Zinchenko, Serhii; Tovstokoryi, Oleh; Sapronov, Oleksandr et al.

Article

Collision avoidance by constructing and using a passing area in on-board controller

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Igor Prasol, *Doctor of Technical Sciences, Professor, Department of Biomedical Engineering, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-2537-7376*

Olexandr Dovnar, *PhD, Associate Professor, Department of Radio-Electronic and Biomedical Computer-Aided Means and Technologies, National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-7171-0024*

✉***Olha Yeroshenko,*** *Assistant, Department of Electronic Computers; Postgraduate Student, Department of Biomedical Engineering, Kharkiv National University of Radio Electronics, Kharkiv, Ukraine, e-mail: olha.yeroshenko@nure.ua, ORCID: https://orcid.org/0000-0001-6221-7158*

✉*Corresponding author*

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**Serhii Zinchenko,
Oleh Tovstokoryi,
Oleksandr Sapronov,
Kostiantyn Tymofeiev,
Andrii Petrovskyi,
Artem Ivanov**

COLLISION AVOIDANCE BY CONSTRUCTING AND USING A PASSING AREA IN ON-BOARD CONTROLLER

The object of research is the processes of automatic optimal passing of one's own ship with many dangerous targets, including maneuvering ones, by the method of constructing the area of permissible passing parameters in the on-board computer. According to the European Maritime Safety Agency (EMSA), the largest number of ship accidents in 2014–2019 occurred due to collision (32 %). On modern ships, for observation and passing with targets, ARPA (automatic radar plotting aid) is used, which allows to automate manual operations, and the built-in function «Playing the maneuver» provides the navigator with a convenient graphic interface for solving passing problems. At the same time, ARPA is an automated system that assumes the presence of an operator in the control circuit. The presence of a person in the control circuit is related to the «human factor», which is a prerequisite for the occurrence of various types of accidents, including ship collisions. The most effective means of reducing the influence of the «human factor» on control processes is the introduction of automatic control modules in automated systems. The paper develops a method for the passing module, which allows automatic and optimal passing with many targets, including maneuvering ones. The number of targets for passing is not limited by the method, but is limited only by the capabilities of the ARPA to track the targets. The obtained results are explained by the fact that at each step of the on-board computer, a region of permissible passing parameters is constructed for all purposes, passing parameters that optimize a given optimality criterion are selected from the constructed region, the selected parameters are used as software in the control law. The developed method can be used on ships, subject to integration into the existing automated system of an on-board computer with an open architecture, to increase the capabilities of automatic traffic control, in this case, the possibility of automatic optimal passing with many objectives, including maneuvering.

Keywords: *passing of ships, safety of shipping, optimization of control processes, automatic control module, simulation stand.*

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1. Introduction

According to the European Maritime Safety Agency (EMSA), the causes of ship accidents in 2014–2019 were: collision (32 %), loss of control (30 %), equipment failure (14 %), grounding (13 %), fires (6 %), flooding (3 %), loss of structural integrity of the hull (1 %) and others (1 %). As can be seen from the given data, the largest share of the causes of accidents is collisions. A radar station is a tool for measuring the parameters of the relative movement of ships and targets, for calculating the passing of ships. The measured radar parameters (bearing and distance) are used for radar laying (calculation of passing parameters). Previously, it was manual laying on a maneuvering tablet, which had low accuracy and was very labor-intensive. On modern ships, for tracking targets, ARPA (automatic radar plotting aid) [1, 2] is used, which allows to automate manual operations, and the built-in function «Playing the maneuver» provides the navigator with a convenient graphical interface for solving the problems of ship passing. At the same time, ARPA has significant disadvantages:

– ARPA is an automated system that assumes the presence of a person in the control circuit;
– ARPA «Maneuver Playback» function provides the navigator only with a convenient graphical interface, but the navigator selects the passing parameters manually, which takes time;
– «Maneuver playback» function allows to determine the passing parameters only for non-maneuvering targets.

The presence of a person in the control circuit is related to the human factor, which is a prerequisite for the occurrence of the above-mentioned accidents. Reducing human influence on control processes can be achieved through the introduction of automated decision support systems, energy systems [3], or automated systems with automatic control modules [4]. An example of an automatic module in an automated system, which is used on almost all ships today, is the autopilot.

The issue of automatic passing of ships was considered by many authors. Thus, in [5], an automatic differentiation system based on deep Q-learning was proposed. The advantage of this method is that the control system receives information from the environment with which the ship interacts, which allows optimizing the passing processes. The disadvantage of the proposed method is that during Q-learning, the system may not work optimally or even erroneously, which threatens with serious consequences.

The work [6] describes the method of assessing the risk of collision of ships, based on the complex non-linear relationship between the degree of risk of collision and influencing factors. Collision risk estimates with expert information on collision avoidance experience are entered into a database for future reference. The solution proposed by the authors involves training the system, which is unacceptable during the passing of ships. In addition, the learning process is associated with the long-term accumulation of information, the use of databases, the organization of a quick search for information in the database, the need for additional database maintenance.

The article [7] describes the route planning method taking into account the collision risk, dynamic characteristics of the control object and COLREG-72 rules. Simulation results are presented, which confirm the workability of the proposed approach to ship passing. The disadvantage of the method is the assessment of the risk of collision only with non-maneuverable targets. Also, the method does not provide for the formation of controls for passing in automatic mode.

As a result of the analysis, the authors of the article [8] came to the conclusion that the ship passing algorithms developed in recent decades do not foresee passing with maneuvering targets, allow passing with one or two targets, use simplified dynamics of the ship and targets. A collision prevention method and system is proposed, which involves visualization of changes in the ship's course and speed leading to a collision. The collision avoidance system can also offer ways to avoid collisions, consistent with the COLREG-72 Rules, which are implemented with a minimum number of operations. The proposed collision avoidance method and systems can be used under manual control, in decision support systems, but do not provide automatic passing with many maneuvering targets.

The passing method using predictive models is considered in [9]. Prediction of the trajectory of the ship and the target is carried out in the on-board computer based on the parameters of the ship's movement measured at the current time and the estimated parameters of the target's movement. This forecast, taking into account COLREG-72 rules, is used to determine the optimal passing management strategy. The disadvantage of the method is the significant load on the on-board computer, as well as the possibility of passing with only one ship.

The aim of research is to develop a method of passing with ships and targets by constructing the area of passing in the on-board computer. This will make it possible to automatically pass from many maneuvering targets, significantly reduce the influence of the human factor on control processes and increase the safety of shipping.

2. Materials and Methods

The object of research is the processes of automatic optimal passing of one's own ship with many dangerous targets, including maneuvering ones, by the method of constructing the area of permissible passing parameters in the on-board computer. The research used a systematic approach, analysis and synthesis, mathematical analysis, methods of automatic control theory, methods of conducting an experiment. As well as equipment: a personal computer with the Windows 10 operating system and a suite of MS Office 2016 application programs, a simulation stand developed by the authors on the basis of the Navi Trainer 5000 navigation simulator.

3. Results and Discussion

Fig. 1 shows the scheme of passing of own ship O with the target $O_j, j=1..n$.

The own ship is placed in the center of the coordinate system OX_gY_g, a circle with a radius R_{sa} (safe passing zone) is drawn around the ship, and the speed vector of the own ship $\mathbf{V}_n$ is depicted. The drawn Line of Relative Motion (RML_j), on which lies the vector of the relative speed $\Delta\mathbf{V}_j$ of the own ship and the target (shown in blue), as well as the expected lines of relative motion $ERML_j^+$, $ERML_j^-$, shown in red lines. Between the lines $ERML_j^+$, $ERML_j^-$ there is a sector of dangerous courses, in which the vector of relative speed $\Delta\mathbf{V}_j$ should not be directed, in order to avoid a collision. Circles with radii $V_{\max}$ and $V_{\min}$, which correspond to the maximum and minimum speed of one's own ship, are drawn around the center O_j. The area between the circles $V_{\max}$ and $V_{\min}$, with the exception of the two dangerous course sectors DFB and AFC, is the area of permissible passing parameters (course and speed) with the j-target.

Fig. 2 shows the area of permissible parameters of passing from the j-target in the Cartesian coordinate system. The vertical axis of the area is the departure speed V_{n1} of the own ship, and the horizontal axis of the area is the departure course of the own ship K_{n1}.

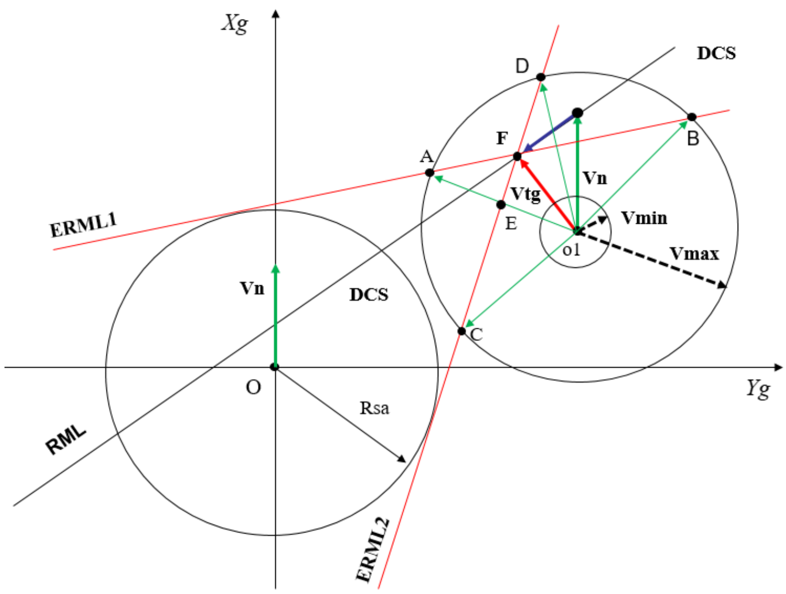

Fig. 1. The scheme of the ship's passing from the *j*-target

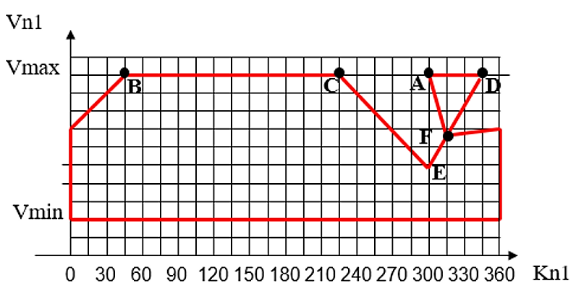

Fig. 2. The area of permissible parameters of passing from the *j*-target in the Cartesian coordinate system

The range Ω of acceptable passing parameters with all targets simultaneously can be determined by combining the ranges $\Omega_j, j=1..n$ of allowable passing parameters with each target separately:

$$\Omega = \Omega_1 \cap \Omega_2 \cap \Omega_3 ... \cap \Omega_n. \quad (1)$$

As can be seen from Fig. 2, the range of permissible passing parameters even with one target is quite complex, so it is advisable to build it in an on-board computer using numerical methods. To do this, let's set trial passing vectors $\mathbf{V}_{n1} = (V_{n1}, K_{n1})$ at grid nodes (Fig. 2) and determine for each of them the relative speed of passing with each target:

$$\Delta\mathbf{V}_j = \mathbf{V}_j - \mathbf{V}_{n1}. \quad (2)$$

If the relative speed vector (2), calculated for the test vector $\mathbf{V}_{n1} = (V_{n1}, K_{n1})$, is not directed inside the sector of dangerous courses of the *j*-target, then such a test vector belongs to the region of safe passing Ω_j.

As can be seen from Fig. 1, the vector of the relative speed $\Delta\mathbf{V}_j$ does not belong to the sector of dangerous courses of the *j*-target, if the vector products $\Delta\mathbf{V}_j \times \mathbf{e}_j^+$ and $\Delta\mathbf{V}_j \times \mathbf{e}_j^-$ have the same sign:

$$\begin{cases} \mathbf{V}_{n1} \in \Omega_j, \text{ if } \left(< \Delta\mathbf{V}_j \times \mathbf{e}_j^+, \Delta\mathbf{V}_j \times \mathbf{e}_j^- > \right) > 0, \\ \mathbf{V}_{n1} \notin \Omega_j, \text{ if } \left(< \Delta\mathbf{V}_j \times \mathbf{e}_j^+, \Delta\mathbf{V}_j \times \mathbf{e}_j^- > \right) < 0, \end{cases} \quad (3)$$

where $\mathbf{e}_j^+$, $\mathbf{e}_j^-$ – orthogonals that specify the directions $ERML_j^+$, $ERML_j^-$, respectively, $< \Delta\mathbf{V}_j \times \mathbf{e}_j^+, \Delta\mathbf{V}_j \times \mathbf{e}_j^- >$ – scalar product of vectors $\Delta\mathbf{V}_j \times \mathbf{e}_j^+$ and $\Delta\mathbf{V}_j \times \mathbf{e}_j^-$.

Unit vectors $\mathbf{e}_j^+$ and $\mathbf{e}_j^-$ are located as follows, Fig. 1:

$$\begin{cases} \mathbf{e}_j^+ = \mathbf{e}_j^0 \times e^{i\Delta\varphi}, \\ \mathbf{e}_j^- = \mathbf{e}_j^0 \times e^{-i\Delta\varphi}, \\ \mathbf{e}_j^0 = (-\cos P_{mj}, -\sin P_{mj}), \\ \Delta\varphi = \operatorname{arctg}\left(\dfrac{R_{sa}}{D_{mj}}\right), \end{cases} \quad (4)$$

where $\mathbf{e}_j^0$ – unit vector, which sets the direction from the target to our ship; $e^{i\Delta\varphi}$ – operator of rotation of the unit vector $\mathbf{e}_j^0$ by the angle $\Delta\varphi$ clockwise to the combination with $ERML_j^+$; $e^{-i\Delta\varphi}$ – the operator of rotation of the unit vectors $\mathbf{e}_j^0$ by an angle $\Delta\varphi$ counterclockwise to the combination with $ERML_j^-$; P_{mj}, D_{mj} – measured radar bearings and distances to targets.

In formula (2), the speed vector $\mathbf{V}_j$ of the target is not available for direct measurement, so it must be constantly estimated with the help of observation devices:

$$\begin{cases} T\dfrac{d}{dt}\left(\Delta\hat{V}_j\right) + \Delta\hat{V}_j = k_1(D_{mj} - \hat{D}_j), \\ \dfrac{d}{dt}\left(\hat{D}_j\right) = \Delta\hat{V}_j + k_2(D_{mj} - \hat{D}_j), \\ \hat{V}_{xj} = V_{xm} + \Delta\hat{V}_j \cos P_{mj}, \\ \hat{V}_{yj} = V_{ym} + \Delta\hat{V}_j \sin P_{mj}, \end{cases} \quad (5)$$

where T – time constant when evaluating the relative speed; $\Delta\hat{V}_j$ – estimation of the relative speed of the *j*-target; $\hat{D}_j$ – estimation of the distance to the *j*-target; $\mathbf{V}_m = (V_{xm}, V_{ym})$ – vector and components of the measured speed of the own ship; $\hat{\mathbf{V}}_j = (\hat{V}_{xj}, \hat{V}_{yj})$ – estimation of the vector and components of the vector of the true speed of the target.

The range Ω of permissible passing parameters (1) constantly changes over time, depending on the relative position and speed of one's own ship and targets. Therefore, its calculation must be performed constantly, at each step of the on-board calculator. For heading grid step $\Delta K_{n1} = 1°$, course change range $-180° \le K_{n1} \le 180°$, high speed grid step $\Delta V_{n1} = 0.5$ knots, speed change range $0 \le V_{n1} \le 20$, when passing with 10 targets, it is necessary to process $N = 360/1 \cdot 20/0.5 \cdot 10 = 144000$ points at each step. For a computer with a clock frequency of $f = 1–2$ GHz, these costs are insignificant. At the same time, the construction of the area of permissible passing parameters in real time allows passing with maneuvering targets. At the same time, the number of targets is not limited by the passing algorithm, but is limited only by the capabilities of ARPA to track targets.

Optimization of passing processes. Fig. 3 shows the range of allowable multi-objective passing parameters.

The presence of a region of admissible passing parameters means the presence of an infinite number of solutions, among which there are optimal ones according to the selected criterion of optimality. Let's consider as a criterion of optimality the minimization of passings from the given course, which is associated with the minimization of fuel consumption in the process of passing. For the position of one's own ship in point 1, the best, from the point of view of the selected criterion, is point 2, which belongs to the area of permissible passing parameters and is at the closest angular distance to point 1. The transition to point 2 can be carried out by a combined maneuver (changing course and speed). For the position of the own ship in item 3, the best, from the point of view of the selected criterion, is item 4, which belongs to the area of permissible passing parameters and is on the same course as item 3. The transition to item 4 from item 3 is possible to carry out by changing the speed of one's own ship.

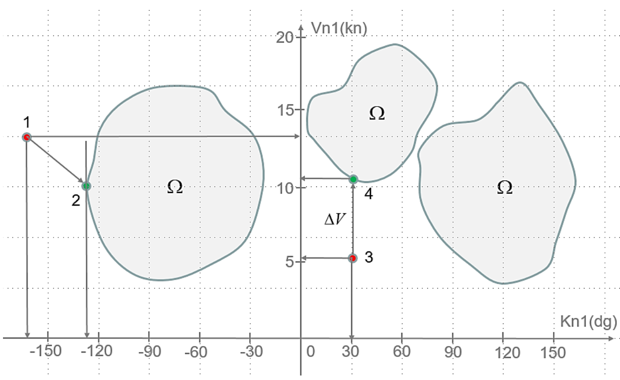

Fig. 3. The area of permissible passing parameters

The defined passing parameters $(V_{n1}, K_{n1}) \in \Omega$ are used as program values in the control law:

$$\begin{cases} \theta = \dfrac{\pi}{2}\dfrac{V_{n1}}{V_{\max}}, \\ \delta = k_{\varphi}(\varphi_m - K_{n1}) + k_{\omega}\omega_{zm} + k_{\int} \int (\varphi_m - K_{n1})\mathrm{d}t, \end{cases} \quad (6)$$

where θ – telegraph deflection angle; δ – stern deflection angle; φ_m – measured rate; ω_{zm} – measured yaw angular speed; $k_{\varphi}, k_{\omega}, k_{\int}$ – gain coefficients of the PID regulator.

The performance and efficiency of the developed method, algorithmic and software of the automatic passing module with many dangerous targets, including maneuvering, tested on a simulation bench, in a closed circuit with models of the Navi Trainer 5000 simulator [10].

At the instructor's workplace, Fig. 4, a problem is created for automatic optimal passing of own ship with nine dangerous targets.

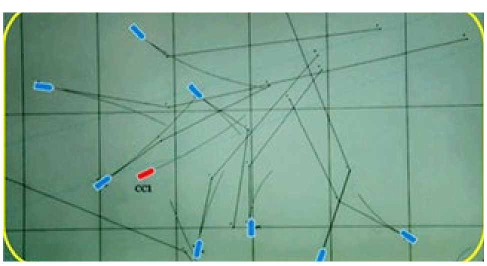

Fig. 4. The instructor's workplace at the beginning of the passing

The own ship is depicted in red; the entire ships are depicted in blue. Planned target trajectories and their trends are shown. Some of the targets create a threat of collision at the beginning of the passing; the other part of the targets becomes dangerous after changing their courses. Moments of course changes are planned at the breaking points of the target trajectories. The radius of the region of safe passing is taken as $R_{sa} = 0.5$ nm.

Fig. 5 shows the instructor's workplace after 5 minutes automatic passing.

Fig. 6 shows the ARPA screen in 5 minutes after passing.

Fig. 7 shows the memory dump of the on-board computer at the fifth minute of passing, displayed in the simulation bench data exchange program [10]. An area containing a dump value of «1» is the own ship's safe passing area for all purposes.

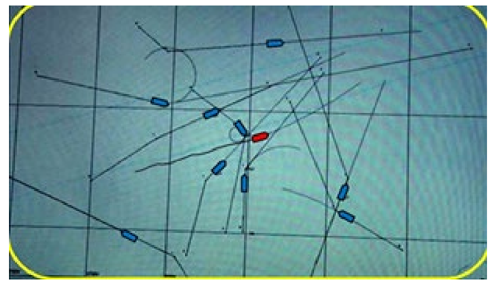

Fig. 5. The instructor's workplace in 5 minutes after passing

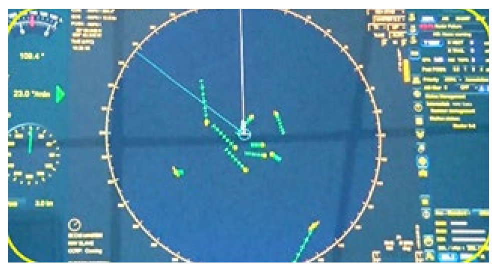

Fig. 6. ARPA in 5 minutes after passing

Fig. 7. Memory dump of the on-board computer

Summing up and taking into account the results of the experiment, it can be noted that the proposed method and the algorithmic and software developed on its basis allow automatic and optimal passing of many dangerous targets, including maneuvering ones. The obtained result is explained by the use of the area of safe passing for all purposes to solve passing problems. The area of safe passing is built using numerical methods at each step of the calculation, which allows to constantly take into account changes in the relative position of your own ship and targets. The departure parameters (course and speed) are selected from the safe departure area according to the established optimality criterion. The passing parameters are used as program values in the PID controller to adjust the ship's current course and speed. Unlike ARPA, the proposed passing method allows for automatic passing with maneuvering targets, which minimizes the influence of the human factor on control processes. Compared to known solutions of automatic passing, the developed method allows passing from many dangerous targets, including maneuvering ones. The maximum number of targets for passing is not limited by the method of passing, but is limited only by the capabilities of ARPA in terms of the number of accompanied targets. The developed method can be used on ships, subject to integration into the existing automated system of an on-board computer with an open architecture, to increase the capabilities of automatic traffic control, in this case, the possibility of automatic optimal passing with many objectives, including maneuvering.

The theoretical significance of the obtained result lies in the development of a method of automatic optimal passing of one's own ship with many dangerous targets, including maneuvering ones. The practical significance of the obtained result lies in the possibility of using the automatic optimal passing module in automated systems with expandable architecture, automating and optimizing, due to this, passing operations, reducing crew fatigue and increasing reliability.

The limitations of the developed method include the impossibility of its application for manual control.

In further works, it is planned to investigate the regularities of changes in the region during passing in order to predict its future forms.

4. Conclusions

A passing method has been developed that allows automatic and optimal passing with many targets, including maneuvering ones. The result was obtained thanks to the construction at each step of the on-board calculator of the safe passing area of one's own ship for all purposes, the selection of the passing parameters from the constructed area, in accordance with the established criterion of optimality, the use of the selected passing parameters as software in the law of controlling the movement of the ship. The developed method can be used to build automatic passing modules in an on-board computer of an automated system. This will make it possible to automate and optimize passing processes, significantly reduce the influence of the human factor on control processes, optimize the performance of a functional task, reduce crew fatigue, and generally improve shipping safety.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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✉***Serhii Zinchenko,*** *Doctor of Technical Sciences, Associate Professor, Department of Ship Handling, Kherson State Maritime Academy, Kherson, Ukraine, e-mail: srz56@ukr.net, ORCID: https://orcid.org/0000-0001-5012-5029*

Oleh Tovstokoryi, *PhD, Associate Professor, Deep Sea Captain, Department of Ship Handling, Kherson State Maritime Academy, Kherson, Ukraine, ORCID: https://orcid.org/0000-0003-3048-0028*

Oleksandr Sapronov, *Doctor of Technical Sciences, Professor, Department of Transport Technologies and Mechanical Engineering, Kherson State Maritime Academy, Kherson, Ukraine, ORCID: https://orcid.org/0000-0003-1115-6556*

Kostiantyn Tymofeiev, *PhD, Associate Professor, Department of Ship Electrical Equipment and Automatic Devices Operation, Kherson State Maritime Academy, Kherson, Ukraine, ORCID: https://orcid.org/0000-0002-8668-6159*

Andrii Petrovskyi, *PhD, Associate Professor, Department of Navigation, Kherson State Maritime Academy, Kherson, Ukraine, ORCID: https://orcid.org/0000-0002-3337-9577*

Artem Ivanov, *PhD, Acting Head of Department of Ship Electrical Equipment and Automatic Devices Operation, Kherson State Maritime Academy, Kherson, Ukraine, ORCID: https://orcid.org/0000-0002-1919-2570*

✉*Corresponding author*