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Cybersecurity of the Processes of Manoeuvring in Confined Waters

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ABSTRACT: In this work, the routes for inbound / outbound from each berth in the port of Chornomorsk were designed according to the ship's pilotage plan for navigational purposes. On the basis of the received information, a computer-aided planning of recommended routes for pilotage of all types of vessels, which would call the port of Chornomorsk, was developed. The results of the automatic analysis by the computer program are designed as the matrix of coordinates for inbound / outbound at the port. In order to verify the cybersecurity of the introduced model of automatic planning of the path by the coordinates of trajectory points and using the decision support systems for the automatic control of the parameters of maneuvering by technical methods, radar observations were carried out. After observation the comparing analysis of the accuracy of ship and shore radar systems was done, the methodology of the observations for coastal systems developed. Conducted radar observation of 300 arrivals and 200 departures of vessels from the port of Chornomorsk according to the developed plans for each berth in the port. The recommended routes were integrated into the expanded computer program «Path Planning IS», which made it possible to obtain the matrixes of coordinates of the observations. A comparative analysis of the computer simulation and practical transition of ships in the recommended water area of the port demonstrated that the introduced model is confirmed by the results of the observations. On the basis of the analysis, it is determined that the developed model ensures the cybersecurity of the processes of maneuvering in confined waters.

1 INTRODUCTION

Marine vessels spend about 80% of their time in the open sea, while this period of time accounts for about 20% of all ship accidents. The remaining 80% of accidents occur in the areas of confined waters of fairways, canals, near-port and port water areas. The reason for this distribution is the proximity of navigational marks, the presence of navigational hazards and the availability of cyberattacks that lead to emergency events.

The vulnerability of ship systems to cyber-attacks and their management are closely related to navigational risks, but the methods of combating them are fundamentally different. So, for example, to manage the level of navigational risk, it is necessary to use high-precision methods of planning the coordinates of the path by trajectory points (TP).

When controlling the movement, to monitor the position of the vessel the satellite method in differential mode is used, the radial mean square error, which is several times smaller than the correction for the position of the satellite antenna, the abscissa of the centre of gravity of the vessel and the turning pole. At the same time, such ship positional data can be cyber-secure as long as it is not broadcasted by automatic identification system (AIS). At the same time, the presence of a cyber-attack can be determined only by means of a comparative analysis of the same parameter of maneuvering in different ways, one of which a priori should not respond to a cyber-attack.

In the case of a significant deviation of the coordinates of the ship's position from the planned ones, first, it is necessary to determine the cause of such an impact - navigation risks or as a result of a cyber-attack. Information on the presence of navigational risks and their types is given in informational documents – charts, sailing directions and notices to mariners. For cyber security, such data is not given in a systematic form, so the navigator must determine the source of the danger himself and make a decision. Recommendations of the International Maritime Organization (IMO) on methods of determining the presence of cyber-attacks and making decisions about reducing their impact are given in the Guidelines on maritime cyber risk management (MSC-FAL.1/Circ3, Guidelines on maritime cyber risk management) [1].

2 LITERATURE REVIEW AND PROBLEM STATEMENT

In July 2020, an online cybersecurity forum reported a 900 percent increase in cyberattacks on operational technology systems in the maritime industry [2]. In a report on cyber readiness by Acronis (Acronis Cyber Readiness Report), based on a survey of experts from 3,400 multinational companies, it was reported that due to the COVID-19 pandemic, 92% of surveyed enterprises work remotely. It is obvious that the actions of hackers are aimed at ships and maritime enterprises that work remotely [3]. In the last three months of 2020, 39% of companies survived attacks on Zoom, Cisco Webex, and Microsoft Teams video conferencing applications [4-5]. Ransomware attacks have increased significantly during the pandemic, with 31% of companies reporting daily cyberattacks, and 50% experiencing them at least once a week [6]. According to estimates by Lloyd's of London, the loss from cyberattacks in the maritime industry is estimated at 200 billion dollars [7]. All these data clearly demonstrate the relevance of creating a cyber defense strategy in the maritime sector. This requires the development of international and national regulatory documents and recommendations, the organization of special state units and information support, similar to what exists in the area of navigational risks.

But organizing such a structure for maritime shipping as a whole is a cumbersome task, therefore, using an analogy that is acceptable for navigational risks, we suggest starting with the voyage cycle of sea vessels. For this purpose, we will use the existing system of organizing information on navigational risks [8-10] during the voyage cycle and improve the recommendations on ways to identify cyberattacks and developed methods of managing their level. This approach is justified by the fact that, based on a generalized table of existing accident-prone areas of the voyage cycle, the shipmaster can determine the areas where cyber-attacks can be expected, and prepare to reduce their negative consequences.

The proposed approach characterizes the relevance of creating a cyber security strategy in the maritime sector, which begins with the ship's voyage cycle, then moves to ports and extends to the entire maritime industry.

The central issue, which has not yet been resolved, is the method of preparation of the ship's navigation plan for the entry/exit of the ship from the port, which should be used during pilotage. The existing recommendations for the preparation of the pilot passage plan of the ship "Pilot passage plan" are not intended for navigational purposes. For this reason, the captain has to use the personal experience of the pilot in managing the ship when entering this port.

The developed planning method [11-12] of the ship navigation pilotage plan when entering/exiting the port and the developed program for automatic calculation of the matrix of planned coordinates of trajectory points [13] by the route method for implementation in the practice of work in the ports of Ukraine need verification.

3 FORMULATION OF THE GOALS OF THE ARTICLE (STATEMENT OF THE TASK)

The aim of this work is to verify the analysis of possible vulnerabilities and cyber risks in the voyage cycle on the basis of a generalized table of accident prone areas of navigation risks and to compile a register of vulnerabilities of navigation equipment in relation to cyber-attacks and to determine the procedures for implementing a cyber-security strategy on each accident-prone section of the route. [14-16]. This will make it possible to organize cyber defense on ships in the areas of expected cyber-attacks and reduce losses from cyber-crimes after the implementation of the appropriate response plan [17-24].

4 PRESENTATION OF THE RESEARCH MATERIAL WITH A FULL JUSTIFICATION OF THE OBTAINED SCIENTIFIC RESULTS

4.1 *Calculation of the accuracy of the coastal radar station (CRS)*

The estimation of the trajectory of the ship's motion according to the planned coordinates is based on the determination of the displacement of the point of the centre of gravity relative to the trajectory points (TP). At the same time, the amount of rudder turning, and the frequency of adjustment depends on the ratio of the amount of lateral shift and the radial root mean square error (RMSE) of the determination of the vessel's position. In order to verify the proposed model for calculating the planned coordinates of the TP when entering/exiting of the vessel, it is necessary to determine their values according to the waypoints (WP), maneuvering characteristics of the vessel and the selected rudder turning angle for curvilinear trajectories. It is necessary to compare the accuracy of the planned coordinates according to the readings of the navigation device, which is the most accurate of the existing ones. The ship's radiolocation station (Radar), Automatic Identification System (AIS) and shore radiolocation station are the devices at disposal of the navigator. To choose a control device, we will perform a comparative analysis of the accuracy of each method and determine its resistance to cyber-attacks.

Let's consider the errors of determining the position of the ship by comparing the planned coordinates and determining the position of the ship using high-precision cyber-independent methods [25-26]. Errors due to various sources of their origin are classified as instrumental, methodological and calculation errors.

Instrumental errors are associated with the final accuracy of the presentation of the original information. They are caused, for example, by the rounding of the input values or the accuracy of their measurements.

Methodological errors are due to the fact that many calculations are solved approximately using special numerical methods. This, in particular, refers to trigonometric, logarithmic, exponential and other functions.

Errors in the calculation results are caused by the propagation or transformation of the errors of the original data during their passage in the calculation algorithm through a number of intermediate results.

In most technical calculations, the level of accuracy of the result, in which its maximum relative error is from 0.1 to 5%, is considered satisfactory.

A qualitative solution to the problem of determining the accuracy of any calculated quantity with random values of the arguments requires the establishment of the RMSE for the definition of the function:

$$Z = f\left(X, Y, ..., t\right) \quad m_Z^2 = \left(m_X \frac{\partial z}{\partial x}\right)^2 + \left(m_Y \frac{\partial z}{\partial y}\right)^2 + \cdots + \left(m_t \frac{\partial z}{\partial t}\right)^2 \quad (1)$$

where X, Y, ..., t – measured parameters, and m_x, m_y …. m_t – their RMSE.

The situation of approaching ships (Fig. 1) is considered in the following way.

At the initial moment of time t_1, the oncoming vessel C_c was at a distance D_{0A} from the vessel C_v. At the moment of time t_2, the mark of the oncoming vessel travelled the distance S_0 by the LRM and the bearing B_2 changed by the value ΔB, and was located at the distance D_{6A}. The angle between the LRM and bearing B_1 was α_1, and between bearing B_2 was α_2. The oncoming vessel passes at a distance CPA relative to its own.

The value of the traveled relative distance S_0 is determined from the obtuse triangle C_v C_c C_c ′ by the formula:

$$S_0 = \sqrt{D_{0A}^2 + D_{6A}^2 - 2 \cdot D_{0A}^2 D_{6A}^2 \cdot \cos\Delta B} \quad (2)$$

Given that the values of angles α_1 and α_2 are unknown, we determine their values using the theorem of sines from the same triangle:

$$\sin\alpha_1 = \left(D_{6A} \cdot \sin \cdot \Delta B\right) / S_0 \quad (3)$$

$$\sin\alpha_2 = \left(D_{0A} \cdot \sin \cdot DB\right) / S_0 \quad (4)$$

For each method of determining the position of the ship [26-28], there are calculation schemes that allow establishing the error of determining the position of the ship relative to the Earth's surface, which is usually represented as a circle on the plane. The use for estimating the position of the error ellipse (Fig. 1) has not been widely used, as it requires the use of three parameters – the minor and major semi-axes and the direction of its location. In order to use a more accurate estimate than the ellipse, a characteristic was introduced into the practice of navigation – the radial RMSE, which, with a safety margin, outlines the area of the probable location of the vessel along the radius. According to the requirements of the IMO, for a 95% probability, it is necessary to multiply the results of the calculations by 2, that is, to take the radius equal to the major semi-axis of the ellipse.

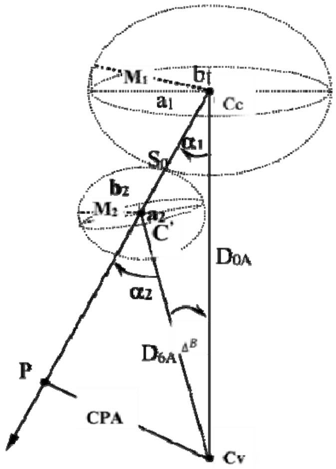

Figure 1. Probable assessment of the situation of approaching ships.

For a more rigorous assessment of the accuracy of determining the location of the vessel, formula (1) is used sequentially for functions (2)-(4), as a result, formula (1) is written:

$$m_{S_0}^2 = \left(\frac{\partial_{S_0}}{\partial_{D_{0A}}} \cdot m_{D_{0A}}\right)^2 + \left(\frac{\partial_{S_0}}{\partial_{D_{6A}}} \cdot m_{D_{6A}}\right)^2 + \left(\frac{\partial_{S_0}}{\partial_{\Delta\Pi}} \cdot m_{\Delta B}\right)^2 \quad (5)$$

$$m_{S_0}^2 = \left(m_{D_{0A}} \frac{D_{0A} - D_{6A}\cos\Delta B}{S_0}\right)^2 + \left(m_{D_{6A}} \frac{D_{6A} - D_{0A}\cos\Delta B}{S_0}\right)^2 + \left(\frac{m_{\Delta B}^0 D_{0A} D_{6A} \sin\Delta B}{57.3 S_0}\right)^2 \quad (6)$$

$$\alpha_1 = \arcsin\left(\frac{D_{6A}\sin\Delta B}{S_0}\right) \tag{7}$$

$$m_{\alpha_1}^2 = \left(\frac{\partial\alpha_1}{\partial_{D_{6A}}}\cdot m_{D_{6A}}\right)^2 + \left(\frac{\partial\alpha_1}{\partial_{S_0}}\cdot m_{S_0}\right)^2 + \left(\frac{\partial\alpha_1}{B}\cdot m_{\Delta B}\right)^2 \tag{8}$$

$$m^2{}_{\alpha_1} = \left(m_{D_{6A}}\frac{tg\alpha_1}{D_{6A}}\right)^2 + \left(m_{S_0}\frac{tg\alpha_1}{S_0}\right)^2 + \left(\frac{m_{\Delta B}^0 tg\alpha_1}{57.3tg\Delta B}\right)^2 \tag{9}$$

$$CPA = D_{0A}\cdot\sin\alpha_1 \tag{10}$$

$$m_{CPA}^2 = \left(\frac{\partial_{CPA}}{\partial_{D_{0A}}}\cdot m_{D_{0A}}\right)^2 + \left(\frac{\partial_{CPA}}{\partial_{\alpha_1}}\cdot m_{\alpha_1}\right)^2 \tag{11}$$

$$m_{\text{CPA}} = \text{CPA}\sqrt{\left(\frac{m_{D_{0A}}}{D_{0A}}\right)^2 + \left(\frac{m_{\alpha_1}}{tg\alpha_1}\right)^2} \tag{12}$$

$$TCPA = \frac{D_{0A}\cos\alpha_1}{V_0} \tag{13}$$

$$m_{TCPA}^2 = \left(\frac{\partial_{TCPA}}{\partial_{D_{0A}}}\cdot m_{D_{0A}}\right)^2 + \left(\frac{\partial_{TCPA}}{\partial_{\alpha_1}}\cdot m_{\alpha_1}\right)^2 + \left(\frac{\partial_{TCPA}}{\partial_{V_0}}\cdot m_{V_0}\right)^2 \tag{14}$$

$$m_{\text{TCPA}} = \sqrt{\left(m_{D_{0A}}\frac{\cos\alpha_1}{V_0}\right)^2 + \left(m_{V_0}\frac{D_{0A}\cos\alpha_1}{V_0{}^2}\right)^2 + \left(m_{\alpha_1}\frac{D_{0A}\sin\alpha_1}{V_0}\right)^2} \tag{15}$$

In the obtained formulas (5)-(15), each value of the RMSE includes all three types of errors – instrumental, unavoidable and inherited from calculations.

As you can see, the calculation of the SCP of the calculated values of the parameters according to the formulas (5)-(15) make it possible to create correct formalized calculation schemes for estimating the accuracy of the place for comparative evaluation.

When measuring the relative distance and direction using radar (Fig. 1), the value of the radial RMSE is determined by the formula:

$$M = \sqrt{\left(\frac{D\cdot m_{\text{B}}}{57{,}3^0}\right)^2 + m_D^2} \tag{16}$$

Table 1. Comparative evaluation of the characteristics of ship radar and shore radar

No	Parameter		Parameter value of shore radar	Parameter value of of ship radar
1.	The real resolution of the system by direction, not worse:		0.3°	1.0°÷2.0°
2.	The real resolution of the system by range on scales up to 2 miles, no worse:		12 м	15 м
3.	Measurement error of the system for a stationary point target at D = 5 miles at P = 0.95, not worse: by range / angle, by route coordinate	5-7м / 5°-10° 15 m	1м/0.8°÷1.0° 30 m	1м/0.8°÷1.0° 30 m
4.	Measurement error of the movement parameters of the target being followed at the stage of the stable car escort is no worse than: route coordinates: by distance/ angle geographical coordinates by latitude and departure, ship's course, ship's speed	7м/0.13° 0.13″ 2° 0.5 knots	20м/0.3° – ≈4°÷8° ≈1÷1.5 knots	20м/0.3° – ≈4°÷8° ≈1÷1.5 knots
5.	The number of accompanying auto targets is not less than		200	–
6.	Carrier frequency		3.34–3.42GHz	3.34–3.42GHz
7.	Minimum detection range, no more than:		20 m	50-70 m
8.	Minimum sensitivity, no less than:		–130 dB	–120 dB
9.	Impulse power:		10 kWt	7-100 kWt
10.	Duration of probing pulses: - in short pulse mode - in the long pulse mode	 0.045 ms 0.15 ms	 0.1 ms 0.5÷1.0 ms	 0.1 ms 0.5÷1.0 ms
11.	Antenna type:		waveguide slot	waveguide slot
11.1	Antenna polarization:		A2- circular, A3- circular, horizontal linear	horizontal linear, A3
11.2	The width of the antenna's directional pattern (expanded L = 2.5 m) in the horizontal plane		0.23 degree	1.0°÷2.1°
11.3	The width of the antenna pattern in the vertical plane A2 – pseudo cosecant quadratic		7 deg 3 deg	20°÷25° –
12.	Antenna gain: A2: 6000, (дБ)		Antenna gain: A2: 6000,	Antenna gain: A2: 6000,
13.	A3:18000 (дБ)		A3:18000	A3:18000
14.	Supply voltage		single-phase variable 50 Hz 220 ± 22	single-phase variable 50 Hz 220 ± 22 V

Based on the data in the table. 1 radar, the accuracy of determining the parameters of the closest approach was calculated using Mathlab, the results of which are shown in Fig. 2 (X = m0radar) and Fig. 3 (y = D; z = M).

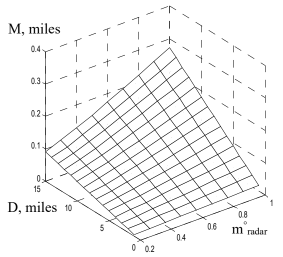

Figure 2. Accuracy surface under the condition of error m_D=0.005D

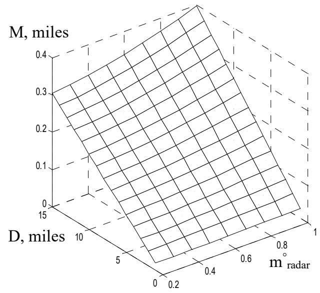

Figure 3. Accuracy surface under the condition of error m_D=0.002D

To determine the calculation error in the VTS of the convergence parameters and the location, we will assume that the two ships are moving as shown in Fig.4.

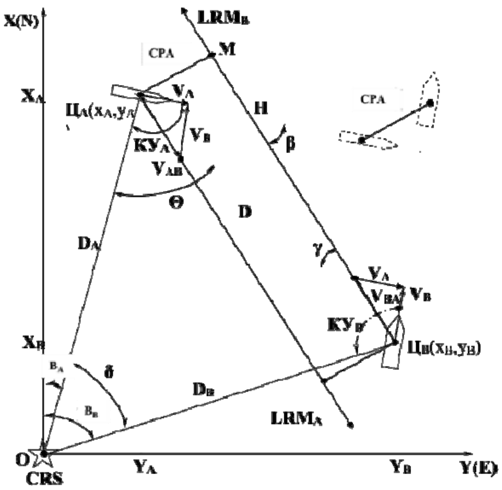

Figure 4. The situation of displacement of vessels in the mode of real movement

Bearings and distances for the vessel $Ц_A$ – B_A and D_A; for a vessel $Ц_B$ – B_B and D_B. Errors in the measurements of bearings B_A, B_B and distances D_A, D_B are random. The distance between ships is determined by the formula:

$$D = \left[D_A^2 + D_B^2 - 2D_A D_B \cos\delta \right]^{1/2} \quad (16)$$

where – the difference in bearings, the value of which is determined by the formula:

$$\delta = B_B - B_A \quad (17)$$

$$m_\delta^2 = \left(\frac{\partial_\delta}{\partial_{B_A}} \cdot m_{B_A} \right)^2 + \left(\frac{\partial_\delta}{\partial_{B_B}} \cdot m_{B_B} \right)^2 \quad (18)$$

$$m_\delta = \frac{\pi}{180} \sqrt{m_{B_B^0}^2 - m_{B_A^0}^2} \quad (19)$$

After applying formula (10) to equation (16), we get the absolute error in determining the distance between ships:

$$m_D^2 = \left(\frac{\partial D}{\partial D_A} \cdot m_{D_A} \right)^2 + \left(\frac{\partial D}{\partial D_B} \cdot m_{D_B} \right)^2 + \left(\frac{\partial D}{\partial \delta} \cdot m_\delta \right)^2 \quad (20)$$

$$m_D^2 = \frac{\left(D_A - D_B \cdot \cos\delta\right)^2 \cdot m_{D_A}^2 + \left(D_B - D_A \cdot \cos\delta\right)^2 \cdot m_{D_B}^2 + D_A^2 \cdot D_B^2 \cdot \sin^2\delta \cdot m^2{}_\delta}{D_A^2 + D_B^2 - 2 \cdot D_A \cdot D_B \cdot \cos\delta} \quad (21)$$

Significantly affects the situation of divergence and the regularity of relative movement, which is provided by the course angle LRM – β.

From Fig. 4, we get the dependence for determining the angle – β:

$$tg\beta = \frac{V_B.\sin\left(TC_A - TC_B\right)}{V_A - V_B.\cos\left(TC_A - TC_B\right)} \quad (22)$$

From here we get:

$$\beta = arctg\left(\frac{V_B.\sin\left(TC_A - TC_B\right)}{V_A - V_B.\cos\left(TC_A - TC_B\right)} \right) \quad (23)$$

After simple transformations, we get:

$$m_\beta^2 = \left(\frac{\partial_\beta}{\partial_{V_B}} \cdot m_{V_B} \right)^2 + \left(\frac{\partial_\beta}{\partial_{V_A}} \cdot m_{V_A} \right)^2 + \left(\frac{\partial_\beta}{\partial_{TC_A}} \cdot m_{TC_A} \right)^2 + \left(\frac{\partial_\beta}{\partial_{TC_B}} \cdot m_{TC_B} \right)^2 \quad (24)$$

$$m_\beta^2 = \frac{\sin^2\left(TC_A - TC_B\right) \cdot m_F^2 + \left(\frac{\pi}{180} \cdot m_{TC_A}^0 \right)^2 \cdot H + \left(\frac{\pi}{180} \cdot m_{TC_B}^0 \right)^2 \cdot C}{\left[F^2 - 2F \cdot \mathrm{Cos}\left(TC_A - TC_B\right) + 1 \right]^2} \quad (25)$$

$$F = \frac{V_A}{V_B} \quad (26)$$

$$m_F^2 = \left(\frac{V_A^2 \cdot m_{V_B}^2 + V_B^2 \cdot m_{V_A}^2}{V_B^4} \right) \quad (27)$$

$$H = \left[F \cdot \mathrm{Cos}\left(TC_A - TC_B\right) - 1 \right]^2 \quad (28)$$

$$C = \left[\mathrm{Cos}2\left(TC_A - TC_B\right) - F \cdot \mathrm{Cos}\left(TC_A - TC_B\right) \right]^2 \quad (29)$$

To calculate the error in determining the angle θ from the triangle *0ЦAЦB*, we obtain by the theorem of sines:

$$\frac{\sin\Theta}{D_B} = \frac{\sin\delta}{D} \tag{30}$$

$$\sin\Theta = D_B . \frac{\sin\delta}{D} \tag{31}$$

$$\cos\Theta = \frac{D_A - D_B .\cos\delta}{D} . \tag{32}$$

From formulas (31-32) we get:

$$tg\Theta = \frac{D_B \cdot \sin\delta}{D_A - D_B \cdot \cos\delta} \tag{33}$$

$$\Theta = arctg\left(\frac{D_B \cdot \sin\delta}{D_A - D_B \cdot \cos\delta} \right) \tag{34}$$

$$m_\Theta^2 = \left(\frac{\partial_\Theta}{\partial_{D_A}} \cdot m_{D_A} \right)^2 + \left(\frac{\partial_\Theta}{\partial_{D_B}} \cdot m_{D_B} \right)^2 + \left(\frac{\partial_\Theta}{\partial\delta} \cdot m_\delta \right)^2 . \tag{35}$$

By differentiating formula (35) in partial derivatives, we obtain dependencies for determining the error:

$$m_\Theta^2 = \frac{K + N^2}{D^4} \tag{36}$$

In formula (36) the notations are adopted:

$$K = \sin^2\delta \cdot \left(D_A^2 \cdot m_{D_B}^2 + D_B^2 \cdot m_{D_A}^2 \right), \tag{37}$$

$$N = m_\delta \cdot D_B \cdot \left(D_A \cdot \cos\delta - D_B \right). \tag{38}$$

To determine the error in calculating the distance of the shortest approach from the triangle *МЦAЦB* we obtain:

$$\mathrm{CPA} = D \cdot \sin(\gamma) = D \cdot \sin\left(B_A - TC_A - \Theta - \beta \right) \tag{39}$$

After differentiating formula (39) in partial derivatives, we get:

$$m_{CPA}^2 = \left(m_D \frac{\partial_{CPA}}{\partial_D} \right)^2 + \left(m_{B_A} \frac{\partial_{CPA}}{\partial_{B_A}} \right)^2 + \left(m_{TC_A} \frac{\partial_{CPA}}{\partial_{TC_A}} \right)^2 + \left(m_\Theta \frac{\partial_{CPA}}{\partial_\Theta} \right)^2 + \left(m_\beta \frac{\partial_{CPA}}{\partial_\beta} \right)^2 \tag{40}$$

$$m_{CPA} = \sqrt{m_D^2 \sin^2\left(B_A - TC_A - \Theta - \beta \right) + D^2 \cos^2\left(B_A - TC_A - \Theta - \beta \right) \left[\frac{Pi}{180} \left(m_{B_A}^0 + m_{B_A}^0 \right) + m_\Theta + m_\beta \right]} . \tag{41}$$

From the given analytical dependencies, it is possible to start determining the error in determining the trajectory of ships at sea by coastal VTS.

A comparative analysis of the accuracy of establishing the positions of ships while moving showed that the total RMSE of the ship radar is approximately 3 times higher than that of the shore radar. The total error when using AIS in normal GPS mode gives errors that are comparable to radar, and when using DGPS it is almost 5 times more accurate.

Based on these prerequisites, it can be argued that it is advisable to use information from radar and AIS in VTS, giving preference to the more accurate of them. Calculation schemes, according to the definition of the parameters of dangerous approach, must have a minimum inherited RMSE.

Taking into account that the coordinates of the axis of the shore antenna are determined by geodetic methods, it does not have a linear movement and is unknown to the attackers who organize cyber-attacks, it can be argued that the radar indicators can serve to verify the TP coordinate planning model when the ship enters / leaves the port for navigation purposes.

4.2 *Construction of a matrix of trajectory points of the vessel's approach to the port of Chornomorsk under the conditions of cyber security*

The essence of the TP route planning method is the high-precision calculation of the coordinates of the given points based on the planned points (WP) of the rectilinear path and the turning characteristics for the selected rudder turning angle and their presentation in the form of a linear matrix of turning coordinates.

At the same time, the calculation algorithm will be as follows: according to the coordinates of the way point, the angle of the steering wheel is selected by the segment method and the starting and ending points of the turn are determined; based on the coordinates of the starting point of the turn, the coordinates of the TP are calculated by the segment method after 3°, 5° or 10°, depending on the scale of the map and the angle of the turn; form a matrix of coordinates of the TP turn at a given waypoint, which starts from the starting point of the rudder shift, then the TP and the end point of the circulation..

The TP matrix of the turn from the first WP to the second can be written as follows:

$$M_{\pi 12} = \left\| \begin{vmatrix} \phi_{n\mu} \\ \lambda_{n\mu} \end{vmatrix}, \begin{vmatrix} \phi_{\pi 11} \\ \lambda_{\pi 11} \end{vmatrix}, \begin{vmatrix} \phi_{\pi 21} \\ \lambda_{\pi 21} \end{vmatrix}, \ldots, \begin{vmatrix} \phi_{\pi i1} \\ \lambda_{\pi i1} \end{vmatrix}, \ldots, \begin{vmatrix} \phi_{n(n-1)1} \\ \lambda_{n(n-1)1} \end{vmatrix}, \begin{vmatrix} \phi_{\pi n1} \\ \lambda_{\pi n1} \end{vmatrix}, \begin{vmatrix} \phi_{k\mu} \\ \lambda_{k\mu} \end{vmatrix} \right\|$$

for all and $\in$ {1, ..., n}, where n is the number of TP of the curvilinear trajectory for the given WP.

In the future, the coordinates of the points of the rectilinear trajectory from the initial first point to the beginning of the turn are calculated and the TP array is formed in the form of the first matrix of the route. The calculation of points is carried out according to the formulas of written calculation, up to the fifth sign of the minute and the next rounding up to four. Such accuracy is necessary due to the small distance between the points that determine the position of the centre of gravity, and the high accuracy of determining the location of the vessel by satellite systems in differential mode, when the radial RMSE reaches a value of ±2m.

To form TP matrices of the entire transition, form arrays of route matrices and TP turn matrices for all way points in the following order:

$M_{01}, M_{n12}, M_{12}, M_{n23}, M_{23}, \ldots, M_{ni(i+1)}, M_{i(i+1)}, \ldots M_{n(m-1)m}, M_{(m-1)m}$

where
M_{01} – is the TP matrix of the linear section from the initial $0th$ WP to the point of s the steering wheel shift command;
$M_{\pi 12}$ – the TP matrix of the turn from the first WP to the second from the beginning of $\Pi_{\mu 1}$ to the end of $K_{\mu 1}$ of the curvilinear segment;
$M_{\pi 12}$, $M_{\pi 23}$, $M_{\pi i(i+1)}$, $M_{\pi (m01)m}$ – matrices of segments of turns;
M_{12}, M_{23}, $M_{i(i-1)}$, $M_{i(i+1)}$ – TP matrices of rectilinear segments.

After calculating the planned TP coordinates, they will be optimal, since they are obtained for the maneuvering characteristics of a specific vessel with a margin of control influences and are safe in relation to navigational hazards.

The task of guaranteed safe management of the movement process will be the need to move the centre of gravity of the vessel along the line of the given route, taking into account the actual width of the maneuvering offset, controlling the position of the vessel by high-precision methods of determining the location and using existing decision support systems for timely and adequate actions to correct emerging deviations. At the same time, it is necessary to take into account the characteristic points of the vessel, which determine the accuracy of determining its position and the width of the maneuvering offset.

These include: the control centre (CC) – the point on the ship's bridge, where the navigator is located, who assesses the ship's condition in relation to the signs of the navigational situation; turning pole (TP); centre of gravity (CG); extreme characteristic points - bow of the left side $H\lambda$, bow of the starboard side Hn, aft of the left side $K\lambda$, aft of the right side Kn; the length of the vessel between the perpendiculars L; the maximum length of the vessel.

5 DISCUSSION OF RESULTS

As an example, the staging of the ship "Lady Laguna" using trajectory point matrices to Berth 5 in the port of Chornomorsk, which was developed using the program "Path Planning IS", is shown. Below is the mathematical base of calculations used by the program.

1. According to hydrographic recommendations, the pilot develops the approach route of the vessel to the pier, which he transmits to the vessel in advance in the form of coordinates of the recommended approach route of the vessel. For these coordinates, formulas (42-46) are used to calculate the courses that the ship will follow (TC), the angles of turns (Θ) and the distance between waypoints (S).

$$TC = arctg\left(\frac{\sin|D_{Lon}|}{tg(\phi_2)\sin(\phi_1) - \sin(\phi_1)\cos(D_{Lon})}\right) \tag{42}$$

where
TC - true heading from the previous point to the next;
D_{Lon} - the difference between the longitudes of the end and start points;
ϕ_1 - latitude of the starting point;
ϕ_2 - latitude of the end point.

$$D_{Lon} = \lambda_{i-1} - \lambda_i \tag{43}$$

$$\theta = TC_i - TC_{i-1} \tag{44}$$

where
θ – turning angle.

$$S = \frac{D_{Lat}}{\cos TC} \tag{45}$$

where
S – distance between waypoints.

$$D_{Lat} = \phi_{i-1} - \phi_i \tag{46}$$

Table 2. Calculation of turning angles

WP	Latitude	Longitude	S, cable	TC,°	Θ,°
0	46⁰ 18,94' N	030⁰ 41,56' E	0	0	0
1	46⁰ 19,17' N	030⁰ 40,46' E	0,8	286,6	78
2	46⁰ 18,83' N	030⁰ 40,19' E	0,39	208,8	67,1
3	46⁰ 18,84' N	030⁰ 40,05' E	0,1	275,9	0

2. Find the angle of the steering wheel for each turn according to the conditions (40):

$$\delta = \begin{cases} 5° \ \ if \quad \Delta\theta \, less \ \ than \ \ 30° \\ 10° \ \ if \quad \Delta\theta = 30° - 60° \\ 5° \ \ if \quad \Delta\theta \, more \, than \ \ 60° \end{cases} \tag{47}$$

Table 3. Turning selection

WP	Latitude	Longitude	S, cable	TC,°	Θ,°	δ,°
0	46⁰ 18,94' N	030⁰ 41,56' E	0	0	0	0
1	46⁰ 19,17' N	030⁰ 40,46' E	0,8	286,6	78	15
2	46⁰ 18,83' N	030⁰ 40,19' E	0,39	208,8	67,1	15
3	46⁰ 18,84' N	030⁰ 40,05' E	0,1	275,9	0	0

3. With the help of formulas (41-42), the distances on the track lines from the point of turn to the beginning and end of the turn are calculated. The coordinates of the turning point are taken as point "M". Segments MП and MK represent the distance from point M on the track line to the start and end points of the turn, respectively. For the accuracy of calculations, it is better to leave 6 decimal places.

$$MC = l_1 - \frac{D_T}{2} + \frac{D_T}{2} \cdot tg\left(\frac{\theta}{2}\right) \tag{48}$$

where
l_1 – shifting of the vessel during circulation;
D_T – the tactical diameter of the circulation.

$$ME = l_2 \cdot tg\left(\frac{\theta}{2}\right) \quad (49)$$

where
l_2 – direct shifting.

Table 4. Calculation of start and end segments of turns

WP	Latitude	Longitude	MC,cable	ME,cable
0	46º 18,94' N	030º 41,56' E	0	0
1	46º 19,17' N	030º 40,46' E	2,97482	2,12863
2	46º 18,83' N	030º 40,19' E	2,58613	1,774288
3	46º 18,84' N	030º 40,05' E	0	0

4. For each turn, it is necessary to calculate segments every 10° using formulas (41-42), where the turning angle will take the value 10, 20, 30, …, *θ*.
5. The obtained data in the form of segments must be converted into geographic coordinates. This can be done using formulas (50-56).

$$D_{Lat_i} = MC_i \cdot \cos K_i \quad (50)$$

where
i – turning angle every 10°;
K_i – the course the vessel follows to the next point.

$$D_{Lon_i} = DMP_i \cdot tgK_i \quad (51)$$

where
DMP_i – the difference of the meridional parts for each segment of the turn.

$$DMP = 3437,75 \cdot \ln \frac{tg\left(45° + \frac{\varphi_E}{2}\right)}{tg\left(45° + \frac{\varphi_C}{2}\right)} \quad (52)$$

where
φ_C – the latitude of the starting point of the turn;
φ_E – the latitude of the end point of the turn.

$$\varphi_n = \varphi_m + D_{Lat_i} \quad (53)$$

where
φ_n – the latitude of the trajectory point at n ϵ ($П_1$, K_{11}, K_{12}, …, K_1, $П_2$, K_{21}, K_{22}, …, K_2, …, $П_k$, K_{k1}, K_{k2}, …, K_k , when *k* – crossing point of track lines on the chart; 01, 02, …, 0η, 11, 12, …, 1η, …, ζ1, ζ2, …, ζη, when η – the number of trajectory points on a straight track line, ζ – waypoint number);
φ_m – the latitude of the crossing point of the track lines.

$$\lambda_n = \lambda_m + D_{Lon_i} \quad (54)$$

where λ_n – the longitude of the trajectory point at *n* ϵ ($П_1$, K_{11}, K_{12}, …, K_1, $П_2$, K_{21}, K_{22}, …, K_2, …, $П_k$, K_{k1}, K_{k2}, …, K_k , when *k* – crossing point of track lines on the chart; 01, 02, …, 0η, 11, 12, …, 1η, …, ζ1, ζ2, …, ζη, коли η – the number of trajectory points on a straight track line, ζ – waypoint number);
λ_m – longitude of the crossing point of the track lines.

Based on the obtained coordinates, we build a matrix of trajectory turning points after each one 10°.

6. Using formulas (44-47), we find the coordinates of rectilinear sections of the ship's path every 0.2 kbt. The calculation of the difference in latitude is based on the following formula:

$$D_{Lat_i} = \beta \cdot \cos K_i \quad (55)$$

where
β ϵ (2, 4, 6, …, *l*+1) – step to calculate.

We summarize the obtained results in a matrix of rectilinear sections of the route.

7. The coordinate matrix of the trajectory points of the ship's approach will have the following form:

$$M_m = M_{01} + M_{n1} + M_{12} + M_{n2} + ... + M_k + M_{(\zeta-1)\zeta} + M_{st} \quad (56)$$

Figure 5. General view of the approach of the ship "Lady Laguna" using the matrices of trajectory points to berth 5 in the port of Chornomorsk

Table 5. General view of the approach of the ship "Lady Laguna" using the matrices of trajectory points to berth 5 in the port of Chornomorsk

TP	Lat	Long	Course	Distance
0	46º 18,94' N	030º 41,56' E	0	0
1	46º 18,96888' N	030º 41,4219' E	286,8	0,1
2	46º 18,9978' N	030º 41,28378' E	286,8	0,1
3	46º 19,02666' N	030º 41,14566' E	286,8	0,1
4	46º 19,08408'N	030º 40,87086' E	286,8	0,2
5	46º 19,11732' N	030º 40,6929' E	285,1	0,13
6	46º 19,11906' N	030º 40,62828' E	272,2	0,04
7	46º 19,11324' N	030º 40,56408' E	262,5	0,04
8	46º 19,09998' N	030º 40,50228' E	252,8	0,04
9	46º 19,0797' N	030º 40,44462' E	243,1	0,04
10	46º 19,053' N	030º 40,39272' E	233,4	0,04
11	46º 18,98358' N	030º 40,31196' E	214	0,04
12	46º 19,05654' N	030º 40,36986' E	208,8	0,08
13	46º 18,9471' N	030º 40,27692' E	210,5	0,13
14	46º 18,91494' N	030º 40,23342' E	223,1	0,04
15	46º 18,88824' N	030º 40,18284' E	232,7	0,04
16	46º 18,86766' N	030º 40,12656' E	242,2	0,04
17	46º 18,85392' N	030º 40,0662' E	251,8	0,04
18	46º 18,84726' N	030º 40,00332' E	261,3	0,04
19	46º 18,84786' N	030º 39,93978' E	270,8	0,04
20	46º 18,84' N	030º 40,05' E	275,9	0,08

The program outputs an xls file that is easily transported to ECDIS or Marine Traffic. In Fig. 5 shows the construction of the "Lady Laguna" approach to berth No. 5 in the port of Chornomorsk.

The technological scheme of mooring will be as follows. On the approach to the first pair of buoys "1" and "2" of the approach channel (TP2), the pilot must be on board and the vessel must proceed at a maneuvering speed, according to the port rules, about 7 knots. The towing ends should be taken through the bow and stern leads as close as possible to the diametrical plane.

The first tug is attached at point TP2, and the second – after passing through the channel (TP 8).

The approach channel of the port, which is 160 m wide, 1400 m long, and 14.5 m deep, is used for ships entering and leaving the seaport of Chornomorsk. According to the water area passport, the depth at the berth is 10 m and is sufficient for slowing down to complete stop, turning on the reverse course with the use of tugs and maneuvering during mooring.

The length of the pier is 220 meters. Thus, the design parameters of the operational water area allow safe mooring and departure of vessels from the pier with a length between perpendiculars of about 200 meters and a width of about 45 m using tugs.

Figure 6. The first turn of the steering wheel

According to the given plan, at point 6, the ship makes a 15-degree turn of the rudder to the port side to set off on a course of 234° (Fig. 6).

In the future, the vessel follows this course to point TP 14, where it performs a 15-degree rudder shift to starboard and approaches the berth (Fig. 7).

Figure 7. The second shift of the steering wheel

After approaching the mooring place, they begin to press the ship to the berth and adjust the position of the ship. The minimum scheme of using mooring lines, which is recommended, is three longitudinal and two springs from forward and aft. After the mooring lines have been tightened, the tugs may be free and the mooring shall be considered complete.

The developed routes for the moorings of the port of Chornomorsk were integrated into the computer program "Path Planning IS", which made it possible to obtain the coordinates matrix of the path of field observations. Comparative analysis of computer modelling and practical passage of ships through the recommended section of the port water area showed that the proposed model is confirmed by the results of observations (Fig. 8).

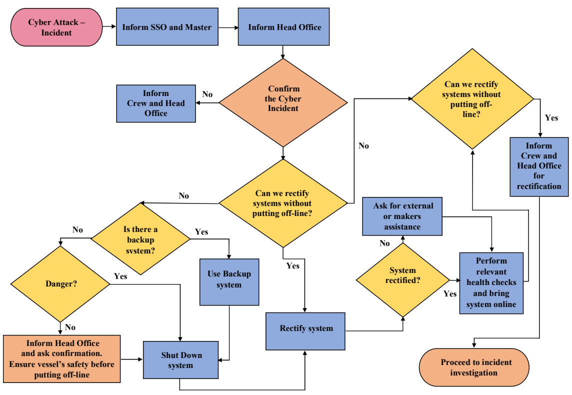

Figure 8. Actions of the navigator during the occurrence of cyber threats

Based on their analysis, it can be concluded that the developed model provides cyber security of maneuvering processes in compressed waters, therefore it can be recommended for implementation in the seaports of Ukraine, to fulfill the requirements of the International Maritime Organization for planning the route of the voyage cycle from the berth of the port of departure to the berth of the port of arrival (Fig. 8).

6 CONCLUSIONS

The main advantage of the method of planning the ship's path according to the table of waypoints by the method of calculating the coordinates of the trajectory points by the angle of the rudder for curved trajectories is the presentation of the path in the form of the sum of linear matrices of the coordinates of straight and curved sections and automatic operational control of movement parameters. The proposed method can be used in the development of control tools for automated vessels and is only possible for vessels with non-shift maintenance. Also, this route construction method is very relevant during the preparation of the approach and exit route plan, as it reduces the risk of misunderstanding between the captain and the pilot during navigation, and even reduces the risk of emergency events in the process of managing the resources of the navigation bridge.

Thus, optimization of information about maneuvering, proper preparation of the bridge team for timely assessment of the emergency situation and taking adequate measures for its prevention make it possible to increase the safety of maneuvering.

To ensure cyber security when using "Path Planning IS", the following rules must be followed:

1. It is forbidden to use ship's personal computers that are not configured with software for planning the route and managing the maneuvering process.
2. If the user accidentally enters the setup program, they should shut down the computer without attempting to change or save any changes.
3. Use the master or any other disk containing the software files to re-install the software on board

the vessel with the prior permission of the Company.

4. Reformat or copy the files to the main disks or any other disk containing the program files for planning and maneuvering in the event of failures in their operation.
5. It is prohibited to install software that has not been authorized by the Company.
6. Use only utility software (eg disk managers, memory generators/managers, Norton Utilities).

If there is a threat during the download of the working file, you must follow the instructions given in Fig. 8.

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