International Journal of
Science and Engineering Investigations
vol. 8, issue 88, May 2019
Received on May 9, 2019
ISSN: 2251-8843

Automated Determination of the Limit Values of Navigation Parameters during Vessel Motion in the Conditions of River e-Navigation

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Abstract-The conducted studies are devoted to the development of ways to automate the operation of functional subsystems of the instrumental navigation method. These subsystems interact and provide navigation on the forecast-planned routes of electronic cartographic intellectualization in various emergency conditions. The navigation parameters for the tasks of stabilizing the vessel motion are determined. The artificial intelligence using fuzzy logic elements when using Inland ECDIS (Inland Electronic Chart Display and Information System) is applied. The stabilization task of the vessel motion, the process of measuring the deviation from the reference program line is considered on the programmed trajectories displayed on the SENC (System Electronic Navigational Chart). The algorithm of automated determination of limit values of navigation parameters during the vessel motion is offered. Possible variants of the position of the relative movement line on the SENC are applied. Mathematical models of vessel motion along the trajectory in different orthogonal coordinate systems are created. A complete expression is proposed for differential corrections to measured depths, which are indicated on the SENC. Thus, the uncertainty of the situational dynamics in the *n*-dimensional vessel motion space is eliminated. The proposed methods allow you to: increase the accuracy of navigation parameters by 10%; reduce the time for making decisions on ensuring the safety of navigation by the shift assistant of the captain by 10 times; increase the efficiency of navigation watch by 30%; increase the probability of safe navigation to 0.97. The practical value of the work is determined by the fact that its main results can be used by the developers of navigation information systems. These systems are designed for locally independent management of the navigation process on the inland waterways of Ukraine.

Keywords*- Safety of Navigation, River e-Navigation, Navigation Parameters, Relative Traffic Line, Inland ECDIS*

I. INTRODUCTION

Ukraine has a fairly high navigable potential of rivers. The length of its waterways suitable for exploitation is about 6,200 km. Inland waterway transport is recognized as a safe, universal, reliable and environmentally friendly form of transport. The most important problem of the effective operation of water vehicles today is the issue of the safety of navigation. The safety and efficiency of vessel motion on inland waterways (IWW) of Ukraine is ensured by various navigation systems and their motion control. Such systems have changed significantly over the past 20 years. The need to improve existing systems and to create new ones is due to the following. According to IMO, United Nations Economic Commission for Europe statistics, the accident rate has not decreased. Moreover, this happened despite significant efforts to solve safety problems and organize efficient vessel motion. Cases of vessel grounding, vessel collision continue to occur. Accidents are usually caused by navigation errors. Moreover, navigation errors and misses account for more than 80% of accidents on IWW. The greatest percentages of accidents occur in conditions of limited maneuvering space (rivers, port areas, coastal navigation).

Every year more and more vessels are switching to the use of electronic cartographic systems. However, the number of emergencies has not decreased. Navigators are not ready for use onboard ECDIS/Inland ECDIS. British inspectors have concluded that the number of emergencies has increased with the presence of ECDIS on board. This is due to system faults, as well as to more general problems of officer training. Safety of navigation is the third most important after fire safety and ensuring decent working and living conditions on the vessel. This is confirmed by the list of the main objectives of the Paris Memorandum of Understanding on Port State Control. The reasons for the above circumstances are also as follows. Thus, well-developed processes and well-known technologies use simplified linearized models of vessel motion and navigation and hydrographic security of shipping. These models do not take into account the real various changes in the nonlinear multivariable characteristics of vessels. This is especially true of their interaction with the environment in difficult motion conditions on IWW, which are rapidly changing.

The effective mechanism for the operation of water vehicles in the modern conditions of the intellectualization of the decision-making system is the transition to the instrumental method of navigation (IMN) (river *e*-navigation). This transition implies the replacement of the existing pilot (visual) method and the further improvement of the safety of water transport on IWW of Ukraine. IMN implementation is considered as a system object, taking into account its systemic nature. Moreover, IMN is considered as a complex of interrelated constituent elements and their properties. Multi-criteria requirements for the use of IMN on IWW of Ukraine cause difficulties with the implementation of computational intelligence. We need modern computer, information and telecommunication technologies. It (the method) is not yet capable of ensuring the safety of navigation on IWW of Ukraine by the criterion of computational complexity. The effectiveness of future navigation and vessel motion control systems should be adequate to the real physical nature. This requires a timely description of the actual state parameter changes. This is ensured by the latest non-linear multivariable models. There is a need to display the vessel motion on an electronic map in a wide operational range on curvilinear sections. The problem associated with the use of IMN (river e-navigation), is acute on Dnieper river.

The conducted studies are devoted to the development of ways to automate the operation of IMN functional subsystems on predicted-planned routes in various emergency conditions. Special attention is paid to the definition of the boundaries of safe distances and directions to the cartographic objects (CO) at SENC (coastline, hazards, etc.) as domains of danger (DD).

II. MATERIALS AND METHODS

The navigation parameters (NP) for solving the problems of safe vessel motion are indicated below. The artificial intelligence using fuzzy logic elements when using Inland ECDIS [1] is applied:

A. *Permissible distance of danger D*

$$m_D < 10\ m,\ m_D = \sqrt{\left(\frac{m_\alpha}{\alpha}\right)^2 + \left(\frac{m_h}{h}\right)^2}\,\Bigg|^{30<\alpha<150,\ m_\alpha \le 1^0}_{m_h = 0{,}5\text{м}}$$

$$M_o = \frac{1}{\sin\theta}\cdot\sqrt{m_{D1}^2 + m_{D2}^2} \le 10\text{м} \qquad (1)$$

B. *Bearing B*

$$\Delta D = \frac{m_B \cdot d}{57{,}3 \cdot \sin\Theta}\Bigg|^{m_B \le 1^0}_{30<\Theta<150}$$

$$M_o = \frac{m_B^o}{57{,}3^o \cdot \sin\theta}\sqrt{{D_1}^2 + {D_2}^2} \le 10\text{м}$$

$$tgB = \frac{\Delta\lambda \cdot \cos\varphi_m}{\Delta\varphi}, \qquad (2)$$

where m is the accuracy of the navigation parameter; α is the optimal value of the bearing B; Θ is the actual value of the bearing B; M_0 is the mean square error (MSE).

Moreover:

$$B \vee D\text{: } f(x_0\text{-}0) = f(x_0\text{+}0) = f(x_0),\ \forall x \in R\ x(t) = T_t x(t_0). \qquad (3)$$

We formalize a safe shipping zone. *D* & *B* values are variable and depend on a number of factors. These factors require separate, special or additional research. Formalized shipping safe zones can be represented as a circle, ellipse, or quadrangle.

To determine the boundaries of *safe distances*, consider CO on SENC (coastline, hazards, etc.) as DD in the form of hazardous fathom lines (Figure 1.). That is, the creation of DD is specified by rhumb line segments (geometric primitives) [3].

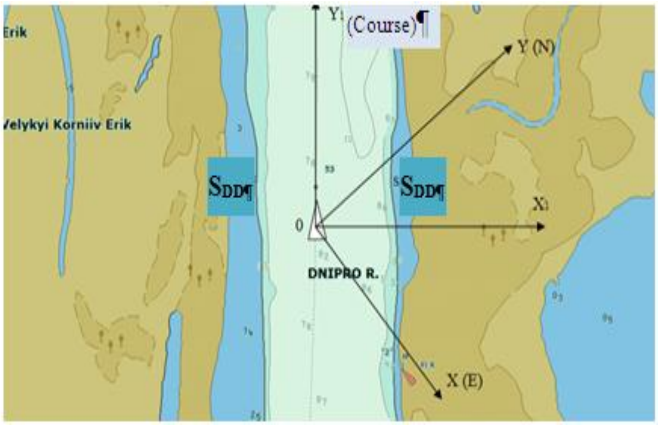

Figure 1. Images on SENC zone of the domain of danger S_{DD} with vessel coordinate systems

To determine the S_{DD}, the complete expression is applied for differential corrections $h(t)$ to measured depths, which are indicated on the SENC. Expression (4) was obtained in work [2]

$$h(t) = \underbrace{\frac{1}{\det(pE - A)}S(p)}_{(C)_{i,j}} \cdot B + \underbrace{y_{01GS} + h_{10}}_{const} + \left\|(\delta y_{01GS})_{i,1}\right\| \qquad (4)$$

Expression (4) is the result of intelligent processing of data flow from gaging stations (GS) by symbolically formalized Laplace transformations when a vessel is moving (using: state matrix *A*, unit matrix *E*, characteristic matrix (*pE-A*), power polynomial of Laplace variable *p* order *n* det(*pE-A*), union matrix *S* (*p*), water level values y_{01GS}, sounding datum h_{10} and deviations from it δy_{01GS}). Taking into account expression (4), the uncertainty of the situational dynamics in the *n*-dimensional space of vessel motion is eliminated.

$$\{H_{SENC}(t) = H_{DL} + h(t)\} \in \{S_{DD}(t)\} : H_{SENC}(t) \ge H_S + \delta, \qquad (5)$$

where H_{SENC} – is the actual depth at SENC; H_{DL} – is a design water level according to RIS; S_{DD} is danger zone of the domain of danger; H_S is a vessel draft; δ – is a safe stock under the keel of the vessel.

The main mode of operation of Inland ECDIS is the relative motion mode. The limit of the safe distances of the closest approach *D*sh at the relative course of the vessel *C*s is the relative traffic line (RTL). An emergency occurs when RTL crosses the center of the screen or $D_{\min} < D$sh. The limiting value *D* is obtained when RTL touches the limits of DD. Note that the DD limit changes only when the water level rises / falls. In other cases, DD = *const*. Thus, the set of points of the DD limit can be considered as a separate or particular case of divergence from the goals:

$$\forall\ \text{CO}\exists!\ V_{\text{DDi}} = 0. \tag{6}$$

Table 1 shows the possible variants of the position of the RTL, which cover three initial situations [3].

TABLE I. POSSIBLE POSITIONS OF RTL ON SENC AT VESSEL MOTION

Initial situations	Possible positions of RTL			
	1	2	3	4
Cod $(B, D)_i$ = const, $i = 1, 2, 3\ldots\ldots n$ $C_S \parallel$ RTL $D_{\min} > D_{\text{Sh}}$, $f\,(x\text{-}x_0,\ y\text{-}y_0)_i \neq$ const Object (by radar) *f* (*B, D*) moves parallel to C_S	V↑∨V↓ Cod $(B, D)_i$ = const, $i = 1,2, 3\ldots\ldots n$ $C_S \parallel$ RTL $D_{\min} > D_{\text{Sh}}$ $f\,(x\text{-}x_0,\ y\text{-}y_0)_i \neq$ const When changing V_S, parallelism is maintained	K↑∨ K↓ Cod $(B, D)_i \neq$ const, $i = 1,2, 3\ldots\ldots n$ $C_S \nparallel$ RTL $D_{\min} > D_{\text{Sh}}$ C_S↑↔ RTL ↓ C_S↓↔ RTL ↑ $f\,(x\text{-}x_0,\ y\text{-}y_0)_i \neq$ const When you change the C_S, RTL turns in the direction opposite to the turn	of RTL ↑∨ RTL ↓ ⇒C↑∨C↓: (C_S, V_S) = const Cod $(B, D)_I \neq$ const $C_S \nparallel$ RTL $D_{\min} > D_{\text{Sh}}$ $f\,(x\text{-}x_0,\ y\text{-}y_0)_i \neq\neq$ const RTL reversal indicates a change in C_{Targ} in the direction of reversal. (C_S, V_S) = const	*f*(x,y) = const Cod $(\Pi, D)_i$ = const, $i = 1,2, 3\ldots\ldots n$ $C_S \parallel$ RTL $D_{\min} > D_{\text{Sh}}$ $f\,(x\text{-}x_0,\ y\text{-}y_0)_i \neq$ const The value $f\,(B, D)_i$ of the immovable object (target) moves parallel to C_S
Cod $(B, D)_i \neq$ const, $i = 1,2, 3\ldots\ldots n$ $C_S \nparallel$ RTL Object (by radar) *f*(*B, D*) moves parallel to CS not parallel to C_S	$D_{\min} < D_{\text{Sh}}$ *B* = const, *D*↓ RTL goes through the origin. There is a danger of collision	$D_{\min} > D_{\text{Sh}}$ $f\,(B, D)_i \neq$ const RTL crosses the K_C. There is no danger	$D_{,\min} > D_{\text{Sh}}$ $f\,(B, D)_i \neq$ const RTL crosses the C_S at the stern. The vessel crosses the $C_{\text{Targ.}}$ There is no danger	–
Cod $(B, D)_i$ = const, $i = 1, 2, 3\ldots n$, $D_{\min} > D_{\text{Sh}}$ $f(x\text{-}x_0,\ y\text{-}y_0)_i$ = const Object (by radar) *f*(*B,D*) is not moving (satellite vessel)	V_S↑↓∨V_{Targ}↑↓ $C_S \parallel$ RTL The appearance of the trace after the glow of $\parallel C_S$. There is no risk of collision	C_S↑↓ ∨ C_{Targ}↑↓ $C_S \parallel$ RTL The appearance of the trace after the glow of $\parallel C_S$. There is no risk of collision	–	–

It follows that in Inland ECDIS:

1) When changing the direction or speed of movement of the radar signal when *C*s & *V*s = const., it is impossible approximately to make a clear conclusion about the type of maneuver of the target. The type of maneuver can only be set using mathematical processing of the primary radar image;

2) Turning the vessel away from the radar signal does not allow approximately assessing the effectiveness of this maneuver. The relative speed of approach decreases, $t_{\text{Sh increases.}}$ As a result, a sharp change in the direction of the RTL is possible. This is determined only by the mathematical processing of the primary radar image.

The main type of orientation in the navigation mode Inland ECDIS is orientation on the course of the vessel C_S. We define different orthogonal coordinate systems for constructing mathematical models of the vessel motion in case of divergence with targets and hazardous CO [4].

- *Shifted Cartesian coordinate systems $X_1 0 Y_1$ i $X0Y$* (Fig. 1).

$$\left\{\begin{array}{ll} \xi = \alpha_1 \bar{x} + \alpha_1 \bar{y} + \alpha_3 \bar{z} & x = x_0 + \alpha_1 \xi + \beta_1 \eta + \gamma_1 \varsigma \\ \eta = \beta_1 \bar{x} + \beta_1 \bar{y} + \beta_3 \bar{z} & y = y_0 + \alpha_2 \xi + \beta_2 \eta + \gamma_2 \varsigma \\ \varsigma = \gamma_1 \bar{x} + \gamma_1 \bar{y} + \gamma_3 \bar{z} & z = z_0 + \alpha_3 \xi + \beta_3 \eta + \gamma_3 \varsigma \end{array}\right\}. \tag{7}$$

Algebraic dependences on the limitation of variations in a given orthogonal-connected system will be as follows

$$\bar{x} = (x - x_0);\ \ \bar{y} = (y - y_0);\ \ \bar{z} = (z - z_0);$$

$$\alpha_i^2 + \beta_i^2 + \gamma_i^2 = 1,\ \ \forall i = 1,2,3;\ \ \alpha_i = \cos < x, y, z\ \ def\ \ \xi, \beta, \varsigma;$$

$$\alpha_1 \alpha_2 + \beta_1 \beta_2 + \gamma_1 \gamma_2 = 0$$

$$\alpha_1 \alpha_3 + \beta_1 \beta_3 + \gamma_1 \gamma_3 = 0$$

$$\alpha_2 \alpha_3 + \beta_2 \beta_3 + \gamma_2 \gamma_3 = 0.$$

- *Cartesian plane with a polar coordinate system*.

$$x = r\cos\varphi;\ \ r = f_1(t),$$

$$y = r\sin\varphi;\ \ r = f_2(t);$$

$$(ds)_r = dr = f_1^1(t)dt,$$
$$(ds)_\varphi = rd\varphi = f_2^1(t)dt;$$

$$ds = \sqrt{dr^2 + r^2 d\varphi^2},$$
$$S = \int_{P_1}^{P_2} \sqrt{dr^2 + r^2 d\varphi^2}. \qquad (8)$$

Algebraic dependencies on the limitation of variations on the polar coordinate system:

$$r = \sqrt{x^2 + y^2},$$
$$\varphi = arctg\frac{y}{x}. \qquad (9)$$

$$S = \int_{r_1}^{r_2} \sqrt{1 + r^2\left[f_1^1(t)\right]^2}\,dr, \;\; S = \int_{\varphi_1}^{\varphi_2} \sqrt{\left[f_2^1(\varphi)\right]^2 + [f_2(\varphi)]^2}\,d\varphi, \qquad (10)$$
$$S = \int_{t_1}^{t_2} \sqrt{\left[f_1^1(t)\right]^2 + [f_1(t)]^2 + \left[f_2^1(t)\right]^2}\,dt$$

We will tightly link the coordinate system $X_1 0 Y_1$ to the vessel. Axis $0Y_1$ lies in the diametral plane (DP) and is directed toward the bow of the vessel. The $0X_1$ axis is located in the plane of the center of the frame and is directed toward the starboard side (Figure 2) [3].

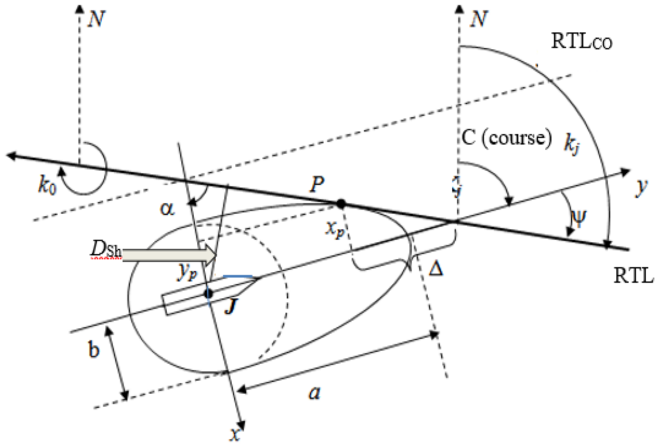

Figure 2. To the definition of *Dsh*

The RTL equations in this system are represented as $y = tg\alpha x + C$, [5], where $\alpha = 90^0 - \psi$, $\psi = C_j - C_j = C_0 - Cj \pm 180^0$, Cj – target rate. Based on expression (6), for CO in the case of the situation depicted (Figure 2) $V_j = 0$, $\psi = 0$, $\alpha = 90^0$. Thus, in this case, CO is safe [6]. Next for SENC Inland ECDIS we get:

$$A = \{a_x, a_y\}, \qquad i = \overline{1, n_a},$$
$$B = \{b_x, b_y\}, \qquad i = \overline{1, n_b}, \Rightarrow$$
$$C = \{c_x, c_y\}, \qquad i = \overline{1, n_c},$$
$$\cdots$$

$$\forall\{A, B, C\ldots\}\exists\,!\,V_j = 0,\ \psi = \pm 180^0,\ \alpha = \pm 90^0. \qquad (11)$$

Regarding the possible options for $V_S\uparrow\downarrow \vee V_{Targ}\uparrow\downarrow$ & $C_S\uparrow\downarrow \vee C_{Targ}\uparrow\downarrow$, you should be guided by the RTL position data (Table I).

When moving the target, the front half of the domain of danger is a semi-ellipse:

$$\frac{y^2}{a^2} + \frac{x^2}{b^2} = 1\ ,\ \ y \ge 0 \Rightarrow \frac{y_P \cdot y}{a^2} + \frac{x_P \cdot x}{b^2}.$$

$$y = tg\alpha \cdot x + \frac{a^2}{y_P}$$

$$tg\alpha = \frac{x_P \cdot a^2}{y_P \cdot b^2} = k \cdot \frac{a^2}{b^2} \Rightarrow k = \left|-tg\alpha\frac{b^2}{a^2}\right|$$

$$y_P = a \cdot b\sqrt{\frac{1}{b^2 + k^2 a^2}},\ \ x_P = k \cdot y_P \qquad (12)$$

$$D_{Sh} = (y_P + \Delta)\cdot \sin\psi =$$
$$= (y_P + x_P \cdot ctg\psi)\cdot \sin\psi. \qquad (13)$$

The expression (12) defines the coordinates of the point of contact RTL x_P, y_P to DD. Expression (13) determines the threshold value D_{Sh} when estimating a dangerous approach or collision when the vessel is moving along the fairway. It should be noted that the DD value for CO and moving targets are not the same in size. The form and size of the DD is determined depending on their navigation status.

When using DD, the value of $Dsh \neq$ const. The standard procedure for identifying the danger of approaching the ratio of closest and maximum allowable distances is unacceptable. In most cases, it is necessary to determine the *limit bearings* to the safety zones of the CO or the target vessel with the definition of the sector of unacceptable courses [7].

Let us define the semi-axes of the ellipse *a* i *b*, which coincide in direction with the longitudinal and transverse axes of the vessel. We calculate the limit bearing, defining many dangerous relative rates.

To do this, we define an analytical expression for the safety zone of CO and moving targets in the reference coordinate system XOY. We introduce two more coordinate systems $X_1O_1Y_1$ i $X_2O_2Y_2$ (Figure 3).

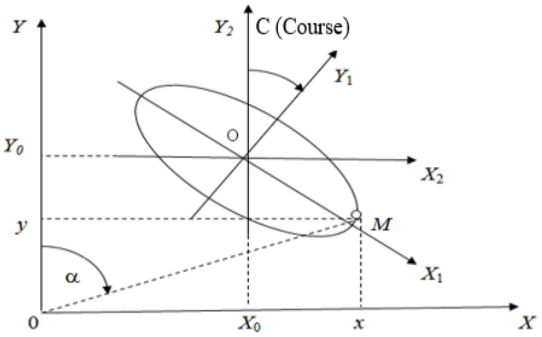

Figure 3. Coordinate systems binding

In the coordinate system $X_1O_1Y_1$.

$$\frac{x_1^2}{a^2}+\frac{y_1^2}{b^2}=1. \tag{14}$$

$x = X_0 + x_2$, $y = Y_0 + y_2$.

$$M\left(x_2, y_2\right) \Rightarrow \begin{cases} x_2 = y_1 \sin C + x_1 \cos C, \\ y_2 = y_1 \cos C - x_1 \sin C. \end{cases}$$

$$\Rightarrow \begin{cases} x = X_0 + y_1 \sin C + x_1 \cos C, \\ y = Y_0 + y_1 \cos C - x_1 \sin C. \end{cases}$$

$$(14) \Rightarrow y_1 = \pm b\sqrt{1-\frac{x_1^2}{a}}$$

$$y_1 = +b\sqrt{1-\frac{x_1^2}{a^2}} \Rightarrow \begin{cases} x = X_0 + b\sqrt{1-\dfrac{x_1^2}{a^2}} \cdot \sin C + x_1 \cdot \cos C, \\ y = Y_0 + b\sqrt{1-\dfrac{x_1^2}{a^2}} \cdot \cos C - x_1 \cdot \sin C. \end{cases}$$

$$\alpha = arctg\,\frac{x}{y} = arctg\,\frac{X_0 + b\sqrt{1-\dfrac{x_1^2}{a^2}} \cdot \sin C + x_1 \cdot \cos C}{Y_0 + b\sqrt{1-\dfrac{x_1^2}{a^2}} \cdot \cos C - x_1 \cdot \sin C} \tag{15}$$

To find the limit bearings $\alpha_{\min}$ and $\alpha_{\max}$ we differentiate expression (15) and then equate the derivative to zero [7]:

$$\frac{\partial \alpha}{\partial x_1} = \frac{1}{1+\left(\dfrac{x}{y}\right)^2} \cdot \frac{\partial}{\partial x_1}\left(\frac{x}{y}\right). \tag{16}$$

$$\frac{\partial \alpha}{\partial x_1} = 0 \Rightarrow \frac{\partial}{\partial x_1}\left(\frac{x}{y}\right) = 0.$$

$$\frac{\partial}{\partial x_1}\left(\frac{x}{y}\right) = \frac{\dfrac{\partial x}{\partial x_1} y - \dfrac{\partial y}{\partial x_1} x}{y^2} \Rightarrow \tag{17}$$

$$\frac{\partial x}{\partial x_1} y - \frac{\partial y}{\partial x_1} x = 0.$$

Next, we use algebraic, trigonometric, and differential transformations and obtain expressions:

$$\det = \begin{cases} x_1^{(1)} = -\dfrac{a^2cb}{a^2+c^2r^2} + \sqrt{\left(\dfrac{a^2cb}{a^2+c^2r^2}\right)^2 - \dfrac{a^2c^2\left(b^2-r^2\right)}{\left(a^2+c^2r^2\right)}}, \\ x_1^{(2)} = -\dfrac{a^2cb}{a^2+c^2r^2} - \sqrt{\left(\dfrac{a^2cb}{a^2+c^2r^2}\right)^2 - \dfrac{a^2c^2\left(b^2-r^2\right)}{\left(a^2+c^2r^2\right)}}. \end{cases}$$

$$\alpha_n = arctg\,\frac{X_0 \pm b\sqrt{1-\dfrac{\left(x_1^{(1)\vee(2)}\right)^2}{a^2}} \sin C + x_1^{(1)\vee(2)} \cos C}{Y_0 \pm b\sqrt{1-\dfrac{\left(x_1^{(1)\vee(2)}\right)^2}{a^2}} \cos C - x_1^{(1)\vee(2)} \sin C} =$$

$$= arctg\,\frac{\eta}{\mu}, \quad n = 1,\ 2,\ 3,\ 4.$$

Let us determine graphically the limit values of the bearings (Figure 4) and the signs of the components of the bearing a_n from the obtained roots (Table II).

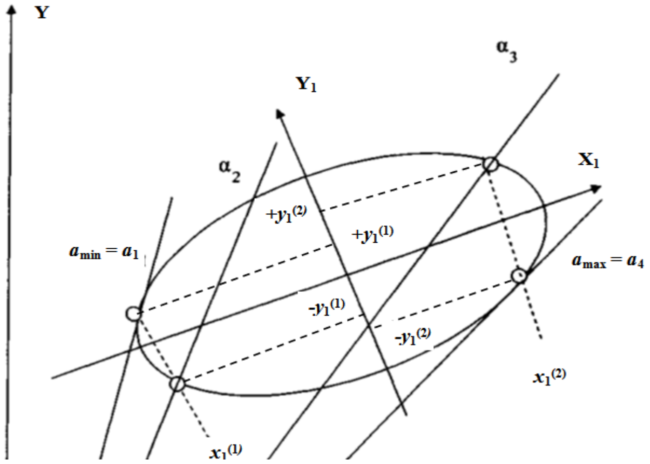

Figure 4. Determination of the limit values of $a_{\min}$ & $a_{\max}$ bearings

TABLE II. VALUE OF THE SIGNS OF THE COMPONENTS OF BEARING A_N WITH THE OBTAINED ROOTS AT $x_1 > 0$, $Y_1 > 0$

№	η	μ	*det*
1	$X_0 + b\sqrt{1-\frac{\left(x_1^{(1)}\right)^2}{a^2}}\sin C + x_1^{(1)}\cos C$	$Y_0 + b\sqrt{1-\frac{\left(x_1^{(1)}\right)^2}{a^2}}\cos C + x_1^{(1)}\sin C$	$x_1^{(1)}$
2	$X_0 - b\sqrt{1-\frac{\left(x_1^{(1)}\right)^2}{a^2}}\sin C + x_1^{(1)}\cos C$	$Y_0 - b\sqrt{1-\frac{\left(x_1^{(1)}\right)^2}{a^2}}\cos C + x_1^{(1)}\sin C$	$x_1^{(1)}$
3	$X_0 + b\sqrt{1-\frac{\left(x_1^{(2)}\right)^2}{a^2}}\sin C + x_1^{(2)}\cos C$	$Y_0 + b\sqrt{1-\frac{\left(x_1^{(2)}\right)^2}{a^2}}\cos C + x_1^{(2)}\sin C$	$x_1^{(2)}$
4	$X_0 - b\sqrt{1-\frac{\left(x_1^{(2)}\right)^2}{a^2}}\sin C + x_1^{(2)}\cos C$	$Y_0 - b\sqrt{1-\frac{\left(x_1^{(2)}\right)^2}{a^2}}\cos C + x_1^{(2)}\sin C$	$x_1^{(2)}$

$a_{\min} = \min\{a_1, a_2, a_3, a_4\}$,

$a_{\max} = \max\{a_1, a_2, a_3, a_4\}$. (18)

$x_1 > 0,\ y_1 = 0 \Rightarrow \alpha = 90^0$,

$x_1 < 0,\ y_1 = 0 \Rightarrow \alpha = 270^0$,

$x_1 < 0,\ y_1 > 0 \Rightarrow \alpha = 360^0 - \text{arctg}\ x_1/y_1$,

$x_1 \neq 0,\ y_1 < 0 \Rightarrow \alpha = 180^0 + \text{arctg}\ x_1/y_1$.

A feature of the proposed algorithm is to overcome the optimization criteria of optimization problems, determining their volume and quality. A number of uncertainties that are inevitable when using the principles of navigation data processing are overcome. The proposed method of automated determination of the limit values of navigation parameters will help to increase reliability when solving navigation problems in order to increase the safety of vessel motion.

III. RESULTS

A technique has been developed for the automated determination of the limit values of navigation parameters during vessel motion. The technique allowed considering the proposed IMN system of two functionally interrelated components of the subsystem:

- River electronic cartographic system,
- Coastal infrastructure, which is indicated on the electronic map by individual CO.

The result of the interaction of the two subsystems is the performance of the tasks with the probability of a safe navigation of $P\text{sn} \geq 95\%$ in terms of:

$$P\text{sn} = 1 - \exp\left(D_{\min}/M\right)^2 \quad (19)$$

In addition, a technique was developed that revealed the need to supplement this system with a new element of inclusion - an automated display of depths and fathom lines for the actual water level on the river electronic chart using expression (4). For its analysis, methods of collective generation of ideas and expert methods are applied.

Experimental studies were performed on a simulator system for the reproduction of river electronic maps SeeMYENC. In accordance with this, when modeling the situation, non-optimal values were set for individual NP systems. The area of NP changes in the vector space was calculated according to information from river electronic maps. Possible parametric variation was controlled within the specified framework of the "exploitation tube" (Figure 5).

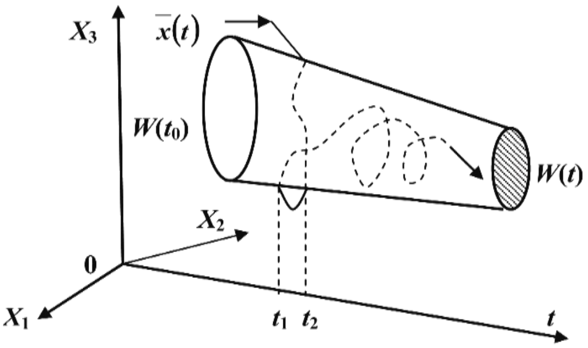

Figure 5. Parametric variation of NP

The process of a dangerous situation is characterized by the exit of NP from the region of a given tube $W(t)$. The area $W(\tau)$ depends on $\tau = t_2 - t_1$ duration of variation of NP. The dangerous change of NP is carried out in the form of a set of control actions $u(t)$ belonging to the set of hyperreal numbers U^* and aimed at neutralizing the consequences in the shortest time τ.

We characterize the processes of such parametric stabilization as stages of ensuring the safe vessel motion. The corresponding subsystems work well in specified intervals of parameter variation. One fact out of the "tube" is recorded.

TABLE III. THE RESULTS OF THE EXPERIMENTS

ENC	Object	C_S, deg	D, m		B, deg		H_{SENC}, m	$H_S+\delta$, m	RTL	det, m	
			Dmin	Dsh	a_{min}	a_{max}				$x_1^{(1)}$	$x_1^{(2)}$
UA7N0071	Target 1	43.4	50.7	31.0	25.7	37.4	17.4	3.1+0,5	C_S not par RTL	42.4	33.7
	CO 1	120.5	40.8	31.0	135.1	140.4	6.2	3.1+0,5	C_S par RTL	37.2	32.1
UA7N0121	Target 2	35.4	50.4	31.0	23.4	31.1	9.2	3.1+0,5	C_S not par RTL	45.7	34.0
	CO 2	26.2	64.4	31.0	25.4	32.2	5.4	3.1+0,5	C_S par RTL	52.0	33.4
UA8N0389	Target 3	112.5	85.5	32.7	120.4	131.5	6.4	3.4+0,5	C_S not par RTL	73.4	35.1
	CO 3	112.5	236.7	32.7	105.0	114.3	4.9	3.4+0,5	C_S par RTL	144.5	34.9
UA7N0531	Target 4	140.6	101.1	32.7	142.9	151.2	7.1	3.4+0,5	C_S not par RTL	74.5	34.1
	CO 4	140.6	101.1	32.7	150.3	158.1	3.6	3.4+0,5	C_S not par RTL	84.4	35.8

IV. DISCUSSION

The existing visual (pilot) method of river navigation was not based on solving problems of applying a scientific approach to the introduction of a modern *e*-navigation system on IWW of Ukraine. Hence, the methods of intelligent processing of navigation data were simplified. Thus, the processing of navigation data with the pilot navigation method was based on considering it as a simple sum of the properties of elements with single-type multi-level links [8]. This does not correspond to the laws of the functioning of a complex object with a modern image of *e*-navigation. Thus, with the current method of river navigation, there are local, sectoral tasks and principles for ensuring its life cycle. The functioning of the modern method of navigation is based on the analysis of a number of factors that are currently not taken into account in connection with the use of approximate models. It should be noted that the problem of defining context-oriented intelligent navigation data processing in the IMN system on IWW of Ukraine remains open today. Problems in the navigation data processing network affect the accuracy of the information received.

To solve the problems of safe vessel motion, the article considers the navigation parameters of hazards (B & D). The formalization of the safe vessel zone showed that B & D values are variable and depend on a number of factors. These factors require separate or additional research. Formalized vessel safe zones are presented in the form of an ellipse. To determine the boundaries of safe distances, cartographic objects on SENC (coastline, hazards, etc.) are considered as domains of danger in the form of dangerous fathom lines. That is, the creation of domains of danger during the vessel motion is specified by rhumb line segments (geometric primitives). The studies used the full expression for the differential corrections h (t) to the measured depths, which are denoted by SENC, obtained in paper work [2].

The main mode of operation of Inland ECDIS is the relative motion mode. The line of relative motion is a feature of safe distances of the closest approach. An emergency occurs when RTL crosses the center of the screen or $D_{\min} < D_{\mathrm{Sh}}$. The limit value of D_{Sh} is obtained when the relative traffic line touches the boundary of the domain of danger. The limit of the domain of danger is changing with water level fluctuations. With a constant water level, the magnitude of the domain of danger is constant. The set of points of the limit of domain of danger can be considered as a separate or particular case of ship-to-target divergence. Mathematical models of vessel motion formalization are defined in different orthogonal coordinate systems [9]. When the vessel is moving, the value $D_{\mathrm{Sh}} \neq$ const and depends on the position of the relative traffic line RTL.

The standard procedure for identifying the danger of approaching the ratio of closest and maximum allowable distances is unacceptable. In most cases, it is necessary to determine the limit bearings to the safety zones of the cartographic objects or the target vessel with the definition of the sector of unacceptable courses. The method of calculation of limit bearings described in work [7] is accepted as a basis. A feature of the proposed algorithm is to overcome the optimization criteria of optimization problems, determining their volume and quality. A number of uncertainties when using the principles of navigation parameters processing are overcome. The experiments confirmed the efficiency and practical applicability of the proposed method.

The prospect of further research is to further research the following elements:

- SENC with the reflection of the actual depth,
- GPS signals received on IWW,
- Placement of GPS antennas on the ship in different coordinate systems with the calculation of the position of points,
- Use of neural networks for mathematical support of a wide range of practical problems of diagnostics and pattern recognition,
- Building an expert system. Thus, the information system for processing navigation data should promptly detect network anomalies, as well as suggest possible solutions for their elimination.

V. CONCLUSIONS

The work paper solved the problem of automated determination of the limit values of navigation parameters during the vessel motion in the conditions of river *e*-navigation.

The advantage of the research is to provide a much greater accuracy in predicting the location of vessels. The essential vagueness and unpredictability of situations of an extreme, risky nature are eliminated. The theoretical incompleteness and the multiple possibility of different interpretations in practice leads to threatening statistics of disasters, accidents, undesirable events with passengers, crews, cargoes, as well as environmental pollution. The calculations confirm the increase in the probability of safe vessel motion to 97%.

The work paper contains materials on scientific research in the field of river transport in terms of determining the mechanisms of structure formation and navigation data processing in the conditions of the modern method of navigation.

The proposed approach is a continuation of the previous study on the use of system analysis of IMN implementation on IWW of Ukraine, described in paper work [10].

VI. ACKNOWLEDGEMENTS

Based on the materials of the article, a report was made at the International Scientific and Practical Conference (May 2018, Italy) «Globaliation of Scientific and Educational Space. Innovations of Transport. Problems, Experience, Prospects». Abstracts published on: Method of automated determination of the limit values of navigation parameters during vessel motion [3].

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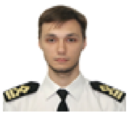

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How to Cite this Article:

Doronin, V., Aleynikov, V., Alieinikov, M. & Spiian, O. (2019) Automated Determination of the Limit Values of Navigation Parameters during Vessel Motion in the Conditions of River e-Navigation. International Journal of Science and Engineering Investigations (IJSEI), 8(88), 54-61. http://www.ijsei.com/papers/ijsei-88819-10.pdf