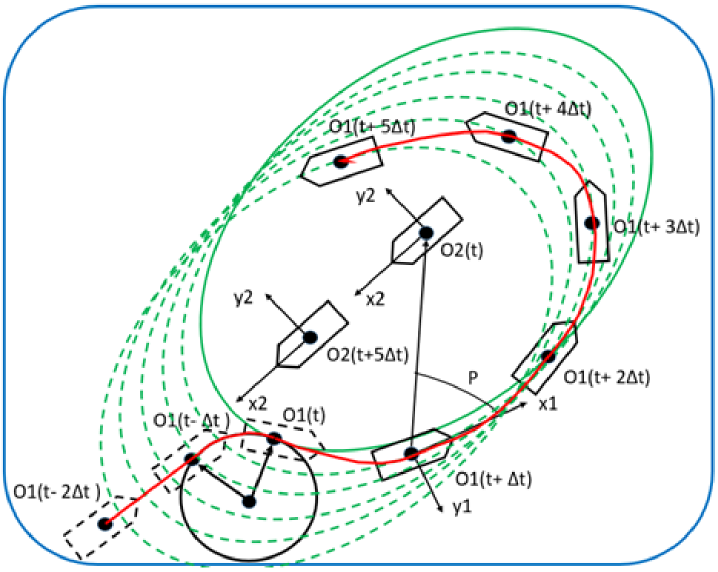
Introduction. The research of the problem of effective methods of preventing ship collisions has become of primary importance in connection with the increase in tonnage, overall dimensions, speed and number of ships involved in sea transportation of goods. An important factor is the emergence of automated systems with automatic control modules, as well as experimental autonomous vessels and systems whose actions have a clear algorithm and a specific goal. The use of such control systems makes it possible to reduce uncertainty in the interaction of vessels, as the influence of the human factor on control processes is minimized. Many works are dedicated to the automation of separation processes using modern on-board computers. As a rule, these methods are related to the construction of optimal divergence algorithms that ensure the optimization of a given control quality function. The existing methods of safe divergence are based on absolute safety criteria [1-2]. However, ship collisions do occur, and an "absolutely" safe trajectory contains the probability of collision. Taking this into account, it is more rational to build divergence trajectories that ensure a given collision probability. The main advantage of this approach is taking into account the distribution of risks near the targets and the possibility of optimizing the divergence processes for a given risk. This section deals with the issue of optimal separation of ships in the field of risks, namely optimal course separation in the "nearby zone", where there is an immediate threat of collision and where, with the correct routing, the ship should not go. Maneuvering the course is justified, since the change in speed takes longer and is not always possible (a transition to maneuvering mode is required). The developed methods and the algorithmic and software based on them allow minimizing the trajectory of divergence, provided that the given risk of collision is not exceeded [3-6].

The relevance of research. The main tool that is used on modern ships to perform separation operations is the ZARP. ZARP greatly facilitates the work of the shipmaster, as it frees him from many manual operations, and the built-in function "Playing the maneuver" allows you to use a convenient graphical interface. At the same time, ARPA remains an automated system and all decisions on ship management are made by the shipmaster, which takes time and does not exclude errors. The ARPA function "Playing the maneuver", as with manual radar laying, does not allow you to diverge from maneuvering targets, since the task is solved once, before the divergence maneuver begins. Therefore, the development and use of optimal automatic divergence modules in automated systems is an urgent scientific and technical task [7-10].

Problem formulation. To select divergence trajectories $S(\mathbf{x})$, risk functions $C(\mathbf{x})$, find the minimum divergence trajectory $L(\mathbf{x})$, at which the specified risk would not be exceeded C^*

$$\begin{cases} \varphi(\mathbf{x}) = \begin{bmatrix} S(\mathbf{x}) \\ C(\mathbf{x}) \end{bmatrix} \\ L(\mathbf{x}) = \min \int_L \varphi(\mathbf{x}) d\mathbf{x} \\ C(\mathbf{x}) \le C^* \end{cases} \quad (1)$$

Research results. The task (1) is a vector task of optimal control of a distributed system. For all its theoretical complexity, it has a simple solution - you need to move along the line of equal risk of the target, then the distance traveled during the maneuver will be minimal at a given risk, and the risk will not exceed the given one. Indeed, when one's own ship moves in the direction of the center of the target's given risk ellipse, the risk of collision increases, and when moving in the opposite direction, away from the center of the ellipse, the risk decreases but the maneuver path increases, since the length of the element of the ellipse arc increases when moving away from the center. Therefore, it is the "sliding" along the trajectory of the given target risk that determines the optimal safe spread. The algorithm of "sliding" along the line of equal risk is simple and unambiguous, and the solution of such optimization problems can be carried out in the on-board controller of the automated ship motion control system. The main advantage of solving the problem of optimal divergence in the field of risks is the consideration of previously undetermined factors when planning divergence, which allows to significantly increase the reliability of divergence operations and significantly reduce the number of collisions. In fig. 1 shows the actual ship O_1, in the moments of time $O_1(t-2\Delta t)$, $O_1(t-\Delta t)$, $O_1(t)$, $O_1(t+\Delta t)$, $O_1(t+2\Delta t)$,.., $O_1(t+5\Delta t)$, the coordinate system associated with the vessel $O_1X_1Y_1$, the target (vessel) at the initial moment of departure $O_2(t)$ and the final moment of divergence $O_2(t+5\Delta t)$, coordinate system associated with the target vessel $O_2X_2Y_2$ and equal-risk ellipses of the target vessel at time points



$O_2(t), O_2(t+\Delta t), O_2(t+2\Delta t),.., O_2(t+5\Delta t)$.

Figure 1 - Optimal divergence in the field of risks

Own ship O_1 and the target (vessel) O_2 moving in opposite directions and there is a danger of collision. To avoid a collision, the own ship, starting from the position $O_1(t-\Delta t)$, moves along the circulation curve to the position $O_1(t)$ on the ellipse of the given risk of the target vessel $O_2(t)$ and continues to move along the given target risk ellipse, which moves with the target. To organize the movement along the ellipse of the given risk, it is necessary to constantly determine the lateral and angular deviation from the ellipse of the given risk and take it into account in the law of steering the vessel. Angular deviation ΔK is defined as the angle of deviation of the longitudinal axis O_1X_1 the own ship from $\overset{\circ}{\mathbf{grad}}\,C(\mathbf{x})$, which sets the direction of movement along the equal risk ellipse of the target in the current position $\mathbf{x}$. To determine this direction, let's write down the equation of the ellipse of the given target risk in the coordinate system of the own ship $O_1X_1Y_1$

$$\begin{cases} \dfrac{(x-x_0)^2}{(\sigma_x R)^2} - \dfrac{r_{xy}(x-x_0)(y-y_0)}{(\sigma_x\sigma_y R)^2} + \dfrac{(y-y_0)^2}{(\sigma_y R)^2} = 1 \\ R^2 = \dfrac{-4(1-r_{xy})\pi\sigma_x\sigma_y C^*}{C_m} \end{cases} \quad (2)$$

We find the components from system (2) $\mathbf{grad}C(\mathbf{x})$.

$$grad_x C(\mathbf{x}) = \frac{2(x-x_0)}{(\sigma_x R)^2} - \frac{r_{xy}}{(\sigma_x\sigma_y R)^2}, grad_y C(\mathbf{x}) = \frac{2(y-y_0)}{(\sigma_y R)^2} - \frac{r_{xy}}{(\sigma_x\sigma_y R)^2} \quad (3)$$

Then, the components of the gradient $\overset{\circ}{\mathbf{grad}}\,C(\mathbf{x})$ are found by rotating the vector $\mathbf{grad}C(\mathbf{x})$ на $\frac{\pi}{2}$ з using the operator $\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$.

$$\overset{\circ}{\mathbf{grad}}\,C(\mathbf{x}) = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \mathbf{grad}C(\mathbf{x}), \Delta K = arctg\left(\frac{\overset{\circ}{grad}_y\, C(\mathbf{x})}{\overset{\circ}{grad}_x\, C(\mathbf{x})} \right) \quad (4)$$

Experiments. The workability and effectiveness of the developed method of optimal divergence along the ellipse of the given risk of the target, algorithmic and software security was tested in a closed loop with mathematical models of ships on a simulation bench created by the authors on the basis of the Navi Trainer 5000 navigation simulator [11-12].

In fig. 2 shows the simulation results, where position 1 is the trajectory of the own vessel entering the target risk ellipse and the exit trajectory from the target risk ellipse, position 2 is the "sliding" trajectory, position 3 is the successive positions of the target risk ellipse at fixed time intervals, which are determined by the operating cycle of the on-board computer, position 4 – the target's speed vector, position 5 – the trajectory of the optimal divergence, constructed as a sequence of positions of the center of rotation of the own ship on the ellipse of the given risk of the target at different moments of time, position 6 – the ship domain of the own ship.

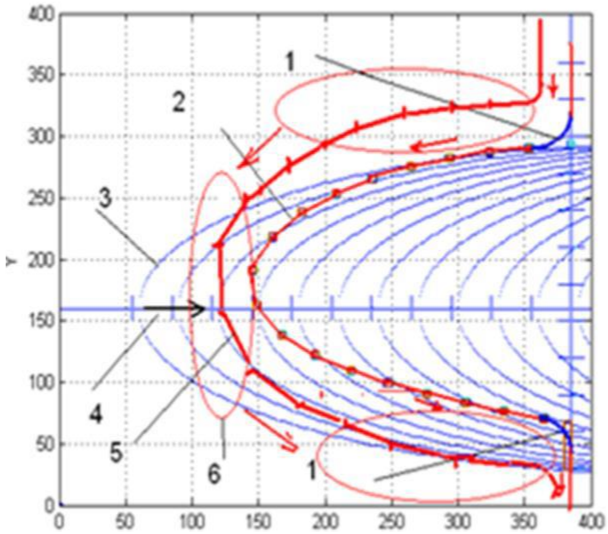


Figure 2. Simulation results

Conclusions. The task of optimal separation of vessels in the field of risks, taking into account the interests of all participants in the operation, is considered. It is shown that taking into account the interests of all participants in the operation is reduced to the organization of such movement of the vessel and goals, in which their ellipses of given risks do not intersect. The method of optimal divergence in the field of risks has been developed, which, in comparison with the existing ones, takes into account the given risk of collision, which allows to scientifically substantiate the size of the zone of safe divergence, taking into account the root mean square values of the most significant uncertainties. The workability and efficiency of the developed methods, algorithmic and software are tested on the simulation bench.

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