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DEVELOPMENT AND EXPERIMENTAL STUDY OF ANALYZER TO ENHANCE MARITIME SAFETY

Pavlo Nosov
Corresponding author
PhD, Associate Professor*
E-mail: pason@ukr.net

Serhii Zinchenko
PhD, Associate Professor
Department of Ship Handling at Sea**

Viktor Plokhikh
Doctor of Psychology, Professor
Department of General Psychology
V. N. Karazin Kharkiv National University
Svobody sq., 4, Kharkiv, Ukraine, 61022

Ihor Popovych
Doctor of Psychology, Professor
Department of Psychology
Kherson State University
Universytetska str., 27, Kherson, Ukraine, 73003

Yurii Prokopchuk
Doctor of Technical Sciences, Associate Professor, Leading Researcher
Department of Systems Analysis and Control Problems
Institute of Technical Mechanics of the National Academy of Sciences of Ukraine
Leshko-Popelya str., 15, Dnipro, Ukraine, 49005

Dmytro Makarchuk
PhD, Associate Professor, Head of Department*

Pavlo Mamenko
Captain Deep Water
Mediterranean Shipping Company (Cyprus) Ltd.
Omonias ave., 57, Strovolos, Cyprus, 2064

Vladyslav Moiseienko
Mate
Adnoc Logistics & Services
Corniche str., 9, Abu Dhabi, United Arab Emirates

Andrii Ben
PhD, Professor, Vice Rector for Research**
*Department of Navigation**
**Kherson State Maritime Academy
Ushakova ave., 20, Kherson, Ukraine, 73009

On the basis of empirical experimental data, relationships were identified indicating the influence of navigators' response to such vessel control indicators as maneuverability and safety. This formed a hypothesis about a non-random connection between the navigator's actions, response and parameters of maritime transport management.

Within the framework of this hypothesis, logical-formal approaches were proposed that allow using server data of both maritime simulators and operating vessels in order to timely identify the occurrence of a critical situation with possible catastrophic consequences.

A method for processing navigation data based on the analysis of temporal zones is proposed, which made it possible to prevent manifestations of reduced efficiency of maritime transport management by 22.5 %. Based on cluster analysis and automated neural networks, it was possible to identify temporary vessel control fragments and classify them by the level of danger. At the same time, the neural network test error was only 3.1 %, and the learning error was 3.8 %, which ensures the high quality of simulation results.

The proposed approaches were tested using the Navi Trainer 5000 navigation simulator (Wärtsilä Corporation, Finland). The simulation of the system for identifying critical situations in maritime transport management made it possible to reduce the probability of catastrophic situations by 13.5 %. The use of automated artificial neural networks allowed defining critical situations in real time from the database of maritime transport management on the captain's bridge for an individual navigator

Keywords: maritime transport management, human factor, ergatic system, navigation safety

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1. Introduction

The development of modern information navigation systems is aimed at the maximum possible coverage of data coming from navigation devices and displayed on captain's bridge information panels [1]. As a result of these trends, a whole class of basic and auxiliary navigation devices and sensors emerged [2], such as:

- electronic navigation and information systems (ECDIS);
- automatic identification systems (AIS);
- integrated navigation systems (INS);
- radar stations (RADAR);
- automatic radar plotting aids (ARPA);
- global navigation satellite systems (GNSS, GPS);
- global maritime communications system (GMDSS);
- vessel traffic control systems (VTS);
- aids to navigation (AtoN).

Also, developments are underway within an integrated management of these information means as part of modern e-navigation strategies: SafeSeaNet, Monalisa, Efficient Sea, etc. (Australia, Sweden, Norway, Canada, Japan, USA) [3].

It should be noted that the introduction of a wide class of these systems can affect the operation of polar navigators. The studies [4] have shown that despite the significant expansion of the information field of data forming the navigator's perception of the navigation situation, the opposite effect is also possible. The reason for this is the large volume of simultaneously perceived heterogeneous navigation data. At the same time, the complexity of data perception affects decision-making processes in the form of both atomic reactions and chains of complex actions-strategies.

Thus, the task of complex human-computer interaction of the navigator with computerized vessel control systems is determined based on the results of navigation situation perception. Considering that at present, autopilot systems and artificial intelligence modules do not allow making effective decisions in complex navigation and critical situations, specialized control systems are needed. It is also important to note that the relevance of the indicated scientific problems directly depends on the approaches to structuring the navigator information model, which has a complex psychological organization. Nevertheless, the number of accidents on marine vessels due to the human factor is growing every year. Thus, there is a need to create automated means for analyzing responses during vessel control in order to prevent catastrophic consequences.

2. Literature review and problem statement

The work [5] describes the development of a software and hardware tool for determining the response time of human operator when performing simple actions. It is shown that the resolution of response time reaches $p<0.05$. The tool also distinguishes between color signals by spectrum and intensity. However, the issue of the operator's complex perception of the situation involving several dynamically changing external sources remains unresolved.

The work [6] examines the influence of stress on decision-making processes. The main factors influencing the operator's behavior in stressful situations are indicated. However, the issue of identifying the threshold of changes in the operator's behavior by automation means remains unresolved, which significantly complicates its application in maritime transport.

The paper [7] shows the results of developing a pattern recognition system, which is 15 times faster than human recognition. However, this development is focused on recognizing simple unit forms, but not their combinations. This fact does not allow encoding the image of the navigation situation to be efficiently and quickly recognized by artificial systems.

In [8], researchers proposed an approach to entropy classification of individual response in time. The approach was based on the Maxwell-Boltzmann model and tested on 24,192 responses, with a coefficient of determination $R^2=0.88$. However, this approach cannot be used due to the heterogeneity of navigation tasks performed by navigators.

The work [9] analyzes the influence of the human fatigue factor on information perception and decision-making processes. The tests found that the delay in human response increases by 40–87 % due to a high level of fatigue. However, this fact does not allow preventing the likelihood of critical situations since an individual analysis of response to specific situations is needed.

The study [10] indicates that the most significant influence of the operator human factor on the occurrence of catastrophes is the inability to eliminate the problem and the state of the operator. These factors can be derived from the navigation situation. However, the issue of practical instructions for leveling the indicated factors during vessel control in difficult situations remains unresolved.

In [11], the dependence of situation perception processes on the presence of a conflict of operators' interests is considered, a model is built on the basis of game theory with an analysis of 1,615 situations. Effective combinations of operators' interactions at the moments of collective situation perception were identified. However, the approaches considered are most effective in systems where subjects have the same rank and the same set of functions and capabilities, which does not fully meet maritime transport conditions.

The work [12] examines the issues related to situation perception by subjects during geometric displacements in the local coordinate system using sensors. The obtained geometric variations made it possible to determine the characteristic state of situations affecting the subjects' perception. However, this research can be effective over a wider area than the captain's bridge, with a defined workplace for each officer.

In [13], it was proved that actions and situational perception are interrelated, aspects of motivation and physical condition of a subject were considered. This fact indicates the possibility of influencing the situational perception of a naval officer by controlling his activities. However, it is required to expand the means and methods of integrated identification of the navigation situation.

The work [14] considers models of adaptive interest, which directly affects situation perception. This study examines the field of scientific interests among scientists, which forms their perception of the situation regarding research directions. The results of the study indicate that interest determines forms of activity affecting information perception by the subject of the ergatic system. As a result, the navigator, performing his functions, selects ways to obtain information from surrounding sources. At the same time, the priority and prevalence of certain systems, devices and sensors that affect the process of navigation situation perception are formed. However, this approach should be developed within the framework of building individually-oriented models of navigators' decision-making in difficult navigation conditions.

In view of the indicated studies, it can be stated that there is a problem associated with the need to analyze the processes of navigator's perception of difficult situations. Solving problems aimed at managing situation perception processes requires the development of specialized mathematical and simulation models.

3. The aim and objectives of the study

The aim of the study is to develop formal and algorithmic approaches for the navigator's response analysis, which will reduce the risk of disasters by maintaining a high level of vessel control safety.

To achieve the aim, the following objectives were identified:

– to propose an approach for analyzing the data of navigation simulator server for automated typing of navigation situations, which allow determining individual time limits for navigator's response manifestation;

– to develop a method for processing navigation data for identifying temporal zones of the vessel's route to highlight the most difficult and critical ones to prevent a decrease in the vessel control parameters such as maneuverability and safety;

– to develop an approach to control the supply of navigation information for navigators when identifying risks of vessel maneuvering reliability loss.

4. Materials and methods

The study is based on an approach of extraction of navigator's response data and their transformation in order to obtain the most effective models of vessel control processes. The proposed approach is based on theoretical methods of identification of primary information P, Q by the navigator at the moment of fast focusing on the object W. In this context, experienced navigators, within the experiment, form a scenario by the software and hardware of the navigation simulator in advance. The points of vessel trajectory corresponding to a certain navigation situation are highlighted. This approach is based on the applied aspects of the theory of risks caused by the human factor [15, 16] and takes into account the psychological patterns of critical situation perception [17], as well as psychological mechanisms of expected behavior [18]. In this case, the navigator, depending on the position F_k on the captain's bridge, focuses attention A on visual and sound images: $AP = Q \Leftrightarrow P \to_A Q$ within the discrete scale N.

The time of information perception depends on the navigator's previous experience $G_S(W)$ in view of natural processes of data filtering H and subsequent intelligent convolution D:

$$\forall P \in G_S(W), \quad A_k P = DHF_k P, \quad k = 1,\ldots,N. \tag{1}$$

The complexity of the task and the danger of processes lie in the fact that in critical situations, the navigator has extremely little time, so makes a decision based on the simplest and most understandable images of navigational situations. In this case, the navigator operates with a variety of possible responses $G_S(\alpha)$ to the observed situation $\alpha \in \Omega$, $\Omega = \{G_S(\alpha)\}$.

In precisely identifiable situations, where the functional entropy does not reach the "non-distinguishing" threshold, the response rate can be maximum [19]. However, with high entropy of situation perception processes, there can be an alternative β response $P_\alpha \in G_S(\alpha,\beta)$:

$$P_\alpha = \\ = \left\{ \begin{matrix} P \in G_S(\alpha) \,|\, \left(\forall \beta \in \Omega \;\; \alpha \neq \beta \;\; \forall Q \in G_S(\beta) \;\; P \neq Q\right) \& \\ \left(\forall P \in O \uparrow (P) \;\; \exists \beta \in \Omega \;\; \alpha \neq \beta \;\; \exists Q \in G_S(\beta) \;\; P = Q\right) \end{matrix} \right\}. \tag{2}$$

In the entropy approach, from conscious P to fully intuitive Q_Ω actions, the navigator's response will be within the following conditions:

1. $P_\Omega = \{P_\alpha, P_\beta, \ldots\} : \forall \alpha, \beta \in \Omega \;\; z_\alpha \neq z_\beta \Rightarrow P_\alpha \neq P_\beta$;
2. $Q_\Omega = \{Q_\alpha, Q_\beta, \ldots\} : \exists \alpha, \beta \in \Omega \;\; z_\alpha \neq z_\beta \;\; Q_\alpha = Q_\beta$.

Thus, to determine how accurately the navigator perceives the navigation situation z, it is necessary to determine a point on the set $\{P^*\}_\Omega$ such that:

$$\{P^*\}_\Omega = \\ = \left\{ \begin{matrix} P_\Omega \in G_S(\Omega) \,|\, \left(\forall \alpha, \beta \in \Omega \;\; z_\alpha \neq z_b \Rightarrow P_\alpha \neq P_\beta\right) \& \\ \left(\forall Q_\Omega \in O \uparrow (P_\Omega) \;\; \exists \alpha, \beta \in \Omega \;\; z_\alpha \neq z_\beta \;\; Q_\alpha = Q_\beta\right) \end{matrix} \right\}. \tag{3}$$

To determine such a point, it is necessary to determine the state y associated with the response $y_r = f(x)$. Considering the occurrence of situations I_r, determining the images of their perception A, as well as a set of probable responses B, the p–adic number theory can be used [20]. In this case, $B = f(A) = \{y = f(x) : x \in A\}$, and subsequent perception images are defined as $A_{n+1} = f(A_n)$.

The emerging response-forming ideas are synchronized with images within the dynamic system $J_{n+1} = f(J_n)$:

$$J' = \{B^\tau = f(A) : A \in J\}, \tag{4}$$

where τ is the order of system organization.

Then the space of the navigator's response can be described by a graph in the p–adic system (2, 3, 4 … n), depending on response complexity. At the same time, depending on the navigator's behavior entropy, the formation of a trajectory of actions on the graph can have a polar orientation (Fig. 1). This is because the closer the initial point of the trajectory to point A, the more accurately the navigator perceives the situation and his initial actions P_Ω are more strictly defined and reasoned. In a situation where the navigator's actions are unconscious Q_Ω, the behavior entropy includes a random set of initial trajectory points, which leads to a critical situation.

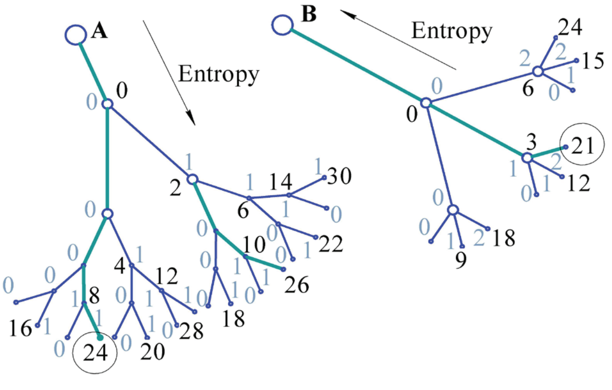

Fig. 1. Direction of the vessel control trajectory with the entropy approach to situation perception

Thus, there is a geometric structure, represented as a kind of pseudometric feature space. As can be seen from Fig. 1, the structure of response trees is subject to the principle of concentricity of its nodes with respect to the circle radii U_r in 2D dimension and, accordingly, spheres in 3D dimension:

$$A_{s_0 \ldots s_{l-1}} = U_r(a), \quad r = 1/p^l, \quad a = s_0 + \ldots + s_{l-1}m^{l-1}. \tag{5}$$

At the moment of perception of the navigation situation, the dynamics of the transition from one radial order to another is subject to formal dependencies:

$$f(U_r(a)) = U_{r'}(a'), \quad a' = f(a). \tag{6}$$

In the case displaying the dynamics of transient dynamic processes of perception, it is possible to unify the coding of the navigator's response time intervals. Testing navigators in the corresponding situations will allow determining an individual-based classification of response behavior [21] on a whole range of navigation problems. Determining the corresponding fractal distances $a \in X$ on the graph, will make it possible to identify a typical individual navigator's response $B \subset X$ by the time feature.

Then the distance $\rho(a,B) = \inf_{b \in B} \rho(a,b)$ will be approximated as a time interval, which allows correlating it with the test data and determining the degree of response entropy.

However, it should be taken into account that the distance between the graph points of more than one edge indicates a complex multistep response, involving a more complex structure than atomic reactions.

Despite this fact, such structures are also subject to classification as they follow the same principles [22].

$$\rho(A,B) = \sup_{a \in A} \rho(a,B) = \sup_{a \in A} \inf_{b \in B} \rho(a,b). \tag{7}$$

This approach is justified in situations where the identified navigator's responses are in the "vicinity" of those already classified. However, it is necessary to determine the order of system actions in case when, at the *i*-th stage of identification, the current response does not correspond to the feature space of the navigator's responses.

This fact indicates that the entropy is very high and the response time also increases significantly.

The criterion for determining such a fact can be an analysis of response appropriateness, which will give grounds to accept or not the entropy approach. Moreover, depending on the situation, the goal will be different. The goal identifier at the level of data coming from navigation systems can be encoded as a trajectory on the graph. The set of navigation information sources determined by the nodes, as well as speed indicators for these nodes, allows determining the navigator's goal at the metadata level.

$$U_\varepsilon(a_{\text{goal}}) = \{x : \rho_m(x, a_{\text{goal}}) \le \varepsilon\}. \tag{8}$$

Therefore, deviation of the time of one response may not affect the goal loss, but indicate a change of the graph node. This approach provides the maximum variety of trajectories for possible combinations of goal achievement.

Based on this, the execution of a navigation task in difficult situations can be approximated in the form of several sequential trajectories – fragments of the graph of one or different *p*-adicity orders, for example:

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It can be seen that the navigator passed from simple actions to complex ones, *p*-adicity is 2, 3, 4.

Automated analysis of response dynamics can identify random fluctuations in the context of trajectories in time, but not in goal. In this case, there is no reason to make decisions to improve safety. Otherwise, a new situation will arise when $\rho_m(x_{n+1}, a_{goal}) > \varepsilon$. There is the problem of determining whether a new situation-state x'_{n+1} is emergency or critical by automated full search of previously formed trajectories and their fragments:

$$x'_{n+1}(\omega) = f_{z_{n+2}(\omega)}(x_n(\omega)),$$

$$z_{n+2}(\omega) = g(z_{n+1}(\omega), x_{n+1}(\omega), \vartheta^n \omega). \tag{9}$$

However, taking into account the "last maneuver" effect, the increase in such vessel control characteristics as maneuverability and reliability determines the emergency navigator's decision support.

In this situation, strict categorical principles of *p*-adic systems may not have a sufficient level of identification, since there is an event different from those of the previous navigation experience.

Within the aim of the study, it is necessary to develop such analyzer functions that would allow not only identifying the risk of maneuverability and reliability loss. These factors carry important vessel characteristics, which implies the use of automation tools in order to level out catastrophic events [23].

For this purpose, situation management when identifying the loss of signs of the goal-oriented trajectory on the graph of the *p*-adic system, as well as when determining risk factors by analyzing physiological and temporal situational data, is considered [24, 25]. To this end, scenarios of switching to safe maneuvering or more cost-effective vessel control must be planned in advance.

In some cases, it is proposed to increase the bridge manning level, in others – switch to automated autonomous vessel control. In the first case, management has an organizational principle, the second assumes an automated mode of management [26]. This means that some functions will be performed by software, limiting, for example, commands to the machine telegraph (vessel speed), the amplitude of rudder blade rotation; control of pumps and thrusters.

Thus, automated control determines the scope of maneuvering and operating modes of the main vessel speed-power units ◊↑ "increase" or ◊↓ "decrease". This directly affects the vessel control characteristics, such as maneuverability, reliability, and cost-effectiveness.

Then, for a formal description of control actions, we assume that λ predetermines the data and metadata obtained from the situation analysis, and Ψ – vessel control modes. The mode time t_i is limited by the stage δ_j, during which the navigation task or maneuver is supposed to be performed [27, 28]. At the moment of switching to automated control, the navigator receives signals prompting actions according to the mode-scenario of actions in the form of a parameter system of the stage limited by the time t_1, t_2 in the system $\psi_{[t_1,t_2]}(X(t_1), u, \upsilon)$.

Then, when switching to the automated mode, the control system will track the navigator's actions regarding prompts and compare them with the time characteristics of responses assumed in the chain of actions [29]. Synchronization of the script program for the navigator's responses will affect the change of stages

$$\delta_{j-1} / \delta_j (j = 1, \ldots, n; \delta_0 = t^*) \Rightarrow \delta_j / \delta_{j+1}(t+1). \tag{10}$$

Thus, the data and metadata extracted using the navigator's response analyzer will positively affect the vessel control characteristics within the formal system:

$$X_{t+1} = \lambda_{R(t+1),\, m} \begin{pmatrix} \psi_{[t,t+1],\, R_\psi}(X_t), \\ u([t, t+1]), \\ \upsilon([t, t+1]) \end{pmatrix} \Rightarrow t^* \notin [t, t+1],$$

$$X_{t^*} = \lambda_{R(t^*),\, m}(X_{t^*}),\ \chi_{t^*}(X_{t^*}) = \text{true},$$

$$\chi_t(X_t) = \text{true} \Rightarrow \chi_{t+1}(X_{t+1}) = \text{true},$$

$$u([t, t+1]) = f_j / \underline{\delta}_j \equiv \{\underline{p}\}_{m,j},$$

$$\upsilon([t, t+1]) = \upsilon(\pi_V) \otimes \upsilon,$$

$$\begin{aligned} &\qquad \rho_m(\alpha(t')), \\ &\textstyle\sum_{t' \le t} \psi_{[t'-1,t'],\, R_\psi} \times > \rho^* \Rightarrow \\ &\qquad \times (X'_{t'-1}, u, \upsilon) \\ &\Rightarrow \Diamond \uparrow R_{t+1} \text{ or if} < \rho^{**} \Rightarrow \Diamond \downarrow R_{t+1}, \end{aligned}$$

where $\upsilon(\pi_V) \otimes \upsilon$ is the composition of physiological parameters and data of external navigation situation.

Thus, the automated system allows performing a double function: improving maritime transport control characteristics and interactive navigator training in the navigation process [30–32].

The proposed approaches were tested in the research laboratory "Development of decision support systems, ergatic and automated vessel control systems" based on the NTPRO 5000 training complex (Wärtsilä Corporation, Finland). During testing and confirmation of the proposed formal and algorithmic approaches, the processes of navigator's response identification were simulated on a stand in critical and difficult navigation situations.

5. Results of simulation of navigator's response using NTPRO 5000 in critical situations of the Singapore location

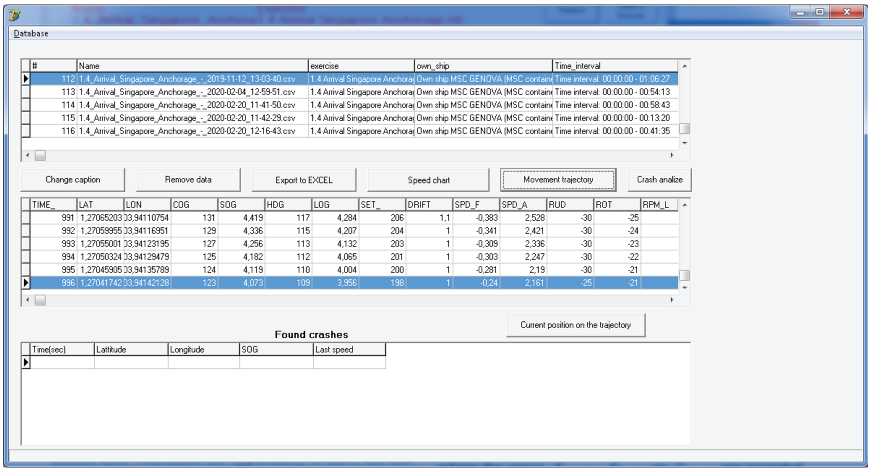
5. 1. Data analyzer of the navigation simulator server

According to the objectives of the study, an approach for analyzing the data of the navigation simulator server was proposed, which makes it possible to typify navigation situations in order to determine individual time limits of navigator's response manifestation. This approach is based on the primary processing of server data by automated determination of the intervals of changes in the main vessel control parameters (Fig. 2), such as:

- COG (Course);
- SOG (Speed_1);
- HDG (Gyrocompass);
- LOG (Speed_2) SET (Drift direction);
- DRIFT (Drift force);
- SPD_F, SPD_A (Longitudinal and transverse speeds);
- RUD (Lapel angle);
- ROT (Rate of turn);
- RPM_L (Revolutions per minute).

As part of the approach, the data on vessel control in difficult navigation conditions by the time factor in difficult navigation areas were processed. At the same time, those vessel trajectories that did not have collisions, but significantly differed from the reference trajectories of expected maneuvering were analyzed.

The data obtained in this way in the amount of 116 experimental sections made it possible to typify those that coincided in navigation and weather conditions, and also correlated by similar navigation characteristics for the use of groups of the main control modules when performing maneuvers.



#	Name	exercise	own_ship	Time_interval
112	1.4_Arrival_Singapore_Anchorage_-_2019-11-12_13-03-40.csv	1.4 Arrival Singapore Anchorag	Own ship MSC GENOVA (MSC containe	Time interval: 00:00:00 - 01:06:27
113	1.4_Arrival_Singapore_Anchorage_-_2020-02-04_12-59-51.csv	1.4 Arrival Singapore Anchorag	Own ship MSC GENOVA (MSC containe	Time interval: 00:00:00 - 00:54:13
114	1.4_Arrival_Singapore_Anchorage_-_2020-02-20_11-41-50.csv	1.4 Arrival Singapore Anchorag	Own ship MSC GENOVA (MSC containe	Time interval: 00:00:00 - 00:58:43
115	1.4_Arrival_Singapore_Anchorage_-_2020-02-20_11-42-29.csv	1.4 Arrival Singapore Anchorag	Own ship MSC GENOVA (MSC containe	Time interval: 00:00:00 - 00:13:20
116	1.4_Arrival_Singapore_Anchorage_-_2020-02-20_12-16-43.csv	1.4 Arrival Singapore Anchorag	Own ship MSC GENOVA (MSC containe	Time interval: 00:00:00 - 00:41:35

TIME_	LAT	LON	COG	SOG	HDG	LOG	SET_	DRIFT	SPD_F	SPD_A	RUD	ROT	RPM_L
991	1,27065203	03,94110754	131	4,419	117	4,284	206	1,1	-0,383	2,528	-30	-25	
992	1,27059955	03,94116951	129	4,336	115	4,207	204	1	-0,341	2,421	-30	-24	
993	1,27055001	03,94123195	127	4,256	113	4,132	203	1	-0,309	2,336	-30	-23	
994	1,27050324	03,94129479	125	4,182	112	4,065	201	1	-0,303	2,247	-30	-22	
995	1,27045905	03,94135789	124	4,119	110	4,004	200	1	-0,281	2,19	-30	-21	
996	1,27041742	03,94142128	123	4,073	109	3,956	198	1	-0,24	2,161	-25	-21	

Found crashes

Time(sec)	Lattitude	Longitude	SOG	Last speed

Fig. 2. Extraction of server data for intelligent processing

5. 2. Development of a method for identifying critical situations

Having identified navigation situations similar in navigation parameters, it became possible to develop a method for identifying fragments of situations based on an analysis of the time limits of the effectiveness of maritime maneuvering stages. The method is based on preventing a decrease in such vessel control parameters as maneuverability and safety.

Within the framework of the method, a number of stages were performed:

1. Analysis of the dynamics of changes in navigation characteristics relative to the server data with a step of 4 seconds, which allows determining the number of parallel-changed parameters. As a result, we determine the p-adicity level of the situation fragment.

2. The time indicator of the fragment of the navigation situation life cycle for each p-adicity in seconds was determined.

3. Based on the p-adicity level, data fragments were identified for their intelligent processing by means of cluster analysis using automated neural networks due to the large volume of multi-criteria information (Table 1).

4. The dependences on the main vessel control parameters COG and LOG during maneuvering in difficult locations were analyzed (Fig. 3).

The resulting clusters made it possible to correlate the trajectory fragments with the activation of vessel control parameters and navigation indicators (Fig. 4).

The analysis of the diagram allowed determining the dynamics of changes in the COG and LOG parameters of the vessel's route. Correlation of the trajectory sections (Fig. 4) with the formed clusters made it possible to decompose them by the criterion of the largest number of parallel control processes (*p*-adicity). As a result, the clusters that exceeded the permissible threshold of information perception and, consequently, adequate decision-making during vessel control were identified.

Table 1

Neural network analysis based on simulation errors

Simulation results					
No.	Network architecture	Learning error	Check error	Test error	Learning algorithm
1	SOFM 10–70	0.0262	0.0383	0.0313	Kohonen 1,000 epochs

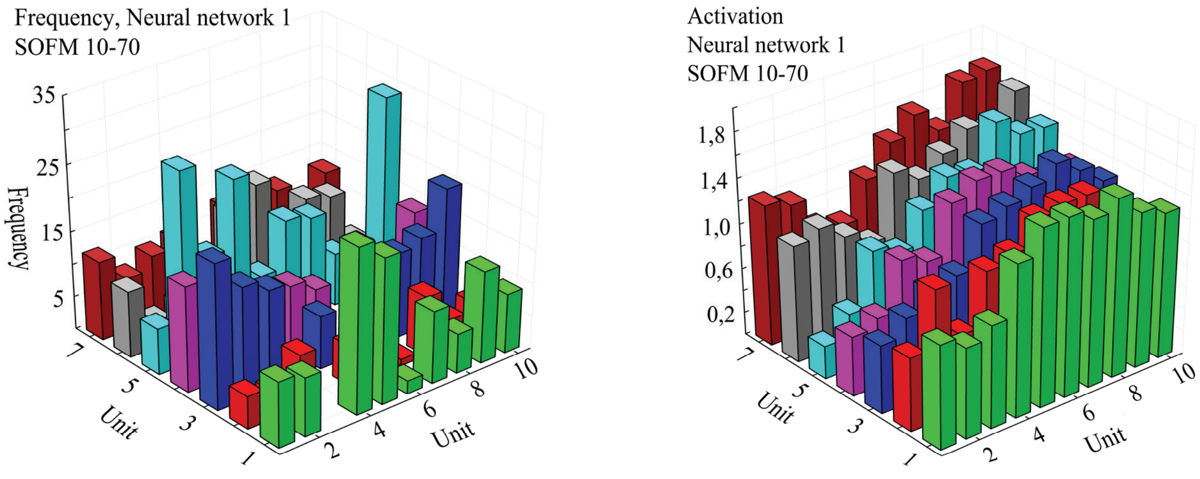
These clusters were analyzed by groups of parameters and classified as "dangerous" for both an individual navigator and the team as a whole.

5. 3. Development of an approach to presenting warning information to ensure navigation safety

Within the framework of the proposed approach, the data of clusters were analyzed, in the time ranges of which an increase in the flow of information data was observed using neural networks. As a result of the analysis, nonlinear dependencies were identified, indicating a sequential increase in the information load on the navigator, which affects the decrease in the vessel control indicators (Fig. 5).

Thus, for each navigator, a set, sequence and intensity of formation of navigation data were determined, which influenced the decrease in the vessel control parameters.

To prevent such manifestations, an approach for on-line analysis of server data to identify sets of parameters on the sections of vessel trajectory was introduced. This approach made it possible to prevent the occurrence of critical situations and loss of vessel control during maneuvering by signaling an increase in the data flow. Automatic redistribution of information flows to other members of the navigation watch by transmitting data to displays, as well as timely increase in the bridge manning level, enhanced the level of navigation safety.



a *b*

Fig. 3. Effectiveness of neural network-based simulation: *a* — triggering frequency of clusters, identifying the situation; *b* — activation level of network neurons, indicating the high significance of input data

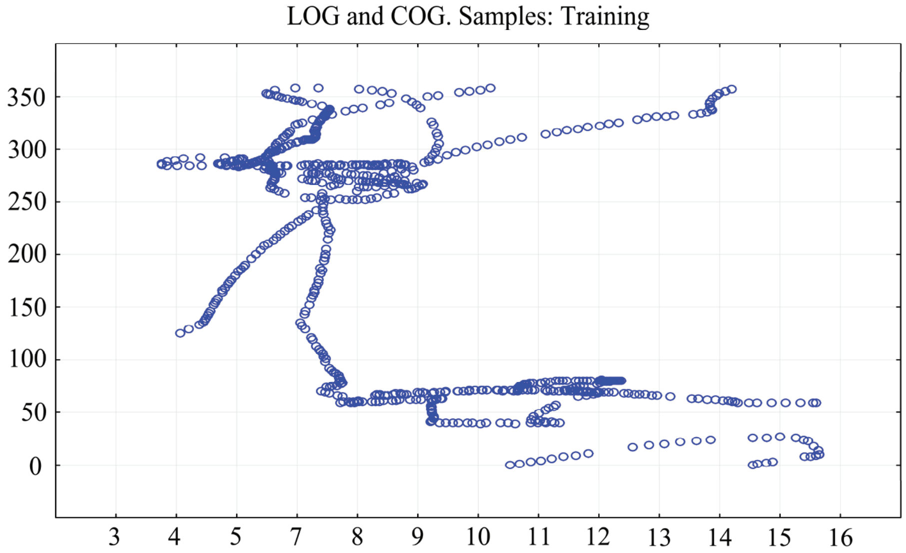
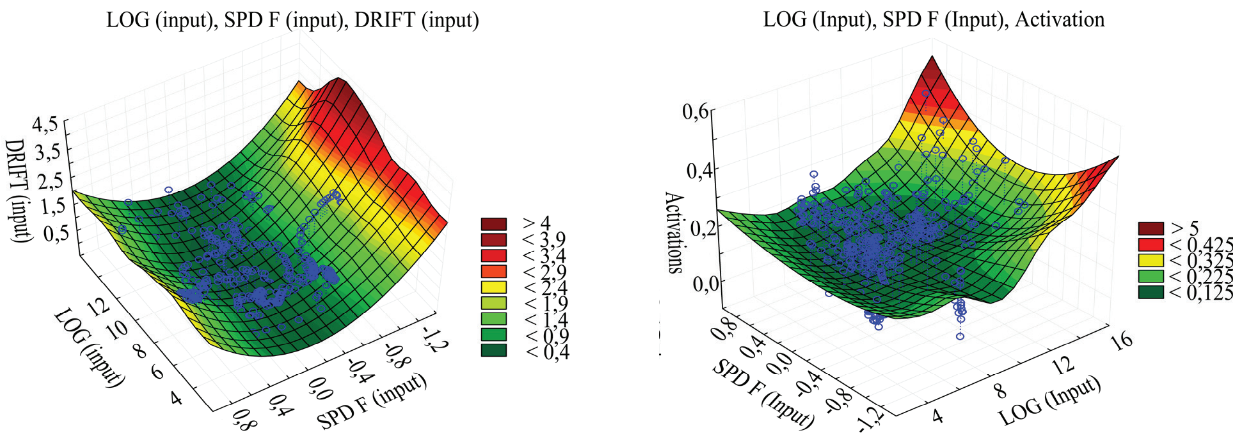


Fig. 4. Diagrams of COG and LOG dependencies in vessel maneuvering



a *b*

Fig. 5. Distribution of information indicators during vessel control: *a* — relative influence of weather conditions DRIFT on vessel maneuvering parameters LOG and SPD F; *b* — dependence of vessel control indicators on navigator's direct actions

6. Discussion of the results of the simulation study

The results of the study are explained by the fact that the proposed approach to analyzing navigation data made it possible to identify and typify classes of situations, as well as to correlate discrete time indicators of the navigator's response to them (Fig. 2). At the same time, it was also possible to identify temporal areas of activation of the vessel control modules relative to the identified classes of situations. And also to correlate the signs of variable characteristics for the navigator's actions during vessel control.

The feature of the proposed method is the analysis of changes in five significant parameters (COG, SOG, LOG, ROT and RPM_L) based on the data of navigation situations in the zones of navigation situation formation according to the scenario and cartography of the location. The analysis of the navigator's time response in the proposed context allowed forming geometric trajectories of sequential response during the maneuvers in terms of p-adic systems of the fractal graph (Fig. 1). The adequacy of the model was confirmed by the indicators of the test error of the applied neural network of 3.1 % and, accordingly, the learning error of 3.8 %.

Thus, based on the comparison of the formed trajectories of the p-adic graph for an individually selected navigator, it becomes possible to track dangerous navigation situations. The situations closest in terms of external conditions will allow identifying obvious time deviations indicating the occurrence of critical situations. During the analysis of 116 trajectories, we identified those that have significant deviations and differ from the reference ones by polar-changing response rate.

Automated analysis based on artificial neural networks by the method of cluster analysis made it possible to identify the most dangerous trends in the formation of trajectories, leading to critical situations with a high degree of probability (Fig. 3). Thus, during the analysis of server data, fragments that indicate deviations in the time parameters, going beyond the expected values, were identified in 36 % of the trajectories (Fig. 4). In 13.5 %, such circumstances entailed a significant deviation in the expected time ranges of vessel control, which identified the current situation as an emergency, requiring support in the form of increasing the bridge manning level (Fig. 5). However, timely identification of deviations in the time trajectories of navigators' behavior and submission of information warnings to the captain's bridge reduced the rates of critical situations by 22.5 %, which confirmed the feasibility of the approaches used.

As the limitations of the developed system, we consider the complexity in the full range of navigator's response analysis. The processing of data on the navigator's actions gives a positive effect within the framework of an individually oriented approach. At the same time, the issue of cooperative behavior in maritime transport management remains unresolved.

The development of this direction involves synchronization with the data of vessels at the time of their interaction, especially in narrow areas and port areas, which will allow identifying the moment of deviations from the expected response-actions in real time. This approach will allow us to identify the reasons for the behavior of all subjects of the interaction system that form the navigation situation, and also to track the beginning of a chain reaction, leading to catastrophic consequences.

7. Conclusions

1. A feature of navigation information analysis is that the approach involves the processing of simulator server data for each subject-navigator on a terminal basis. This made it possible to determine individual time limits of navigator's response manifestation in the context of the identified classes of situations or their fragments. On the basis of collected data, this approach made it possible to increase the level of maritime transport management during the simulator training by analyzing the temporal navigator's response within the space of critical situations.

2. The uniqueness of the developed method for processing navigation data lies in identifying such temporal zones of the vessel route that correspond to the reduced efficiency of maritime transport management. The proposed logical-formal approaches to extracting and processing data made it possible to explicitly present the most dangerous fragments of the chronology of maritime transport management based on time deviations from the reference ranges. The synthesis of data determined the course of research on using artificial neural networks by means of the automated cluster analysis method.

3. The analysis of Navi Trainer 5000 navigation simulator experimental data made it possible to identify those *p*-adic trajectories of the navigator's actions based on temporal features that, with a high degree of probability, influenced the emergence of a critical situation. Since the principles of response triggering and time indicators are significantly different for each navigator, it is not possible to unify the behavior model. However, when accumulating vessel control data and increasing the reliability of forecasting, using simulation models of artificial neural networks, individual decision support algorithms were obtained, which make it possible to level 62 % of dangerous situations. At the time of extreme danger, it is envisaged to increase the bridge manning level or replace the navigator with the captain.

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