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Automatic collision avoidance system with many targets, including maneuvering ones

The article considers the issues of automatic collision avoidance with many targets, including maneuvering ones, which is especially important when navigating a vessel in narrownesses. Was made a brief review of literature devoted to the problem of collision avoidance and conclusion was drown on the relevance of developing such systems. There were developed mathematical and algorithmic support of the combined collision avoidance with many targets, including maneuvering ones. Based on the synthesized algorithms, there was developed software in the MATLAB environment for a simulator of an onboard controller of a ship control system, the operability and efficiency of mathematical, algorithmic and software was tested in a closed circuit with a Navi Trainer 5000 navigation simulator for various types of ships, navigation areas and weather conditions. The experiments confirmed the efficiency of the proposed method and algorithms and allow to recommend them for practical use in the development of modules for automatic collision avoidance with many targets, including maneuvering ones, an onboard controller of the ship's control system.

Keywords: collision avoidance system, automatic collision avoidance, collision avoidance with many targets, collision avoidance with maneuvering targets, collision avoidance in narrowness, collision avoidance control systems.

Introduction

The main international legal document regulating the safety of navigation today is the rules COLREGS [1], adopted in 1972 and put into operation since 1977. For 47 years, they are significantly outdated and require the speediest revision. Thus, the COLREG provide collision avoidance only two vessels (while the radar-tracking equipment (ARPA) installed on the vessels allows capturing and tracking up to 40 targets at a time), are verbal (and therefore are sometimes interpreted differently by boatmasters), are recommended character and don't always give a definite answer to avoid collision in a particular situation. The COLREG are human-oriented and don't fit into the concept of automation of control processes, they are a braking factor for the development of automatic systems.

At the same time, over the past 10–20 years, the intensity of shipping and the speed of ships has significantly increased, and with them the flow of information has increased. It becomes increasingly difficult for boatmasters to find the right management decisions, especially in critical situations (when operating in narrow spaces), which is the reason for the increasing number of accidents in maritime transport. Accident statistics in global shipping indicate that 75 % of all accidents occur due to the human factor.

Therefore, according to experts, a significant reduction in accidents can be achieved only by reducing human intervention in management, namely through the creation of decision support systems (DSS) and automatic control systems (ACS). DSS control the operation of individual navigation modules and, in the event that the operating parameters of the modules exceed the permissible limits, give warning messages or may even give «advice» on the management of the vessel. The boatmaster should comprehend the information received before making a decision, which also takes time [2–5].

In this regard, automatic control systems for the movement of the vessel deserve special attention when the human factor is completely excluded from the control loop. In this case, the skipper only makes a decision to activate the automatic control mode and monitors its implementation from the side. Currently, many ships have autopilots that implement two automatic control modes — automatic course maintenance and/or trajectory. The decision to activate these modes is made by the skipper, however, the vessel is further controlled without his participation. According to the authors of the article, such an approach to the construction of control systems is the most rational, as it allows the skipper to be freed from routine operations to control the vessel, while at the same time leaving him overall control over the development of the situation. A special place is occupied by the tasks of escorting the vessel in narrow places, where there is a large traffic flow and the constant maneuvering of ships — targets.

The object of the research in the article is the process of automatic collision avoidance with many vessels — targets, including maneuvering ones.

The subject of the study is the methods and algorithms implemented in the software of the onboard controller of the control system, and allowing to diverge from many targets, including maneuvering ones.

The purpose of the Article is the development of methods and algorithms for automatic collision avoidance with many vessels — targets, including maneuvering ones, for the collision avoidancemodule of the onboard controller of the ship control system.

Problem statement

A mathematical model of a controlled object (own ship) is set in the form of a system of nonlinear differential equations

$$\frac{d\mathbf{X}_n}{dt} = \mathbf{f}_n(\mathbf{X}_n, \mathbf{W}, \mathbf{U}, \theta, \delta);$$

$$\mathbf{X}_n = (\mathbf{V}_n, \omega_n, \Psi_n, X_n, Y_n),$$

model of external disturbances from the wind $\mathbf{W} = \mathbf{f}_w(\mathbf{t})$ and currents $\mathbf{U} = \mathbf{f}_u(\mathbf{t})$. In the measured data of the ship's linear speed $\mathbf{V}_m$, angular rotation speed ω_m, yaw angle Ψ_m, bearings P_{mj} and distances D_{mj} to targets, measurement errors are taken into account according to the passport data of each sensor. The mathematical model of targets is defined as a system of nonlinear algebraic equations $\mathbf{f}_{tgj}(X_{tgj}, Y_{tgj}, V_{tgj,} K_{tgj})$, $j = 1,2,..., N_{tg}$ that determine the parameters of the movement of targets along the trajectory (speed and course), as well as the breakpoints of the trajectory to simulate maneuvers of targets.

It is required, for given initial conditions (the initial state vector of the vessel $\mathbf{X}_n(0)$, the initial state vector of the targets $\mathbf{X}_{tgj}(0), j = 1,2,..., N_{tg}$, routes, parameters of the movement of targets along the routes), external disturbances, measurement errors of the motion parameters, to determine such telegraph θ and rudder δ controls that would allow to diverge with all the targets, including maneuvering ones, at a safe distance

$$(X_n - X_{tgj})^2 + (Y_n - Y_{tgj})^2 >= D_{s.a}{}^2, j = 1,2,..., N_{tg}.$$

Literature review

The issues of automatic collision avoidance were considered in many works of domestic and foreign authors. So, in [6], there was proposed a method for forming an area of unacceptable values for the course of one of the vessels and the speed of another vessel, taking into account its inertial characteristics with external control of the process of their collision avoidance. Depending on the parameters of the situation of dangerous approach and the braking mode of the vessel, there were obtained analytical expressions for calculating the boundaries of the area of unacceptable course values and speed of approaching ships. The method is based on an analytical description of unacceptable course values, which limits its ability to diverge from only one non-maneuvering vessel.

The article [7] describes a control system with deep Q-learning. The advantage of the system is the possibility of optimization based on information about the interaction with the environment. The disadvantages of the system are the need to organize the storage of information in the database, its quick search and retrieval, maintenance of the database. In addition, any training of the control system, including Q-training, is simply unacceptable in extreme situations, for example, when managing in narrow places, since during training the system may not work optimally or incorrectly, which is fraught with serious consequences.

The article [8] describes a path planning method taking into account the dynamic characteristics of the control object and COLREGS rules to prevent possible collisions. The method takes into account the uncertainty of the trajectory over time. Collision risk is calculated using the probabilistic method, and the collision risk area is adjusted based on the predicted trajectory. Simulation results are presented that demonstrate the feasibility of the proposed method. The proposed method allows you to assess the risk of a collision with only one non-maneuvering targets, since the rules of COLREGS don't consider other situations, does not form controls to prevent collisions in the automatic mode, and can only be used in automated decision support systems.

The article [9] describes the use of AIS for tracking the movement of targets through the electronic exchange of navigation data between ships with airborne transceivers, ground and/or satellite base stations. The collected data contains a large amount of information useful for maritime safety and is used to detect target maneuvers, route estimation, collision forecasting. The use of AIS data provides great opportunities for preventing collisions due to more accurate information about the parameters of their movement, however, this method cannot be used on ships that are not equipped with AIS transponders or vessels that hide information about the parameters of their movement.

As a result of the analysis, the authors of [10] came to the conclusion that collision avoidance algorithms developed over the past decades allow diverging from only one or two non-maneuvering targets, using the simplified dynamics of the ship and targets. The collision avoidance algorithms proposed by the authors of the article make it possible to visualize dangerous heading and speed of the vessel, which can lead to a collision. The system may also offer optimal solutions for discrepancies in accordance with the rules of COLREGS. However, the described system belongs to DSS and cannot solve the problems of collision avoidance in the automatic mode.

In [11] there was proposed a collision avoidance method using predictive models. Mathematical modeling in the on-board controller allows predicting the trajectory of the ship and the target using the currently measured parameters of the ship and the calculated parameters of the target. This forecast, taking into account the rules of COLREG, is used to determine the optimal control strategy for the collision avoidance. The disadvantage of this method is the difficulty in realizing multiple forecasts in the on-board controller of the vessel in real time, as well as the inability to diverge from several targets.

In [12, 13] the authors proposed a method of collision avoidance with many vessels — targets, including maneuvering ones. The method involves measuring, with the processing of information in the on-board controller, the true speed of the vessel and the relative speeds of the vessel and the targets, estimating the true speeds of the targets, building the area of acceptable controls for the collision avoidance with all targets, choosing the optimal parameters of the collision avoidance from the constructed area, forming controls for implementing selected options. The disadvantage of this method is the computational cost of constructing area of acceptable controls.

Material and method

Figure 1 shows a diagram of collision avoidance with two vessels. The results obtained are also valid for discrepancies with a large number of vessels. The vessel (control object) is located at point O. Around the vessel, an area of safe collision avoidance is drawn. When manually operated, the recommended area of safe collision avoidance in open waters should be at least 2 nautical miles (nm), and in cramped waters at least 0.7 nm.

The recommendations cited took into account the human factor, namely the delays associated with assessing the situation and making a decision by the skipper. With automatic control, the area of safe collision avoidance can be reduced. Thus, the standard deviation of the radar measurement, according to IMO requirements, should not exceed 1 % of the measured distance, i.e. for a measurement range of 10 nm, the standard deviation will be 0.1 nm, or, with a probability of 99.7 %, $3\sigma = 0.3$ nm. Therefore, $D_{s.a} = 0.3$ nm is sufficient for safe automatic collision avoidance.

The smaller size of the area allows to reduce the distance of departure from the original course in case of collision avoidance, reduce time and fuel consumption. Figure 1 also shows the measured vector of the true speed of the vessel $\mathbf{V}_m$ and the circle of maneuvering capabilities outlined by this vector. The positions of the target echoes $j = 1{,}2$ are plotted on the measurement steps $n-2, n-1, n$ through which the line of relative motion RML_j is drawn.

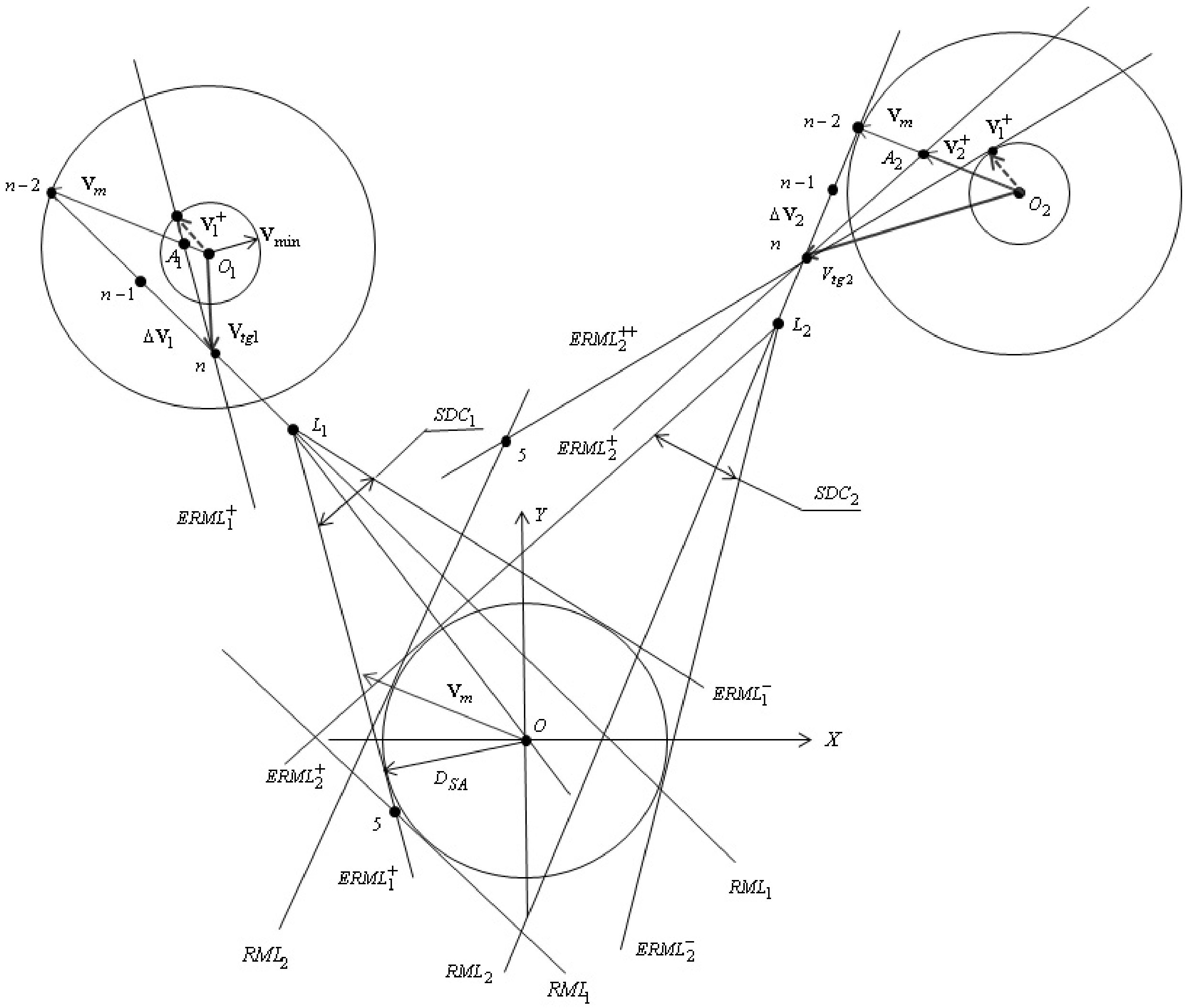

Figure 1. Diagram of collision avoidance with two vessels

The lead point L_j is moved forward along RML_j for a time sufficient to change the motion parameters of the vessel, taking into account its inertial characteristics. From the point L_j, the expected relative motion lines $ERML_j^+, ERML_j^-$ are drawn, tangent to the area of safe collision avoidance. Sector of dangerous courses SDC_j — the angle between $ERML_j^+, ERML_j^-$. When the relative speed vector $\mathbf{\Delta V}_j$ enters in sector of dangerous courses, the target echo will necessarily cross the area of safe collision avoidance. $ERML_j^+, ERML_j^-$ are the lines of optimal collision avoidance, since the movement of the target echo along given trajectories satisfies both the conditions of safe collision avoidance and the conditions of minimal flipping from the original trajectory. $ERML_j^+$ corresponds to collision avoidance by turning to the right, and $ERML_j^-$ corresponds to collision avoidance by turning to the left. Since the variants of the collision avoidance along $ERML_j^+$ and $ERML_j^-$ are constructed in a similar way, we will further consider the construction of only one of them, for example, the variant of the collision avoidance by $ERML_j^+$. Figure 1 shows the speed triangles $\mathbf{V}_m + \mathbf{\Delta V}_j = \mathbf{V}_{tgj}$, where $\mathbf{V}_{tgj}$ is the instantaneous speed vector of the j-target, estimated from the results of radar observations. These speed triangles correspond to the positions of the vectors before maneuvering. To direct the vector of the relative speed of collision avoidance along $ERML_j^+$ it is necessary to reduce the vessel's speed vector to a point A_j. In this case, the collision avoidance will be provided only by changing the speed, without changing the course, this maneuver is most applicable in narrownesses and is optimal in terms of fuel consumption. However, the collision avoidance speed cannot be less than the minimum $V_{\min}$, at which controllability is still maintained. In Figure 1, the collision avoidance vector for the first target turned out to be less than the minimum speed. Therefore, it is not always possible to conduct a clean speed maneuver. In this case, the collision avoidance speed vector must be turned to the point of intersection the line $ERML_j^+$, drawn through the point n, with the circle $V_{\min}$. The resulting speed vector will correspond to a combined maneuver of course and speed with a minimum turn from the original course.

Define the positions of the target echoes in the Cartesian coordinate system for measurement n.

$$X_{mj}(n) = D_{mj}(n)\sin P_{mj}(n);$$
$$Y_{mj}(n) = D_{mj}(n)\cos P_{mj}(n), j = 1..N_{tg}.$$

Using a series of consecutive measurements $n, n-1, n-2, \ldots$, using the least squares method, find the equations of the line of relative motion RML_j

$$Y = k_j^{RML} X + b_j^{RML}, j = 1..N_{tg}.$$

In order to remove noise, for the last two measurements $X_{mj}(n), X_{mj}(n-1)$, specify the coordinates $Y_{mj}(n), Y_{mj}(n-1)$ using the obtained equation RML_j

$$Y_{mj}(n) = k_j^{RML} X_{mj}(n) + b_j^{RML};$$
$$Y_{mj}(n-1) = k_j^{RML} X_{mj}(n-1) + b_j^{RML},\ j = 1..N_{tg}.$$

We estimate the vector of relative vessel speeds and targets using RML_j

$$\mathbf{\Delta V}_j = (\Delta V_{xj}, \Delta V_{yj});$$
$$\Delta V_{xj} = \frac{X_{mj}(n) - X_{mj}(n-1)}{\Delta T};$$
$$\Delta V_{yj} = \frac{Y_{mj}(n) - Y_{mj}(n-1)}{\Delta T}, j = 1..N_{tg},$$

where ΔT is the radar update tact.

Determine the lead point L_j at a distance ΔT from the last measurement n.

$$\mathbf{L}_j = \mathbf{X}_j(n) + \mathbf{\Delta V}_j \Delta T.$$

Determine the unit vectors defining the basic directions from p. $\mathbf{L}_j$:

– ort $\mathbf{E}_{0j}$ is the direction to the vessel (to the p. O);

– ort $\mathbf{E}_j$ is the direction along RML_j;

– ort $\mathbf{E}_j^+$ is the direction along $ERML_j^+$;

– ort $\mathbf{E}_j^-$ is the direction along $ERML_j^-$.

$$\mathbf{E}_{0j} = \left(\frac{L_{xj}}{|\mathbf{L}_j|}, \frac{L_{yj}}{|\mathbf{L}_j|}\right), \mathbf{E}_j = \left(\frac{\Delta V_{xj}}{|\mathbf{\Delta V}_j|}, \frac{\Delta V_{yj}}{|\mathbf{\Delta V}_j|}\right);$$
$$\mathbf{E}_j^+ = \mathbf{E}_{0j} e^{i\Theta_j}, \mathbf{E}_j^- = \mathbf{E}_{0j} e^{-i\Theta_j}, \Theta_j = \frac{SDC_j}{2} = \arcsin\left(\frac{D_{SA}}{|\mathbf{L}_j|}\right).$$

Determine the vector of the collision avoidance speed by $ERML_j^+$.

$$|\mathbf{V}_j^+| \mathbf{E}_{mj}^+ = \mathbf{V}_{tgj} - |\mathbf{\Delta V}_j^+| \mathbf{E}_j^+, \quad (1)$$

where $\left|\mathbf{V}_j^+\right|$ is the modulus of the collision avoidance speed vector; $\mathbf{E}_{mj}^+ = (\sin K_{mj}^+, \cos K_{mj}^+)$ is the unit vector of collision avoidance speed; K_{mj}^+ is collision avoidance course; $\left|\Delta\mathbf{V}_j^+\right|$ is module of the relative speed vector.

The modulus of the relative speed vector $\left|\Delta\mathbf{V}_j^+\right|$ is determined by the solution of the vector equation (1)

$$\left|\Delta\mathbf{V}_j^+\right| = \langle \mathbf{V}_{tgj}, \mathbf{E}_j^+ \rangle \pm \sqrt{\langle \mathbf{V}_{tgj}, \mathbf{E}_j^+ \rangle^2 + \left|V_j^+\right|^2 - V_{tgj}^{\ 2}} \,. \tag{2}$$

Equation (2) can have one solution when the radical expression is zero, two solutions when the radical expression is greater than zero and have no solutions when the radical expression is less than zero. In Figure 1, $ERML_2^-$ drawn through p. n, doesn't intersect the circle of maneuvering capabilities and the vector equation (2) in the case of collision avoidance along the line $ERML_2^-$ has no solutions. First of all, we are interested in one solution of equation (2), which corresponds to a maneuver of speed. Equating the radical expression to zero, we determine the modulus of collision avoidance speed $\left|V_j^+\right|$. If $\left|V_j^+\right| < V_{\min}$, where $V_{\min}$ is the minimum speed at which the ship maintains controllability, then we solve equation (2) again for $\left|V_j^+\right| = V_{\min}$. Find the collision avoidance speed vector $\mathbf{V}_j^+ = \mathbf{V}_{tgj} - \Delta\mathbf{V}_j^+$.

Among the vectors $\mathbf{V}_j^+, j = 1..N_{tg}$ we find the limiting collision avoidance speed vector having the largest deviation in angle from the initial speed vector $\mathbf{V}_m$

$$\langle \mathbf{V}_m, \mathbf{V}^+ \rangle = \min_{j=1..Ntg} \langle \mathbf{V}_m, \mathbf{V}_j^+ \rangle ,$$

where $\langle \ \rangle$ — scalar multiplication; $\mathbf{V}^+ = V^+(\cos K^+, \sin K^+)$ — the limiting vector of the collision avoidance speed.

In Figure 1 it will be a vector $\mathbf{V}_1^+$. Similarly, determine the limiting vector of the collision avoidance speed when turning to the left $\mathbf{V}^- = V^-(\cos K^-, \sin K^-)$. Of the two limiting vectors, choose the smaller one by the angle of the turn $\mathbf{V}^* = \max(<\mathbf{V}_m, \mathbf{V}^+>, <\mathbf{V}_m, \mathbf{V}^->)$.

The collision avoidance speed vector $\mathbf{V}^* = V^*(\cos K^*, \sin K^*)$ is implemented by the PID controller

$$\delta = k_\Psi (K_m - K^*) + k_\omega \omega_{mz} + k_\int \int (K_m - K^*) dt \,;$$

$$\theta = \frac{\pi}{2} \frac{V^*}{V_{\max}} ,$$

where k_Ψ, k_ω, $k_\int$ are the gains of the PID controller for the mismatch angle, the angular velocity and the integral of the mismatch angle; K_m, ω_{mz} — measured course and angular velocity of rotation of the vessel.

Experiments

The operability of the collision avoidance algorithm was tested on the navigation simulator of the Kherson State Maritime Academy [14–17]. The block diagram of the simulator is shown in Figure 2. In the computer network of the simulator, additional system units 14–16 were connected, with which information exchange was organized. Blocks 14–16 contain control system modules, which provide collision avoidance according to the above algorithm. A task was created in the Navi Trainer Instructor program of the Instructor's workplace (block 6 of the structural diagram of the simulator), a screenshot is shown in Figure 3.

As you can see from the screenshot above, at the time of the beginning of the collision avoidance, our SS1 vessel is surrounded by dangerous targets that also maneuver (the trajectories of the targets have kinks). Vessel and targets trends are also shown.

Figure 4 shows a screenshot of the radar at the time the collision avoidance began.

Figure 5 shows a screenshot of the Navi Trainer Instructor after 10 minutes of collision avoidance.

Figure 6 shows a screenshot of the radar after 10 minutes of collision avoidance.

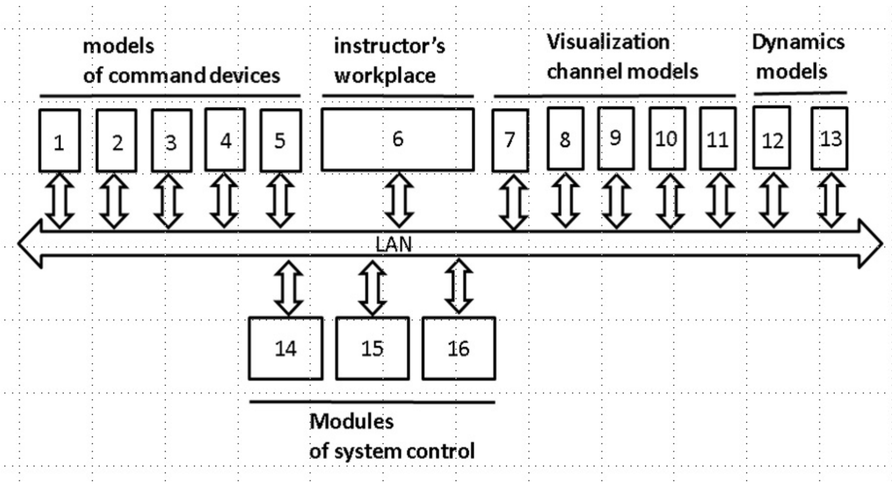

Figure 2. Block diagram of the simulator

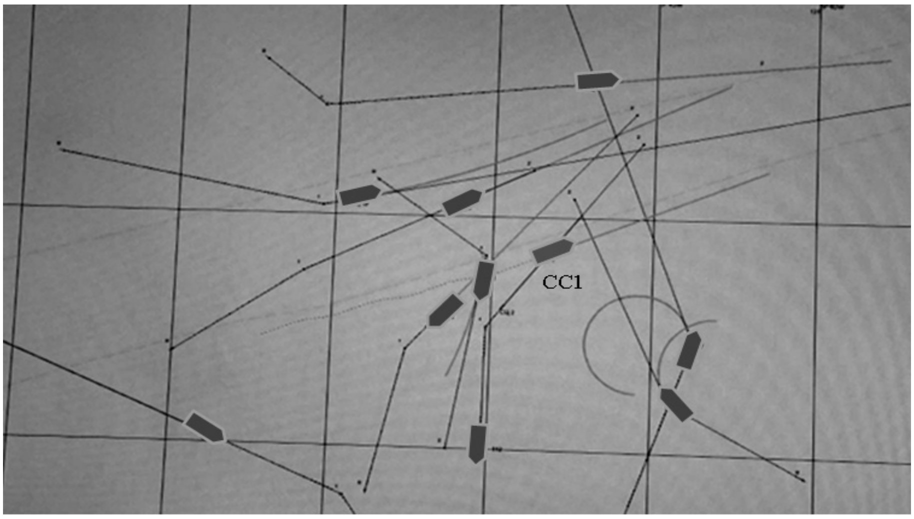

Figure 3. Screenshot of the Navi Trainer Instructor

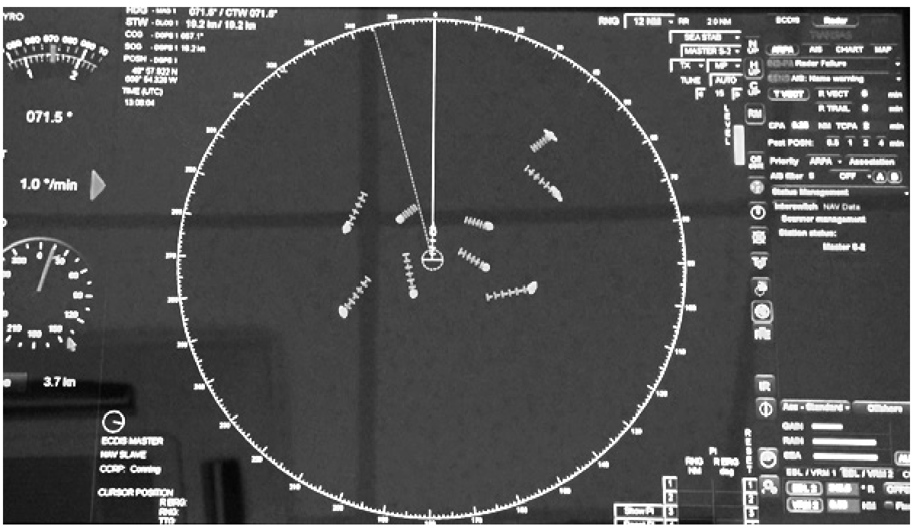

Figure 4. A screenshot of the radar at the time the collision avoidance began

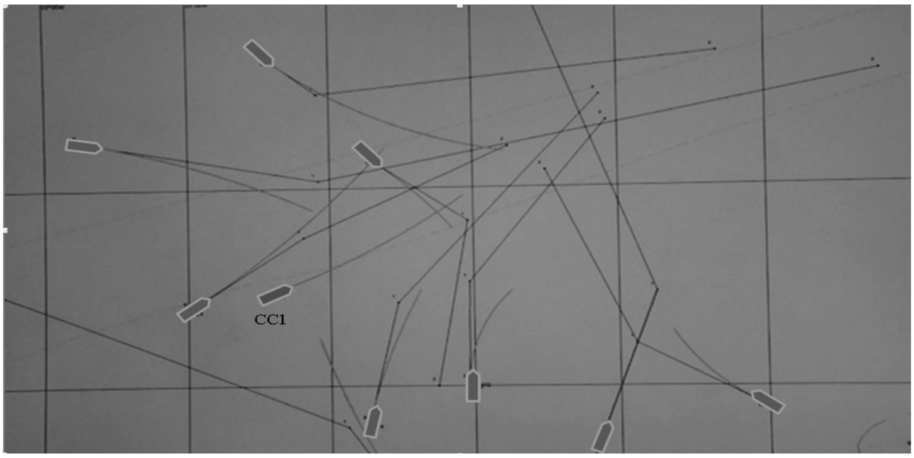

Figure 5. Screenshot of the Navi Trainer Instructor after 10 minutes of collision avoidance

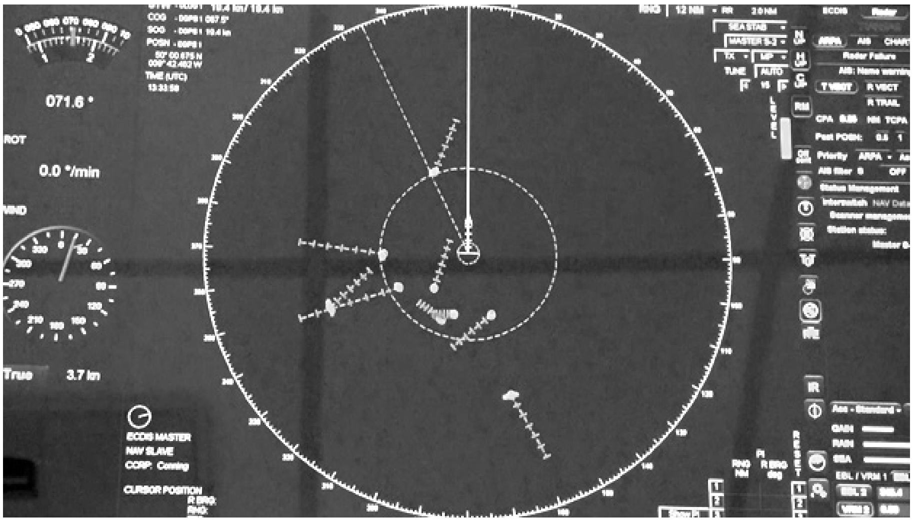

Figure 6. Screenshot of the radar after 10 minutes collision avoidance

As can be seen from the results, the control system has almost completed the collision avoidance from dangerous maneuvering targets.

Conclusions

There are proposed a method and algorithms for automatic collision avoidance with many targets, including maneuvering ones.

The scientific novelty of the results obtained is the possibility of collision avoidance with many targets, including maneuvering ones, in a fully automatic mode, which is especially useful in extreme situations, for example, when the vessel avoid collision in narrownesses. This is achieved through periodic, with the onboard controller operation, measuring the true speed of the vessel and the relative speeds of the vessel and the targets, averaging the measured information in order to remove noise, estimating the true speeds of the targets, determining for the left and right maneuvers the speed vector discrepancies for each target separately, definitions for the left and right maneuvers of the limiting collision avoidance speed vector, selection from the limiting collision avoidance vectors of the left and right maneuvers of the required collision avoidance vector using the criterion of a smaller angle of rotation, the implementation of the required vector of the collision avoidance speed in the control system.

The practical value of the obtained results lies in the fact that the developed method and algorithms are implemented in software and investigated by solving the problem of automatic collision avoidance with several targets, including maneuvering ones, in a closed loop with the Navi Trainer 5000 simulator for various types of ships, targets, navigation areas and weather conditions. The experiments confirmed the efficiency of the proposed method and algorithms and allow to recommend them for practical use in the development of modules for automatic collision avoidance with many targets, including maneuvering ones, an onboard controller of the ship's control system.

Further research may consist in the development of methods and algorithms for processing radar information that allow to consider small and nearby objects, for example, small fishing vessels, as one impassable cluster and solve the problem of collision avoidance not with each such object, but with a whole cluster, which will significantly increase speed and reliability solutions.

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С. Зинченко, П. Носов, В. Матейчук, П. Маменко, И. Попович, О. Грошева

Көптеген мақсаттары бар автоматты айырылу жүйесін синтездеу, соның ішінде маневрлар

Мақалада басқа кемелерден айырылу кезінде кеменің қозғалысын автоматты түрде басқару мәселелері қарастырылған — нысандар, оның ішінде маневрлар, бұл кемелерді тар жолдарда навигациялау кезінде өте маңызды. Кемелердің айырылу мәселесіне арналған әдебиеттерге қысқаша шолу, осындай жүйелерді әзірлеудің өзектілігі туралы қорытынды жасалды. Кеменің бұрылу кезінде, соның ішінде маневрмен үйлескен айырмашылықты математикалық және алгоритмдік қамтамасыз ету әзірленді. Синтезделген алгоритмдердің негізінде кемені басқару жүйесінің борттық контроллерін модуляциялау үшін MATLAB жүйесін бағдарламалық қамтамасыз ету жасалды, математикалық, алгоритмдік және бағдарламалық қамтамасыз етудің жұмыс қабілеттілігі мен тиімділігі Navi Trainer 5000 навигациялық тренажеры көмегімен түрлі кемелерге, навигациялық аймақтарға және ауа-райына байланысты жабық схемада сыналды. Эксперименттер ұсынылған әдіс пен алгоритмдердің жарамдылығын растады және көптеген мақсаттарға, соның ішінде маневрлік, кемені басқару жүйесінің борттық контроллеріне арналған автоматты сәйкессіздік модулдерін жасау кезінде оларды практикалық пайдалануға ұсынуға мүмкіндік береді.

Кілт сөздер: соқтығысуды болдырмау, автоматты айырылу, көптеген мақсаттары бар айырылу, маневрлік мақсаттардағы айырылу, таршылықтағы айырылу, айырылуды басқару жүйелері.

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Синтез системы автоматического расхождения со многими целями, включая маневрирующие

В статье рассмотрены вопросы автоматического управления движением судна при расхождении с другими судами — целями, включая маневрирующие, что особенно актуально при проводке судна в узкостях. Проведен краткий обзор литературных источников, посвященных проблеме расхождения судов, сделан вывод об актуальности разработки таких систем. Разработано математическое и алгоритмическое обеспечение комбинированного расхождения со многими целями, включая маневрирующие. По синтезированным алгоритмам создано программное обеспечение в среде MATLAB для имитатора бортового контроллера системы управления судном, работоспособность и эффективность математического, алгоритмического и программного обеспечения проверены в замкнутой схеме с навигационным тренажером Navi Trainer 5000 для различных типов судов, районов плавания и погодных условий. Эксперименты подтвердили работоспособность предложенного способа и алгоритмов и позволяют рекомендовать их для практического использования при разработке модулей автоматического расхождения со многими целями, включая маневрирующие, бортового контроллера системы управления судном.

Ключевые слова: системы расхождения, автоматическое расхождение, расхождение со многими целями, расхождение с маневрирующими целями, расхождение в узкостях, системы управления расхождением.

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