Decision Support During the Vessel Control at the Time of Negative Manifestation of Human Factor

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Abstract. The simulation and program implementation approaches are presented in the tasks of determining the periods of loss of control due to the fault of the human factor in the operation of marine transport while carrying the navigation watch. Experiments have been carried out confirming the problem of the negative influence of the human factor on the example of navigational tasks in the Bosphorus and Hong Kong Straits. Automated tools have been developed to identify hazardous areas for navigation on location mapping by analyzing the accident geolocation in the Hong Kong Strait and the Bosphorus, which is a decision support system for emergency situations. A software module has been developed that makes it possible to identify the time periods for the manifestation of the human factor of the navigator by analyzing the ECDIS database in real time. Mathematical models of the triggering of the vessel automated course alteration system (VACA) and the actions of the navigator when controlling/navigating the vessel in difficult maneuvering zones are proposed.

Keywords. human factor, decision support, automated divergence, model of behavior, emergency situations

1 Introduction

During the passage planning, preliminary and executive plotting is performed in ECDIS, but the navigator cannot be fully confident in its effectiveness [1-2]. A number of factors associated with oncoming traffic and random obstacles, weather conditions and the composition of the watch bring in adjustments which leading to emergency situations and catastrophic consequences [3-4]. A lot of research is aimed at analyzing risks due to the human factor at the time of maneuvers and divergences, at obtaining a priori probability of a catastrophe occurring depending on the situation [5-6]. In the most difficult locations, such as Hong Kong, Singapore, the Bosporus and Dardanelles straits require the help of experienced pilots, but even their preparation also includes the full range of possible situations leading to disasters [7-9]. Despite a lot of research in such area, this study is relevant because the human factor is still the most significant cause of collisions and accidents in maritime transport [10-13].

Analysis of the literature showed that the main problem is the lack of models for identifying the manifestation of the human factor in the early stages. The complexity of constructing such models is that each navigator responds to a particular situation differently, as a result of which it is difficult to predict at what point a “human error” occur [14]. Generalized statistics do not allow for the effective monitoring of ship management/handling processes with a high degree of reliability.

The purpose of the article is to develop formal models and software for determining periods of loss of control due to the human factor of the navigator and methods for switching to automated vessel control in emergency situations.

To achieve the goal of the article it is necessary:

1. To develop means of automated identification and display on the cartographic panel of the most dangerous navigation zones within the framework of the expert decision support system during emergency situations.
2. Determine periods of loss of ship control dependent on individual stable reactions of navigators, affecting control parameters and dependent on location and complexity by automated analysis of ECDIS databases.
3. Carry out a mathematical simulation of the human factor manifestation in the time of vessel management/handling when the vessel automated course alteration (VACA) is triggered in areas of high attention.
4. Develop an algorithm and software for emergency transition to the automated control mode of the vessel in order to automatically diverge with target vessels in critical situations.

The solving of this task will allow at a qualitatively new level to approach the solution of the problem of intellectual data mining in the management/handling of the vessel and prevent catastrophic situations in maritime transport.

2 Materials and method

To build adequate mathematical models, behavioral responses of navigators in the Hong Kong Strait were analyzed to identify signs of occurrence of abnormal and catastrophic situations due to the human factor of navigators.

In order to obtain reliable results for the experiments, the “TRANSAS NAVIGATIONAL SIMULATOR NTPRO 5000” navigation simulator was used to enable utilize information navigation panels of Navi-Sailor 4000 ECDIS Multifunction Display (ECDIS, Radar, Conning) at Kherson State Maritime Academy, Ukraine.

A preliminary analysis of the location showed that the entire passage of Hong Kong Strait is difficult due to several points [15]. The main point is a lot of cross over ways by different type’s of fishing boats, special service fleet (tugboats, floating cranes and etc.), coastal fleet and ferries. Additional difficulties which occur during passage are weather condition [16-18].

Strong winds (mostly NE-li) and very often showers and fogs. Shower and fog require from navigators to pay high attention to controlling their own vessel's position, as well as control of other target vessels, which includes small and bad targets for plotting. A strong wind increases wind resistance (especially on ships with a huge sailing area, such as large container ships), and also requires additional efforts by the navigator to control the trajectory of the vessel (Fig. 1). In addition, it is difficult to get through the Hong Kong Strait because it is a restricted zone for maneuverability controlled by the Hong Kong TSC/VRS (MARDEP) [19]. The entire path from the Round Island to Urmston Road has clear zones and boundaries that are bounded by shallows, shore lands, rocks, islands and many anchored boats and vessels.

Fig. 1. Ship target paths in Hong Kong strait and the geographically determined complexity of maneuvering near the Ma Wan Island

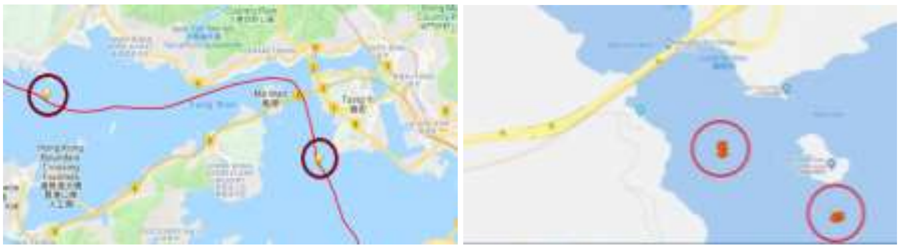
The passage from the Round Island to Ma Wan Island is always busy with intersecting traffic as indicated above and as an addition to the incoming-outgoing traffic to container and tanker terminals located to east of the TSC/VRS.

A huge alteration in the course (over 90 degrees) a beam of Ma Wan Island requires from navigator to pay more attention to the position of the vessel, as well as to control the trajectory of the vessel movement (Fig. 1).

The passage from Ma Wan Island to Urmston Road includes all the hazards described above with less intensity and practically eliminates cross-over passage by huge merchant ships.

All the difficulties and dangers described lie in force on the return passage of the Hong Kong Strait. According to statistics, the most severe collisions occur in the open sea, in the straits and fairways in conditions of restricted visibility or at night, due to high speeding and increased complexity of observation, especially for areas of intensive navigation. For a more detailed consideration of the passage of the straits, an experiment was conducted using the navigation simulator Transas - NTPRO 5000, in which about 247 cadets took part. The task was to pass the Hong Kong Strait and the Bosporus Strait in conditions of heavy traffic and numerous divergences under normal visibility. As a result, the test helped to divide the passage of the strait into zones: easy, moderate and difficult. The analysis showed that the greatest difficulty is the passage under the bridges and maneuvering in narrow areas.

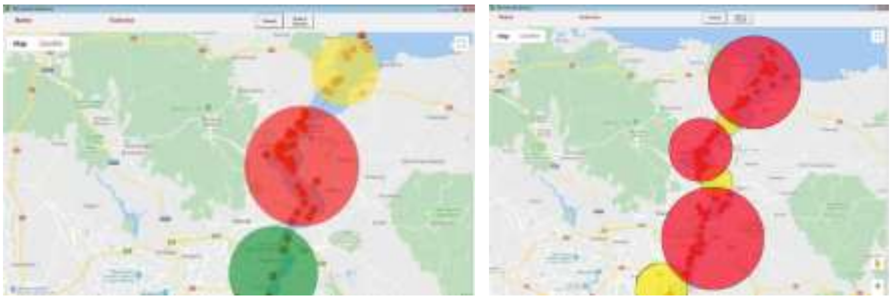
When analyzing accidents in the Hong Kong Strait, areas near the narrowness of Ma-Wan Island were clearly distinguished (Fig. 2). At Fig. 2(a) stated main traffic route to the East from Ma Wan island which common use by all kind of vessels and applicable for all large merchant vessel of different types. At Fig. 2(b) mentioned traffic route to the West from Ma Wan Island restricted by shallows, bridge high and in use by small and coastal vessels only.



a b

Fig. 2. **a** Identification trajectories of routes, **b** Determination of collision sites

Also analyzed the routes of the vessel in the Bosporus Strait for collisions (Fig. 3 a). Bosporus Strait was divided into zones according to the levels of difficulty of passage. Those zones where up to 2 collisions were recorded within a radius of 0.5 mm were considered simple (green); from 3 to 5 - medium difficulty (yellow); more than 5 - complex (red).



a b

Fig. 3. **a** In the heavy traffic, **b** In the reduced traffic intensity

Then the process of passing the location was changed – weather conditions deteriorated, which resulted in restricted visibility, while the traffic intensity was reduced by 32% (Fig. 3 a).

As a result of the experiment, an increase in the area of the complex zone was recorded from 37% to 83%. This suggests that for navigators the conditions of restricted visibility are more dangerous than the intensity of the traffic.

There is a need for timely identification of the moment of loss of control over the vessel. To do this, must clearly identify and classify the factors that most often lead to navigation errors.

Among the numerous mistakes made by navigators, there is a clear tendency to their repeatability, which makes it possible to classify the main types of errors by category: the multifactorial situation, false identification, stress, habits, fatigue.

Taking into account this classification, it becomes possible to create a computerized system for monitoring the behavior of the navigator, which will help to identify in time the loss of control over the vessel by analyzing the database of control parameters (Fig. 4).

To identify the moment of loss of control, a software / hardware module was developed that allows tracking control parameters such as the speed and rotation of the steering wheel. Distinctive features are the frequent change of positions, such as rudder shifts for a short time. This fact testifies to the impossibility of taking a firm decision and a strategy for maneuvering the diverge with obstacles. Figure 6 shows a graph indicating a clear loss of control over the situation by the navigator in 69 seconds. The system consists of several modules, each of which will be responsible for controlling certain factors. Information from all modules will be accumulated in a single database, and then processed by the central system, which is responsible for making certain decisions aimed at assisting to the navigator.

Fig. 4. ECDIS database analysis and management graph analysis

Analysis of the vessel’s trajectory through the Bosporus Strait from the Black Sea shows that incorrect decision making during the divergence maneuver led to vessel crossing the dangerous isobath near the coastline of Rumelihisar, Turkey (Fig. 5 a, b).

a b

Fig. 5. a Satellite view, **b** Display of trajectory on the map

The formalization of control tasks at the time of loss of control over the vessel in the framework of mathematical models can lead to the formulation of the next class of problems of managing complex coordination processes in systems with latency responses of the navigator [20,21].

The process of loss of control over a ship at the moment of an oversupply of information factors may well be described by a system of differential equations [22] with delays containing VACA as a function of time:

$$\frac{ds}{dt} = f\left(s(t), s(t-\tau_1), \ldots, s(t-\tau_s), d(t)\right) \tag{1}$$

Where condition $s(t) = (s_1(t), \ldots, s_n(t))$, and $d(t) = (d_1(t), \ldots, d_m(t))$, $\tau_i > 0, i = \overline{1, z}$ is the navigator response to an emergency situation *z*, $d = d(t)$ - VACA, which takes into account the influence of considered corrective actions process. Corrective actions imply a transition to VACA or the impact of a decision support system at the time of exacerbation of the situation while controlling/handling the vessel [23].

Then system (1) can be considered in conjunction with the following initial conditions:

$$s(t_0) = s_0,\ s(t) = \varphi(t), t \in \left[t_0 - \max_{1 \le i \le z} \tau_i, t_0\right] \tag{2}$$

Where t_0 - the moment of the beginning of VACA.

The class of functions [24] is considered as admissible ranges of VACA, on the range of values *D*, on which additional constraints related to the specifics of the task can be imposed. These restrictions may take into account the location mapping, the maneuverability of the vessel and its parameters, weather conditions, ice cover, environmental conditions, etc. [25]. Then in the general case the condition is considered:

$$d(t) \in D \subset Y^m \tag{3}$$

Where *D* is a compact set in Y^m. It should be noted that the VACA process can be broken down into stages due to the difficulty of getting out of this situation.

Given that the main goal of VACA is formalized in the framework of (1), then a number of conditions must be fulfilled:

$$\eta_{q-i+1}(d) \ge \eta,\ i = \overline{1, y},\ \ y \le q \tag{4}$$

Here $\eta_{q-i+1} = \eta_{q-i+1}(d),\ i = \overline{1, y}$ - the length of the time intervals relative to the stages of VACA $[t_0, T]$, determined from the conditions:

$$c(s(t)) \le 0,\ \ t \in \left[t_1^i - \eta_i, t_1^i\right],\ \ i = \overline{1, q} \tag{5}$$

Where $t_0^i = t_1^i - \eta_i, t_1^i$ - the boundary points of successive stages on the segment VACA , in which the inequality holds $c(s(t)) \le 0$. The magnitude $\eta > 0$ and number of stages $y \ge 1$ for which conditions (4) must be satisfied are specified.

The interval at which inequality (5) is fulfilled is interpreted in emergency situations models as a stage of a substantial reduction in the risk of a catastrophe between dangerous sections of the route relative to the location [26,27].

A specific condition may be, for example, a condition $m(t) \le \overline{m}, t \in \left[t_1^i - \eta_i, t_1^i\right], i = \overline{1, q}$ where $m(t)$ is an indicator of the complexity of the situation. Conditions (4) are interpreted as the goal of increasing, to a predetermined value, the intervals of corrective action during a cyclically exacerbating situation, recurring factors leading to loss of control over the vessel.

The specified number of intervals *q, y* are selected from the analysis of the vessel's passage plan relative to the location and independent of *q, y*. The selection of *q, y* values also depends on the capabilities of the VACA, the maneuverability of the vessel, etc., and determined by the restrictions on the VACA.

The task allows the constraints on VACA not only in the form of condition (3), but also in the form of a set of constraints of the type of inequalities imposed on the final state of the system at the time t_1^q, which determines the end moment of the VACA process:

$$J_i(d) = q_i\left(s\left(t_1^q\right)\right) \le 0,\ \ i = \overline{y+1,\ y+\eta} \tag{6}$$

As functionals VACA can be considered the time $t_1(d) = t_1^q - t_0$ to achieve a safe state for the transition to manual control. Thus, a task that can be presented in a single form $J_j(d) \le 0,\ \overline{j = 1, y+\eta}$ is considered.

3 Results

Consider the use of VACA in constrained conditions. Let the sea electronic navigation chart presented on a plane be an orthogonal grid. Then the process of moving the vessel in difficult constrained conditions and narrows can be represented as a grid trajectory.

Let us compare to the waypoints the position of the vessel, which coincides with the set of states depending on the state of the neighboring grid frames.

These waypoints or grid nodes will be represented as a field superimposed on the chart. The neighbors of the frame in which the vessel is currently located are frames that are in contact with the frame of the vessel. A set of target vessels located in proximity and relative to the vessel frame forming the interaction field considered in this model. In the case of the standard cartographic Mercator projection [28], we will call the four frames as the transition framework, which have a common side with the vessel frame. At each time point, the state of the vessel frame varies depending on the state of the interaction field.

In order to apply the developed model in practice, the frames are transformed according to the principles of vessel movement in space. For each specific case, the transition frame will have different outlines. For example, if the speed of the vessel increases, the frame will be extended.

Suppose that each vessel seeks to move in a certain (one of the four) direction. If it is impossible to move in the preferred direction, the presence of insurmountable cartographic obstacles on the way, constraining by the draft vessel or a significant amount of marine traffic, the navigator tries to change the direction of vessel course, choosing one at which the obstacles are minimal.

Accepting the fact that navigators of maritime transport can view the situation through radar and NIS (Nautical Information Systems) [29] in a location at a distance *r* and choose the direction in which they observe the least amount of marine traffic and the absence of cartographic obstacles (Fig. 6).

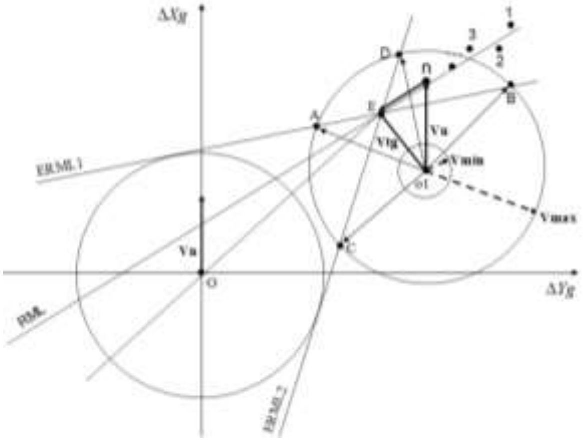
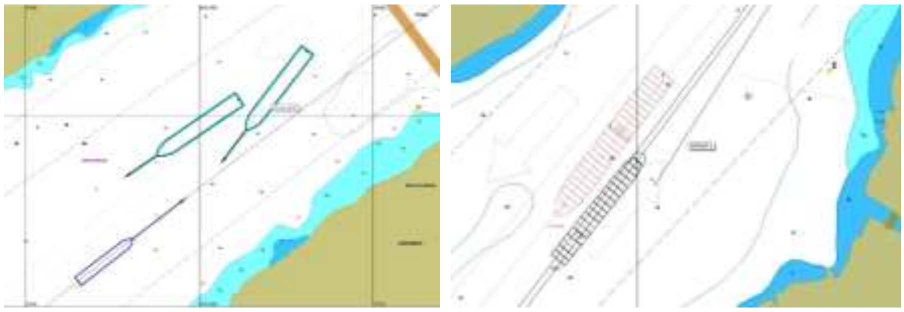


Fig. 6. Definition of productive discrepancy vectors

VACA performs the task of defining the frames on the map and forms the trajectory of the ship for safe divergence $\Omega = \Omega_1 \bigcap \Omega_2 \bigcap \ldots \bigcap \Omega_{\mathrm{Ntg}}$. The approach defines two stages: the use of the on-board controller of the determining constraint (fixed and dynamic); a module that defines a discrete change in time constraints [30].

This approach allows you to track dynamic spatial changes of restrictions on the map by analyzing displacement vectors. The approach creates a trajectory of safe movement of your own ship through conditionally defined grid nodes and test vectors are used: $\bar{V}_{\mathrm{T}} = \left(V_T \cdot \cos K_T, V_T \cdot \sin K_T\right)$. The most effective divergence vectors determine the strategy for the automated divergence of the vessel during dynamically changing constraints. The use of VACA allows the identification of the fact of loss of control of the vessel's maneuverability due to the human factor to bring the vessel to the safest cell (area) at location (Fig. 7).



a

b

Fig. 7. a Before VACA launch, **b** After starting the system

In the Figure 8, the number "1" denotes the areas of permissible screpancy parameters for many targets, including maneuvering ones, as well as obstacles in the coordinates speed - screpancy course at different points in the time.

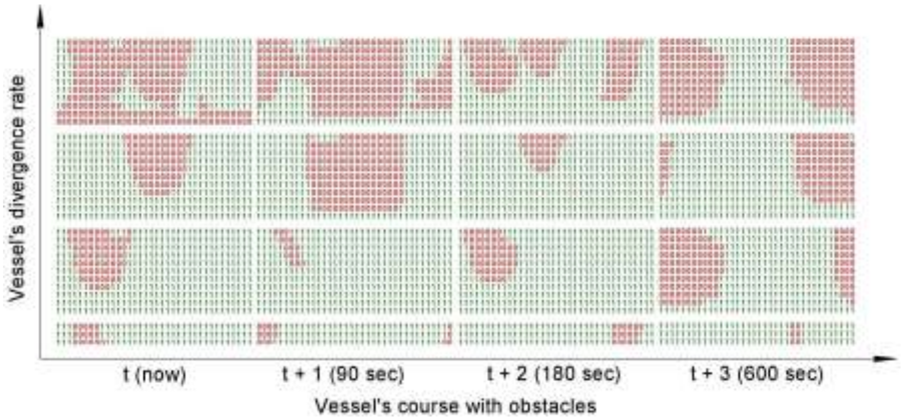


Fig. 8. VACA transition matrix

As can be seen from the presented matrices, fragments with the value “0” prevail after a certain period of time, which indicates the expansion of non safe maneuvering zones. In situations where the matrix elements with a value of "0".

An analysis of the database for the feasibility of using VACA is shown on the graph in the form of the number of accidents along the Bosporus Strait, 15.66 Nm (Fig. 9). The presented dependence indicates that the accident rate drops by 44% when using VACA.

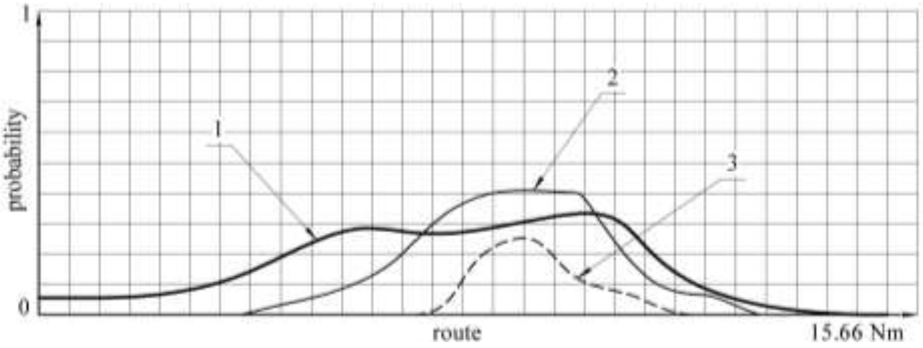


Fig. 9. Expediency use of VACA

The operation of VACA was also analyzed according to the levels of interaction with the navigation watch when passing a location. In this case, the VACA trigger levels are divided into three options (Fig. 10):

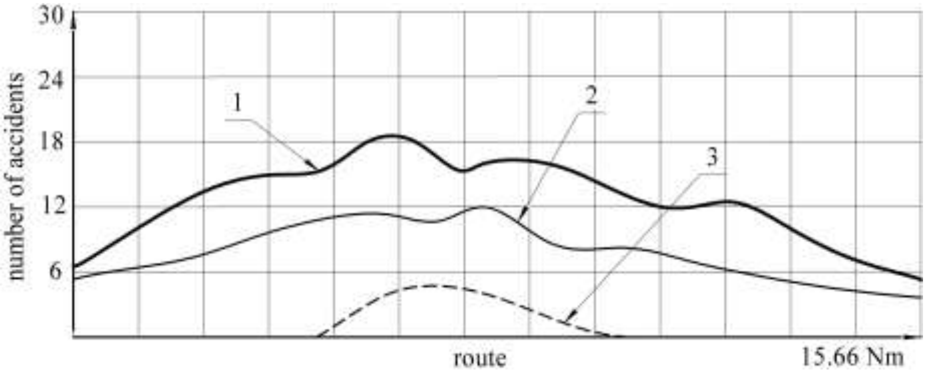


Fig. 10. Probability of operation of VACA

1 - VACA warns the navigational watch with a signal that the ship enters the zone of heightened attention, with no visible danger, but the probability is 20-30%.

2 - VACA warns the navigation watch with a signal that the vessel enters the zone of heightened attention, while informing the captain or chief officer that need to climb the bridge and take vessel control, the probability of an emergency is from 31 to 50%.

3 - VACA will switch the vessel handling to fully automated control mode, calling the captain and chief officer to the bridge with arise sound of vessel general alarm. At

the same time, the VACA urgently reduce main engine RPM till “Dead Slow Ahead” and determining the zones of zero probability of collision, performs an automated divergence maneuver.

In order to determine the effectiveness of the VACA application, a module was developed in the form of a three-dimensional graph (Fig. 11). The graph allows displaying the coverage of VACA during the execution of maneuvers on the ship’s passage. During the VACA operation, the function of plotting along the axes is activated: *Y* is the complexity of the route zone, *X* is the order of the route zone, *Z* is the number of accidents.

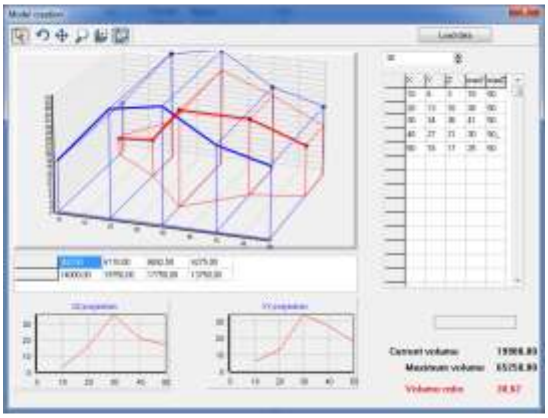


Fig. 11. Analysis of the effectiveness of the use of VACA

The graph shows that the three-dimensional figure in red reflects the complexity of the route, taking into account both geographic parameters and the characteristics of the experience of the navigation watch. The blue three-dimensional shape represents the precautionary response of VACA. In the area of the third zone, there is a small warning of a negative situation due to the human factor, which indicates the need to strengthen the navigation watch in this area of the vessel’s passage. The total reserve of VACA functionality over the time is 69%, which indicates its feasibility for use in the route planning and passage process. This graph allows us to perform an analysis of the likelihood of an emergency situation while keeping a navigation watch, as well as to prevent the human factor of the navigator in its early stages. The general scheme of interaction of the vessel automated course alteration system with the navigator is presented in Figure 12.

The base of navigator’s reactions to the stimulus accumulates over a long time. A selection of parameters that affects the loss of control of the situation can be interpreted as objects x_i on task classes $\kappa_i = \{0,1\}$. The objective of VACA is to reduce the likelihood of errors when using navigation hazard classification algorithms a_j.

A formal description of this process will be based on threshold classifiers, taking into account the specifics of VACA, [31]:

$$a_j(x_i)\kappa_i > 0 \Leftrightarrow \begin{cases} j > i,\ \kappa_i < 0, \\ j \le i,\ \kappa_i > 0. \end{cases}$$

Then the condition $E_{(i)}$ for determining classification algorithms a_j giving error-free samples of object parameters will look like:

$$E_{(i)} = \left\{ X : x_i \in \overline{X},\ \forall \mu \in M \to \mu(X) = a_j : \begin{cases} j > i,\ \kappa_i < 0 \\ j \le i,\ \kappa_i > 0 \end{cases} \right\}.$$

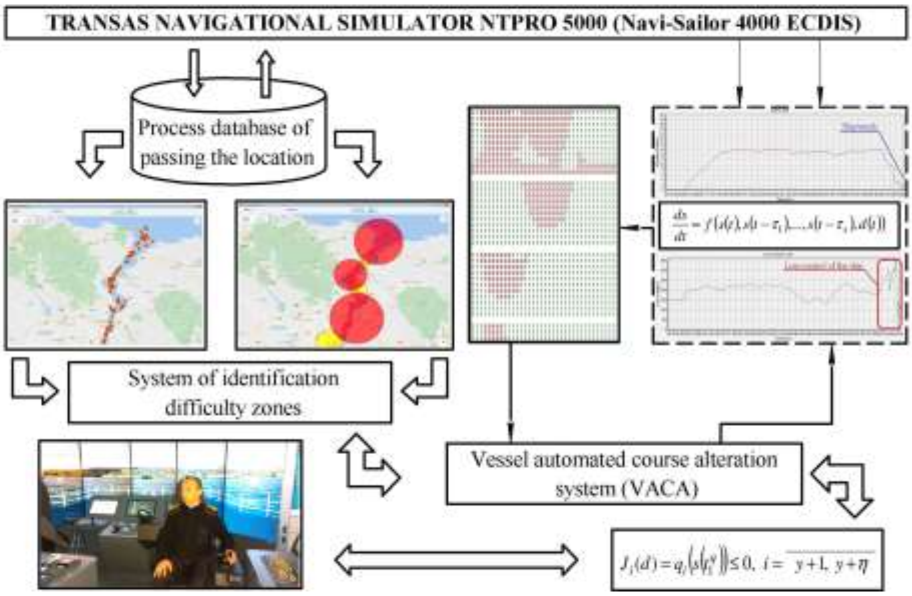


Fig. 12. The general scheme of interaction of the vessel automated course alteration system with the navigator

4 Discussion

The basic principles and research were discussed at the 10th International scientific and practical conference MINTT-2018 [32].

The introduction of software will allow quickly and efficiently process large amounts of data and highlight the classification signs of the negative manifestation of the human factor, both among cadets and experienced seafarers during traineeships and advanced training in accordance with the standards of IMO and STCW 78/85. It will also allow developing the professional competence of the cadets with the use of innovative learning and psychological technologies [33-36]. In the future, further research is planned to develop software, in the form of an expert system that determines deviations from a given course during the passage, as well as inadequate reactions when performing classical maneuvers when vessels diverge in constrained areas.

5 Conclusion

Analysis of the effectiveness of the developed models and software gives grounds to assert that the approaches described in the article allow increasing the safety of navigation in restricted navigation areas, reducing the periods of the negative influence of the human factor due to the transition to automated vessel control.

- Software tools have been developed that allow identifying on the cartographic panel the zones with the highest risk of accidents by analyzing the passage of locations on the NTPRO 5000, as part of an expert disaster prevention system.
- A module for automated analysis of the ECDIS database has been developed, which allows determining geolocation on Google maps, as well as periods of loss of control over the management of the vessel due to persistent negative reactions of the navigator during difficult navigation.
- Algorithmic software has been developed for automated recognition of the critical number of target vessels by AIS means for switching to autopilot in areas with the highest risk of accidents.
- The analysis of the performance of VACA in maritime transport was carried out by statistical analysis of simulator training data for cadets of the Kherson State Maritime Academy (Ukraine), confirming the appropriateness of the use of the designated approaches and software.

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