

UDC 656.61.052

Volodymyr Mamontov

THE EVALUATION SYSTEM OF MOVING OBJECTS' CLOSE-QUARTERS SITUATION

National Marine Academy
Didrikson street 8, 65029, Odessa, Ukraine
E-mail: Volodymyr.mamontov@gmail.com

Abstract. *This work reflects synthesis of the evaluation system of moving objects' close-quarters situation and support of decision making on maneuvering for prevention of collision. A method of reducing the load on navigation devices calculators was suggested. This method offers to remove those vessels from processing that are moving away from own ship. This method creates the preconditions for reducing data downloading to operator controlling vessel's movement process. Getting data in such a way ready for decision-making allows operator to give commands directly during the process of controlling that leads to confident actions and reduces the likelihood of collision. The results can be used in maritime training institutions, refresher and update training for navigators and while pilotage.*

Keywords: decision-making; excessive convergence; navigation devices; prevent crashes.

1. Introduction

The track of moving objects on air or at sea is normally preliminary planned.

Such a task is performed graphically on a chart or analytically.

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It's necessary to monitor further the object's movement on the assigned track.

Passage planning is normally carried out at two control locations.

One is onboard centre, located at the moving object, and the other is onshore centre.

For example, for air navigation there is a control station at the airport with radar equipment and communication facilities.

And there is a cockpit onboard the aircraft where all controlling tools and equipment are located.

For marine navigation there are vessels traffic control centers equipped with nets of radar equipment and communications.

There is a navigation bridge onboard the vessel where navigation control systems and equipment are located.

The fundamental difference of the vessel's navigation bridge from the cockpit is the fact that in confined waters a marine navigator uses mostly visual observation methods.

But a pilot onboard the aircraft preferably observes by means of electronic aids to navigation.

Due to the presence of two centers (onboard and onshore) a conflict appears between them by the reason of different approaches to evaluation of the situation and the priority of commands.

Every control center has the system that consists of several operators with different functional responsibilities to subordinate single supervisor, responsible for decisions making on traffic control.

Additionally, there is a third center onboard the vessel presented by a pilot of the coastal State, who has functions of coordinator providing specific information regarding to safety of navigation. In stressful conditions for the operator the number and composition of elementary operations increase, and he acts at the level of his sustainable skill.

But in extreme situations it is necessary to use calculations and intellectual operations for decision making that leads to a retarding of control process.

For this reason, systems and devices for navigation support process should be designed the way the information is processed by automatic devices and given to operator as knowledge sufficient for decision making immediately and adequately to current situation.

For this reason, the questions of improvement the information ensuring process of moving objects approaching and passing by are highly relevant.

2. Analysis of recent achievements and publications

It is noted in the work [1] that the formation of initial and sustained skill of vessel maneuvering control was carried out by trial-and-error method.

However, there is more preferable method of developing the skill through awareness of algorithm of intelligent action of navigator.

It is noted in the work [8] that the specific of process control traffic moving objects defines as the main visual receptor (- eye) and auditory receptor (- ear) analyzers.

However, visual information takes about 90%, use of hearing signals and speech is on the second place, the other analyzers place insignificant sector.

In the work [2] the ways to develop criteria for matching factors of maneuvering and psycho-physiological characteristics of the operator are considered, by analyzing, organizing and summarizing the causes of the emergency incident.

It was established that the navigational maneuvering safety of determined deterministic operator actions, harmonized with the movement factors, where evaluation of consistency defines many vector criterion consistency.

In the work [7] the issues of navigation safety including pilotage are considered.

For the first time the methodology of passage planning by inverse mode while anchoring and mooring operations.

The ways of planning the curved tracks based on the characteristics of maneuverability.

The questions of organizing the bridge team work in emergency situations are not considered.

In the work [3], the complex of psycho-physiological research among students of senior courses, navigation department who were passing radar simulation training were discussed.

The purpose of research – the study of information and identification of individual indicators and definition of the opportunities of their usage for evaluating the level of formation of the dynamic stereotype production skills for process control.

They include: analysis of sensor motor reactions, running tests on attention, memory, thinking, strength and mobility of nervous processes.

In the work [5] the scientific and methodological basis is developed for the preparation of information for the operator in critical and emergency situations and for submission it in the form of knowledge, which allows early to make a decision to prevent emergency.

However, it is not considered in this work the operator of aircraft and its responsibilities in such situations and responsibility for the decision made.

In the work [6] substantiation of efficient ways of using modern information technologies for the prevention of accidents is performed.

However, the relationship of onshore operator and aircraft operator is not considered.

At the same time in the given work the list of all possible emergency conditions is not considered and the technique of forming both operators (onshore and onboard) sustained skill of determination the

moment of close-quarters situation occurrence and operator's interaction on the prevention of accidental incidents are not considered as well.

The **purpose** of this article is processing of formalized models and algorithms for determining the moment of vessels' emergency close-quarter situation and decision making support for its prevention.

3. Presentation of research material with substantiation of scientific results

When approaching within a small distance the operators of moving objectives have little time to assess the situation and make a decision.

For this reason, they have to give orders on the basis of lack of information using personal experience and knowledge of the principles that describe the situation of approaching and maneuvering.

The airport dispatchers have some difficulties due to heavy traffic of aircrafts and the need to draw attention to several tasks simultaneously.

Operators of onshore centers have difficulty in determining the moment of close-quarters situation occurrence when urgent actions are required.

It happens due to lack of instrumental tools accuracy, the lack of methodology in onshore centre's for assessing the risk of collision and legal responsibility for their recommendations.

Captain makes decisions and is solely responsible for, and he leaves the functions of coordinator and the source of information to onshore centre.

Confirmation of the problem is the situation that has arisen around the tragedy in the sky over Switzerland and in the Black Sea region at Novorossiysk area.

They both have exactly the same reasons - the uncertain actions of the operators in the close-quarters situations.

Despite the fact that after collision of ships "Admiral Nakhimov" and "Peter Vasyov" decades have passed, and after the collision of aircraft the world community had not been taking adequate steps to prevent such accidents for several years.

The responsibility had been imposed on the aircrafts' pilots and the masters of the ships.

The responsibility of airport traffic control service was not completely determined, and the question of vessels' traffic control liability was not considered at all.

At the same time it was determined that before the moment of collision the system of Russian aircraft had

been warning the pilot about collision, but he either ignored that information, or it was too late.

Further presentation will be related to marine vessels, although the results obtained can be used for aircraft and submarines as well.

Solution of the problem is the combinatorial procedure of consideration the relative motion of all combinations of two vessels and maneuver types.

To determine the number of combinations of elements it's necessary to calculate factorials $r!$ and $K!$ and their combinations as per known formulas:

$$r! = \prod_{r=1}^n r \quad \text{and} \quad K! = \prod_{k=1}^m K$$

$$C_r^K = \frac{K!}{r!(K-r)!}$$

For computing factorials we will use approximate formula of Sterling $r! \approx r^r e^{-r} \sqrt{2\pi r}$.

When 20 vessels are being detected on the radar screen, the number of combinations for the two vessels is equal to 190.

The number of possible maneuvers of own and other vessel, including all modes of maneuvering, is 16. The characteristic of possible passing-clear situations, taking into account the relative location of own and other ships, is 18.

When two ships pass each other there are 288 maneuvering situations available.

With 20 vessels the number of combinations of two vessels is 190 and the total number of situations and maneuvers is 54720.

A navigator cannot handle with such a large amount of information and he needs assistance.

It appears to be necessary to arrange the automation of data processing and issuing recommendations.

There are three sources of information for obtaining initial data from shore based systems:

1. Highly accurate coordinates of the receiving antenna location of the onshore Vessel Traffic System Radar (VTSR) or Automated Information System (AIS), defined by geodetic methods, in the form of latitude and longitude φ_0, λ_0 ;

2. Bearing and distance to the observed vessels, obtained by VTSR: $\Pi_{01}, D_{01}; \Pi_{02}, D_{02}; \dots; \Pi_{0n}, D_{0n}; \dots; \Pi_{0n}, D_{0n}$, where n – the number of vessels in the area of responsibility;

3. Coordinates of observed vessels obtained using AIS

$$\varphi_1, \lambda_1; \varphi_2, \lambda_2; \dots; \varphi_i, \lambda_i; \dots; \varphi_n, \lambda_n,$$

where n – the number of vessels in the area of responsibility.

When vessel's navigating devices control the process of vessel's movement there are three sources of obtaining initial data as well:

2. Position of own vessel's receiving antenna, obtained by satellite systems in normal and high-accurate differential mode φ_1, λ_1 , which is marked by index 1;

2. Bearing and distance from own vessels to the observed ones, obtained by radar $\Pi_{12}, D_{12}; \Pi_{13}, D_{13}; \dots; \Pi_{1i}, D_{1i}; \dots; \Pi_{1n}, D_{1n}$, where n – number of vessels observed on the radar screen;

3. Observed vessels' positions data obtained using AIS, $\varphi_1, \lambda_1; \varphi_2, \lambda_2; \dots; \varphi_i, \lambda_i; \dots; \varphi_n, \lambda_n$, where n – number of vessels observed on the radar screen.

Carefully analysis of the close-quarters situation and taking into account all the factors allow proposing a problem solving algorithm and obtaining analytical formula for selection the only possible maneuver.

Two axioms are used while solving this problem [4]: if there is a risk of collision a convention should be apply as following ($d\Pi/dt = 0$, $(dD/dt) < 0$; optimal course of turn for the prevention of collisions should be parallel course or opposite course of dangerous vessel.

Selection algorithm type of maneuver will consist in calculating the distance between the vessels and the timing of the last moment situation taking into account the geometry of approaching, parameters of target movement and own ship, its maneuvering characteristics and targets for all alternatives of performing including the latest one.

The moment, when a close-quarters situation has started to develop, should be considered when a navigator initially has three opportunities to prevent collision: stopping by "full astern" order, order to the helm "hard a port" or "hard a starboard".

Here we assume that "the last moment maneuver" will be those which come last.

The design formulas of calculation of the distance and time of close-quarter situation can be determined from Fig. 1.

For obtaining analytical dependences we will consider the triangle AMB, from which we obtain the relations counting that bearing is not changing:

$$\sin q = \frac{k \sin P}{\sqrt{1 - 2k \cos P + k^2}} \quad \text{and}$$

$$D_b = V_A t_{\text{cross}} \sqrt{1 - 2k \cos P + k^2},$$

where P – relative course, which varies from 0 to 180°;

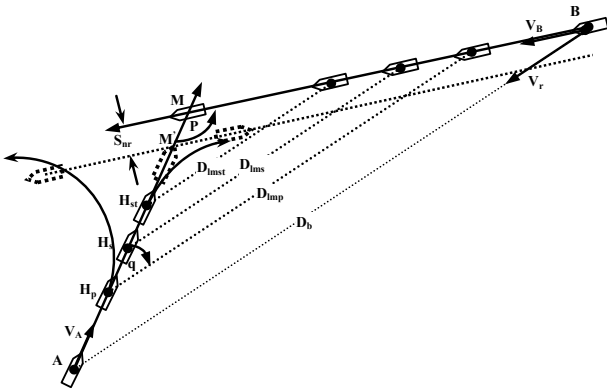


Fig. 1. Close quarter situation scheme

t_{cross} – the duration from start of observations to the moment when the courses have crossed;

k – ratio of velocities V_A / V_B ;

D_b – initial distance between the vessels;

q – relative bearing.

Let's denote the expression under the square root by the symbol

$$R = \sqrt{1 - 2k \cos P + k^2}.$$

Subject to the measurement error, geometric dimensions of vessels and probable unfavorable maneuver of oncoming vessel, we should implement a “navigational reserve”

$$S_{nr} = f(L, m_D, B_t, \ell_{2t}).$$

Taking into account the dependencies [4] we will obtain:

$$D_{lms} = (S_s + MM')R;$$

$$D_{lmp} = \left[\left(a_p + b_p \operatorname{tg} \frac{\Delta k_p}{2} \right) + MM' \right] R;$$

$$D_{lmst} = \left[\left(a_{st} + b_{st} \operatorname{tg} \frac{\Delta k_{st}}{2} \right) + MM' \right] R;$$

where S_s – the stopping distance for mode full astern;

a_p, b_p – coefficients of turning ability while turn to port;

a_{st}, b_{st} – coefficients of turning ability while turn to starboard;

Δk – angle of turn, which is defined by the formulas:

$$\Delta k_p = P \text{ when } q_{st},$$

$$\Delta k_{st} = 180 - P \text{ when } q_{st},$$

$$\Delta k_p = 180 - P \text{ when } q_p;$$

$$\Delta k_{st} = P \text{ when } q_p.$$

The distance from the courses crossing point to the line of safety margins, which can be determined from the expression:

$$MM' = \frac{S_{nr} R}{k \sin P},$$

where S_{nr} – navigational reserve.

The last moment maneuvers by stopping

$$T_{lms} = (D_b - D_{lms}) / V_r R.$$

The last moment maneuvers by turn to port

$$T_{lmp} = (D_b - D_{lmp}) / V_r R.$$

The last moment maneuvers by turn to starboard

$$T_{lmst} = (D_b - D_{lmst}) / V_r R.$$

The value of the relative velocity V_r is determined from the expression:

$$V_r = \sqrt{V_o^2 + V_t^2 - 2k \cos P}$$

where V_o – own ship speed;

V_t – target ship speed.

For further discussion we will consider algorithms of information processing by navigation devices to assess close-quarters situations, dangerous or emergency approaching own ship with others, as well as the situation observed on the radar screen.

We will form three matrices for information processing: matrix of bearings and distances between observed vessels by radar (RLS) M_{BD} , matrix of vessels' positions obtained by AIS M_{AIS} and matrix of distances M_D between them.

Further information processing should be performed according to the following algorithm.

1. Transfer polar coordinates of matrix M in rectangular geographical coordinates

$$\varphi_{2RLS}, \lambda_{2RLS}, \dots; \varphi_{iRLS}, \lambda_{iRLS}, \dots; \varphi_{nRLS}, \lambda_{nRLS}.$$

2. Calculation of the distance matrix M_{DRLS} by geographical coordinates in real time mode

$$M_{DRLS}(t_{i+1}) - M_{DRLS}(t_i) > 0.$$

3. Analysis of the distance matrix, and if other vessels are moving away of the own vessel then they are dropped from further processing, however monitoring of all targets continues.

If the situation changes, they will be included in the processing.

This algorithm of information processing allows reducing processor load and eliminate operator's distraction from the analysis of information about passing other vessels between themselves.

It is beneficial for onshore navigation system that controls over safety of navigation in the area of responsibility.

4. The calculation of accuracy of determining the relative course P and relative bearing q should be carried out and more accurate initial data for further processing should be chosen.

5. The classification of approached situation as per the value of parameters of approaching (relative course P and relative bearing q) should be performed.

There are 10 such situations of approaching for vessels on port side and starboard side [8], as per the Table , and there are 30 design diagrams.

As an example, the design diagram $P=90^\circ$ and $q < 90^\circ$ is shown at Fig. 2.

The following symbols are used in the design diagrams: H_s, H_p, H_{st} – position of own ship at the moment of giving the order to start stopping by FA, order the rudder hard a port or hard a starboard; D_b – the distance at the moment of assessing the risk of collision; M – course crossing point and M' taking into account the navigational reserve S_{nr} [4].

Analyzer determines the design scheme of close-quarters situation, performs its visualization and makes a determination of distance to dangerous vessel and the moment of giving the appropriate order on ship's handling to prevent close-quarters, dangerous and emergency situation.

Algorithm of issuing recommendations to the operator on making decision for the vessel on port side design diagrams depicted in Fig. 2, is shown in Fig. 3.

There are similarsupport decision making systems for each of the 30 close-quarters situations showed in Table.

Close-quarter situation always comes first when a navigator has more two alternatives to avoid collision.

The situation of dangerous approach comes second and a navigator has one more alternative maneuvers in this way.

When third and final opportunity to prevent a collision arises, emergency approach situation occurs, recommendation of maneuvering type is issued on the operator's radar screen and sound & light alarm switches on.

If a navigator misses this moment then the last moment maneuver is recommended and the command "Full astern" should be given for reducing damages from collision.

4. Conclusions

Analysis of collision cases has shown that the main causes of cases reflects lack of information about vessel's maneuvering characteristics and lack of recommendations on the organization of bridge team management in close-quarters situations.

Priority of maneuvers types when targets are observed on starboard and port sides

q, st	P	Type of maneuvers		
		Stopping	Turn to port	Turn to star-board
$<90^\circ$	$>90^\circ$	Stopping	Turn to port	Turn to star-board
		Turn to port	Stopping	Turn to star-board
		Turn to port	Turn to star-board	Stopping
$<90^\circ$	$=90^\circ$	Stopping	Turn to port	Turn to star-board
		Turn to port	Turn to star-board	Stopping
		Turn to star-board	Turn to port	Stopping
	$<90^\circ$	Stopping	Turn to star-board	Turn to port
		Turn to star-board	Stopping	Turn to port
		Turn to star-board	Turn to port	Stopping
$=90^\circ$	$<90^\circ$	Stopping	Turn to star-board	Turn to port
		Turn to star-board	Stopping	Turn to port
		Turn to star-board	Turn to port	Stopping
$>90^\circ$	$<90^\circ$	Stopping	Turn to star-board	Stopping
		Turn to star-board	Stopping	Turn to port
		Turn to star-board	Turn to port	Stopping
$<90^\circ$	$>90^\circ$	Stopping	Turn to star-board	Turn to port
		Turn to star-board	Stopping	Turn to port
		Turn to star-board	Turn to port	Stopping
	$=90^\circ$	Stopping	Turn to port	Turn to star-board
		Turn to port	Stopping	Turn to star-board
		Turn to star-board	Turn to port	Stopping
	$<90^\circ$	Stopping	Turn to port	Turn to star-board
		Turn to port	Stopping	Turn to star-board
		Turn to port	Turn to star-board	Stopping
$=90^\circ$	$<90^\circ$	Stopping	Turn to port	Turn to star-board
		Turn to port	Stopping	Turn to star-board
		Turn to port	Turn to star-board	Stopping
$>90^\circ$	$<90^\circ$	Stopping	Turn to port	Turn to star-board
		Turn to port	Stopping	Turn to star-board
		Turn to port	Turn to star-board	Stopping

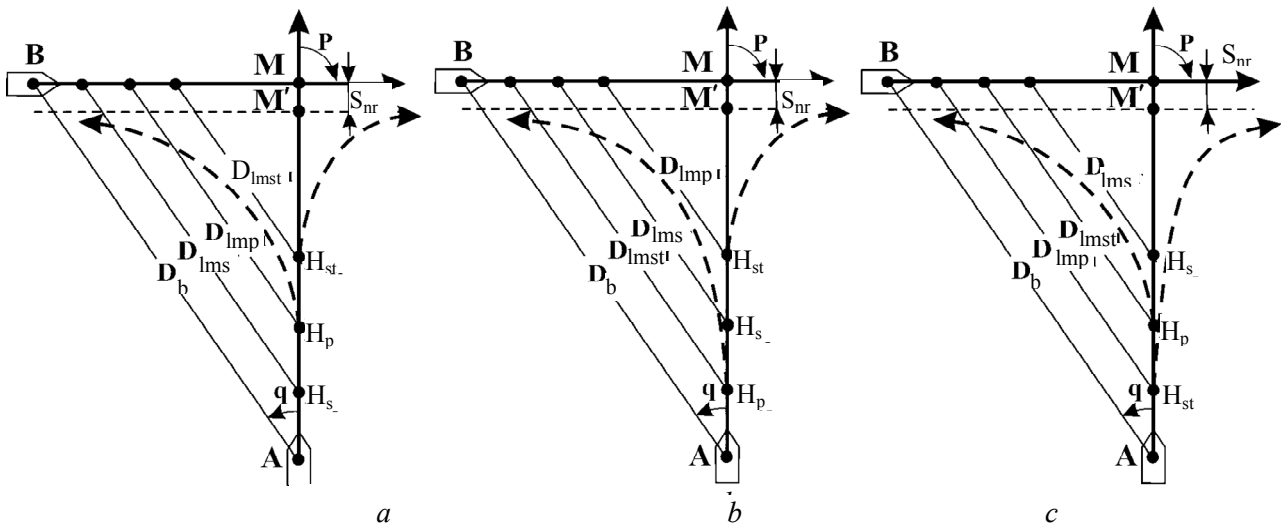


Fig. 2. Design diagrams, the dangerous vessel on port side and $P=900$, $q < 900$:
 a – priority of maneuvers – stopping FA, turn to port, turn to starboard;
 b – priority of maneuvers – turn to port, stopping FA, turn to starboard;
 c – priority of maneuvers – turn to starboard, turn to port, stopping FA

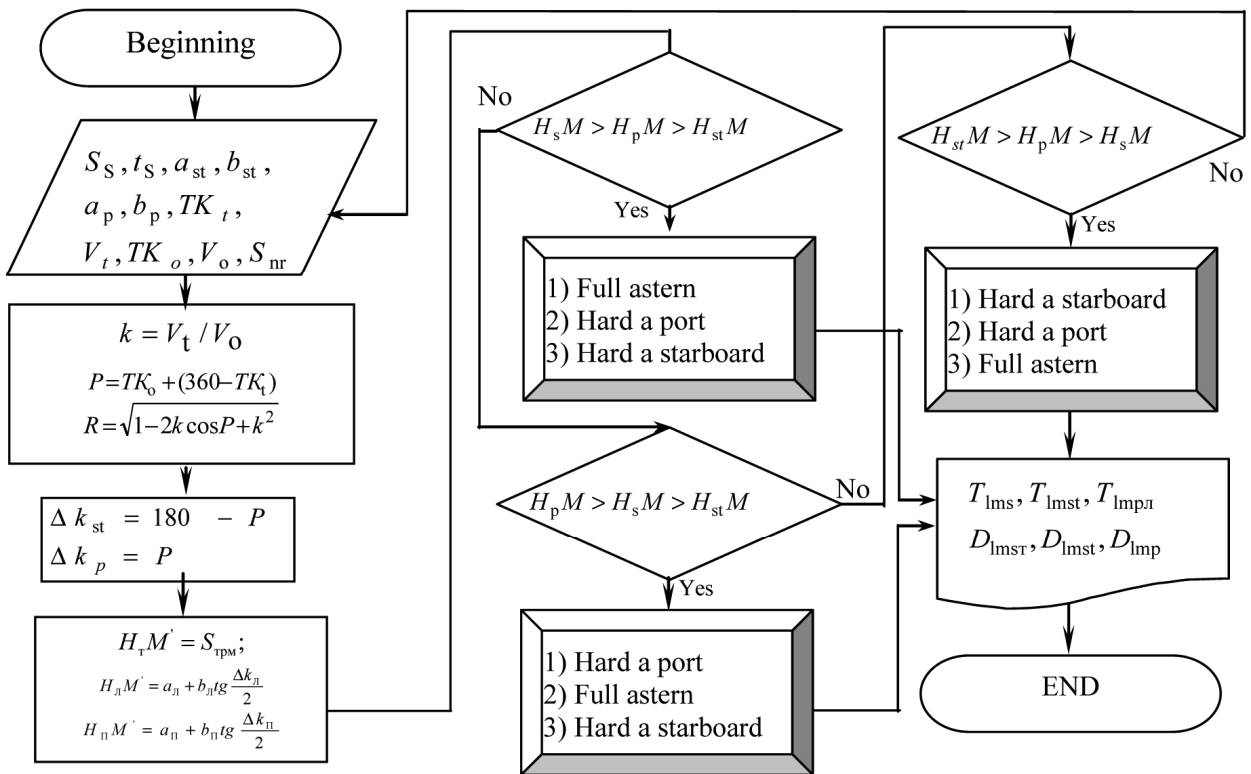


Fig. 3. Maneuvering decision making system flow-chart

The proposed method for determining the scope of close-quarters, dangerous or emergency approach situations allows creating a support for making decision on maneuvering system. It creates prerequisites for guaranteed safety while maneuvering.

In order to perform this work the existing navigational devices should be upgraded, as well as new ones should be created, which will allow to a navigator to obtain information in the form ready for a decision making on maneuvering.

The results received can be used in maritime institutions and colleges, updated and refresher training courses for navigators and while pilotage planning.

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Received 4 April 2014.

В. В. Мамонтов. Система оцінки надмірного наближення рухомих об'єктів

Національна морська академія, вул. Дідріхсона, 8, Одеса, Україна, 65029

E-mail: Volodymyr.mamontov@gmail.com

Виконано синтез системи оцінки надмірного зближення суден та підтримки прийняття рішення по маневруванню для попередження аварійної події. Запропоновано спосіб зменшення завантаження обчислювачів навігаційних пристроїв шляхом зняття з обробки суден, які віддаляються від власного судна. Показано, що цей спосіб створює передумови для зменшення інформаційного завантаження оператора, керуючого процесом руху. Відзначено, що отримання даних у вигляді, готовому для прийняття рішення, дозволяє оператору віддавати команди безпосередньо під час керування, що зменшує ймовірність виникнення аварійних подій.

Ключові слова: навігаційні пристрої; надмірне зближення; попередження аварій; прийняття рішення.

В. В. Мамонтов. Система оценки чрезмерного сближения подвижных объектов

Национальная морская академия, ул. Дидрихсона, 8, Одесса, Украина, 65029

E-mail: Volodymyr.mamontov@gmail.com

Выполнен синтез системы оценки избыточного сближения судов и поддержки принятия решения по маневрированию для предупреждения аварийного события. Предложен способ уменьшения загрузки вычислителей навигационных устройств путем снятия из обработки судов, которые отдаляются от собственного судна. Показано, что этот способ создает предпосылки для уменьшения информационной загрузки оператора, управляющего процессом движения. Отмечено, что получение данных в виде, готовом для принятия решения, позволяет оператору отдавать команды непосредственно при управлении, что уменьшает вероятность возникновения аварийных происшествий.

Ключевые слова: навигационные устройства; предупреждение аварий; принятие решения; чрезмерное сближение.

Volodymyr Mamontov (1976). Deep Sea Captain. Assistant of lecturer. Ship's Handling Department, National Maritime Academy, Odessa, Ukraine. Education: Odessa National Maritime Academy, Odessa, Ukraine (1998). Research area: theoretical principals' development of assured safety of navigation. Publications: 11. E-mail: Volodymyr.mamontov@gmail.com