Multi-level Model for Ships Risk Assessment by Coastal Vessel Traffic Services

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Abstract. The article is devoted to the problem of navigation safety of sea vessels’s movement. An approach is considered that allows generating alarm signals with the allocation of various levels of danger. The criterion for the division of hazard levels is based on the trajectory properties of the movement of ships. A system of rules is proposed, which appeals to model representations of the “ship-to-ship” type and allows to streamline the actions of the dispatcher when controlling the collective movement of ships. The results of modelling and field study of traffic in the water area of the port of Vladivostok, which confirm the constructiveness of the proposed ideas, are presented.

1. Introduction
The navigation safety of the collective movement of ships is an urgent problem of the operation of water transport routes. Onshore vessel traffic control systems provide its support. Their tasks are implemented using measurement information, which is delivered using radars and satellite measurements (transponders of the Automatic Identification System) in accordance with the generally accepted concept of building such systems [1].

Currently, five existing and future generations of vessel traffic systems can be distinguished.

The 1st VTS generation uses standard radars as an information base for a circular view and implements only visualization of primary measurement information (reflected echo signal of the observed water area). These systems became widespread in the 1950-60s.

The 2nd VTS generation has an increased level of visualization of radar information due to the support of automatic target tracking functions and the ability to display ship marks with their coordinates and speeds. These systems were common in the late 1960s.

The 3rd VTS generation implements the automation of navigation functions, which makes it possible to recognize dangerously approaching vessels. This was implemented in addition to the functions of visualizing the navigation situation (displaying the primary radar signal and target marks). The third VTS generation appeared in the 1970s along with the first mainframes. To date, the vast majority of VTS that serve the ports of the world are third generation systems. These systems have received additional development of navigation and service functions in the last decade due to the widespread introduction of the Automatic Identification System (AIS). AIS is based on the use of transponders on ships. AIS transponders transmit to the coast at the request of the coastal VTS the
coordinates of the vessel, which were determined by the second-generation satellite navigation system, its name, registration data and service information. This greatly simplifies the work of dispatchers and opens advanced automation capabilities. Such VTS with AIS support can be classified as 3+ generation (“three plus”).

The 4th VTS generation is built on the principles of intelligent information systems and, in addition to visualizing navigation information, can provide the operator with possible solutions for the optimal and safe movement of ships. For example, for dangerously approaching vessels, such systems can offer recommendations (expert solutions) for changing either course, or speed, or course and speed at the same time, in accordance with regulation 8b of the International Convention for the Prevention of Collisions between Ships (COLREGs - 72). Currently, the 4th VTS generation has not yet become widespread. And their specific functions are used as research prototypes rather than everyday industrial automation tools.

The 5th VTS generation is characterized by advanced traffic dispatching functionality. In particular, the 5th VTS generation can solve the tasks of safe route and path planning of the vessel, considering the current traffic (collective traffic) and the characteristics of a particular water area. Also, the 5th VTS generation can plan optimal traffic patterns in the water areas, depending, for example, on meteorological conditions and the time of year. Currently, the fifth VTS generation is in the stage of research and development. Thus, the 5th VTS generation can be considered promising.

Identification of vessels whose movement is potentially dangerous (leading to a collision) and the generation of alarms is the central function that realizes the purpose of the VTS. The alarm signal serves as an indication to the VTS operator, based on which he decides about the need to change the course and speed of movement. The number of objects for which an alarm signal can be generated at the current time increases with increasing traffic intensity [2]. This leads to the expansion of a variety of management solutions that can ensure safe traffic. It can also lead to increased uncertainty when making a specific decision. This is an incentive to additionally consider the type of navigation situation and highlight different levels of danger (such as "very dangerous", "dangerous", "almost safe", etc.) [3]. This approach allows the VTS operator to order his actions according to the established priority. For example, in cases where several alarms are present at the same time, the operator will make decisions on the most dangerous of them.

The movement of sea transport has its own specific industry specificity. The methods of controlling their movement are not applicable for navigational practice, despite the development of technologies for autonomous moving objects (for example, unmanned aerial vehicles, ground robots, etc.). [4]. This is since each situation that occurs during the movement of ships is unique and depends on many factors: The International Rules for the Prevention of Collisions between Vessels (COLREGs), the rules of navigation in a specific water area, the state of the water environment (current, waves), weather conditions, nature movements of other vessels in the water area, etc. In addition, the dynamics of a ship as an object moving in a liquid medium is also complex. Therefore, the established term VTS does not imply ship management in the classical sense. this is the task of automatic radar plotting systems and autopilots. The task of the VTS is the general coordination (dispatching) of traffic by issuing instructions by the VTS operator (for example, about reducing the speed or changing the lane). And the way of carrying out these instructions is chosen by the captain of the vessel. Thus, the VTS is a decision support system.

In this paper, we consider possible models of a multi-level system for identifying hazardous situations in the collective movement of sea vessels, focused on application in a VTS. The proposed models are used by the authors when creating new promising methods of VTS operation.

2. Method and materials

When modelling the navigational safety of collective traffic, we will resort to building a “ship-to-ship” safety model for each pair of ships. This is common practice [5].
Figure 1. Model of the relative movement of the “ship-to-ship” pair.

Consider two ships with coordinates \( x^{(1)}, y^{(1)} \) and \( x^{(2)}, y^{(2)} \) and speeds \( v_{x}^{(1)}, v_{y}^{(1)} \) and \( v_{x}^{(2)}, v_{y}^{(2)} \). We will describe their collective movement by a set of values \( s = (r, r, v, \eta, w) \) - the vector of the state of the collective movement of two ships, where \( r_{x} = x^{(2)} - x^{(1)}, \ r_{y} = y^{(2)} - y^{(1)} \) are the coordinates of the vector of the relative position of the ships; \( v = \sqrt{(v_{x}^{(1)} - v_{x}^{(2)})^2 + (v_{y}^{(1)} - v_{y}^{(2)})^2} \) - speed of relative movement of vessels; \( \eta \) - the direction of the velocity vector of the relative movement of the vessels, \( w = \frac{d\eta}{dt} \) - the rate of change of the angle \( \eta \) (Fig. 1).

The main condition for safe collective movement is the prevention of dangerous convergence of ships. This is ensured by the observance of a certain "safety zone" around the ship, also called the "ship's domain" [4]. In this paper, we consider a ship's domain of a static type, rigidly tied to the ship numbered and interpreted as a circle of a given radius \( R_{\eta} \). Let's introduce the following values (Fig. 1):

1) \( \eta_{r} = \arctan \left( \frac{r_{x}}{r_{y}} \right) \) - vector azimuth \( r \); \( w_{r} = \frac{d\eta_{r}}{dt} = \frac{r_{y}v_{y} - r_{x}v_{x}}{|r|^2} \) - the rate of change of the vector azimuth \( r \); \( \theta = \arcsin \left( \frac{|R_{1} + R_{2}y|}{|r|} \right) \) - the angle determined by the distance between the ships and the size of the domains (it is believed that in a safe state, ship domains should not "invade" each other); \( \dot{\theta} = \frac{d\theta}{dt} = -\frac{R_{1} + R_{2}}{|r|^{2}} \frac{d|r|}{dt} \) - the rate of change of the angle \( \theta \);

\[
\frac{d|r|}{dt} = -\frac{r_{x}v_{y} - r_{y}v_{x}}{|r|^{2}} \frac{d|r|}{dt} - \text{the rate of change in the distance between ships;}
\]

\[
T = \frac{|r|^{2}}{r_{x}v_{y} - r_{y}v_{x}} - \text{the approximate time remaining until the ships' closest approach;}
\]

\( T^{*} \) - threshold value for time \( T \).

A potentially dangerous approach of two ships can be formalized as follows:

\[
|\eta - \eta_{r}| < \theta, \quad (1)
\]

\[
|w - w_{r}| < \dot{\theta} \quad (2)
\]

\[
0 < T < T^{*} \quad (3)
\]
Condition (1) formalizes a dangerous situation in case of uniform and rectilinear movement of ships. Condition (2) supplements it if the vessels are maneuvering. And condition (3) selects from the general array those ships for which the time to approach is less than the threshold.

The vectors can be found from coastal radar data or from GPS data in various ways (see, for example, [3]).

Kinematic trajectory properties may appear during external observation as an informative feature that determines the degree of danger of a particular navigation situation. The practice of navigation shows that maneuvering and non-maneuvering vessels have fundamental differences from the point of view of collective traffic safety. First, a reliable prediction of the trajectory of a maneuvering object is completely impossible with external observation [6]. Secondly, in practice, the maneuvering of the vessel usually indicates an attempt by the navigator to give the movement a safe character and his control over the situation. Therefore, the verbal level of danger for a maneuvering object is obviously lower than for a non-maneuvering one [7]. Consequently, the following discrete assessment of the level of danger of the situation takes place, depending on the truth of conditions (1), (2) and (3) (tab. 1). Hazard level 0 (minimum) corresponds to a safe situation. Hazard Level 1 (Nearly Safe) are situations where vessels may approach each other if they continue to maneuver. Level 2 (Medium Hazard) are situations where vessels may approach each other if they stop maneuvering. And level 3 (maximum) are situations when the ships will approach each other if they do not start an evasive maneuver.

Table 1. System of rules for discrete hazard level assessment (basic model).

|   | (1) | (2) | (3) | Level |
|---|-----|-----|-----|-------|
| 1 | -   | -   | -   | 0     |
| 2 | -   | -   | +   | 0     |
| 3 | -   | +   | -   | 0     |
| 4 | -   | +   | +   | 1     |
| 5 | +   | -   | -   | 0     |
| 6 | +   | -   | +   | 2     |
| 7 | +   | +   | -   | 0     |
| 8 | +   | +   | +   | 3     |

A discrete assessment of the level of danger of a situation of the type "very dangerous", "dangerous", "almost safe" allows to draw the attention of the VTS dispatcher, first, to the most dangerous situations. It is also possible to represent the hazard level as a continuous value. Ideas of problems of fuzzy logic systems for this turn out to be productive. In this case, rules (1), (2), (3) and the hazard level are represented by linguistic variables with corresponding terms and membership functions. And the system of rules (Table 1) is transformed into a system of fuzzy rules. In this case, a model interpretation of the problem is possible as a fuzzy system of the Mamdani type (fuzzy input and output), and a fuzzy system of the Sugeno type (input - fuzzy, output - clear). The use of fuzzy logic systems makes it possible to flexibly adapt the problem to the peculiarities of the traffic of a particular water area using expert training or on a training sample.

The main problem in the practical implementation of the considered model is the need to estimate the angular velocities included in rule (2). This estimate is unstable under conditions of instrumental measurement errors at large distances between ships [8]. This does not make it possible to reliably recognize dangerously approaching vessels in advance. One of the ways to solve this problem is a simplified interpretation of rule (2), that is, replacing it with a maneuver detector. The function is a maneuver detector that allows you to estimate the degree of intensity of the ship's maneuvering and can be built in a variety of known ways (see, for example, [3]). In this case, instead of rule (2), we will have:
If $D > 0$, then the observed vessel maneuvers, if $D < 0$ - the vessel moves straight and uniformly. Considering the above, we will have the following system of rules for the simplified model, depending on the truth of conditions (1), (3) and (4) (table 2).

|   | (1) | (4) | (3) | Level |
|---|-----|-----|-----|-------|
| 1 | -   | -   | -   | 0     |
| 2 | -   | -   | +   | 0     |
| 3 | -   | +   | -   | 0     |
| 4 | -   | +   | +   | 0     |
| 5 | +   | -   | -   | 0     |
| 6 | +   | -   | +   | 1     |
| 7 | +   | +   | -   | 0     |
| 8 | +   | +   | +   | 2     |

Hazard level 0 (minimum) corresponds to a safe situation. And hazard level 1 (medium hazard) is a situation when ships can approach each other, but at the same time they are maneuvering. That is, the navigator is most likely in control of the situation. Level 2 (maximum) are those situations where the vessels will approach each other if they do not initiate an evasive maneuver. For the simplified model, as well as for the previous one, it is possible to interpret the fuzzy logic system and represent the hazard level as a continuous value. The simplified system is more stable at large distances between ships, as studies show [9]. This makes it possible to recognize their dangerous approach in advance.

3. Results
Let us consider a model example of the movement of three vessels to demonstrate the features of the proposed model of a multi-level assessment system (Figure 2). Let two ships, I and II, move straight and uniformly at a speed of 5 m / s, and ship III maneuver. The simulation was carried out at the values of $R_1 = R_2 = R_3 = 200$ m and $T^* = 300$ s.

![Simulated ship trajectories](image)

Figure 2. Simulated ship trajectories.

Figure 3 illustrates the determination of the hazard level of a navigation situation as a continuous value $u$ as the vessels move over time: “vessel I - vessel III” (left column) and “vessel II - vessel III” (right column).
Figures 3a and 3b show the assessment of the hazard level of the situation by a fuzzy system built based on the system of rules in Table 1. It can be seen (Figure 3a) that the hazard level for ships I and III increases as they approach, reaching a maximum at \( t = 450 \text{ s} \). When \( t = 550 \text{ s} \), the ship III starts the maneuver by turning to the right. Thereafter, the hazard level "ship I - ship III" quickly decreases. Figure 3b shows that vessels II and III move safely at first. After the start of the third maneuver by the vessel, the hazard level "vessel II - vessel III" abruptly increases to \( u \approx 2 \). And then, it decreases to the level and then to 0, as the vessel continues to turn III. Estimates of the value \( u \) are irregular due to the influence of instrumental errors at large distances between ships. Although, in general, they allow you to solve the problem.

Figures 3c and 3d show the assessment of the hazard level of the situation by a fuzzy system, which is based on the system of rules in Table 2. Figure 3c shows that the hazard level for a pair of vessels I - III is stable and constantly increases as they approach. After the start of the ship's maneuvering, the III level of danger decreases rapidly. Figure 3d shows that vessels II and III move safely at first. After the start of the vessel's maneuvering, the III level of danger for a pair of vessels II - III increases abruptly. And then, it drops to a safe level as the vessel continues to turn III.

Note the following information about the "shaded" hazard level zone in Figure 3. Values above the shaded area represent an unambiguously hazardous situation. The VTS dispatcher should immediately pay attention to this situation (the so-called "red alert"). Values \( u \) below the shaded area represent an unambiguously safe situation. And the VTS dispatcher does not need to be distracted by this situation. If the values \( u \) lie within the shaded area, then this is the case when a certain degree of danger occurs. This situation must be notified to the VTS dispatcher. But the dispatcher makes his own decision on the need to issue recommendations to the skipper, based on an informal, intuitive expert assessment of a specific situation (the so-called "yellow alert"). This is a situation where the dispatcher most likely should not intervene immediately but should wait for its further development.

For the considered models, field experiments were carried out on traffic data in the water area adjacent to the port of Vladivostok. The typical example below was obtained from data on the movement of ships for one day in the summer [10], [11]. At that time, about 80 vessels were simultaneously in the VTS area of responsibility.

Figure 4 shows the position of vessels in the water area at those times when the level alarm was generated for them, respectively, "yellow" and "red" (yellow and red dots). The greatest number of alarms occurs in inland port waters. In those places where the vessels are located close to each other and the traffic intensity of small watercraft (boats, tugs) is high. Both alarm levels also occur when vessels move outside port waters: Amur (left), Ussuriysk bays (right), Eastern Bosphorus Strait. The percentage of yellow alarms is about 20%. The places of their generation do not form stable zones.
Figure 4. Movement of vessels in the water area of the port of Vladivostok: the position of vessels with alarms of the "red" and "yellow" level.

4. Conclusion
The article considers an approach to the construction of a multi-level system for assessing the state of navigation safety in the sea area. It allows you to visualize the features of the navigation environment. The proposed color interpretation of the red and yellow alert levels is intuitive for skippers and VTS operators. The proportion of situations of the "yellow" level in a typical water area is quite significant. This suggests that a multilevel assessment of the situation is relevant for practice. And its application can help streamline the work of VTS operators in conditions of high traffic intensity [12].

The results of the work are focused on expanding the functions of modern vessel traffic systems.

5. References
[1] Zhou F, Pan S, and Jiang J 2019 Journal of Navigation 72(6) 1345–1358
[2] Liu Z, Wu Z, and Zheng Z 2020 Journal of Navigation 73(3) 628-645
[3] Grinyak V M, and Devyatissilynnyi A S 2004 Journal of Computer ond Systems Sciences International 43(3) 448-457
[4] Tam Ch K, Bucknall R, and Greig A 2009 Journal of Navigation 62(3) 455–476
[5] Goodwin E M 1975 Journal of Navigation 28 328 – 341
[6] Grinyak V M, Devyatissilynnyi A S, and Tropimov M V 2016 Marine intellectual technologies 1–3(33) 252-257
[7] Szlapczynski R, and Szlapczynska J 2015 Journal of Navigation 68(6) 1041–1055
[8] Grinyak V M, and Devyatissilynnyi A S 2016 Journal of Computer ond Systems Sciences International 55(2) 249-259
[9] Golovchenko B S, Grinyak V M, and Devyatissilynnyi A S 2015 Vestnik Gosudarstvennogo universiteta morskogo i rechnogo flota imeni admirala S. O. Makarova 1(25) 15–25
[10] Golovchenko B S and Grinyak V M 2014 Vestnik Gosudarstvennogo universiteta morskogo i rechnogo flota imeni admirala S. O. Makarova 2(24) 156–162
[11] MarineTraffic. Web. 1 Apr. 2021 <http://www.marinetraffic.com>
[12] Wang L, Li Y, Wan Zh, Yang Z, Wang T, Guan K and Fu L 2020 Ocean Engineering 204

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