FORMING THE AREA OF UNACCEPTABLE VALUES OF THE PARAMETERS OF VESSELS' MOVEMENT FOR THE VESSELS' DIVERGENCE AT REMOTE CONTROL PROCESS

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Highlight
Safety of the vessels' divergence process can be ensured using the method of forming the unacceptable values areas of vessels' motion parameters.

Abstract
Navigation traffic and the danger of collision are steadily increasing. Features of navigation in narrow corridors (water, air, etc.) require the development of modern methods for assessing the situation of convergence and the choice of maneuvering divergence of vessels. A method is proposed for forming the area of inadmissible values of the parameters of the movement of any vehicles (including marine) with remote control of the process of their divergence. Situations are considered when a collision of sea vessels can be avoided only by changing the speed in case such vessels cannot change course. The proposed method can be generalized to any environment of navigation.

Keywords
navigation safety; collision avoidance; divergence maneuver; area of unacceptable values of vessels' movement parameters.

Introduction
In the modern era, the intensity of both crewed and unmanned navigation is steadily increasing [1]. Inland shipping is an important pillar of the European transport system. According to statistics, about 20–30 collisions per year result in damage to waterway infrastructure, damage to vessels, or even injury to people [2]. In this regard, it is relevant to increase the requirements for the accuracy of maneuvering vessels using both coastal and onboard equipment.
The frames for the safety of navigation are indicated in the European Code for Inland Waterways CEVNI EG/2021/11 [3]. According to Article 6.16 of the said Code, the vessel's maneuvers may be carried out safely in such a way that other vessels are not forced to suddenly change their course or speed. When simulating vessel maneuvers, it must be considered that the vessel performing the maneuver must give priority to any vessel going upstream. In addition, when simulating a speed reduction, it should not be lower than the speed necessary for the safe management of the vessel before entering the port, near ships that are moored to the

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shore and in other situations provided for within the scope of Article 6.20 of the CEVNI Code. At the same time, the safe speed must be determined considering the deterioration of the visibility restriction, the presence and movement of other vessels, as well as local conditions by Article 6.30 of the CEVNI Code. When maneuvering, vessels should, as far as possible, clear the fairway and pass to the port.
In addition, in the process of determining the parameters of the safe divergence of vessels, it is very important to exclude the influence of the human factor on the speed and quality of the choice of courses during the maneuver for vessels [4]. For this, the possibilities of computer simulation modeling are best suited [5].
The avoiding of collisions between maritime transport provides in accordance with the international protocol COLREGs [6]. In considering scenarios of the vehicles' (including maritime) divergence process, researchers mainly use vehicle trajectory data [7]. Moreover, when choosing their course, the vessels must coordinate their decisions with neighboring vessels. In this case, vessels can only change their course, while maintaining their speed, taking into account the parameters of the vessels as a whole [8]. However, taking into account the possibilities of solving more complex future situations, it is necessary to consider the possibility of changing the speed of the vessel as well [9]. One of the criteria in the development of collision avoidance algorithms is the observance of the minimum distance between vessels following each other [10]. Consideration of this task as a multi-criterion is necessary to avoid the collision of vessels with other vehicles (for example, mobile robots or drones), which are under remote control [11]. In this case, maneuvers can be performed as a change of the course for both vessels, a change in their speed, as well as a change of the course of one vessel, and a change of the speed of the other vessel [12].
To control the navigation process and control the movement of dangerously approaching vessels, they are equipped with an onboard radar station supported by Vessel Traffic Service (VTS). VTS collects up to 560 million location records [13] since VTS works not only with navigation but also with bathymetric and meteorology information [14]. VTS can use automatic identification system (AIS) data, local radar data, meteorological data, and video camera data [15,16].
For a comprehensive operational analysis of the actual situation on the movement of vessels using the obtained data, it is very important to construct a graphical display of the area of unacceptable values of the parameters of the movement of vessels. Then, based on visual analysis, it is easier to understand the trend of vessels' movement in the navigable waterway in real-time [17,18]. Integrated information can be comprehensively and realistically interpreted and effectively used to prevent a collision. However, to use such data, anomalies must be excluded from them, for example, using the K-means-based anomaly detection method [19] or rearrangement task [20].
After obtaining data without anomalies, they are used to analyze and predict trends in vessel traffic, both on the remote control and the man steering. During analyzing navigational measurements, mixed probability distribution laws are effectively applied to random errors [21,22]. Also, attention should be paid to the fact that the means of control and management of navigation, which are based on radio technology, may not work in conditions of numerous complex (noise-like) signals, which are close to "white noise". To reduce the effect of noise and interference, one can use, for example, the algorithm ASBD-RC [23] or CCRP [24].
The work of such systems is especially difficult for the safety of sailing in coastal sea areas in a bay and a port, so-called "narrow/compressed areas" with particularly heavy traffic [25]. With this trend in the near future, all shipping routes will be laid in narrow areas [26].
To ensure the safe divergence of vessels, it is necessary to develop modern means of preventing collisions of vessels, which use methods of safe divergence of two or more vessels. In this case, it is necessary to consider both autonomous and remote control to prevent collisions. The forming of the area of unacceptable values of the vessels' movement parameters is also promising.
Therefore, the analysis of dangerous convergence of vessels and the definition of the area of unacceptable values of the parameters of the movement of vessels for their differences over time is becoming increasingly important.

Methods

To solve the problem of collisions between vessels, it is necessary, first of all, to simulate the forms of interaction between vessels in case of disappearance and the procedure for calculating safe maneuvers. The problem of the absence of vessels collisions can be solved by using the flexible food travel method [27]. To determine the individual and used trajectory of the situation on the vessels, one can use the methods of applied dynamic programming with the constraints of the neural state in rare navigational observations at sea [28]. With this degree of discreteness of calculations, the headquarters are distributed along the vessels' route.
To ensure maximum safety of vessels during divergence, it is necessary to determine as accurately as possible the coordinates of each of the vessels participating in the divergence process. In this case, a good result can be obtained by the vessel's observed coordinates estimation using the mixed laws of distribution errors of the first and second type for lines of position (LOP) [29].

Formalization of the vessels' interaction in case of divergence can be carried out by methods of differential games. In this case, an approximation mathematical model as a triple linear programming problem allows synthesizing a safe trajectory of a vessel's movement as a multi-stage solution process [30].
Multistage is also introduced into the trajectory clustering method for reliable clustering of AIS trajectories. Dynamic Time Warping (DTW-algorithm) can be used to measure distances between trajectories. It allows describing vessels' interactions in case of divergence [31]. This method is competitive with traditional clustering methods such as spectral clustering and fast affinity propagation.
In some cases, the study of the safety of navigation can be carried out using Bayesian networks for the synthesis of a priori information and sample information. Through establishing the Bayesian network model, the prevention of ship grounding, collision, and fire may be achieved [32]. Using Bayesian networks to study the safety of navigation is not only easy for understanding, but also has a clear causal relationship. It can be easily improved and updated in later work.
The idea of generating evasive trajectories or optimizing the trajectories of all ships involved is not new [33]. Such trajectories should not only be collision-free, but they should also additionally guarantee that an evasive maneuver can be performed at any time.
The analyzed methods of vessel divergence are mainly used for locally independent control. Recently, methods of remote control of the vessel divergence process are being developed, which are addressed to the operators of the Vessel Traffic Services (VTS). Insufficient attention has been paid to the accounting and use of such modern methods.
In the presented work, the determination of the divergence strategy of the vessels is carried out using the developed method of forming the area of unacceptable values of the vessels' motion parameters during their remote control.

Results and discussion

Full (remote) control of the vessels' divergence process is carried out by an external manager who forms a strategy of vessels' divergence. He observes the current situation and, in the presence of situational indignation, compensates for it by a joint maneuver of divergence. Such a manager can be both a VTS and a Vessel Traffic Management Systems (VTMS). VTMS is installed on each of the vessels and has the same capabilities compared to VTS. This approach solves the problem of collective compensation of situational disturbances and implements the individual strategy obtained as a result of the decision.
In general, a group of two vessels will be called an “elementary group”. Then it is advisable to formalize it using the following mathematical model. Suppose at the initial moment of time, the relative position of the vessels is characterized by the parameters α_o and D_o. At the same time, many possible combinations of their motion parameters (as components of the control vector) can be described by a four-dimensional space of motion parameters K_1, V_1, K_2, V_2, which we will call the space of true motion. Likewise, the space of relative motion is a two-dimensional space of the motion relative parameters – course K_{ot} and speed V_{ot}. The relative position, that is, the values of the bearing α and the distance D, is invariant for both spaces.
Traditionally, the maximum permissible rapprochement distance D_d does not depend on the relative position of the elementary vessels group and is assumed to be unchanged in magnitude for the rapprochement situation that has taken place. This means that the vessel safe domain is circular and is set in the relative motion space.
The boundary between the subset of safe situations S_s and the subset of situations S_ω leading to dangerous rapprochement is determined by the equality of the distances of the shortest vessels ’rapprochement and the maximum allowable rapprochement, that is, $D_{\min} = D_d$, provided that the vessels approach each other ($\dot{D} < 0$). The values $D_{\min}$ and $\dot{D}$ are defined by initial relative position and relative motion parameters:

$$D_{\min} = |D\, sin(K_{ot} - \alpha)| \qquad (1)$$
$$\dot{D} = -V_{ot}\cos(\alpha - K_{ot})$$

Since when vessels’ rapprochement $\dot{D} < 0$, then $0 \leq (\alpha - K_{ot}) < \pi/2$.
As follows from the above expressions for $D_{\min}$ and $\dot{D}$, the boundary between subsets of situations S_s and S_ω defined by one point (K_{otg},V_{otg}) in the relative motion space. This point corresponds to the boundary in the true movement space, depending on the parameters of the vessels movement that satisfy the relationship:

$$D_d = F_{rt}(K_1, V_1, K_2, V_2) \qquad (2)$$

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where F_{rt} – mapping from relative motion space to true motion space.

If the boundary (2) of a four-dimensional space is projected onto one of its planes, then it is possible to obtain the boundaries of two-dimensional regions of unacceptable movement parameters of a vessels' elementary group. The axes of such planes are the movement parameters of the different vessels in an elementary group, i.e., $K_1 \times K_2$, $V_1 \times V_2$ or $K_1 \times V_2$,

As a result, one can obtain an expression for the boundary of two-dimensional areas of unacceptable movement parameters of a vessels' elementary group:

(3) $$V_1(\sin K_1 \cos \gamma - \cos K_1 \sin \gamma) = V_2(\sin K_2 \cos \gamma - \cos K_2 \sin \gamma)$$

where $\gamma = \alpha \pm \arcsin\left(\frac{D_d}{D}\right)$.

The resulting equation for a given value of γ connects the values of vessel traffic parameters K_1, V_1, K_2 and V_2, at which the boundary is reached in the space of true motion between the sets of dangerous and permissible situations during vessels' rapprochement. In the process, γ is determined by the initial relative position of the ships. Thus, the equality $\min D = D_d$. Therefore, if in the space of true motion, the boundary (3) is projected on the plane, then using equation (3) it is possible to obtain the dependence between the parameters P_x and P_y (4). In this case, the axes of the agreed planes are the parameters of the movement of different vessels. In this case, out of four vessel traffic parameters two parameters P_a and P_b can be fixed, and consider the remaining two parameters P_x and P_y as variables.

(4) $$P_y = f(\gamma, P_a, P_b, P_x)$$

The relationship between the parameters P_x and P_y in (4) represents a curve on the plane $P_x \times P_y$, which is the boundary of the area Ω of unacceptable values of the parameters P_x and P_y.
For points $(\rho_x, \rho_y) \in \Omega$ vessels' rapprochement is dangerous. If the points (ρ_x, ρ_y) are on the boundary Ω or outside it, then the rapprochement is safe, and the situation of vessels' rapprochement is acceptable.
With a free water area for maneuvering, the most preferable is the divergence maneuver by changing the course. Therefore, courses of approaching vessels K_1 and K_2 are selected as variable parameters P_x and P_y. In this case, $P_x = K_2$ and $P_y = K_1$, parameters V_1 and V_2 are unchanged. In this case, expression (4) describes the boundary of the area of unacceptable course values for an elementary group of vessels and takes the following form:

(5) $$K_1 = \gamma + \arcsin(\rho[\sin(K_2 - \gamma)]),$$

where $\rho = \frac{V_2}{V_1}$ and $V_1 \geq V_2$.
Since $\rho < 1$, the course K_2 takes all values from 0 to 2π.

Figure 1 shows the area of unacceptable course values S_{Dij} for V_1=20 knots, V_2=15 knots.
Thus, having an area of unacceptable values of the courses S_"Dij" for two ships, you can choose their safe avoidance courses belonging to the boundary of the area S_"Dij". The selected courses of avoidance provide a divergence at a distance equal to the maximum allowable distance of the vessels' rapprochement.
In narrow waters, there are situations in which vessels cannot change their course due to dangerous rapprochement. Therefore, their collision can be prevented only by changing the speeds. In this case, the vessel speeds are selected as variables, i.e., $P_x = V_2$ and $P_y = V_1$, and the vessel courses K_1 and K_2 are unchanged. With this formulation of the problem, an area of unacceptable values of the speeds of an elementary vessels' group is formed.

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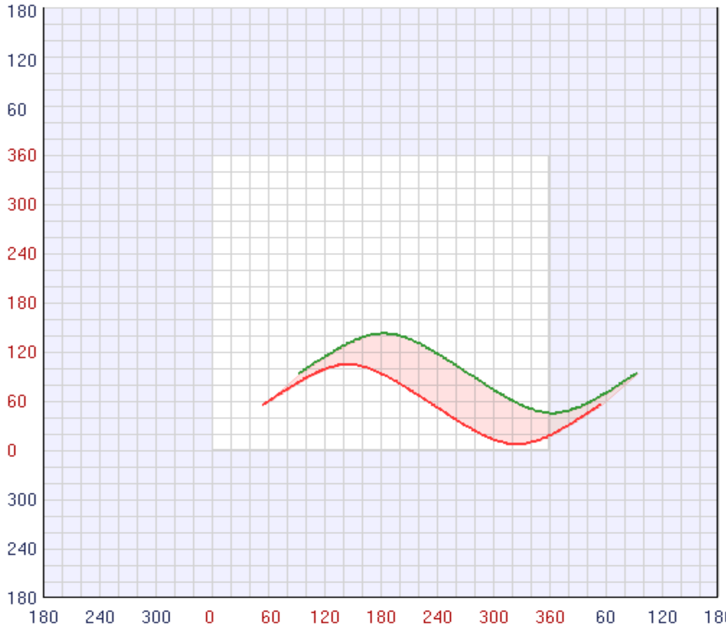

Figure 1. The area S_{Dij} of the courses K_1 and K_2 for $V_2 < V_1$. *Source: Author's.*

From expression (3), an equation can be written for the boundaries of the dangerous area of speeds, including for the upper boundary:

(6) $$V_1^* = V_2 \frac{\sin(K_2 - \gamma^*)}{\sin(K_1 - \gamma^*)}$$

where $\gamma^* = \alpha - \arcsin(D_d/D)$.

The lower boundary is expressed as follows:

(7) $$V_{1*} = V_2 \frac{\sin(K_2 - \gamma_*)}{\sin(K_1 - \gamma_*)}$$

where $\gamma_* = \alpha + \arcsin(D_d/D)$.

Obviously, with constant values of the courses K_1, K_2 and parameters γ^*, γ_* the boundaries of the dangerous area of speeds are straight lines. Figure 2 shows the area of unacceptable speeds for a pair of dangerously vessels' rapprochement, the courses of which are unchanged. In this example, the parameters of the rapprochement situation have the following meanings:

(8) $$\alpha_0 = 45°,\ D_0 = 3 \text{ miles},\ D_d = 1 \text{ mile},\ K_1 = 90°,\ K_2 = 180°$$

At initial speeds $V_1 = 18$ knots and $V_2 = 21$ knots the closest approach distance is $D_{\min} = 0.23$ mile.
If the maneuver of the divergence of ships by a decrease in their speeds is characterized by short-term transient processes, then the determination of the speeds of the divergence V_{1y} and V_{2y} can be made using the considered area of dangerous speeds. In this case, the values of the indicated speeds are chosen from the boundary speeds. However, reducing the speed of vessels by braking, as a rule, requires considerable time. So, in this case, the inertial-braking characteristics of the vessels should be considered.

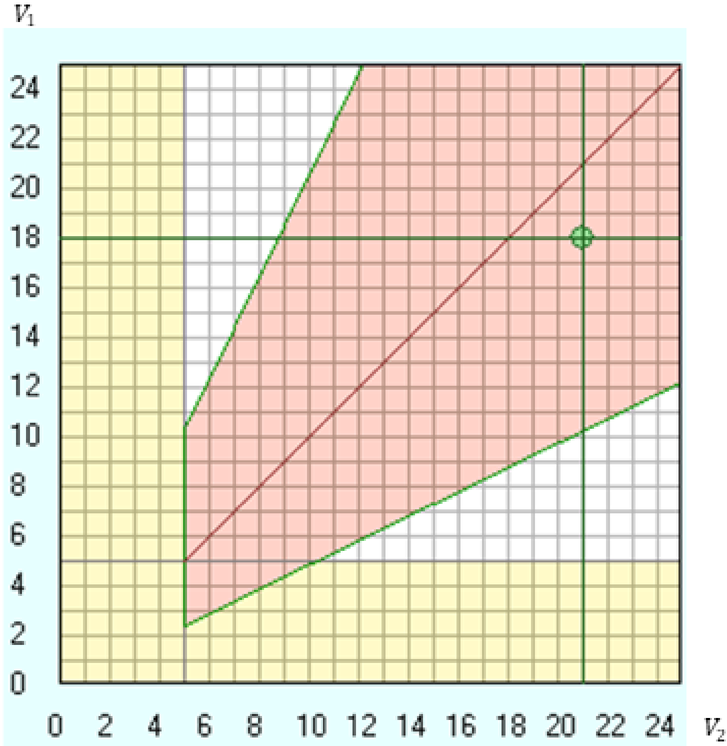

Figure 2. An area of dangerous ship speeds. *Source: Author's.*

The inertial-braking characteristics of ships are considered in the following way. Suppose the initial situation of a vessels' dangerous approach for the initial moment of time $t_0 = 0$ is characterized by a bearing α_0 and a distance D_0. The inertial-braking characteristics of vessels are considered in the following way. Since the bearing α_0 is set from the first vessel to the second, for the first vessel it is advisable to take the initial coordinates $X_{10} = 0$ and $Y_{10} = 0$. Obviously, the initial coordinates of the second vessel have values $X_{20} = D_0 \sin \alpha_0$ and $Y_{20} = D_0 \cos \alpha_0$.
Over time, the coordinates of the vessels X_{1t}, Y_{1t}, X_{2t} и Y_{2t}, as well as the current values of the distance D_t and bearing α_t change. Denote by c_{mx} a vessel, the transition period of change in speed of which is greater than or equal to the duration of the total transient process t_p. A vessel with a shorter transition period we denote as c_{mn}.
If the start time of the divergence maneuver t_n equal to the initial moment of time t_0, then vessels during the transition process t_p go the following distances:

(9)
$$L_{\text{mx}} = S_{\text{mx}},$$
$$L_{mn} = S_{mn} + V_{mny}(t_p - \tau_{mn})$$

where S_{mx} and S_{mn} – the distances that the ships c_{mx} and c_{mn} take to go respectively during the transient process of changing the speeds τ_{mx} and τ_{mn}.
By the time of the end of the general transient process t_p coordinates of vessels X_{mxp}, Y_{mxp}, X_{mnp} and Y_{mnp} are defined by the following expressions:

(10)
$$X_{mxp} = L_{mx} \sin K_{mx} = S_{mx} \sin K_{mx};$$
$$Y_{mxp} = L_{mx} \cos K_{mx} = S_{mx} \cos K_{mx};$$
$$X_{mnp} = L_{mn} \sin K_{mn} = [S_{mn} + V_{mny}(t_p - \tau_{mn})] \sin K_{mn};$$
$$Y_{mnp} = L_{mn} \cos K_{mn} = [S_{mn} + V_{mny}(t_p - \tau_{mn})] \cos K_{mn}.$$

Expressions of bearing α_p and distance D_p at the moment of time t_p:

(11)
$$D_p = \sqrt{(X_{mxp} - X_{mnp})^2 + (Y_{mxp} - Y_{mnp})^2}$$
$$\alpha_p = \arcsin\left(\frac{X_{mxp} - X_{mnp}}{D_p}\right)$$

At the time of the end of the transient process t_p the parameters of the movement of both vessels, as well as the relative course K_{otp}, become unchanged. Therefore, the distances value of the vessels' shortest rapprochement $D_{\min}$ can be calculated using the formula:

(12)
$$D_{\min} = \Delta_p D_p \, sin(K_{otp} - \alpha_p)$$

where $\Delta_p = \mathrm{sign}[\sin(K_{otp} - \alpha_p)]$.
Setting the value of one of the speeds V_{1y}, find the value of the second speed V_{2y}, at which the obtained value of $D_{\min}$ is equal to D_d. If $D_{\min}(V_{1y}, V_{2y}) < D_d$, then safe divergence with speed V_{1y} is impossible.
The values τ_{1y}, τ_{2y}, S_1 and S_2 the first and second vessels can be calculated using the formulas given in the work [34]. Using the obtained parameters and setting the speed V_{1y}, the values L_{mx} и L_{mn} are first calculated, and then the distance of the shortest vessels' rapprochement $D_{\min}$. In this case, you should start with the speed V_{2y}=V_2 and decrease it in each cycle by the selected value ΔV_{2y}.
Calculations continue until equality occurs $D_{\min}(V_{1y}, V_{2y}) = D_d$, at which the sought value V_{2y} is determined. The values of speed V_{1y} are set from the range $V_{1y} \in [V_1, V_{1\min}]$, where $V_{1\min}$ – the minimum speed at which the vessel is steered. For each value V_{1y} from the specified range according to the described algorithm the speed V_{2y}, is calculated, satisfying the equality $D_{\min}(V_{1y}, V_{2y}) = D_d$. As a result, the boundary of the area Ω_{Vj} of unacceptable vessels' speeds values will be obtained given the inertial-braking characteristics of their passive braking.
As an example, let us consider the situation of the vessels' dangerous rapprochement with the parameters: bearing α = 154°, distance $D = 4$ miles, vessel traffic parameters $K_1 = 237\,°$, $K_2 = 278\,°$, $V_1 = 15$ knots and $V_2 = 20$ knots, $D_d = 1$ mile.
In Figure 3 is shown the area Ω_{Vj} of unacceptable values of the vessels' speed, during the forming of which the inertial-braking characteristics of their passive braking had been considered. For divergence, points (V_{1y}, V_{2y}) should be selected on the boundary Ω_{Vj}, for which equality $D_{\min}(V_{1y}, V_{2y}) = D_d$ is true. So, Figure 3 shows the point on the boundary Ω_{Vj}, corresponding to the velocities $V_{1y} = 13.6$ knots and $V_{2y} = 13.2$ knots, for which $D_{\min} = 1.0$ mile is calculated by the software.

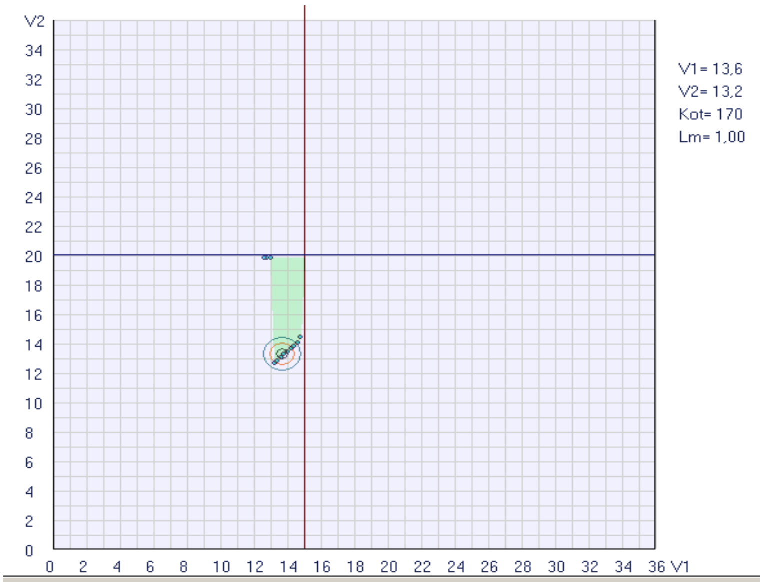

Figure 3. The area Ω_{Vj} of the unacceptable values of vessels' speeds. *Source: Author's.*

Thus, using the area Ω_{Vj}, it is possible to determine the values of the speeds obtained by passive braking, which ensure a safe divergence at a given distance.
If necessary, another type of divergence strategy can be used, in which one of the vessels changes its course, keeping its speed unchanged, and the second vessel on a constant course can reduce its speed. In this case, an area of inadmissible values of the course of one vessel and the speed of another vessel is formed, when the course of one vessel K_1 (K_2) and the speed of the second vessel V_2 (V_1) are selected as variable parameters. Then $P_x = V_2(V_1)$ and $P_y = K_1(K_2)$, but vessel traffic parameters K_2 (K_1) and V_1 (V_2) are unchanged.
Computer simulation modeling was used as an experiment to verify the validity of the proposed vessel collision avoidance methods. Let us present the results of checking the correctness of the method for determining the divergence maneuver by changing the courses of vessels. For this, a computer program was developed to simulate the divergence process.
As an example, the initial situation of a dangerous approach of vessels is shown in Figure 4. Figure 4 also shows the parameters of this situation.

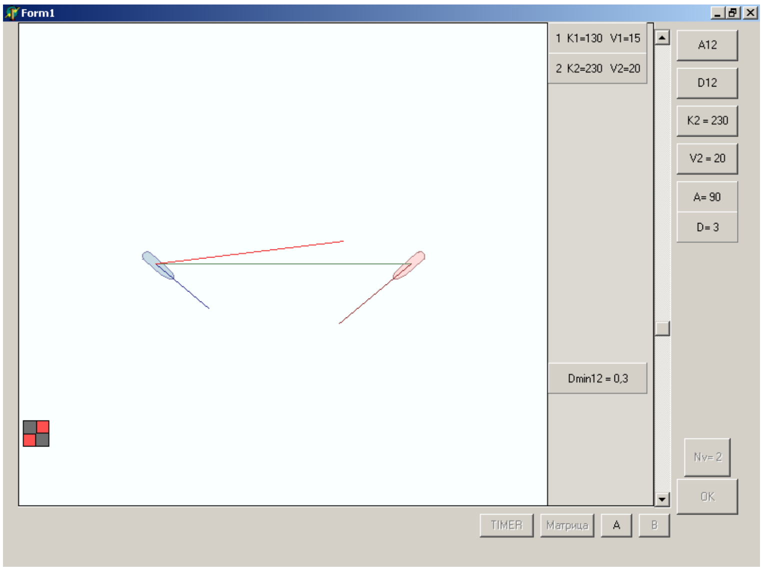

Figure 4. The initial situation of a dangerous approach of vessels. *Source: Author's.*

This situation is characterized by the closest approach distance of 0.3 miles. Therefore, it is necessary to select a diverging maneuver that increases the closest approach distance to 1 mile. For this purpose, an area of dangerous courses for this pair of vessels was formed, which is shown in Figure 5. To select a safe course of divergence of vessels, it is necessary to change the course of the first vessel by 19˚, and of the second – by 11˚, i.e., up to 111˚ and 219˚ respectively. In this case, the point of intersection of the current courses is on the border of the area of dangerous courses, and the closest approach distance of 1.07 miles is approximately equal to the maximum allowable distance, the given value of which is assumed to be 1 mile, as shown in Figure 5.
To check the correctness of the chosen courses of vessels' divergence, the maneuver of diverging ships was played using the third module of the simulation program.
At the same time, an animation of the current position of vessels with the selected evasion courses is displayed on the monitor screen, and the current value of the distance between vessels is shown in the upper left corner of the screen.
Figure 6 shows the situation of vessels' divergence at the time of 5 s.
Figure 7 shows the situation of the closest approach of vessels now of time equal to 351 s, at which the distance of the closest approach is equal to 1.06 miles, i.e., practically the maximum allowable distance.
Figure 8 shows the situation when the maneuver is completed.

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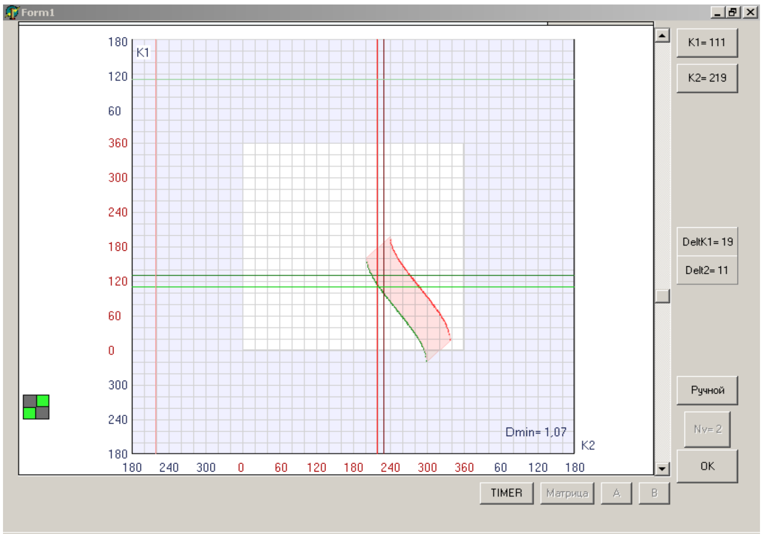

Figure 5. The selection of a safe course of divergence of vessels. *Source: Author's.*

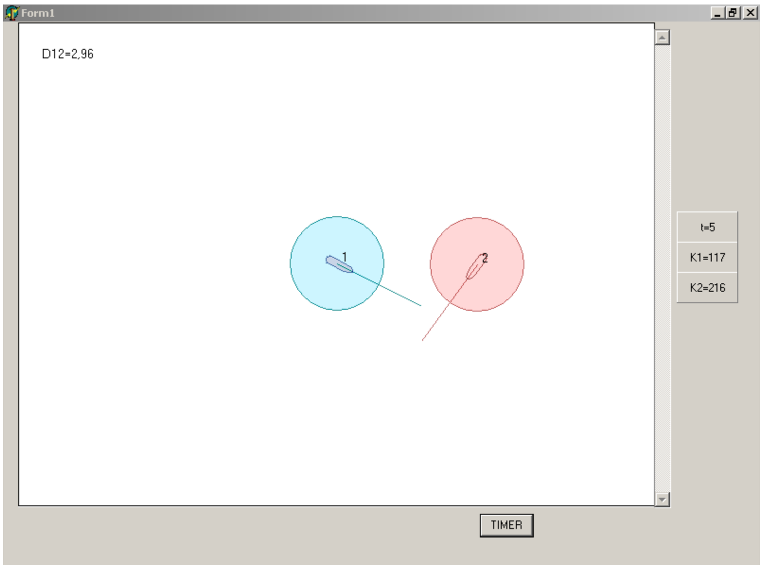

Figure 6. The initial situation when playing the maneuver. *Source: Author's.*

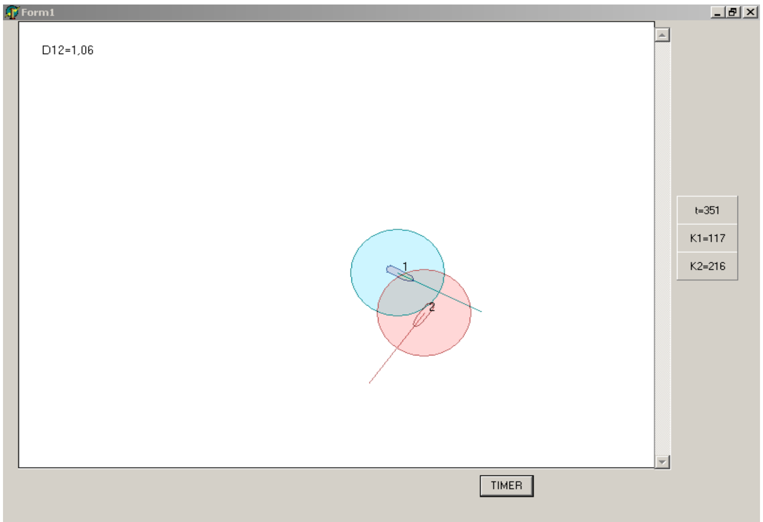

Figure 7. The situation of the closest approach of vessels. *Source: Author's.*

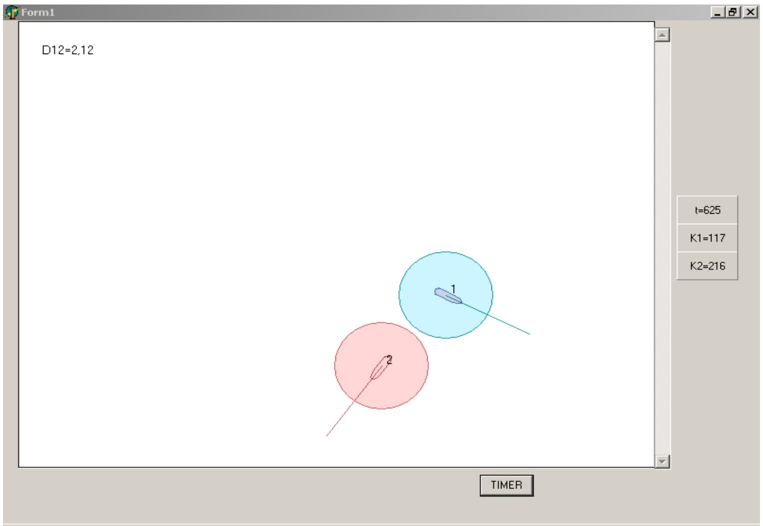

Figure 8. The completion of the process of playing the maneuver. *Source: Author's.*

Simulation modeling has shown the correctness of the proposed method of vessel divergence by changing their courses when using a dangerous course area.
In the event of a situation of dangerous approach, in the presence of sufficient water space, the method of vessel divergence by changing courses should be applied. If there are navigational restrictions, then it is advisable to use a divergence maneuver by changing the course of one vessel and the speed of another vessel. If it is impossible to perform such a maneuver, it is necessary to use the method of divergence by changing the speeds of both vessels at constant courses.

Impact

The developed method for the formation of areas of parameters' unacceptable values of the vessels' movement during their remote control offers navigators a behavior strategy for each of the ships, depending on the situation of approaching. The agreed method is applicable for the safe divergence of two or more vessels in narrow waters.
The perspectives for the inland waterway transport development are very great virtually in all countries. The EC White Paper on Transport notes that goods by inland waterways (IWW) are significantly inferior in volume to other modes of inland transport, in particular rail and road. Thus, freight traffic in terms of IWW in Poland is 6 times less than in France and almost 60 times less than in Germany. Moreover, they do not exceed 1% of freight traffic by road [35]. In Ukraine, the situation is similar. At the same time, in the United States, the share of freight traffic in IWW averages approximately 11% of all intercity freight traffic.
The inland navigation reduction in comparison to road transport can be explained by the determining influence of the geographic factor. The Danube countries are in the best conditions, characterized by a higher degree of IWW utilization along the Rhine and Danube rivers. Italy, Poland, Ukraine and other countries have a large list of important bottlenecks with low capacity. In addition, E waterway networks have a significant number of missing links, listed in the UNECE Blue Book [36]. The Polish government considers it necessary to upgrade class I, II or III to class Vb on the "major bottlenecks" of routes E 30, E 40 and E 70. However, today nothing is known about such projects, which would be included in the agenda of the Polish government. At the same time, in the indicated water area the majority of a waterway has a width below 8.5 times of the vessels' beam, which counts them as IWW with complicated navigation, that is, to "narrow water". In Ukraine, the IWW infrastructure is also expanding with the inclusion of missing links in the E-category IWW network [26]. However, such areas are characterized as narrow water with insufficient maximum draught (1.20 m) [36].
In addition, the number of voyages during the navigation period is increasing every year. That is, an increase in the intensity of navigation along the IWW complicates the already rather dangerous process of divergence of a vessels' group of two or more vessels in waterways.
Under such conditions, the introduction of the developed method using remote control will expand the possibilities of vessel divergence in narrow waters for safe navigation based on joint divergence maneuvers.
In the absence of the possibility of changing the vessel course in case of a dangerous rapprochement in narrow waters, the situation of preventing a dangerous vessels' rapprochement by changing the speed of one or each of the vessels is considered. Thanks to the research carried out, the areas of the vessel movement parameters are considered, in which the vessels' collision can be prevented only by changing the speed.

One of the projects, the main theme of which is the implementation of a new concept of communication between interacting vessels based on the VHF data exchange system (VDES) of the next generation of AIS communication, is the LAESSI project (Dresden, Germany) [37]. One of the advantages of this project is the transmission of all necessary phase and code corrections within a limited amount of data.

It should be considered that the global system for mobile devices (GSM) does not currently meet the requirements for the availability and stability of communications on inland waterways. Therefore, the possibility of using the Automatic Identification System (AIS) to transmit data between evading vessels in real-time in complex scenarios is being studied.

The implementation of VTS and VTMS into the management of the divergence process eliminates the need for mutual coordination of vessels' maneuvers by the interaction mechanism, i.e., the principle of remote control of the divergence process is applied.

It is expected that the implementation of the proposed scientific and technical solution will have a social and ecological effect, bring economic benefits to society, and prevent environmental damage. This is attributed to the fact that it will be possible not to expand IWW to the detriment of social projects, but to optimize the parameters of vessel safe domains during divergence.

The use of areas' unacceptable values of the vessels' movement parameters during their remote control, obtained by the developed method, will generally form the competitiveness of freight transport on IWW and a positive effect on the environment due to emission reduction at road freight due to decreasing in the amount of freight traffic. Thus, a method of vessels' divergence maneuver has developed. It has applied innovative aspects for forming areas of unacceptable values of vessel movement parameters. The developed method is based on a larger number of vessel variable parameters compared to the existing technologies. This method improves the efficiency of navigation in narrow waters while reducing material and energy costs.

It should also be noted that the use in the developed method of remote control of the process of diverging vessels provides for the availability of qualified personnel of both VTS and VTMS. This will contribute to the creation of new jobs, the number of which will continue to increase as grown the implementation scale of the proposed development.

Conclusions

A general method for the formation of an area of unacceptable values of the parameters of the vehicles' movement has been proposed. The combination of the developed method and algorithm for the formation of an area of unacceptable values of vehicles' traffic parameters with the categories of COLREGs rules makes it possible to increase the efficiency of collision avoidance following the requirements of the specified protocol.

The obtained analytical dependencies for calculating the boundaries of the area of unacceptable values of the vessels' course and the area of unacceptable values of their speeds make it possible to carry out the so- called "road tests" for autonomous marine vehicles before their operation, considering the parameters of the test environment. Situations of avoidance of dangerous approach of vessels not only by changing their courses, but also by changing the speed of one or each of the vessels is considered. This is important since, in narrow waters, vessels cannot change course in case of a dangerous rapprochement, therefore, situations have been considered when a collision of vessels can only be prevented by changing the speed.

The presented graphical display of the area of unacceptable values of vessel movement parameters facilitates the visual perception of given situations of dangerous approach and, thereby, accelerates the decision-making on the safe navigation parameters of a vessels' group.

In addition, the proposed method can be generalized to other (besides maritime, both surface and underwater) environments of navigation, such as aircraft flight rules, movement of ground-based autonomous unmanned/ uncrewed vehicles with remote control, etc.

Conflict of interest

There are no conflicts to declare.

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