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Research of divergence trajectory with a given risk of ships collisions

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***Abstract* — There were considered the issues of the optimal collision avoidance in the target's risk field. A method of optimal divergence by course maneuvering is proposed, which makes it possible to minimize the divergence trajectory for a given risk of collision and consists in organizing the movement of the vessel along the trajectory of a given risk. The risk field of the target is a normal distribution law characterized by the root-mean-square parameters of the uncertainties associated with measurement errors of the parameters of the vessel's state vector and target, errors of actuators, errors of the used mathematical models, errors of calculation, etc. The operability and efficiency of the proposed method, algorithmic and software were tested on the Imitation Modeling Stand, which is the Navi Trainer 5000 navigation simulator and a model of on-board controller included in its local network with the software of the risk divergence module. The Imitation Modeling Stand allows to work out the software of control systems, including the considered optimal divergence module, in a closed circuit with the Navi Trainer 5000 navigation simulator, using all its advantages**

***Keywords* — collision avoidance; control systems; automatic control; navigation simulator.**

I. Introduction

Over the past 10–20 years, the intensity of navigation and the speed of vessels have significantly increased, and with them the flow of information has also increased. It becomes more and more difficult for navigators to find the right management decisions, especially in critical situations, which is the reason for the increasing number of accidents and disasters in maritime transport. According to the United Kingdom

Protection and Indemnity Club human error is responsible for 89–96% of vessel collisions, 84–88% of tanker accidents, 79% of vessel towing yards, and costs the maritime industry approximately $ 541 million a year. A detailed analysis of the causes of vessel accidents at sea due to the human factor is given in [1]. Studies of the human factor influence on vessel control are considered in the works of many authors, in particular [1–5]. Organizational measures taken to strengthen the training and retraining of boat masters, amendments to the International Convention on Standards for the Training, Certification and Watch keeping of Seafarers [1], other measures did not lead to a significant reduction in accidents. Experts note that the only way to achieve the desired result is the development and implementation of automated control systems.

In works [6–8], the issues of using ergatic systems to control the influence of the human factor on control processes are considered. Ergatic systems allow to detect deviations in the behavior of the navigators in the early stages of manifestation, to prevent their development and thus reduce the influence of the human factor on the processes of traffic control.

The modeling of information potential management of complex systems in the conditions of risk and forecasting of multidimensional no stationary data flows in the conditions of uncertainty is devoted to works [9–11].

Automatic control systems can radically reduce the impact of the human factor on control processes, as the operator only decides on the use of a module, and further vessel control is fully automatic. Automatic control systems allows to optimize control processes, significantly improve the reliability and efficiency of control. An example of an automatic control module, which has long and reliably served as navigators, is autopilot, which allows to maintain a given course and trajectory in fully automatic mode. Other software modules of automatic control (dynamic positioning, automatic avoid collision, optimal control, etc.) are also known [12, 13]. Of these works, the most interesting for the article are the works [14, 15], devoted to solving the problems of vessel diverging.

As follows from the above review, the proposed methods require large computational costs. Therefore, the development of more effective control methods remains an urgent scientific and technical task.

In this paper, the authors considered the divergence method using risk fields. Despite the fact that the problem is optimization, it does not require significant computational costs, since it is reduced to the problem of sliding along a trajectory with a given risk.

II. RESEARCH RESULTS

To solve the problem of divergence in the field of risks caused by the presence of other vessels, define the function of risks $C(\mathbf{x})$ in the form [16]

$$C(\mathbf{x}) = C_m f(\mathbf{x}) = \frac{C_m}{2\pi\sigma_x\sigma_y\sqrt{1-r_{xy}^2}} \cdot e^{-\frac{1}{2(1-r_{xy}^2)}\left[\frac{(x-x_0)^2}{\sigma_x^2} - \frac{2r_{xy}(x-x_0)(y-y_0)}{\sigma_x\sigma_y} + \frac{(y-y_0)^2}{\sigma_y^2}\right]}, \quad (1)$$

where C_m is the maximum penalty value, $f(\mathrm{x})$ is the risk distribution function, σ_x, σ_y – are the root-mean-square deviations along the axes of the related coordinate system, r_{xy} is the correlation coefficient between σ_x, σ_y, x_0, y_0 are the measured position of a target, x, y are the current coordinates for which the probability of collision risk is calculated.

Root-mean-square deviations σ_x, σ_y is determined by various uncertain factors (errors in measuring the position of the vessel and targets, partial uncertainty of the vessel and targets characteristics, partial uncertainty of the used mathematical model, etc.). The influence of many random factors is described by the normal or Gaussian distribution law [17], represented by equation (1).

Thus, equation (1) can be considered as a risk field of one target with the existing uncertainties. The first important point is that this field is smooth and extends to the entire space of operations, which means that gradient methods can be used to find the optimal solution. The second important point is that the method under consideration does not guarantee complete safety in case of divergence of the vessels (as well as any other method), but allows to set the risk of collision and organize the vessel control in case of divergence with a risk not exceeding the specified one.

Let's set in equation (1) the value of the function $C(\mathbf{x}) = C^*$, where C^* is the given risk and let's logarithm the expression. After simple transformations, we obtain a curve of a given risk C^*, which is an ellipse, the semi-axes of which are functions of parameters $\sigma_x, \sigma_y, r_{xy}$ and a given risk C^*

$$\frac{(x-x_0)^2}{a^2} + \frac{(y-y_0)^2}{b^2} = 1. \quad (2)$$

Moving along the risk line (ellipse) keeps the risk of collision, moving to inside the ellipse increases the risk of collision but decreases the path of divergence $S(\mathbf{x})$ and moving out of the ellipse reduces the risk of collision but increases the path of divergence $S(\mathbf{x})$. Thus, we obtain a vector function $\varphi(\mathbf{x})$ as integrand of the objective functional in form (3):

$$\varphi(\mathbf{x}) = \begin{bmatrix} S(\mathbf{x}) \\ C(\mathbf{x}) \end{bmatrix}; L(\mathbf{x}) \to \min \int_L \varphi(\mathbf{x}) d\mathbf{x}. \quad (3)$$

Problem (3) is a vector problem of optimal control for distributed system. However, for all its theoretical complexity, it has a simple solution – you need to move along the line of equal risk, then the distance covered by the divergence will be minimal for a given risk, and the risk will not exceed this one.

Suppose that our vessel is on an ellipse of equal risk. Then the position of our vessel at the next calculation step can be determined by the formulas

To enter the sliding trajectory and exit the sliding trajectory, it is necessary to determine coordinates of the touch point B (x_B, y_B) of the circulation circle $(x_1 - x_A)^2 + (y_1 - r)^2 = r^2$ to the ellipse of a given risk by jointly solving these two equations.

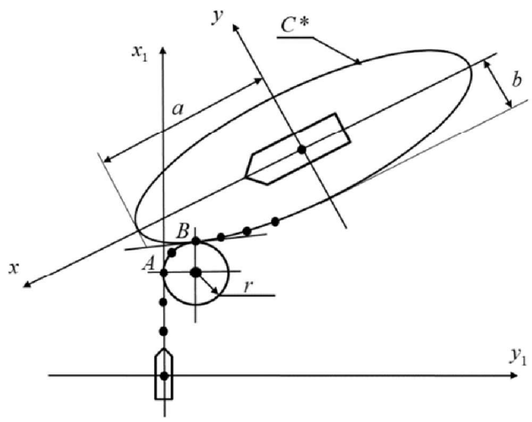

Figure 1. Entering the trajectory of a given risk

After finding the coordinates of p. B, we substitute them into the circulation circle $(x_B - x_A)^2 + (y_B - r)^2 = r^2$ and determine the p. A ($x_A, 0$) coordinates of transition beginning to the ellipse of a given risk C^*.

$$x_A = x_B - \sqrt{2y_B r - y_B^2}. \quad (4)$$

The coordinates of the departure point from the trajectory of equal risk are determined in a similar way.

There are two solutions for divergence with target. The first solution corresponds to the sliding of our vessel along the line of a given risk in the direction to the target stern, and the second corresponds to sliding in the direction to the target bow. Of these two options, the first is preferable, since it does not involve crossing the target course line.

Consider the features of divergence depending on the ratio $k = \frac{V_{tg}}{V}$, where V_{tg} is the target speed. Variants of divergence for $k = 2;\ 1;\ 0,5$.

Evasion trajectory **a** corresponds to the case when the target speed is twice ($k = 2$) the speed of own vessel. If the slip problem is solved and the accuracy ε is achieved, then the trajectory of the own vessel is determined from the slip task along the equal risk line, otherwise, if the own vessel does not keep up with the target, the course is assumed to be opposite or equal to the initial course.

The longest divergence trajectory along the constant risk line corresponds to the case of divergence with a slow target ($k = 0{,}5$). This case is typical for large-tonnage targets, the divergence from which is carried out at the maximum safe distance.

To carry out mathematical modeling of the optimal divergence with a given risk criterion, in Control System Model of Imitation Modeling Stand were flashed programs.

At the instructor's workplace, a task has been created to simulate a divergence of two vessels MSC Container Ship (Dis. 32025t). Vessel characteristics : engine's type is low-speed diesel $(1x15890)\,kWt$, propulsion type is FPP, bow thruster is present, stern thruster isn't present, displacement is $Dis = 32025\,t$, maximum speed is $V\max = 19{,}4\,kn$, length is $L = 203{,}6\,m$, width is $B = 25{,}4\,m$, bow/stern draft is $d = 9{,}6/10\,m.$

The probability of finding a target in an ellipse of a given risk is assumed to be 99.7%, which corresponds to a collision risk 0.3%. This probability corresponds to the 3 σ range of the spread of the set of random parameters. Of all the possible random processes affecting safety, we will choose the most significant ones: the error in measuring the RADAR range (root-mean-square error $\sigma = 20\,m$), the influence of external factors on the accuracy of program execution by the control system (root-mean-square error $\sigma = 15\,m$). Since these random processes are not correlated, the total root-mean-square error $\sigma = 35\,m$ and $3\sigma = 105\,m$. The semi-axes of the ellipse of a given risk, taking into account the size of the vessel, are equal to $a = \frac{L}{2} + 3\sigma = 101{,}8 + 105 = 206{,}8\,m$,

$b = \frac{B}{2} + 3\sigma = 12{,}7 + 105 = 117{,}7\,m.$

From this moment, the automatic control system deflects the rudder to the right and the vessel starts circulation with the calculated radius r to exit tangentially to the ellipse of the given risk. Further movement of the vessel occurs along the ellipse of a given risk 3, which moves along the X-axis at the speed of the target V_{tg}. Fig. 3 shows the positions of the target's equal risk ellipse at subsequent times, as well as the positions of our vessel on the equal risk ellipses during the divergence. The positions of the vessel on the ellipses of equal risk form the trajectory of optimal divergence. When the vessel approaches along the trajectory of the optimal divergence 2 to the line of the initial course for the calculated distance, the control system deflects the rudder to the right to start circulation with a given radius and reach the line of the initial course.

As can be seen from the examples considered, the optimal divergence along the minimum path and the given risk is carried out in three stages: entering the trajectory of the given risk, moving along the trajectory of the given risk, moving from the trajectory of the given risk to the trajectory of the initial course, and further movement along the trajectory of the initial course. Movement along the trajectory of a given risk is the longest stage of the vessels divergence, in which the own vessel slides along the elliptical trajectory built around the target. Such movement involves a constant change in the course of own vessel.

III. CONCLUSIONS

Solved the optimal divergence problem with a target minimizing the divergence trajectory for a given collision risk. It is shown that the optimal trajectory is obtained by organizing the sliding of the vessel along the ellipse of a given risk. There are determined the coordinates of the circulation beginning for the conjugation of the initial course line with an ellipse of a given risk by the circulation circle of a given radius. There were developed algorithmic and software for optimal divergence with a target. In comparison with the known solutions of the optimal divergence, the proposed method does not require large computational costs, since it has a simple geometric interpretation - sliding along the line of a given risk, which can be easily implemented in automatic divergence systems. In comparison with manual control, the proposed solution can significantly increase the accuracy and safety of the discrepancy. The operability and efficiency of the method, algorithmic and software was tested at the Imitation Modeling Stand in a closed circuit with a navigation simulator Navi Trainer 5000. The simulation results confirmed the possibility of using the method, algorithmic and software in the development of modules for the optimal divergence of on-board controllers of automatic divergence systems.

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