РІЧКОВИЙ ТА МОРСЬКИЙ ТРАНСПОРТ

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MATHEMATICAL MODELING TRAJECTORY OF A SHIP AS A CONTROL OBJECT IN GLOBAL PLANNING

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Summary
In today's world of wars and pandemics, devices are needed that can control a ship without a human, solve complex navigational tasks, and carry cargo/people to/from the affected area. If it is a warship – to perform a combat mission without loss of personnel. Such devices require conditional classification of scenarios and the formation of global planning tasks in real time. A mathematical model of the global planning task has been elaborated. Changing the trajectory in real time is a change in the route matrix in global planning, which allows to rebuild the matrix of local planning. Each scenario is a coincidence of certain circumstances and conditions; circumstances and conditions are written in the form of programming code. It is proposed to use track matrices for global planning of the ship's trajectory. The binary path matrix (incidence matrix) can vary depending on the operational scenario. There are 4 possible scenarios and a scenario matrix that shows the correlation between the scenario and the waypoints. The proposed elaboration does not contain a conflict of priorities. All global planning scenarios run on time. A sudden scenario is not included in the scenario matrix, but it stops the global planning task. The three-column filter moves the braking unit diagonally in the path matrix depending on the number of missed points and allows the vessel to stop in front of the correct vertex by moving the braking unit diagonally across the path matrix. The control device modifies the trajectory in accordance with the execution of a scenario. The vessel is considered to be a control object which, in accordance with the decision of the control device, changes trajectory and/or stops by active or passive braking. Relevant graphic simulations are presented in the article. Economic efficiency is calculated on the basis of open data on the salaries of the ship's crew.
Key words: *global planning, scenario matrix, control device, control object, path matrix, route matrix.*

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ТРАЄКТОРІЇ СУДНА ЯК ОБ'ЄКТА УПРАВЛІННЯ В ГЛОБАЛЬНОМУ ПЛАНУВАННІ

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Анотація
У сучасному світі війн та пандемій необхідні пристрої, що здатні виконувати управління судном без людини, розв'язувати складні навігаційні задачі, виконати

перевезення вантажу/людей у/із зони ураження. Якщо це військове судно, − виконати бойову задачу без втрат особового складу. Для таких пристроїв необхідна умовна класифікація сценаріїв та формування завдань глобального планування в реальному часі. Розроблена математична модель завдання глобального планування. Зміна траєкторії у реальному часі – це зміна координатної матриці у глобальному плануванні, що дозволяє перебудувати матриці локального планування; кожний сценарій – це співпадіння певних обставин і умов; обставини і умови прописані у вигляді коду програмування. Пропонується застосувати путьові матриці для глобального планування траєкторії руху судна. Бінарна путьова матриця (матриця інцидентності) може змінюватись залежно від оперативного сценарію. Запропоновано 4 можливі сценарії і матриця сценаріїв, яка показує кореляцію між сценарієм і путьовими точками. Запропонована розробка не містить конфлікту пріоритетів. Усі сценарії глобального планування працюють у визначеному часі. Раптовий сценарій не входить у матрицю сценаріїв, але зупиняє виконання завдання глобального планування. Фільтр, що складається з трьох стовпців, рухає одиницю гальмування по діагоналі в путьовій матриці залежно від кількості пропущених пунктів і дозволяє зупинити судно перед правильною вершиною за рахунок переміщення одиниці гальмування по діагоналі путьової матриці. Управляючий пристрій модифікує траєкторію у відповідності до виконання того чи іншого сценарію. Судно розглядається як об'єкт управління, який відповідно до рішення управляючого пристрою змінює траєкторію і/або зупиняється шляхом активного або пасивного гальмування. Відповідні графічні симуляції представлені у статті. Економічна ефективність розраховується на основі відкритих даних про зарплати команди судна.

Ключові слова: *глобальне планування, матриця сценаріїв, управляючий пристрій, об'єкт управління, путьова матриця, координатна матриця.*

1. Introduction

The development of the modern transport industry in the world is characterized by the intensification of the use of unmanned vehicles. This is typical for the water transport industry. An important feature is the need to increase the carrying capacity of such vessels, expanding the range of tasks. In today's world of wars and pandemics, devices are needed that can control a ship without a human, solve complex navigational tasks, and carry cargo/people to/from the affected area. If it is a warship – to perform a combat mission without loss of personnel and eliminate unnecessary risks.

The article is devoted to the elaboration of a global planning task for programming the control device that will control the vessel in accordance with the requirements for unmanned vessels [1]. In connection with the above, the topic of the work seems to be relevant.

One of the important tasks of the commercial operation of the vessel is to ensure the possibility of reducing the costs of highly qualified command personnel by increasing the level of automation of the vessel's control. The proposed mathematical model will save the costs of the crew on merchant ships and reduce the loss of human resources on military ships during hostilities.

The formation of a global planning task for modeling the trajectory of a ship is an important step towards the creation of an unmanned ship with the fourth degree of autonomy, according to the classification of MARITIME AUTONOMOUS SURFACE SHIPS (MASS) [1]. The fourth degree of autonomy implies making decisions by the control device without human intervention.

2. Analysis of literature data and problem statement

The normative basis for programming the control device is described in the works [1–5].

Modern elaborations should be guided by the report of the Maritime Safety Committee at its hundredth session, annex 2 [1]. Source [1] the classification of unmanned vessels according to the degree of autonomy is given:

"**Degree one:** Ship with automated processes and decision support: Seafarers are on board to operate and control shipboard systems and functions.

Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control.

Degree two: Remotely controlled ship with seafarers on board: The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.

Degree three: Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.

Degree four: Fully autonomous ship: The operating system of the ship is able to make decisions and determine actions by itself". "The aim of the regulatory scoping exercise is to determine how safe, secure and environmentally sound Maritime Autonomous Surface Ships (MASS) operations might be addressed in IMO instruments. (INTERNATIONAL MARITIME ORGANIZATION). The objective of the regulatory scoping exercise on MASS conducted by the Maritime Safety Committee is to assess the degree to which the existing regulatory framework under its purview may be affected in order to address MASS operations" [1].

Source [2] is a code that applies to ship signals and indicators.

Source [3] is a convention consisting of rules for preventing collisions of ships at sea.

Source [4] is a code of general and specific requirements for ship positioning systems.

Source [5] is the International Convention for the Safety of Life at Sea, which governs the construction and operation of a ship from keel laying to decommissioning.

The autopilot system is known from the Japanese patent [6], which allows the operation of the ship's steering gear to be adapted to the environmental conditions in a way by choosing the control mode. In this patent, on the basis of weather data, the parameters of the steering gear are changed, but constant monitoring by a person on board is required.

From a Chinese patent application [7], a method for optimizing the route of an unmanned vessel based on environmental information is known. Functionally, this design is similar to design [6], but creates a recommended trajectory. This elaboration, like the previous one, has limited functionality and cannot provide the 4th level of ship autonomy [1].

The works [6] and [7] have a significant drawback, which does not allow the ships with such devices to be called autonomous: these devices do not classify operational scenarios in real time and do not form a global planning task.

Work [8] is the elaboration of an unmanned boat, called "Surface robot". It is a water robot that does not require a human presence to operate and can perform its task autonomously without remote control. It is more suitable for dangerous or routine and repetitive military and civilian tasks such as military strikes (commensurate with the size of the ship), patrolling, geomorphology, environmental monitoring and rescue operations, but cannot be used to transport goods and people.

Thus, the functionality of existing unmanned vessels does not allow performing complex large-scale tasks on a par with human-driven vessels.

The elaboration outlined in the article will increase the tonnage of commercial unmanned vessels and the size of military unmanned vessels (their striking power as a result). All these models are inferior to the elaboration proposed below already at the modeling stage, since the proposed model classifies possible scenarios and it becomes possible to moor a large unmanned vessel to the berth without tugs.

Works [9–11] are devoted to the accident rate in the fleet. According to statistics, errors in the work of people are the causes of 75–80% of all accidents [9–11]. Human errors are errors that occur when receiving and transforming information, when making and implementing a decision.

The problem statement for the global planning of the ship's movement was to establish a connection between the vertex of the graph and the corresponding scenario, avoiding a conflict of priorities when performing a global planning task in local planning.

Investigating this problem, the possibilities of discrete mathematics were studied [12]. The paper [12] describes the capabilities of discrete mathematics, its basic laws, but no tool is proposed to skip the vertex in the middle of the graph, and there are also no suggestions on how to connect the vertex of the graph with a scenario (some coincidence of conditions and circumstances). The theoretical justification for considering the vessel as a control object is the sources [13; 15–18].

In work [13] a person is defined as a control device, a conceptual separation of a person from control means is made, and a ship is considered as a control object. Also in [13], much attention is paid to the maneuvering characteristics of the ship, their calculation and comparison with the experiment. The integral control system includes a control body (control device) and controls (steering machine, engines, bow thruster, surface and underwater surveillance equipment, etc.) and a control object (ship).

In the work [14] a clear separation of the concept of a program and a device is given.

The work [15] describes the use of sensors for constructing the trajectory of global and local planning.

Work [16] is a high-quality textbook on automation as applied to naval targets, which contains block diagrams of interaction between controls and a ship as a control object.

Work [17] describes the maneuvering of ships in case of divergence, taking into account the minimum specified time for maneuver.

Work [18] contains kinematic models of robotic systems and control algorithms.

Source [19] contains the minimum ITF rates for crew salaries, which are used to calculate the economic efficiency from the introduction of a control device operating on the basis of the elaboration proposed in the article.

Work [20] covers the main provisions of hydromechanics.

3. The aim of elaboration and its tasks

The purpose of the research is to elaborate global planning task for unmanned control of the ship by a control device, to present the elaboration in numerical and graphic form, which will ensure the safety and economy of resources in the military and merchant marine.

To achieve the aim, the following tasks were set:

– to elaborate a matrix that will connect the graph vertex and the scenario and modification of the path matrix in accordance with the scenarios, avoiding a conflict of priorities;

– to propose a filter that will move the task of passive or active braking and ensure that the vessel stops at the corresponding peak;

– to show graphical simulation in MATLAB environment and in the electronic map of OpenCPN, to assess the safety and economic efficiency of elaboration.

4. Materials and methods used for elaboration

The material for the study was the plans for the passage of ships from one port to another, their passage through straits, narrows, rivers, as well as the maneuvering of ships in limited water areas.

The research methods were numerical and graphic simulation using Microsoft Excel and MATLAB and OpenCPN (USA).

A terminological basis for this article was formed, consisting of terms, the definitions of which were transformed taking into account the subject of research.

Below are the definitions for this article:

– mathematical modeling is a research method consisting of numerical and graphic simulation, used to elaborate mathematical instruments;

– path matrix (MP) – a matrix that represents the connection between the vertices of the ship's track [12];

– route matrix – a matrix consisting of a series of sequential coordinates, coordinates are taken from the control device database;

– active braking – the process of stopping the movement of the vessel by rotating the propeller (screws) in the opposite direction to rotation, which set the vessel in motion, respectively, forward or backward [13];

– passive braking – the process of stopping the movement of the vessel by stopping the rotation of the propeller (screws) to the speed at which the loss of controllability occurs [13];

– a scenario is the coincidence of certain conditions, under which, at a specified time, actions occur that lead to a change in the planned path or movement of the vessel in real time, with the exception of deceleration or acceleration actions that do not affect the vessel's path; at the same time, these scenarios are elaborated in accordance with the International Regulations for the Prevention of Collision of Vessels at Sea (COLREG 1972) and other mandatory international and state regulations, as well as taking into account meteorological data;

– the set time is the minimum time until a probable event to determine the scenario and make a decision in non-emergency mode by changing the global planning task;

– scenario matrix (MS) – a matrix that represents the relationship between points (vertices) of the ship's track and the corresponding scenarios;

– pilot-operator – a person who remotely, using a computer or telephone, downloads input data to a control device that affects the route or movement of the vessel;

– global planning – planning a ship's route in the water area through the establishment of alternate waypoints as a chain of route vertices nested in a route matrix based on a binary path matrix;

– point B – the destination (final point of the route), which has a berth, anchorage, a ship's drift, a place of refuge for a ship, or a place of holding the ship's position using thrusters, the last vertex of the graph;

– a ship, from the point of view of the theory of ship steering and automation, is an object of control;

– from the point of view of hydrodynamics, a ship is a body, the behavior of which depends on draft, stability, size, displacement, hydrodynamic coefficients, external factors, rudder position, characteristics of engines, thrusters and other data [20];

– control device – a device connected to the Internet, programmed for a microcontroller, which can be a computer, smartphone, regulator or navigation robot;

– a sudden scenario is a scenario of active braking with the possibility of changing the direction of the vessel's movement, initiated through the control device or the pilot-operator, or the shipowner, executed in emergency mode, stopping the execution of the global planning task;

– database – collection of navigation-related data, which is updated via the Internet.

5. Results of the elaboration of the necessary mathematical tools

5.1. Elaboration of the scenario matrix and modification of the path matrix

When modeling the trajectory from point A to point B, the data of the final point B are received from the pilot-operator. The control device converts the information received and builds the trajectory of movement (Fig. 1, 2). The circuit for determining the trail by the control device from the start point A1 to the end point B before transforming it; the final point B sent by the pilot-operator or shipowner is shown in Fig. 1. Conversion of the route from point A1 to point B, taking into account the lines of the safety corridor T1 and T2, which determine the possible range of movement of the vessel is shown in Fig. 2. The scenario matrix in Figure 5 is an absolute innovation and basic mathematical tool for creating a global ship trajectory planning task.

A route matrix represents a matrix of path points in the form of geographic coordinates, where φ is latitude and λ is longitude (Figure 3). The initial binary path matrix for the route from point A1 to point B without any scenarios is shown in Fig. 4.

In the path matrix, "1" shows the movement of the vessel from one point to another, and "-1" shows the impossibility of moving backward, "0" means there is no connection between the points. To increase the automation of ship control and simplify the decision-making algorithm, a matrix of scenarios with 4 different defined scenarios is proposed in case any scenario is not executed at any point. In this case, the MS contains 4 possible scenarios: S1, S2, S3, S4, – modifying the trajectory of the vessel. If even one scenario is not executed, then the scenario matrix consists only of zeros. S1 scenario means passive braking

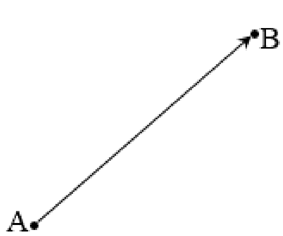


Fig. 1. Scheme for determining the route

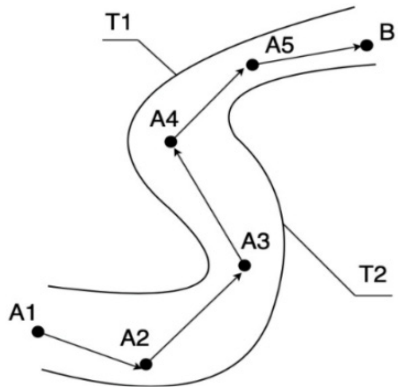


Fig. 2. Scheme of the converted trace

$$\left[\begin{vmatrix}\varphi_{A1}\\ \lambda_{A1}\end{vmatrix};\begin{vmatrix}\varphi_{A2}\\ \lambda_{A2}\end{vmatrix};\begin{vmatrix}\varphi_{A3}\\ \lambda_{A3}\end{vmatrix};\begin{vmatrix}\varphi_{A4}\\ \lambda_{A4}\end{vmatrix};\begin{vmatrix}\varphi_{A5}\\ \lambda_{A5}\end{vmatrix};\begin{vmatrix}\varphi_{B}\\ \lambda_{B}\end{vmatrix}\right]$$

Figure 3. Route matrix

-	A1	A2	A3	A4	A5	B
A1	0	1	0	0	0	0
A2	-1	0	1	0	0	0
A3	0	-1	0	1	0	0
A4	0	0	-1	0	1	0
A5	0	0	0	-1	0	1
B	0	0	0	0	-1	0

Fig. 4. Initial path matrix

-	S1	S2	S3	S4
A1	0	0	0	0
A2	0	0	0	0
A3	1	0	0	0
A4	0	0	0	0
A5	0	0	0	0
B	0	0	0	0

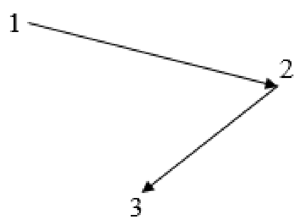
Fig. 5. Scenario matrix (execution of scenario 1 for vertex 3)

scenario, denoted as “1” in the path matrix. Scenario S2 means active braking scenario, denoted as “-1” in the path matrix. Braking scenarios always take place not at the vertex, but in front of the vertex, at a sufficient distance from the vertex so that the ship could continue to move and make a turn if necessary. For these purposes, in global planning, one more point is shown in the route matrix (Fig.6, *b*), so that when processing a task in local planning, the control device can calculate the minimum distance to the vertex sufficient to make the corresponding turn if it is necessary to continue the movement after stopping. S3 scenario is a scenario of skipping a planned point (s). S4 scenario means a scenario of active braking and sideways movement (lag movement) at the same time. S4 programming allows you to moor the vessel to the berth without tugs. Figure 5 – represents a similar matrix of scenarios in case the first scenario S1 is executed in point A3. Figure 6 – represents a diagonal matrix, a graphical illustration of scenario 1 at point 3, built on the basis of the scenario matrix shown in Fig. 5.

The route matrix in Figure 6 changes accordingly.

-	A1	A2	A3	A4	A5	B
A1	0	0	0	0	0	0
A2	0	0	0	0	0	0
A3	0	0	1	0	0	0
A4	0	0	0	0	0	0
A5	0	0	0	0	0	0
B	0	0	0	0	0	0

$$\left[\begin{vmatrix}\varphi_{A1}\\ \lambda_{A1}\end{vmatrix};\begin{vmatrix}\varphi_{A2}\\ \lambda_{A2}\end{vmatrix};\begin{vmatrix}\varphi_{A3}\\ \lambda_{A3}\end{vmatrix};\begin{vmatrix}\varphi_{A4}\\ \lambda_{A4}\end{vmatrix}\right]$$



A *B*

Fig. 6. Illustration of scenario 1 at vertex 3

In Fig. 7 shows the addition of two matrices (the path matrix and the diagonal matrix) into one matrix in the case of passive braking (scenario 1). Passive braking at point A3 is transmitted through “1” in coordinates A3_A3.

$$\begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{vmatrix} + \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{vmatrix}$$

Fig. 7. Addition of the path matrix and the diagonal matrix in scenario 1

In Fig. 8 shows the addition of two matrices (path matrix and diagonal matrix) into one in the case of active braking (scenario 2).

Active braking at point A3 is transmitted through “-1” in coordinates A3_A3.

$$\begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{vmatrix} + \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{vmatrix}$$

Fig.8. Addition of the path matrix and the diagonal matrix in scenario 2

In Fig. 9, b shows a variant of scenario 3 (skipping point A3). Substitution occurs by moving the vertical A6 Fig. 9, a. The path matrix has been modified to establish a link between the second and fourth point and eliminate all links to the third point, based on the scenario matrix in Fig. 10, in which “1” is at position A3_S3.

Thus, the article proposes a new simple logic for replacing links in the path matrix when skipping a point in the middle of the graph, if the missing point was at the end, then there would be no links with it, as shown in Fig. 9, *a*. It follows from this that when the missing point is moved in the matrix, the absence of links should be preserved, and the diagonals will move one cell from the central diagonal. In this case, there will be less feedbacks than direct connections by the number of missing vertices. The shift occurs starting from the first links of the vertex before the missing one. This is the first time such a transformation has been proposed.

$$\begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \qquad \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \end{vmatrix}$$

A *B*

Fig. 9. Execution of scenario 3 in the path matrix for the vertex A3

$$\begin{vmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix}$$

Fig. 10. An example of a matrix of scenarios with the implementation of scenario 3

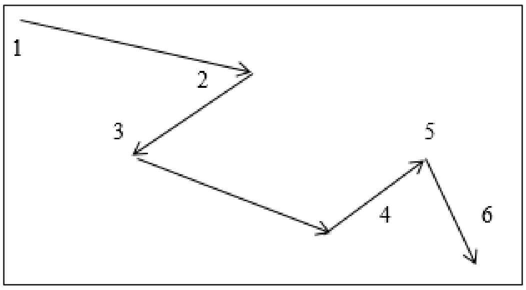


Fig. 11. Initial graph

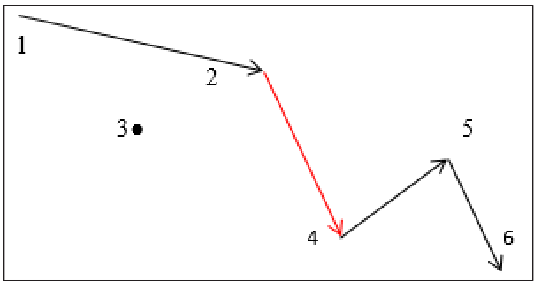


Fig. 12. Graph of the path matrix with the missing third vertex

In Fig. 11 shows the graph for the path matrix in its initial form based on the matrix in Fig. 4, and in Fig. 12 shows the graph of the path matrix based on the matrix in Fig. 9.

The graphs of path matrices are a clear illustration of the effectiveness of the proposed matrices connecting the vertex and the scenario, in particular, the skipping of vertex 3 in Figure 12 is the result of scenario 3.

5.2. Elaboration of a braking scenario filter

To filter the determination of the braking point, a filter was developed, shown in Fig. 13. The novelty of the proposed filter is the diagonal movement of the braking scenario.

In Fig. 13 shows 3 filter options: no vertex skip, one forgiven vertex and two skipped vertices.

The filter consists of three columns: ***I*** is the number of skipped points, ***P*** is the initial position "1" of deceleration, ***K*** is the end position "1" of deceleration.

In column *I*, the number of skipped vertices is calculated as

$$In = MAX(I1;In\text{-}1) + 1.$$

At the same time *In* always stands in a row *An*.

In column K the values are as follows:

$$Kn = If(MAX(I1;IB)=k;Pn+f),$$

where *f* is quantity of skipping points.

The transformed path matrix MP' depends on the position "1" in column K. The maximum number of skipped points before braking in the first column I of the filtration matrix, denotes the number of rows by which "1" will rise along the diagonal, transformed by the path matrix MP'.

The row in column K of the filtration matrix, which contains "1", coincides with the coordinates of the cell of the transformed path matrix MP', in which "1" or "-1" will

No skipped vertices

	I	P	K
A1	0	0	0
A2	0	0	0
A3	0	0	0
A4	0	0	0
A5	0	1	1
B	0	0	0

(a)

One skipped vertex

I	P	K
0	0	0
0	0	0
1	0	0
0	0	1
0	1	0
0	0	0

(b)

Two skipped vertices

I	P	K
0	0	0
1	0	0
2	0	1
0	0	0
0	1	0
0	0	0

(c)

Fig. 13. Filter of braking scenarios

appear. If A5, then the coordinates are in MP' A5_A5, if A4, then the coordinates are in MP' A4_A4, and if A3, then the coordinates are in MP' A3_A3.

When skipping points, the feedback "-1" in the corresponding columns is replaced by "0" to exclude the possibility of conflict of priorities during programming, the braking scenario rises up the diagonal. This is clearly seen in Fig. 14 and 15. In these figures, the transformed matrix with the missing point is aligned with the diagonal matrix, in which the unit of passive braking in Figure 14 or active braking in Figure 15 lies on the diagonal. This is the first time such a replacement is proposed. In these two figures, the deceleration at the apex A5 moves diagonally to the coordinates A4_A4.

$$\begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \end{vmatrix} + \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \end{vmatrix}$$

Fig. 14. The unit of passive braking at the vertex of 5 rises 1 cell diagonally

$$\begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \end{vmatrix} + \begin{vmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} = \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \end{vmatrix}$$

Fig. 15. A unit of active braking at vertex 5 rises 1 cell diagonally

In Fig. 16 shows how "-1" moves with active braking at vertex 5 diagonally with one missed point 16 (*a*) and two missed points 16 (*b*).

$$\begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & -1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \end{vmatrix} \begin{vmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ -1 & 0 & -1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

(a) (b)

Fig. 16. Braking at the vertex 5 with two options

In Fig. 17 shows the route matrix without omitting the points in Fig. 17, a with deceleration at vertex 5, with one missing point and deceleration at vertex 5 (Fig. 17, b) and with two missing points and deceleration at vertex 5 (Figure 17, c).

$$\left[\begin{vmatrix}\varphi_{A1}\\ \lambda_{A1}\end{vmatrix},\begin{vmatrix}\varphi_{A2}\\ \lambda_{A2}\end{vmatrix},\begin{vmatrix}\varphi_{A3}\\ \lambda_{A3}\end{vmatrix},\begin{vmatrix}\varphi_{A4}\\ \lambda_{A4}\end{vmatrix},\begin{vmatrix}\varphi_{A5}\\ \lambda_{A5}\end{vmatrix},\begin{vmatrix}\varphi_{B}\\ \lambda_{B}\end{vmatrix}\right] \left[\begin{vmatrix}\varphi_{A1}\\ \lambda_{A1}\end{vmatrix},\begin{vmatrix}\varphi_{A2}\\ \lambda_{A2}\end{vmatrix},\begin{vmatrix}\varphi_{A4}\\ \lambda_{A4}\end{vmatrix},\begin{vmatrix}\varphi_{A5}\\ \lambda_{A5}\end{vmatrix},\begin{vmatrix}\varphi_{B}\\ \lambda_{B}\end{vmatrix}\right] \left[\begin{vmatrix}\varphi_{A1}\\ \lambda_{A1}\end{vmatrix},\begin{vmatrix}\varphi_{A4}\\ \lambda_{A4}\end{vmatrix},\begin{vmatrix}\varphi_{A5}\\ \lambda_{A5}\end{vmatrix},\begin{vmatrix}\varphi_{B}\\ \lambda_{B}\end{vmatrix}\right]$$

(a) (b) (c)

Fig. 17. Route matrices with deceleration at point 5

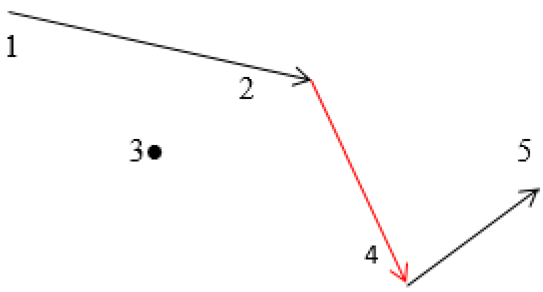


Fig. 18. Braking graph at vertex 5

In Fig. 18 shows a graphical simulation of the active braking scenario at the vertex 5 with a missing point.

As follows from the proposed circuit solution, the developed mathematical model is a powerful mathematical tool for solving the assigned tasks. The use of such a transformation of matrices to change the trajectory of a ship has not been previously carried out by anyone.

5.3. An example of a graphical simulation of a global scheduling task in MATLAB and OpenCPN, elaboration evaluation

A vivid example of changing the trajectory in real time is skipping point 14 in Fig. 20, which was in Figure 19. Fig. 19 – simulation of ship movement in global planning without skipping vertex 14. Fig. 20 is a graphical simulation of the S3 scenario for vertex 14 in MATLAB. In Figures 19 and 20 show a simulation of the movement of a vessel in the Bosphorus Strait and on the Sea of Marmara. In fig. 21, *a, b* shows the simulation of the ship's movement on the electronic OpenCPN charts without skipping point 14.

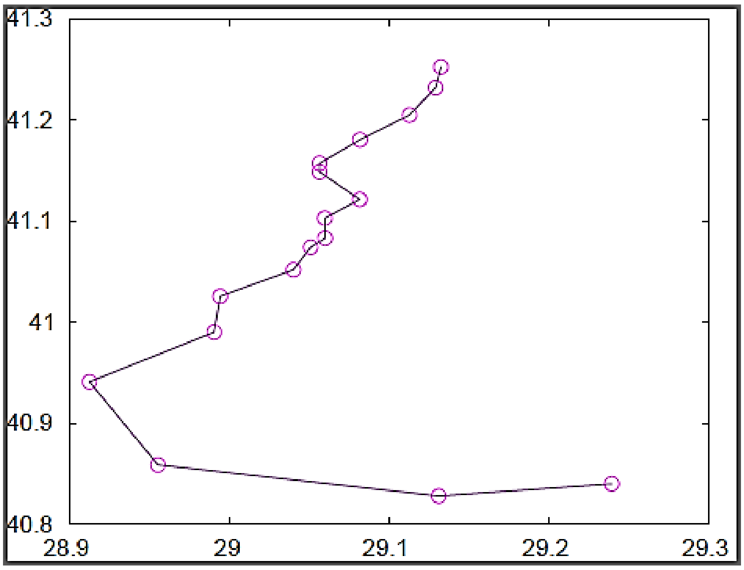


Fig. 19. Graphical simulation of the trajectory without skipping the vertex

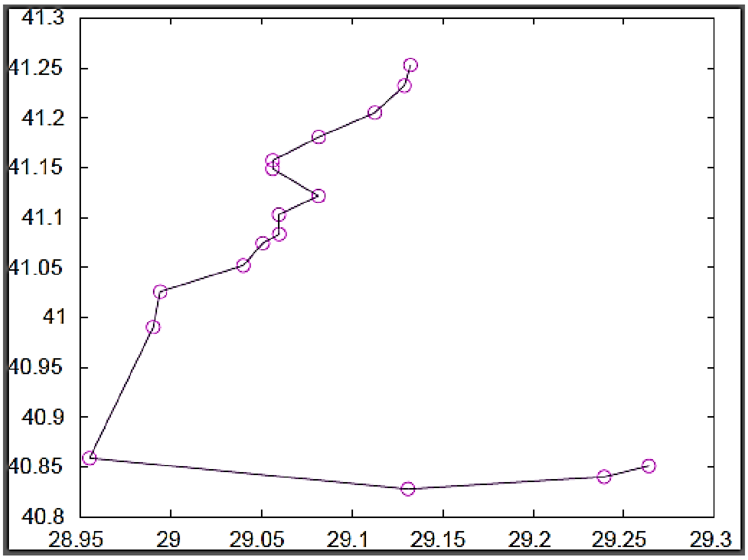
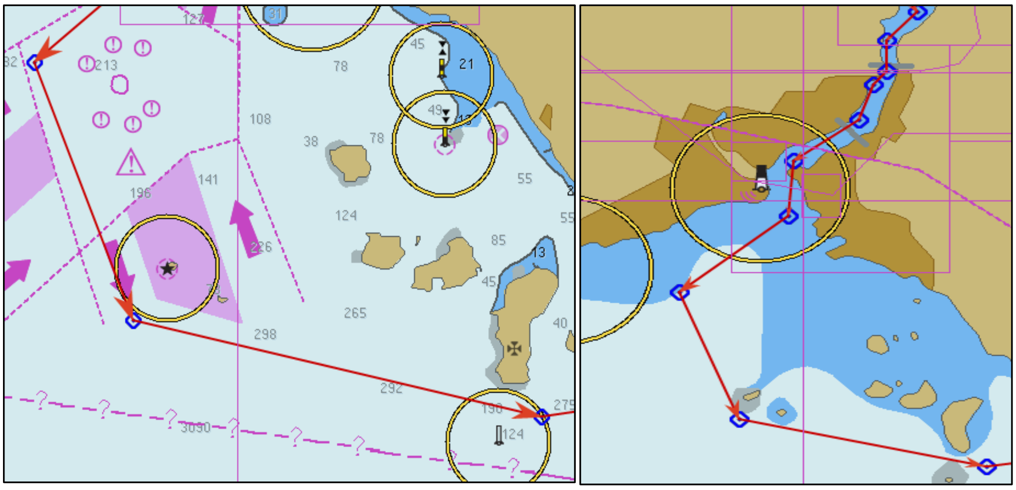


Fig. 20. Graphical simulation of the trajectory with the skipping of the vertex

In Fig. 22, (a) 22 (b) shows a graphical simulation of the movement of the vessel in the same area with the missing vertex 14.

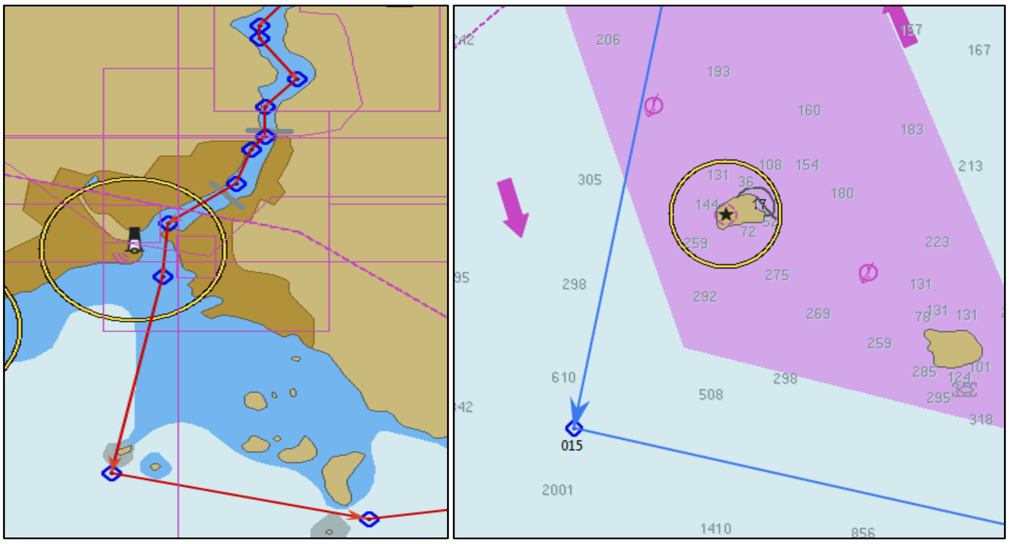
Simulations in MATLAB and OpenCPN show that the developed mathematical model has practical applications in navigation.

According to statistics, errors in the work of people are the causes of 75–80% of all accidents [9–11]. Therefore, the relative reliability of the device based on this elaboration is 1,33 and the economic efficiency of $ 37626 per month for one merchant ship with a crew of 23 people according to the ITF ILO Minimum Wage Scale [19].



A *B*

Fig. 21. Graphic simulation in OpenCPN of a ship leaving the Bosphorus Strait



A *B*

Fig. 22. Graphical simulation in OpenCPN with skipped vertex

On military ships, this elaboration can save life for crew, when performing combat missions. It eliminates unnecessary risks for navy.

6. Discussion of the results of the proposed mathematical modeling

When carrying out numerical and graphic simulations in Fig. 1–12, it was found that the algorithm for creating a global planning task does not contain a priority conflict, in particular, due to zero substitutions of the feedback cell. The route matrix changes in real time depending on the execution of a particular scenario.

Special attention should be paid to the fact that all global planning scenario work at the set time, a sudden scenario is not included in the scenario matrix, but stops the execution of the global planning task.

The global planning scenario matrix does not contain an off-course scenario; the off-course scenario will be considered in local planning as it is a product of local planning.

Scenarios S1, S2, S3, S4 are the basis for changing the global planning task in real time.

The S4 scenario should be disclosed when developing local planning, since S4 is a global planning scenario that looks like an active braking S2 scenario in a graphical global planning simulation. And the graphic simulation of the lateral movement is possible only after calculating the coordinates of the lateral movement end point in local planning. In Fig. 13–18, numerical and graphic simulation of the filter of braking scenarios 1 and 2 was carried out.

This filter moves the braking unit diagonally according to the number of missing points. Such mathematical modeling makes it possible to stop the vessel in front of the desired vertex, regardless of the number of skipped points before braking.

In Fig. 19–22 show graphical simulations in MATLAB and OpenCPN (USA). The simulation data shows the usefulness of this mathematical simulation in creating a global planning job.

The electronic control device, operating on the basis of the proposed global planning, will reduce the number of accidents significantly by eliminating the conflict of priorities and subjective perception of a person.

Evaluation of economic efficiency shows that this elaboration has the prospect of becoming the basis for the operation of the control device in the military and merchant fleets.

7. Conclusions

1. The elaborated matrix of scenarios and the modified matrix of the path make it possible to program a high-quality task of global planning, since they do not contain a conflict of priorities.

2. The braking scenario filter allows you to stop the boat at the correct vertex by moving the braking unit along the diagonal of the path matrix.

3. The practical usefulness of this elaboration is shown through graphical simulation in MATLAB and OpenCPN, as well as the relative reliability of the device based on this development is calculated as 1,33 and the economic efficiency of $ 37626 per month for one merchant ship with a crew of 23 people according to the ITF ILO Minimum Wage Scale [19]. On military ships, this elaboration can save many lives when performing combat missions in obviously unequal conditions.

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