УПРАВЛІННЯ У ТЕХНІЧНИХ СИСТЕМАХ

CONTROL IN TECHNICAL SYSTEMS

УПРАВЛЕНИЕ В ТЕХНИЧЕСКИХ СИСТЕМАХ

UDC 004.942:656.61.052

AUTOMATIC COLLISION AVOIDANCE WITH MULTIPLE TARGETS, INCLUDING MANEUVERING ONES

Zinchenko S. M. – PhD, Senior Lecturer of Ship Management Department, head of the laboratory of electronic simulators, Kherson State Maritime Academy, Ukraine.

Nosov P. S. – PhD, Associate Professor of Navigation Systems Department, Kherson State Maritime Academy, Ukraine.

Mateychuk V. M. – Assistant of Ship Management Department, head of the laboratory of electronic simulators, Kherson State Maritime Academy, Ukraine.

Mamenko P. P. – Senior Lecturer of Ship Management Department , deep sea captain, Kherson State Maritime Academy, Ukraine.

Grosheva O. O. – Senior Lecturer of Ship Management Department, Kherson State Maritime Academy, Ukraine.

ABSTRACT

Context. There is considered the task of automatic collision avoidance with multiple targets, including maneuvering ones. The object of the research is the process of automatic collision avoidance with multiple targets, including maneuvering ones. The subject of research is the method and algorithms that implement the process of automatic collision avoidance from multiple targets, including maneuvering ones.

Objective. The purpose of the article is development a method and algorithms for automatic collision avoidance from multiple targets, including maneuvering ones, for the module of the onboard controller of the ship control system.

Method. This goal is achieved by periodically measuring the true speed of the vessel and relative speeds of the vessel and targets, averaging the measured information to remove noise, estimating the true speeds of the targets, building, for the obtained estimates of the true speeds of the targets, areas of allowable collision avoidance controls with each targets by numerical iteration of the collision avoidance parameters (speed and course) at the nodes of a given grid in the area of their possible changes, determining the relative speeds at the nodes of the grid ship and target movement and checking that the relative speeds don't belong to sectors of dangerous courses, building a general area of acceptable collision avoidance controls with all targets by combining areas of allowable collision avoidance controls with each target, choosing collision avoidance parameters from the general area of acceptable collision avoidance controls according to specified criteria. This allows to diverge from multiple targets, including maneuvering ones, in a fully automatic mode. Changing the criteria for selecting discrepancy parameters leads to a change in the ship's behavior in case of discrepancy without changing the program code.

Results. The developed method and algorithms are implemented in software and investigated by solving the problem of collision avoidance from multiple targets, including maneuvering ones, in a fully automatic mode in a closed circuit with the simulator Navi Trainer 5000 for various types of ships, targets, navigation areas and weather conditions.

Conclusions. The experiments confirmed the performance of the proposed method and algorithms and allow to recommend them for practical use in the development of modules for automatic collision avoidance with multiple targets, including maneuvering ones, of the onboard controller of the ship control system.

KEYWORDS: ship collision avoidance system, automatic collision avoidance, collision avoidance from maneuvering targets, collision avoidance, area of allowable controls.

ABBREVIATIONS

AIS is a Automatic Identification System;

ARPA is a automatic radar plotting aid;

BCS is a bound coordinate system; is located in the center of rotation of the vessel, the axis OX lies in the center plane and is directed forward, the axis OY is perpendicular to the center plane and directed towards the starboard, the axis OZ complements the system to the "right" one.

COLREG is an international rules for preventing collisions;

ERML is an expected relative movement line;

DOI 10.15588/1607-3274-2019-4-20

GCS is a geographical coordinate system; is located in the center of rotation of the vessel, the axis OXg is directed along the meridian towards the North, the axis

LOG is a device for determining the speed of the vessel;

LSM is a least– squares method;

OYg is directed along the parallel towards the East, the axis OZg complements the system to the “right”;

RADAR is a radar station;

RML is a relative movement line;

SDC is a sector of dangerous courses;

NOMENCLATURE

b_j is a linear coefficients of the RML equation for the *j*-target;

D_{mj} is a measured distance to the *j*-target;

D_{sa} is a area of safe collision avoidance;

$\mathbf{E}_{0j}$ is a ort, wich indicates the direction from lead point of *j*-target to the vessel;

$\mathbf{E}_{1j}$ is a ort, wich indicates the direction of $ELRM_1$ for the *j*-target;

$\mathbf{E}_{2j}$ is a ort, wich indicates the direction of $ELRM_2$ for the *j*-target;

k_j is a angular coefficients of the RML equation for the *j*-target;

K_{n1} is a course of safe collision avoidance;

K_{tgj} is a-true course of *j*-target;

K_T is a trial values of course;

k_Ψ is a angle gain factor;

k_ω is a angular speed gain factor;

$k_\int$ is a angle integral gain factor;

N is a number of RADAR measurements for building RML.

N_{tg} is a number of targets;

OE_j is a distance to lead point of *j*-target.

P_{mj} is a measured bearing to the *j*-target;

$\mathbf{U}$ is a flow influence;

$\mathbf{V}_m$ is a measured linear speed vector;

$V_{\max}$ is a maximum ship speeds;

$V_{\min}$ is a minimum ship speed;

$\mathbf{V}_n$ is a linear speed vector;

V_{n1} is a speed of safe collision avoidance;

$\mathbf{V}_T$ is a trial vector of speed;

V_T is a trial values of speed;

$\mathbf{V}_{tgj}$ is a-true speed vector of *j*-target;

V_{tgj} is a module true speed vector of *j*-target;

$\mathbf{W}$ is a wind influence;

$\mathbf{X}_n$ is a state vector of own vessel;

X_n is a absolute ship movement along the axis OX_g in GCS;

$\mathbf{X}_{tgj}$ is a state vector of *j*-target;

X_{tgj} is a-absolute movement of the *j*-target along the OX_g – acis in GCS;

Y_n is a absolute ship movement along the axis OY_g in GCS;

Y_{tgj} is a absolute movement of the *j*-target along the OY_g is a acis in GCS;

δ is a angles deflection of rudder;

ΔT is a period of information processing in the onboard computer;

$\mathbf{\Delta V}_j$ is a relative speed vector of the vessel and *j*-target;

$\mathbf{\Delta V}_{Tj}$ is a trial values of the relative speed of the vessel and the *j*-target;

ΔV_{xj} is a relative speed OX-projection in BCS;

ΔV_{yj} is a relative speed OY-projection in BCS;

ΔX_{mj} is a measured OX-projection of distance between the vessel and the *j*-target in GCS;

ΔY_{mj} is a measured OY-projection of distance between the vessel and the *j*-target in GCS;

θ is a angles deflection of telegraph;

Θ_j is a angle, equal to half the SDC for the *j*-target;

Ψ_m is a measured heading;

Ψ_n is a heading;

Ω_j is a areas of admissible control of collision avoidance with *j*-target;

ω_{mz} is a measured angular speed in BCS;

ω_{nz} is a angular speed in BCS.

INTRODUCTION

The article discusses the issues of automatic collision avoidance with multiple targets, including maneuvering ones. Currently, the main international legal document, regulating the safety of navigation, is the Rules COLREG-72 [1], adopted in 1972 and put into operation since 1977, and the technical equipment of collision avoidance are RADAR / ARPA [2–3].

Recently, the speed of ships and the intensity of navigation have significantly increased, which has caused a significant increase in the flow of information per unit of time. It becomes increasingly difficult for navigators to make the right decisions to prevent the development of dangerous situations. Statistics of accidents in the global maritime industry shows that 75–80% of all accidents occur with the direct participation of a person. The human factor today is the most dangerous element of the ship management system. Analyzing these data, the experts

DOI 10.15588/1607-3274-2019-4-20

concluded that a significant reduction in accidents can be achieved only by reducing the influence of the human factor on the management process. Modern ships have become increasingly equipped with automatic and automated control systems. The use of such systems improves reliability, accuracy and flexibility, and also provides new opportunities through the use of modern mathematical tools. Automatic systems are also much cheaper than traditional ones with the crew.

Technical equipmet of collision avoidance RADAR / ARPA allow to capture, track and diverge with 40 targets at the same time. However, RADAR / ARPA is an automated equipment and involves the participation of man in the collision avoidance. Thus, neither the COLREG-72 Rules nor the RADAR / ARPA technical equipment meet the current trends in the automation of ship traffic control in conditions of increased speeds and traffic flows.

In open sources [5–13], a more detailed analysis of which will be done in the next section, various solutions to the problems of automatic collision avoidance are proposed, but all of them allow to collision avoidance with only a few (from one to three) non-maneuvering targets, despite the fact that the existing RADAR / ARPA equipment allows to capture and accompany a much larger number of targets (up to 40). Therefore, the development of systems of collision avoidance with multiple targets, including maneuvering ones, is an actual scientific and technical problem.

The object of research is the process of automatic collision avoidance with multiple targets, including maneuvering ones.

The subject of research is the method and algorithms that implement the process of automatic collision avoidance from multiple targets, including maneuvering ones.

The purpose of this article is development a method and algorithms for automatic collision avoidance from multiple targets, including maneuvering ones, for the module of the onboard controller of the ship control system.

1 PROBLEM STATEMENT

The are specified a mathematical model of a controlled object (own vessel) in the form of a system of nonlinear differential equations

$$\frac{d\mathbf{X}_n}{dt} = \mathbf{f}_n(\mathbf{X}_n, \mathbf{W}, \mathbf{U}, \theta, \delta),$$
$$\mathbf{X}_n = (\mathbf{V}_n, \omega_n, \Psi_n, X_n, Y_n),$$

models of external influences of wind $\mathbf{W} = \mathbf{f}_w(\mathbf{t})$ and flow $\mathbf{U} = \mathbf{f}_u(\mathbf{t})$. The measured linear speed of the vessel $\mathbf{V}_m$, angular velocity ω_m, yaw angle Ψ_m, bearing P_{mj} and distance D_{mj} to each target take into account the measurement errors determined by the passport data of each sensors. Mathematical models of targets are also specified in the form of a system of nonlinear algebraic equations $\mathbf{f}_{tgj}(X_{tgj}, Y_{tgj}, V_{tgj}, K_{tgj}),\ j = 1, 2, ..., N_{tg}$ that define the parameters of the movement of targets along a route (speeds and courses), as well as target paths with break points to simulate target maneuvers.

Required for given initial conditions – the position of own vessel $\mathbf{X}_n(0)$, the position of targets $\mathbf{X}_{tgj}(0),\ j = 1, 2, ..., N_{tg}$, specified parameters of movement of targets on routes, specified routes, external influences, measurement errors of motion parameters, determine such controls that would allow to diverge from specified targets, including maneuvering ones at a safe distance $(X_n - X_{tgj})^2 + (Y_n - Y_{tgj})^2 >= D_{s.a}{}^2,\ j = 1, 2, ..., N_{tg}$.

2 LITERATURE REVIEW

The main international legal document regulating the safety of navigation today is the COLREG–72. The rules apply only in cases where there is a danger of collision. Rules COLREG–72 are verbal (and therefore sometimes interpreted by navigators differently), are more focused on the intuition of the navigator and not on exact mathematical calculation, consider only the consistent collision avoidance of the two vessels. After installation on ships of the radar, it became possible to measure the parameters of the relative movement of the vessel and targets, as well as to carry out manually graphic constructions on a maneuverable tablet to determine the parameters of collision avoidance [2]. This method of calculating the parameters of the collision avoidance has not high accuracy and is also very labor intensive. To automate calculations, modern radar systems have been installed on modern ships. ARPA [3–4] frees the navigator from a variety of manual operations, and the built-in function “Playback maneuver” provides the navigator with a convenient graphical interface for solving problems of collision avoidance. However, ARPA has significant drawbacks:

–ARPA is an automated system that assumes the presence of a person in the control loop;

“The Replay Maneuver” function of the ARPA provides the navigator with only a convenient graphical interface, but the determination of the parameters of the collision avoidance is still carried out manually “by eye”, rather than relying on an exact mathematical calculation that takes time;

–ARPA function “Playing maneuver”, as with manual radar laying, does not allow to diverge from maneuvering targets, since the task is solved one-time, before the beginning of the diversion maneuver.

A lot of works of authors are also devoted to the issues of automatic collision avoidance.

Thus, in article [5] proposed an automatic collision avoidance system based on deep Q-learning. The advantage of this method is to obtain information from the environment with which the system interacts, which can be used to optimize the behavior of the system. At the

DOI 10.15588/1607-3274-2019-4-20

same time, Q-learning takes time, organizing storage of information, its quick retrieval, as well as database maintenance. In addition, during Q-training, the system may not work optimally or even mistakenly, which is fraught with serious consequences.

The article [6] describes a method for assessing the risk of collision of ships, based on a complex non-linear relationship between the degree of risk of collision and the influencing factors. Collision risk assessments with expert information on collision avoidance experience, are entered into a database for subsequent use. The authors proposed a regression model that is trained on the basis of existing samples, in order to increase the accuracy and speed of prediction. The solution proposed by the authors involves training the system, which is not permissible during ships diverge. In addition, the learning process is associated with a long accumulation of information, the use of databases, the organization of quick retrieval of information from the database as well as the need for additional maintenance of the database.

The article [7] describes the track planning method, taking into account the dynamic characteristics of the control object and the rules of COLREGS-72 to prevent possible collisions. The method takes into account the uncertainty of the trajectory in time. The risk of collision is calculated using the probabilistic method, and the risk zone of collision is adjusted to the predicted trajectory. Also presented are simulation results that demonstrate the feasibility of the proposed approach with examples of shipping. The propoused method allows to estimate the risk of collision with non-maneuvering targets, does not form controls for implementing the collision avoidance in the automatic mode and can only be used in automated decision support systems.

The article [8] describes the use of AIS for tracking the movement of targets through electronic exchange of navigation data between ships with onboard transceivers, ground and / or satellite base stations. The data collected contains a large amount of information useful for safety at sea and is used for: detecting anomalies of movement of targets, route estimation, collision prediction and path planning. The use of AIS data provides great opportunities for ships collision avoidance due to more accurate information about the parameters of their movement, however, this method doesn't allow to diverge from not equipped with AIS ships or ships that hide information about the parameters of their movement.

The article [9] describes the method of support decisions in the case of collision avoidance of ships at sea. The method is based on the use of the COLREG-72 and the accumulated experience of collision avoidance. The described method assumes the presence of a person in the control loop and the use of the Rules of the COLREG-72 for collision avoidance. Since the COLREG-72 Rules regulate collision avoidance with only one non-maneuvering vessel, it cannot be used to automatically diverge with multiple targets, including maneuvering ones.

As a result of the analysis, the authors article [10] came to the conclusion that the collision avoidance algorithms developed over the past decades suppouse the absence of maneuvering targets in the collision avoidance process; collision avoidance from only two targets, simplified dynamics of vessel and targets, etc. A collision avoidance algorithm and a collision avoidance system are proposed. The system visualizes changes course and speed of the vessel, leading to a collision, that can be used in manual control and in decision support systems. Collision avoidance system can also offer evading controls that comply with the Rules and have a minimum number of operations.

This system is closest to the proposed by the authors system of automatic collision avoidance with multiple targets, including maneuvering ones.

A method of collision avoidance using predictive models was described in [11]. Mathematical modeling in the onboard computer predicts the trajectory of the vessel and the target using the measured at the current time parameters of the movement of the vessel and the estimated movement parameters of the target. This forecast, taking into account the rules of the COLREG – 72, is used to determine the optimal collision avoidance management strategy. The disadvantage of this method is the large load on the onboard computer due to the need to implement a variety of forecasts in real time, as well as the possibility of collision avoidance with only one vessel.

The article [12] describes the method of probabilistic obstacle handling based on information from a radar sensor with target tracking, that considers measurement and tracking uncertainties is proposed. A grid based path search algorithm, that takes the information from the probabilistic obstacle handling into account, is then used to generate evasive trajectories.

The article [13] presents a combined Nonlinear Model Predictive Control for position and velocity tracking of underactuated surface vessels, and collision avoidance of static and dynamic objects into a single control scheme with sideslip angle compensation and environmental disturbances counteraction. A three-degree-of-freedom dynamic model is used with only two control variables: namely, surge force and yaw moment. Nonlinear disturbance observer is used to estimate disturbances in order to be fed into the prediction model and enhance the robustness of the computer. Collision avoidance is embedded into the trajectory tracking control problem as a time-varying nonlinear constraint of position states to account for static and dynamic obstacles.

The article [14] describes an approach to real-time collision avoidance that complies with the COLREGS rules for Unmanned Surface Vehicle. The Evidential Reasoning theory is employed to evaluate the collision risks with obstacles encountered and trigger a prompt warning of a potential collision. Then, is extended and adopted the optimal reciprocal collision avoidance algorithm so as to determine a collision avoidance maneuver that is COLREGS compliant. The proposed

DOI 10.15588/1607-3274-2019-4-20

approach takes into consideration the fact that other obstacles also sense their surroundings and react accordingly, conforming to a practical marine situation when making a decision concerning collision-free motion.

3 MATERIALS AND METHODS

This article solves the problem of collision avoidance from multiple targets, including maneuvering ones. The structural diagram of the simulation objects is shown in Fig. 1.

The onboard computer 7 receives the parameters of the state vector of the vessel in the ACS as well as the distances and bearings to each target, measured by the radar 12 and comparator 5.

Block 8 of receiving and converting information reads incoming data with a period of information processing, scales it, translates it into a numeric code and feeds the inputs of modules 7.1–7.n to solve various applied control problems, in particular, in module 7.1. The considered problem of managing the collision avoidance with multiple targets, including maneuvering ones, is solved. The required course values and speeds of collision avoidance from the output of module 7.1 of the calculator are fed respectively to autopilot 3 and to the power energy installation 6, the outputs of which, taking into account the inertia and delays, are controls of the object 4. In addition to the considered controls, the object 4 is also affected by external disturbances 1 in the form of wind and current speeds. The combined effect of controls and disturbances on the control object 4 determines its movement, which at each moment of time is characterized by a state vector. Unit 2 models the movement of targets in the same GCS, in which the movement of the control object 4 itself is modeled. Fig. 2 shows the scheme of collision avoidance of own ship O with two ships – targets O_1 and O_2. The reasoning below is also valid for collision avoidance from any number of targets.

Own ship O (see Fig. 2a) moves with measured speed $\mathbf{V}_m$. Around own ship is drawn the safe area Ds.a. Through the point of the last measurement (p. N) of the target position, the relative movement lines RML_1, RML_2 are drawn, which are built in the onboard computer of the vessel according to a series of observations $1, 2, ..., N$ from the radar, using the least-squares method.

The essence of the LSM is the preliminary accumulation of the measured radar information on the bearing and the distance for each target for 15–30 antenna turns, recalculation of the measured data in the Cartesian coordinate system

$$\Delta X_{mj}(i) = D_{mj}(i)\cos(P_{mj}(i)),$$
$$\Delta Y_{mj}(i) = D_{mj}(i)\sin(P_{mj}(i)), i = 1, 2, ..., N;$$

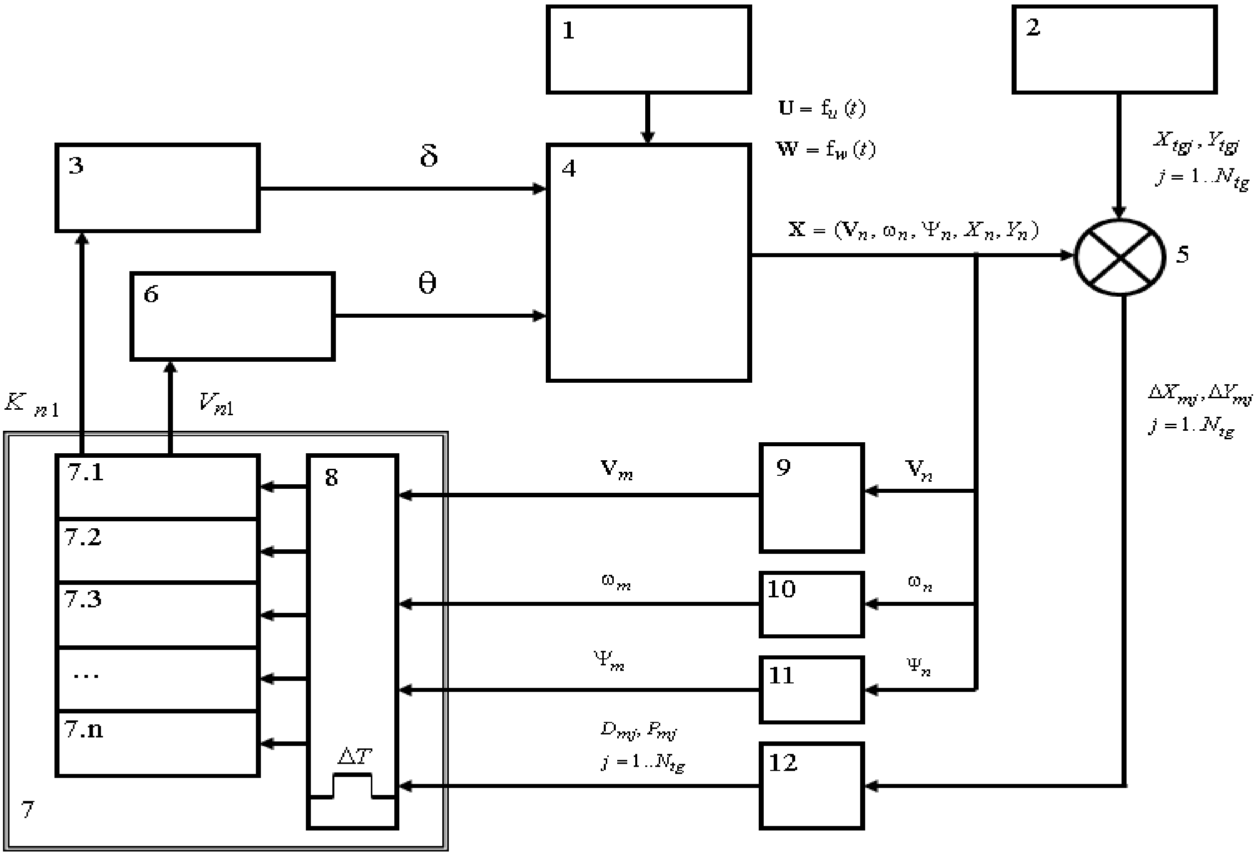

Figure 1 – Structural diagram of the objects of modeling

DOI 10.15588/1607-3274-2019-4-20

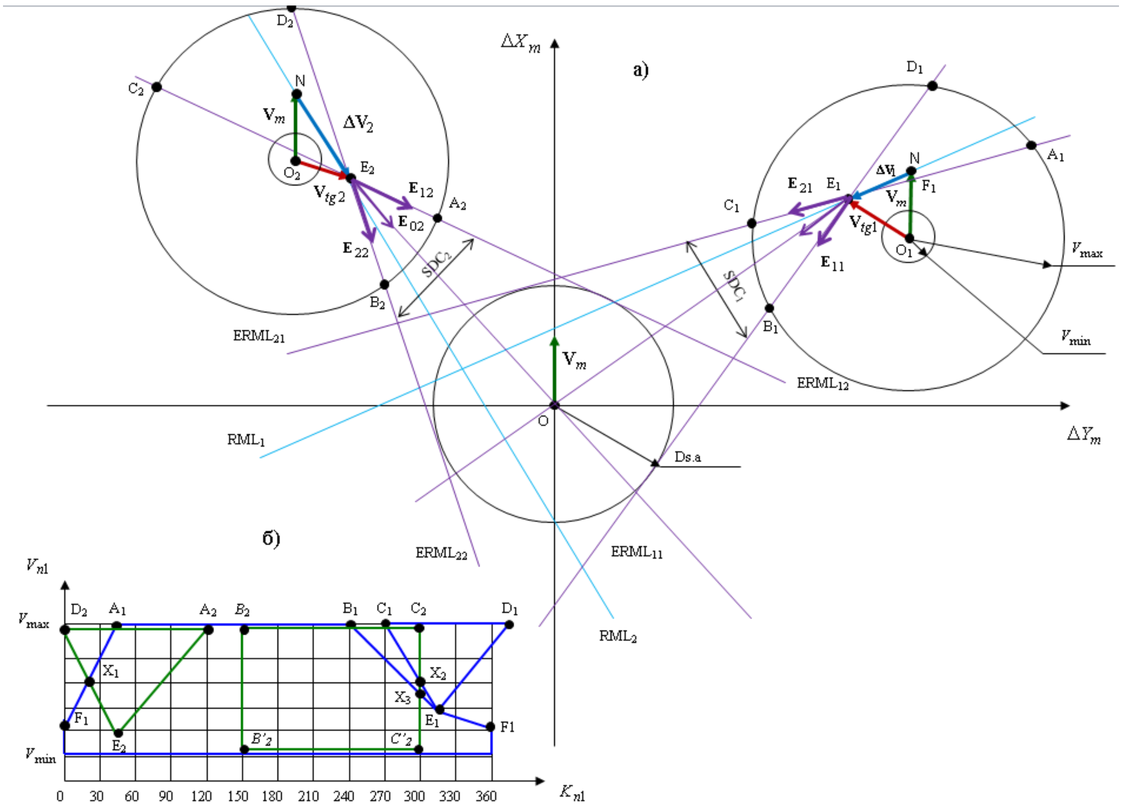

Figure 2 – Diagram of the collision avoidance

with the subsequent approximation of the accumulated data by a RML. This method is currently widely used in ARPA. Further, using the koefficients $k_j, b_j, j = 1,2,...., N_{tg}$ RML equation, the measured coordinates of the target are specified so that they lie on the RML, thus eliminating fluctuation errors in radar measurements

$$\Delta X_{mj}(1) = k_j \Delta Y_{mj}(1) + b_j,$$

$$\Delta X_{mj}(N) = k_j \Delta Y_{mj}(N) + b_j,\ j = 1,2,....,\ N_{tg},$$

estimated vector $\mathbf{\Delta V}_j = (\Delta V_{xj}, \Delta V_{yj})$ relative vessel speed and j-target

$$\Delta V_{xj} = (\Delta X_{mj}(N) - \Delta X_{mj}(1)) / (\Delta T(N-1)),$$

$$\Delta V_{yj} = (\Delta Y_{mj}(N) - \Delta Y_{mj}(1)) / (\Delta T(N-1)),$$

and also computes the true speed vector of the j-target

$$\mathbf{V}_{tgj} = \mathbf{V}_m + \mathbf{\Delta V}_j.$$

In Fig. 2a shows speed triangles $(\mathbf{V}_m, \mathbf{\Delta V}_j, \mathbf{V}_{tgj}, j = 1,2)$, built for 2 targets at last measurement points (p. N). Lead points E_1 (E_2), pushed forward by RML_1 (RML_2) regarding p. N the distance required to change the motion parameters of the vessel in case of collision avoidance (determined by its maneuverability characteristics). $ERML_{11}$, $ERML_{21}$, $ERML_{12}$, $ERML_{22}$ – tangents to the safe area, drawn from points E_1 (E_2). $ERML_{11}$, $ERML_{21}$ and $ERML_{12}$, $ERML_{22}$ form sectors of dangerous courses SDC_1 and SDC_2 accordingly, in which the vector of relative speed of the vessel and targets should not be located in case of collision avoidance. In the Fig. 2 vector $\mathbf{\Delta V_1} \in SDC_1$ and vector $\mathbf{\Delta V_2} \in SDC_2$, both targets are dangerous and collision avoidance is required. Change the direction of vectors $\mathbf{\Delta V_1}$, $\mathbf{\Delta V_2}$ can only be due to a change in the speed vector of the own vessel (the speed vector of the target is not available for control). As can be seen from Fig. 2a, fulfillment of conditions $\mathbf{V}_m \in \Omega_1$ and $\mathbf{V}_m \in \Omega_2$ allows to avoid colission with both targets, where Ω_1 – the area of allowable controls in case of collision avoidance with the first targets, is the area between the circles V_{max} and V_{min}, without SDC_1, and Ω_2 – the area of admissible controls in case of collision avoidance with the second targets, is the area between the circles V_{max} and V_{min}, wthout SDC_2. In Fig. 2b, these areas are also shown in Cartesian coordinates. (Ω_1 bounded by blue lines, and Ω_2 bounded by green lines).

General area $\Omega = \Omega_1 \bigcap \Omega_2$ consists of three subdomains: A1-X1-E2-A2, B2-B2'-C2'-X3-B1, C1-X2-C2 and is an area of allowable controls in case of collision avoidance with two targets at the same time.

As you can see, the area Ω is complex even for two targets and its analytical construction is difficult. In this regard, the authors proposed:

– the area of allowable controls should be built numerically in the onboard computer, which allows obtaining complex forms for any number of targets;

– the area of allowable controls should be built with a period of processing collision avoidance algorithms in the

DOI 10.15588/1607-3274-2019-4-20

onboard computer, which allows to take into account any changes in the mutual movement of the vessel and the targets, and therefore to diverge from the maneuvering targets.

To build the area $\Omega_j, j = 1..N_{tg}$ allowable control of collision avoidance with the j-target are taken trial vectors of collision avoidance $\mathbf{V}_T = (V_T \cos K_T, V_T \sin K_T)$ in the grid nodes of the whole area (in Fig. 2b between $V_{\min}, V_{\max}$ on the speed and between 0 and 360 degrees on the course), for each trial vector, a trial vector of relative motion is calculated with the j-target $\mathbf{\Delta V}_{Tj} = \mathbf{V}_{tgj} - \mathbf{V}_T$, which is checked for belonging SDCj:

$$(\mathbf{\Delta V}_{Tj} \times \mathbf{E}_{1j} \ \& \ \mathbf{\Delta V}_{Tj} \times \mathbf{E}_{2j}) < 0. \quad (1)$$

Orts $\mathbf{E}_{1j}, \mathbf{E}_{2j}$ are found by turning ort $\mathbf{E_{0j}}$ clockwise and counter-clockwise by an angle $\Theta_j = \arcsin(\frac{D_{sa}}{OE_j})$, equal to half SDCj:

$$\mathbf{E}_{1j} = \mathbf{E}_{0j} \times e^{-i\Theta j}, \mathbf{E}_{2j} = \mathbf{E}_{0j} \times e^{i\Theta j}.$$

Single vector $\mathbf{E}_{0j}$ and distance OEj to p. E_j, used in the above equations, are determined by the formulas:

$$\Delta X_{mj}(E) = \Delta X_{mj}(N) + \Delta V_{xj} \Delta T_m,$$

$$\Delta Y_{mj}(E) = \Delta Y_{mj}(N) + \Delta V_{yj} \Delta T_m,$$

$$OE_j = \sqrt{\Delta X_{mj}{}^2(E) + \Delta Y_{mj}{}^2(E)},$$

$$\mathbf{E}_{0j} = (\frac{\Delta X_{mj}(E)}{OE_j}, \frac{\Delta Y_{mj}(E)}{OE_j}).$$

If condition (1) is not met, trial vector $\mathbf{V}_T = (V_T \cos K_T, V_T \sin K_T)$ belongs to the areas of admissible controls. The area of permissible controls in case of collision avoidance with all targets can be obtained by combining the areas of permissible controls with each target separately.

$$\Omega = \Omega_1 \cap \Omega_2 \cap ... \cap \Omega_{Ntg}.$$

Any pair of collision avoidance parameters $(V_{n1}, K_{n1}) \in \Omega$ is valid for discrepancies with all targets simultaneously. Therefore, further selection of the parameters of the collision avoidance from Ω determined by additional conditions, for example, the conditions for optimizing the collision avoidance, the stability conditions (the invariance of the selected collision avoidance parameters), the Rules of the COLREG –72, etc. The deflection angle of the rudder δ and the deflection angle of the telegraph θ are determined as

$$\delta = k_\Psi(\Psi_m - K_{n1}) + k_\omega \omega_{mz} + k_\int \int (\Psi_m - K_{n1}) dt,$$

$$\theta = \frac{\pi}{2} \frac{V_{n1}}{V_{\max}}.$$

4 EXPERIMENTS

Algorithms for automatic collision avoidance with multiple targets, including maneuvering ones, were checked in a closed circuit with electronic simulators. As an example, the data on the collision avoidance with the five dangerous targets located around the vessel are given below.

Fig. 3 shows a screenshot of the vessel, targets and weather conditions from the visualization channels of the simulator.

Fig. 4 presents a screenshot from the instructor's workplace, which shows the position of the own ship CC_1 and the target ships $СЦ_1$-$СЦ_5$ at the time of the start of the collision avoidance. Trajectories of target ships have fractures, i.e. they are supposed to be maneuvered in the course of the task.

Figure 3 – Screenshot of the vessel, targets and weather conditions from the visualization channels of the simulator

DOI 10.15588/1607-3274-2019-4-20

Fig. 5 shows the position of the ships – the targets on the radar screen at the moment of the beginning of the collision avoidance. As you can see, 3 dangerous targets (their relative motion vectors are highlighted in red).

In Fig. 6 shows the areas of permissible controls in the process of collision avoidance at different points in time (at the beginning of the collision avoidance, in the process of collision avoidance and at the end of the collision avoidance). Each time point is represented by a vertical fragment with a common area of collision avoidance with all targets simultaneously, as well as two areas of collision avoidance with the first and second targets separately.

Fig. 7 shows a screenshot from the instructor's workplace at the end of the collision avoidance.

Fig. 8 shows the position of the targets on the radar at the end of the collision avoidance.

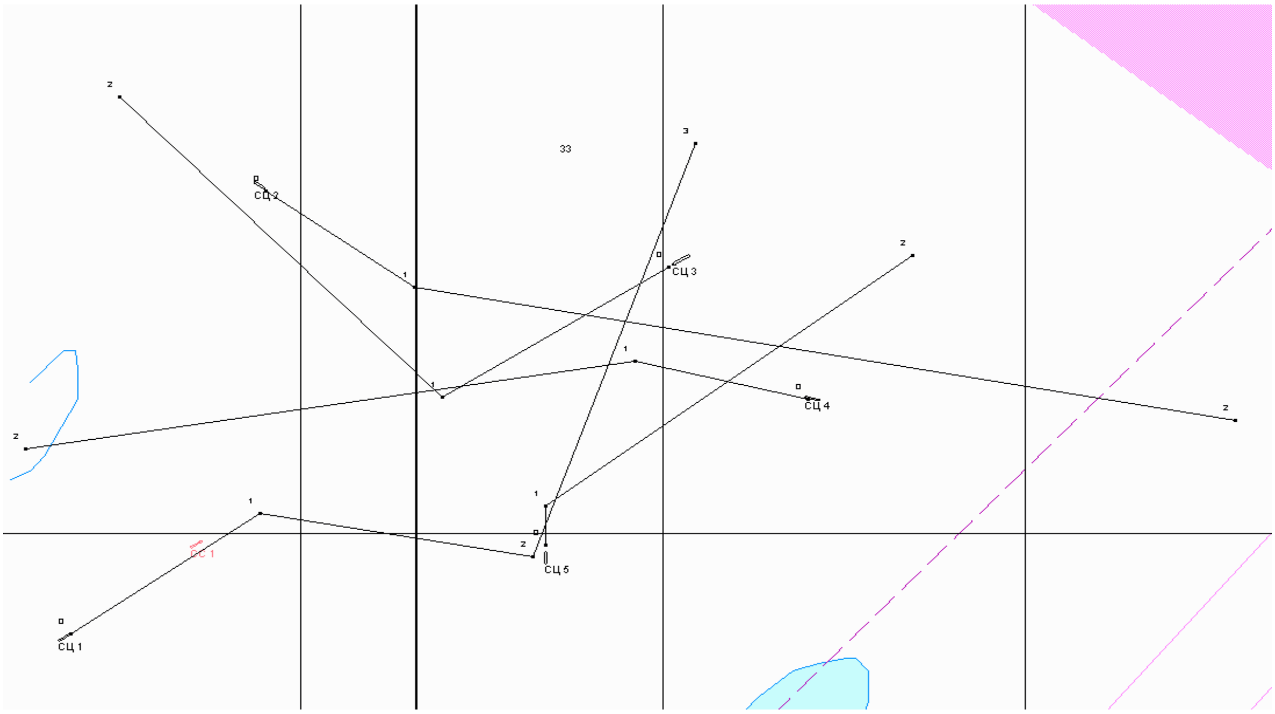

Figure 4 – The position of the vessel and targets at the beginning of the collision avoidance

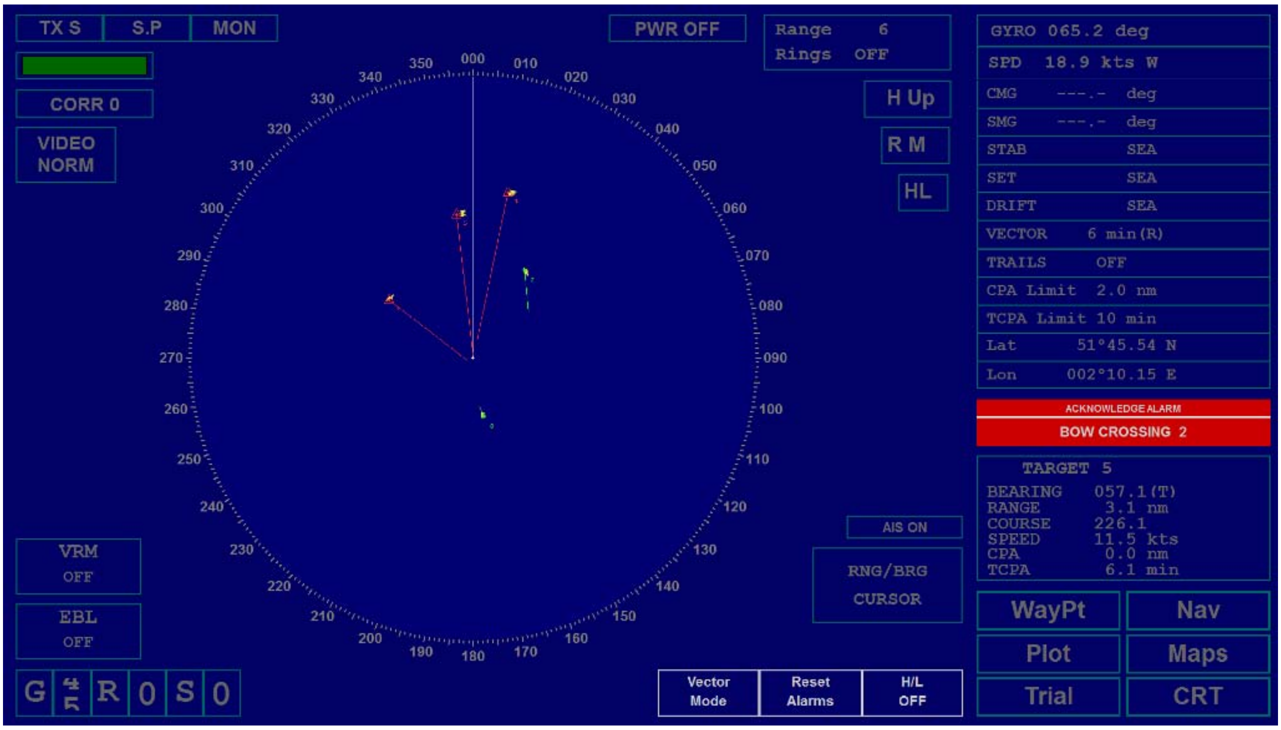

Figure 5 – Position of targets on the radar screen at the moment of the beginning of a collision avoidance

DOI 10.15588/1607-3274-2019-4-20

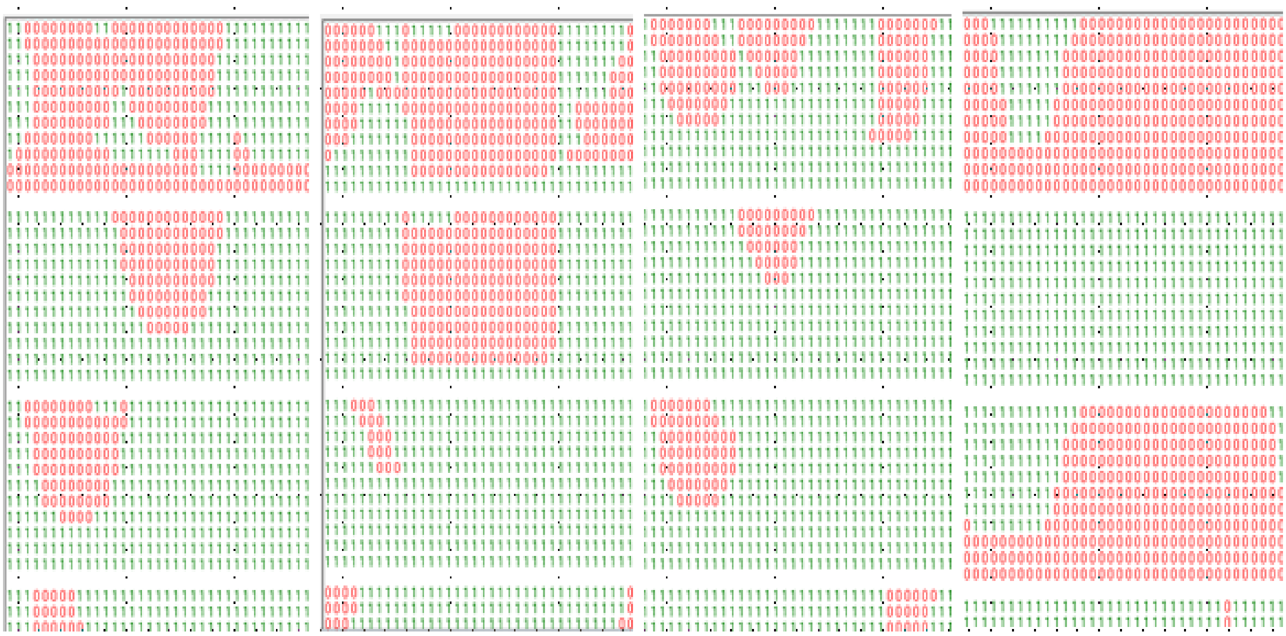

Figure 6 – Areas of permissible controls in the process of collision avoidance

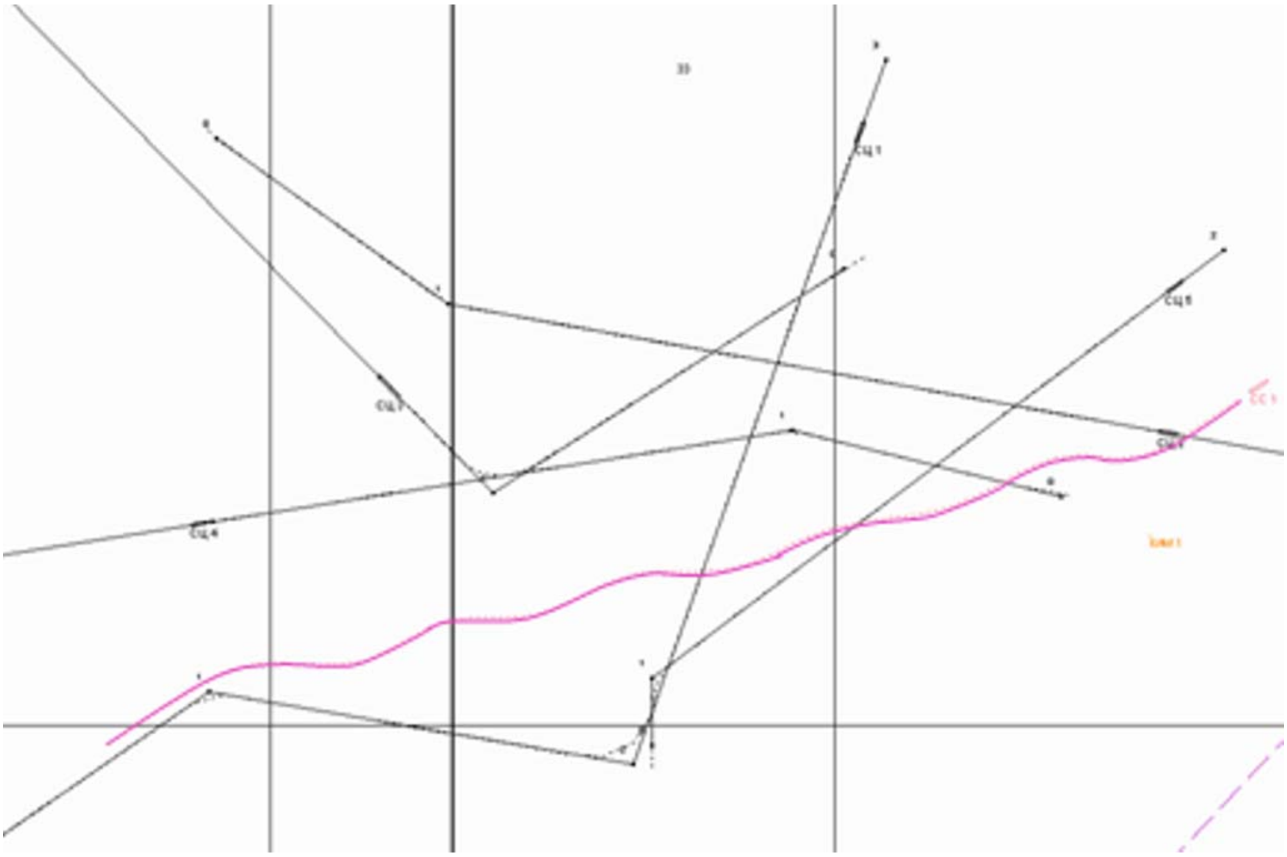

Figure 7 – Screenshot from the instructor's workplace at the end of the collision avoidance

DOI 10.15588/1607-3274-2019-4-20

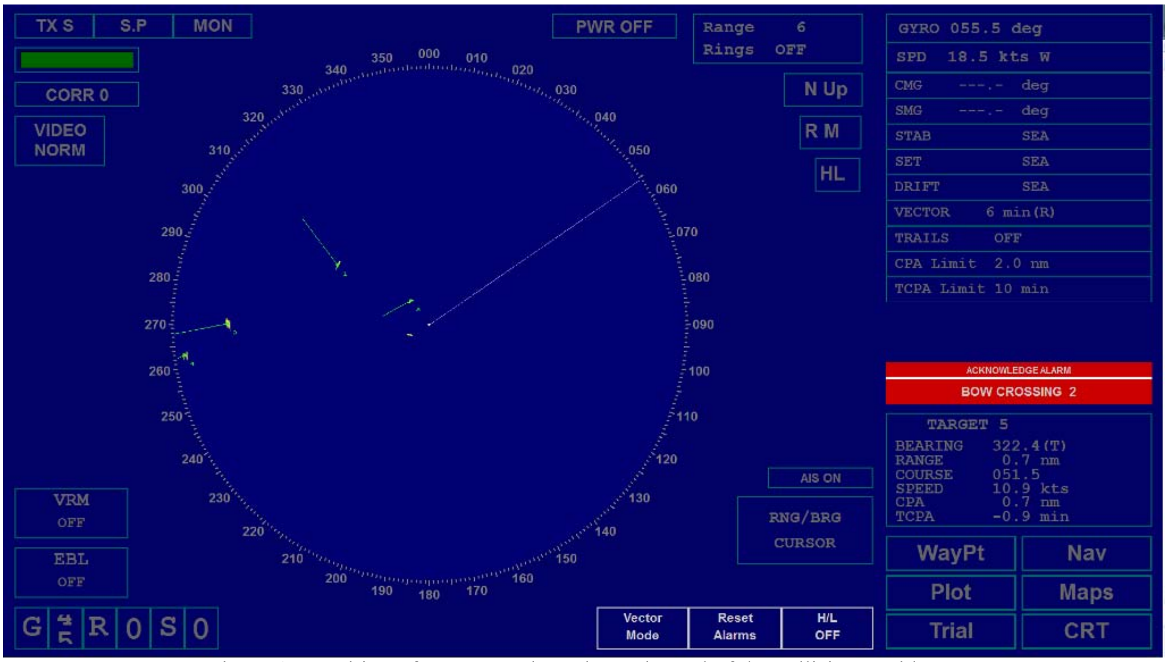

Figure 8 – Position of targets on the radar at the end of the collision avoidance

5 RESULTS

There were considered the issues of collision avoidance with many targets, including maneuvering ones, in a fully automatic mode.

There were analyzed existing methods of automatic collision avoidance of ships, their shortcomings were revealed and the relevance of the solution of this problem was substantiated.

There were developed a method and algorithms, which allow solving the problem of collision avoidance with multiple targets, including maneuvering ones, in onboard computer.

The efficiency of the method and algorithms was tested by mathematical modeling in a closed circuit with an electronic simulator Navi Trainer 5000 for various types of ships, targets, navigation areas and weather conditions.

6 DISCUSSION

The developed method and algorithms make it possible to diverge from multiple targets, including maneuvering ones, and can be used to create the software of the collision avoidance module of the onboard computer of the ship control system.

As shown by the simulation results in a closed circuit with the NTPRO 5000 simulator, the proposed method and algorithms, compared with the previously described solutions [5–14], allow to diverge from multiple targets, including maneuvering ones, in fully automatic mode.

CONCLUSIONS

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

The scientific novelty of the results obtained is that for the first time a method and algorithms for automatic divergence with many targets, including maneuvering ones, were developed. This one is achieved by periodically measuring the true speed of the vessel and relative speeds of the vessel and targets, averaging the measured information to remove noise, estimating the true speeds of the targets, building, for the obtained estimates of the true speeds of the targets, areas of allowable collision avoidance controls with each targets by numerical iteration of the collision avoidance parameters (speed and course) at the nodes of a given grid in the area of their possible changes, determining the relative speeds at the nodes of the grid ship and target movement and checking that the relative speeds don't belong to sectors of dangerous courses, building a general area of acceptable collision avoidance controls with all targets by combining areas of allowable collision avoidance controls with each target, choosing collision avoidance parameters from the general area of acceptable collision avoidance controls according to specified criteria. This allows to diverge from multiple targets, including maneuvering ones, in a fully automatic mode. Changing the criteria for selecting discrepancy parameters leads to a change in the ship's behavior in case of discrepancy without changing the program code.

The practical value of the obtained results is that the developed method and algorithms are implemented in software and investigated by solving the problem of collision avoidance from multiple targets, including maneuvering ones, in a fully automatic mode in a closed circuit with the simulator Navi Trainer 5000 for various types of ships, targets, navigation areas and weather conditions.

The experiments confirmed the performance of the proposed method and algorithms and allow to recommend them for practical use in the development of modules for automatic collision avoidance with multiple targets, including maneuvering ones, of the onboard controller of the ship control system.

DOI 10.15588/1607-3274-2019-4-20

Prospects for further research may lie in the development of methods for selecting the optimal parameters of the collision avoidance from the area of admissible controls.

ACKNOWLEDGEMENTS

The work is carried out within the framework of "Creation of high-accuracy intellectual systems for military-oriented and commercial ship's navigation" (state registration number 0117U002176), of navigation and ECDIS departments of Kherson State Maritime Academy Navigation Faculty (scientific adviser: PhD, Associate Professor, Deputy Rector for scientific and pedagogical work, Head of the Navigation and Electronic Navigation Systems Department, Kherson State Maritime Academy, Ukraine, Ben A.P.).

REFERENCES

1. COLREGS – International Regulations for Preventing Collisions at Sea [Electronic resource], *Lloyd's Register Rulefinder,* 2005, Version 9.4, 2009. Access mode: http://www.jag.navy.mil/distrib/instructions/COLREG-1972.pdf
2. Radar navigation and ship collision avoidance [Electronic resource], *Nautical Almanac*, 2019. Access mode: https://nauticalalmanac.it/en/navigation-astronomy/radar-navigation-maneuvering-board.html
3. Bole A., Wall A., Norris A. Radar and ARPA manual : Radar, AIS and Target Tracking for Marine Radar Users. Third Editon [Electronic resource], *Elsevir*, 2013, 552 p. Access mode: https://www.amazon.com/Radar-ARPA-Manual-Target-Tracking-ebook/dp/B00GY5XEYO #reader_B00GY5XEYO
4. Pipchenko A. Radar Plotting or... Do we really understand what ARPA does? [Electronic resource], *Learnmarine,* 2018. Access mode: //https://learnmarine.com/blog/Radar-Plotting-or...-Do-we-really-understand-what-ARPA-does?
5. Shen H., Hashimoto H., Matsuda A. et al. Automatic collision avoidance of multiple ships based on deep Q-learning, *Applied Ocean Research Journal,* 2019, Vol. 86. pp. 268–288. DOI: 10.1016/j.apor.2019.02.020.
6. Yishan L., Zhiqiang G., Jie Y. et al. Prediction of ship collision risk based on CART, *IET Intelligent Transport Systems,* 2018, Vol. 12, Issue 10, pp. 1345–1350. DOI: 10.1049/iet-its.2018.5281
7. Park J., Choi J., Choi H. COLREGS-compliant path planning considering time-varying trajectory uncertainty of autonomous surface vehicle, *Electronics Letters*, 2019, Vol. 55, Issue 4, pp. 222–224. DOI: 10.1049/el.2018.6680.
8. Tu E., Zhang G., Rachmawati L. et al. Exploiting AIS date for intelligent maritime navigation: a comprehensive survey, *IEEE Transactions on itelligent transportation system,* 2016, Vol. 19, Issue 5, P. 99. DOI: 10.1109/TITS.2017.2724551.
9. Smeaton G., Coenen F. Developing an intelligent marine navigation system, *Computing & Control Engineering Journal*, 1990, Vol. 1, Issue 2, P. 95–103. DOI: 10.1049/cce:19900024.
10. Huang Y., Chen L., Gelder P. Generalized velocity obstacle algorithm for preventing ship collisions at sea, *Ocean Engineering Journal,* 2019, Vol. 173, pp. 142–156. DOI: 10.1016/j.oceaneng.2018.12.053.
11. Johansen T. A., Cristoforo A., Perez T. Ship Collision Avoidance Using Scenario-Based Model Predictive Control [Electronic resource], *IFAC*, 2016. Access mode: https://pdfs.semanticscholar.org/34a3/c1a0b699774fadab417ca2f5ef422edb1f0b.pdf
12. Blaich M., Kohler S., Reuter J. et al. Probabilistic Collision Avoidance for Vessels, *IFAC – PapersOnLine,* 2015, Vol. 48, Issue 16, pp. 69–74. DOI: 10.1016/j.ifacol.2015.10.260
13. Abdelaal M., Franzle M., Hahn A. Nonlinear Model Predictive Control for trajectory tracking and collision avoidance of underactuated vessels with disturbances, *Ocean Engineering,* 2018, Vol. 160, pp. 168–180. DOI: 10.1016/j.oceaneng.2018.04.026
14. Zhao Yu., Li W., Shi P. A real-time collision avoidance learning system for Unmanned Surface Vessels, *Neurocomputing*, 2016, Vol. 182, pp. 255–266. DOI: 10.1016/j.neucom.2015.12.028

Received 06.02.2019.
Accepted 12.10.2019.

УДК 004.942:656.61.052

АВТОМАТИЧНЕ РОЗХОДЖЕННЯ З БАГАТЬМА ЦІЛЯМИ, ВКЛЮЧАЮЧИ МАНЕВРУЮЧІ

Зінченко С. М. – канд. техн. наук, ст. викладач кафедри управління судном, завідувач лабораторії електронних тренажерів, Херсонська державна морська академія, Україна.

Носов П. С. – канд. техн. наук, доцент кафедри навігаційних систем, Херсонська державна морська академія, Україна.

Матейчук В. М. – асистент кафедри управління судном, завідувач лабораторії електронних тренажерів, Херсонська державна морська академія, Україна.

Маменко П. П. – ст. викладач кафедри управління судном, капітан далекого плавання, Херсонська державна морська академія, Україна.

Грошева О. О. – ст. викладач кафедри управління судном, Херсонська державна морська академія, Україна.

АНОТАЦІЯ

Актуальність. Розглядається задача автоматичного розходження з багатьма цілями, включаючи маневруючі. Об'єктом дослідження є процес автоматичного розходження з багатьма цілями, включаючи маневруючі. Предметом дослідження є метод і алгоритми, що реалізують процес автоматичного розходження з багатьма цілями, включаючи маневруючі.

Мета. Метою статті є розробка методу і алгоритмів автоматичного розходження з багатьма цілями, включаючи маневруючі, для модуля бортового контролера системи управління судном.

Метод. Ця мета досягається періодичним, з тактом роботи бортового контролера, вимірюванням істинної швидкості судна і відносних швидкостей судна і цілей, усередненням виміряної інформації для видалення шумів, оцінкою істинних швидкостей цілей, побудовою, для отриманих оцінок істинних швидкостей цілей, областей допустимих управлінь розходженням з кожною ціллю шляхом чисельного перебору параметрів розходження (швидкості і курсу) на вузлах заданої сітки в області їх можливих змін, визначенням на вузлах сітки відносних швидкостей руху судна і цілей і перевіркою їх на не приналежність секторам небезпечних курсів, побудовою загальної області допустимих управлінь розходженням з усіма цілями шляхом об'єднання областей допустимих управлінь розходженням з кожною ціллю, вибором параметрів розходження із загальної області допустимих управлінь розходженням у відповідності із заданими критеріями. Це дозволяє розходитися з багатьма цілями, включаючи маневруючі, у повністю автоматичному режимі. Зміна критеріїв вибору параметрів розходження призводить до зміни поведінки судна при розходженні без зміни програмного коду.

Результати. Розроблені метод та алгоритми реалізовані в програмному забезпеченні і досліджені шляхом вирішення задачі розходження з багатьма цілями, включаючи маневруючі, у повністю автоматичному режимі у замкнутій схемі з тренажером Navi Trainer 5000 для різних типів суден, цілей, районів плавання і погодних умов.

DOI 10.15588/1607-3274-2019-4-20

Висновки. Експерименти підтвердили працездатність запропонованого способу і алгоритмів і дозволяють рекомендувати їх для практичного використання при розробці модулів автоматичного розходження з багатьма цілями, включаючи маневруючі, бортового контролера системи управління судном.

КЛЮЧОВІ СЛОВА: система розходження суден, автоматичне розходження, розходження з маневруючими цілями, попередження зіткнень, область допустимих управлінь.

УДК 004.942:656.61.052

АВТОМАТИЧЕСКОЕ РАСХОЖДЕНИЕ СО МНОГИМИ ЦЕЛЯМИ, ВКЛЮЧАЯ МАНЕВРИРУЮЩИЕ

Зинченко С. Н. – канд. техн. наук, ст. преподаватель кафедры управления судном, заведующий лабораторией электронных тренажеров, Херсонская государственная морская академия, Украина.

Носов П. С. – канд. техн. наук, доцент кафедры навигационных систем, Херсонская государственная морская академия, Украина.

Матейчук В. Н. – ассистент кафедры управления судном, заведующий лабораторией электронных тренажеров, Херсонская государственная морская академия, Украина.

Маменко П. П. – ст. преподаватель кафедры управления судном, капитан дальнего плавания, Херсонская государственная морская академия, Украина.

Грошева О. А. – ст. преподаватель кафедры управления судном, Херсонская государственная морская академия, Украина.

АННОТАЦИЯ

Актуальность. Рассматривается задача автоматического расхождения со многими целями, включая маневрирующие. Объектом исследования является процесс автоматического расхождения со многими целями, включая маневрирующие. Предметом исследования являются метод и алгоритмы, реализующие процесс автоматического расхождения со многими целями, включая маневрирующие.

Цель. Целью статьи является разработка метода и алгоритмов автоматического расхождения со многими целями, включая маневрирующие, для модуля бортового контроллера системы управления судном.

Метод. Эта цель достигается периодическим, с тактом работы бортового контроллера, измерением истинной скорости судна и относительных скоростей судна и целей, усреднением измеренной информации для удаления шумов, оценкой истинных скоростей целей, построением, для полученных оценок истинных скоростей целей, областей допустимых управлений расхождением с каждой целью путем численного перебора параметров расхождения (скорости и курса) на узлах заданной сетки в области их возможных изменений, определением на узлах сетки относительных скоростей движения судна и целей и проверкой их на не принадлежность секторам опасных курсов, построением общей области допустимых управлений расхождением со всеми целями путем объединения областей допустимых управлений расхождением с каждой целью, выбором параметров расхождения из общей области допустимых управлений расхождением в соответствие с заданными критериями. Это позволяет разойтись со многими целями, включая маневрирующие, в полностью автоматическом режиме. Изменение критериев выбора параметров расхождения приводит к изменению поведения судна при расхождении без изменения программного кода.

Результаты. Разработанные метод и алгоритмы реализованы в программном обеспечении и исследованы путем решения задачи расхождения со многими целями, включая маневрирующие, в полностью автоматическом режиме в замкнутой схеме с тренажером Navi Trainer 5000 для различных типов судов, целей, районов плавания и погодных условий.

Выводы. Эксперименты подтвердили работоспособность предлагаемого 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: система расхождения судов, автоматическое расхождение, расхождение с маневрирующими целями, предупреждение столкновений, область допустимых управлений.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. COLREGS – International Regulations for Preventing Collisions at Sea [Electronic resource] // Lloyd's Register Rulefinder 2005 – Version 9.4. – 2009. – Access mode: http://www.jag.navy.mil/distrib/instructions/COLREG–1972.pdf
2. Radar navigation and ship collision avoidance [Electronic resource] // Nautical Almanac. – 2019. – Access mode: https://nauticalalmanac.it/en/navigation-astronomy/radar-navigation-maneuvering-board.html
3. Radar and ARPA manual : Radar, AIS and Target Tracking for Marine Radar Users. Third Editon [Electronic resource] / A. Bole, A. Wall, A. Norris. – Elsevir, 2013. – 552 p. – Access mode: https://www.amazon.com/Radar-ARPA-Manual-Target-Tracking-ebook/dp/B00GY5XEYO #reader_B00GY5XEYO
4. Pipchenko A. Radar Plotting or... Do we really understand what ARPA does? [Electronic resource] / A. Pipchenko // Learnmarine. – 2018. – Access mode: //https://learnmarine.com/blog/Radar-Plotting-or...-Do-we-really-understand-what-ARPA-does?
5. Automatic collision avoidance of multiple ships based on deep Q-learning / [H. Shen, H. Hashimoto, A. Matsuda et al.] // Applied Ocean Research Journal. – 2019. – Vol. 86. – P. 268–288. DOI: 10.1016/j.apor.2019.02.020.
6. Prediction of ship collision risk based on CART / [L. Yishan, G. Zhiqiang, Y. Jie et al.] // IET Intelligent Transport Systems. – 2018. – Vol. 12. – Issue 10. – P. 1345–1350. DOI: 10.1049/iet-its.2018.5281
7. Park J. COLREGS-compliant path planning considering time-varying trajectory uncertainty of autonomous surface vehicle / J. Park, J.Choi, H. Choi // Electronics Letters. – 2019. – Vol. 55, Issue 4. – P. 222–224. DOI: 10.1049/el.2018.6680.
8. Exploiting AIS date for intelligent maritime navigation: a comprehensive survey / [E. Tu, G. Zhang, L. Rachmawati et al.] // IEEE Transactions on itelligent transportation system. – 2016. – Vol. 19, Issue 5. – P. 99. DOI: 10.1109/TITS.2017.2724551.
9. Smeaton G. Developing an intelligent marine navigation system / G. Smeaton, F. Coenen // Computing & Control Engineering Journal. – 1990. – Vol. 1, Issue 2. – P. 95–103. DOI: 10.1049/cce:19900024.
10. Huang Y. Generalized velocity obstacle algorithm for preventing ship collisions at sea / Y. Huang, L. Chen, P. Gelder // Ocean Engineering Journal. – 2019. – Vol. 173. – P. 142–156. DOI: 10.1016/j.oceaneng.2018.12.053.
11. Johansen T. A. Ship Collision Avoidance Using Scenario-Based Model Predictive Control [Electronic resource] / T. A. Johansen, A. Cristoforo, T. Perez // IFAC. – 2016. – Access mode: https://pdfs.semanticscholar.org/34a3/c1a0b699774fadab417ca2f5ef422edb1f0b.pdf
12. Probabilistic Collision Avoidance for Vessels / [M. Blaich, S. Kohler, J. Reuter et al.] // IFAC –PapersOnLine. – 2015. – Vol. 48, Issue 16. – P. 69–74. DOI: 10.1016/j.ifacol.2015.10.260
13. Abdelaal M. Nonlinear Model Predictive Control for trajectory tracking and collision avoidance of underactuated vessels with disturbances / M. Abdellal, M. Franzle, A. Hahn // Ocean Engineering. – 2018. – Vol. 160. – P. 168–180. DOI: 10.1016/j.oceaneng.2018.04.026
14. Zhao Yu. A real-time collision avoidance learning system for Unmanned Surface Vessels / Yu. Zhao, W. Li, P. Shi // Neurocomputing. – 2016. – Vol. 182. – P. 255–266. DOI: 10.1016/j.neucom.2015.12.028

DOI 10.15588/1607-3274-2019-4-20