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THE SYSTEM OF PRECISION PLANNING MARINE SHIP'S VOYAGE

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Abstract

The paper considers the navigational path planning complex, which includes new original methods of developing a given algorithm of ship handling system operation and control over the process of moving on motion paths, including curved portions. We propose the algorithms of control over the process of movement and precision control methods in the management of the ship's position. We created automatic place planning and control systems for curvilinear motion. The proposed concept gives a new direction to ensure the safe navigation of vessels in all driving conditions. This makes it possible to automate the process of planning and ship control when moving along the trajectories of arbitrary curvature. These benefits are achieved through: the development of high-precision methods of trajectory planning, which take into account the maneuvering characteristics of the vessel; improvement, using support systems control algorithms of decision-making in real-time; the use of automatic control of the center of gravity of the deviation from the set path precision methods; conversion of high-precision coordinate space satellite antenna on the determination of the vessel's center of gravity; the use of high-precision calculation methods maneuvering characteristics; visualization process of movement and improving the efficiency of adjustment movement with a single remote control. The results can be used on ships to create a navigation device transition planning, as part of the pilot of the individual information devices and simulators for training navigators to control in cramped conditions.

Keywords: curvilinear motion; handling; navigation complex; path planning; trajectory point; system.

1. Introduction

The track of moving ships in restricted waters preliminary planned carefully. In accordance with the requirements of International Marine Organization (IMO) planning of passage of marine ship must be executed from moorage of port of departure to moorage of point of arrival. Thus the way of ship is represented as rectilinearly and planning of turns are not produced. The results of such planning are recorded as a table and entered in the receivers of navigation devices that determine the location of ship.

In the restricted waters, on channels and fairways width of navigable part of comparable with the sizes of ship. It considerably complicates a management motion and promotes a requirement of exactness in planning of way and determination of the ship's position. Transience of process of change of navigational situation and duration of process of control of position of ship relatively planned by a classic method, comparing of the set and current position, results to the delay of

information about a rejection and creates pre-conditions for the origin of danger situation.

During maneuvering in the straitened waters the planning of the turn acquires a primary important and requires that maneuvering properties, degree of shoal and presence of other vessels be taken into account.

To plan a curvilinear trajectory by hand prior to navigating can be done, however control of motion on the vessel is impossible in practice, from the velocity process of turn. The automatic systems of planning and control of place at curvilinear motion are not created.

Therefore a navigator estimates the turn duration by gauging with a naked eye survey-comparative method, which substantially reduces exactness of location and creates the pre-conditions for a navigational accident.

2. Analysis of recent achievements and publications

It is noted in the work [1] that the operational management of the vessel and solutions to navigational problems is considered as a material point. The solving of the operational problems is

considered a constant solid, the current position of which is described by the coordinates of the center of gravity, including linear and angular velocity, and the angle of rotation of the drift.

When planning a predetermined path in the usual way, the navigator selects the safe ways points (WP), calculates the true course (TC), sailing from the previous to next one and presents the passage in tabular form, as shown in Table 1.

The control of movement along straight sections is produced by the nonobservational method, by applying current position on the chart, and graphically lateral deviation relative to the path previously applied. In some cases, the rotation is planned by applying the point of its start and end.

Table 1. Preliminary Passage Plan

N WP	TC	S, miles	φ	λ
1	-	-	$38^O06,8^I$ S	$144^O23,3^I$ E
2	147^0	0,8	$38^O07,5^I$ S	$144^O23,8^I$ E
3	83	2,6	$38^O07,2^I$ S	$144^O27,2^I$ E
4	102	3,7	$38^O07,9^I$ S	$144^O31,7^I$ E
5	55	4,0	$38^O05,7^I$ S	$144^O36,1^I$ E
6	67	0,7	$38^O05,5^I$ S	$144^O36,9^I$ E
7	73	0,4	$38^O05,3^I$ S	$144^O37,4^I$ E
8	80	2,7	$38^O04,7^I$ S	$144^O41,8^I$ E
9	118	3,4	$38^O06,4^I$ S	$144^O45,6^I$ E
10	172	4,9	$38^O11,3^I$ S	$144^O46,4^I$ E
11	226	2,5	$38^O13,0^I$ S	$144^O44,3^I$ E
12	204	3,7	$38^O16,3^I$ S	$144^O42,3^I$ E
13	254	2,7	$38^O17,0^I$ S	$144^O39,0^I$ E
14	222	8,5	$38^O23,0^I$ S	$144^O32,0^I$ E
15	126	94	$39^O16,8^I$ S	$146^O09,0^I$ E
16	90	19,1	$39^O16,8^I$ S	$146^O33,8^I$ E
17	65	75,5	$38^O42,5^I$ S	$148^O16,8^I$ E
18	55	100	$37^O45,0^I$ S	$150^O00,0^I$ E
19	58	285	$35^O14,5^I$ S	$155^O00,0^I$ E
20	55	302	$32^O20,9^I$ S	$160^O00,0^I$ E
21	52	321	$29^O02,8^I$ S	$165^O00,0^I$ E
22	50	350	$25^O19.3^I$ S	$170^O00,0^I$ E
23	47	478	$20^O00,0^I$ S	$176^O20,0^I$ E
24	20	130	$17^O57,0^I$ S	$177^O07,0^I$ E
25	77	6,3	$17^O55,8^I$ S	$177^O13,2^I$ E
26	10	4,3	$17^O51,5^I$ S	$177^O14,0^I$ E
27	41	9,2	$17^O44,6^I$ S	$177^O20,4^I$ E
28	14	6,2	$17^O38,5^I$ S	$177^O21,9^I$ E
29	50	4,0	$17^O36,0I$ S	$177^O25,0I$ E
30	82	1,6	$17^O35,8I$ S	$177^O26,6IE$

Movement along a curved path is often not controlled because of the fact that the determination of the place takes a long time, and such information is delayed by the time of control decision.

The disadvantage in this form of pre-passage development, is a lack of information about the moment at which a turn begins ends. From the analysis of the passage it shows that when leaving port the ship should have made 12 turns and 6 turns at the entry to the magnitude of change of a rate of 20 to 95 degrees.

In work [2] for the first time the graphical methodology of turn planning by segments mode is offered.

In work [3] a method has been refined and formalized accounting model of turning characteristics when planning a curved section of track was proposed.

In work [4] an algorithm and a program for calculating the coordinates of the curved path from the point of intersection of courses before and after the turn were developed.

In work [5] the theory of planning exercises with the dynamic characteristics of the vessel in carrying out offshore operations for anchoring and mooring was considered.

In work [6] the problems of improving the accuracy of planning and execution of pilotage through the use of an individual pilot device, which uses a method of preventing vessel stranding, described in [7] were considered.

Work [8] is a methodological framework to ensure the guaranteed safety of navigation, and its implementation when navigating in confined waters by high-precision motion planning of trajectory points (TP), is considered in [9] and the concept of a guaranteed safety of divergence discussed.

Work [10] contains basic principles of ships management in cramped conditions. However, precise control issues are not addressed.

In the existing published methods, path planning algorithms implemented in relevant calculations are not use in the training of navigators. This issue is especially relevant for the pilots who are working in cramped conditions and often perform turns. The necessary data for the planning of turns they are not usually available to them.

It is therefore proposed that the navigational device "path planning" used to calculate the coordinates of the trajectory of the vessel, including curved portions and process control movement (manual, semi-automatic or automatic) for marine navigation and the pilotage personal information device.

The purpose of this article is processing of formalized models and algorithms for planning trajectory points of vessels' and decision making support for its realization.

3. Presentation of research material with substantiation of scientific results

We know three methods of characteristics for turning in planning curvilinear motion - graphic (segments and perpendicular), analytical (segments and perpendicular) and ellipse method; there are three ways to perform the rotation - manual, automated and automatic.

In manual planning the skipper defines necessary input data for the maneuvering characteristics before turning. They include the coordinates of the beginning and end of rotation and the bearing and distance to the notable landmarks in these moments. There is a sailor on the wheel in the process of turning. Control of the process is determined in the maneuvering of the vessel at the time from start and finish. Movement along a curved path is often not controlled because of the fact that the determination of the position takes a long time, and such information is delayed by the time control decision. In order to control the drift during turning usually used fast methods of ship position detect. In this case, preparation for sailing, grid contours are plotted, which significantly speeds up the process control and allows for the receiving of timely information about the location of the vessel.

When automate performance of turning, the calculation of the required data: the start of the turn, the choice of rudder angle, determining the coordinates of the current situation, when the moment of checking the helm is made on a computer. Navigator sends the necessary commands to the helmsman and controls on the steering computer screen position relative to the planned movement and adjusts the vessel.

When performing an automatic rotation process is planned and implemented by a computer without navigator and helmsman, The navigator oversees its normal operation and, where possible, to visually evaluate the ship's position according to navigational signs.

Selecting the rudder angle is performed on the largest change rate, calculating coordinates or transferring of the corresponding part of the curve characteristics of the turning capacity on the card, followed by the definition of the coordinate

beginning, end and intermediate points of circulation.

The second method is based on selecting rudder angle according to the magnitude of the radius of curvature of the established path. It involves maintaining a constant angular velocity of rotation for the entire circulation time and variable rudder. Monitoring is carried out by using turning the angular velocity sensor and gyro. The disadvantage of this method is that it does not allow establishing the adequacy of the actual and planned way. Operation is carried out by a constant value of the angular velocity (and hence the radius of gyration), while the boat is moving while maneuvering. The variable angles of the rudder which are used then increase the bandwidth maneuverable shifting. Main attention, in dangerous areas and restricted waters.

For high-precision automatic path planning procedures of sailing in restricted conditions and automatic control of the vessel it is offered the navigation device "path planning", a functional diagram is shown in Fig. 1.

In order to organize the work of a decision support system for motion in restrictive conditions it is necessary to consider the direction of their work - precision specified path planning and control of the parameters of this motion with the issuance of decisions on the adjustment of the motion. To do this, use the following navigation devices: the calculation of brake performance; calculating the characteristics of turning capacity; the definition of high-precision location coordinates of the receiving antenna and recalculation of the center of gravity; calculation of the coordinates of the trajectory of motion in the form of way points (WP), courses and sailing on them; calculation of angles of rotation for each of the WP and select rudder angle for each WP; plan the way in the form TP 0,5 cbts in cramped conditions and 2 cbts length on the high seas, since the start and end points for each WP turns and corresponding TP, forming them into a rotation matrix; TP payment for each straight section from the end of the turning points of the previous WP prior to the subsequent rotation, forming a matrix of straight sections TP; calculating the deviation of the current position of the plan and to develop proposals to adjust the motion.

The calculation results are represented as an array of travel matrices and matrices TP rotation for all WP in the following sequence:

$$M_{01}, M_{t12}, M_{12}, M_{t23}, M_{23}\ldots M_{ti(i+1)}, M_{i(i+1)},\ldots$$
$$\ldots M_{t(m-1)m}, M_{(m-1)m}. \tag{1}$$

Transition matrices do not contain information about the trajectory of the way from the dock to the

pilot of disembarkation point during the withdrawal and the place of receiving the pilot to the pier at the port of arrival. This section describes the formation of a pilot plan for navigation and pilotage of the ship in the form of a ship sailing under the plan pilotage, and formed a separate procedure.

A functional diagram of a high-precision path planning of the center of gravity of the vessel and the continuous automatic monitoring of traffic safety in restricted conditions is shown in Fig. 1. To perform the calculations the following notations are adopted.

Length between perpendiculars: $L_{\perp\perp}$, м.
Breadth overall: B, м.
Draft Forward D_f, м.
Draft Aft D_{aft}, м.
The number of propellers / rudders: n/m/
Speed steady reversal: 9 knt
The number of propeller blades: Z.
Propeller diameter D_p, м.
Propeller disk attitude :θ_p.
Pitch ratio of propeller: H/D_p.
Square the rudder: S_r, м^2.

The number of turns of the propeller reverse n_{ast}, t/min

The conversion factor of abutment P γ_p.
The estimated coefficient of resistance K_p.
The conversion coefficient of resistance $\gamma_к$.

The coefficient of completeness midship bulkhead $\delta_\otimes$.

time of reversal t_{rev}.
Command Passing Time t^1.
Permissible lateral deviation from the TP d_{per}.
Current lateral deviation from the set path d_{cur}.

During automatic turning, the process of moving is controlled and implemented by a computer without navigator and helmsman. Navigator oversees its normal operation and, where possible, to visually evaluate the ship's position according to navigational signs.

For understanding whole processes which takes place let us consider the three figures that consistently show the transformation of the processing of information, as shown in Fig. 2.

Currently, they use a system of path planning center of gravity of the vessel , graphical representation of the path, as shown in Fig. 2.1) and a table of courses and navigating on them. Presentation of the trajectory in the form of an

array of points, the coordinates of which 0.5 cbs in restricted conditions and clearly distinguished coordinates of the start and end of the TP_1, TP_2 …TP_n rudder while turning, as shown in Fig. 2.2). Such an array is a predetermined control algorithm of the vessel and external influences can not change it. Adjustment may be required only when the variable restrictions in the form of other vessels or dangers suddenly arise.

By controlling the rate and speed, the master must hold the point of the actual position of the vessel, which receives data from the block 3 of the intended track. Typically, management of the ship as a point of intersection takes the midsection - the frame and the center plane.

It is believed that the center of gravity is exactly in it and deviations from the given path visually on the display screen, or automatically in block 11 by comparing the current and tolerance.

If the magnitude of this difference is less than acceptable, the unit 12 calculates the control action to bring the system to a predetermined state in blocks 4 and / or 8. If the control is done
manually, the detection of unacceptable deviations navigator gives a command to the controls. As a measure of the MSE it should be a radial position fixing, the sensitivity of the human eye, which allows you to determine the offset, or the ratio of width and maneuverable offset the navigable part of the marine waters. In view of the accuracy of modern satellite systems of differential determination of the place and the ability of the eye to detect the amount of displacement can be taken as 5 m.

Development of formal planning models of the vessel demanded knowledge of analytical methods, taking into account the effect of shallow water on maneuvering characteristics, which are now, unfortunately, absent. For obtaining such dependencies the comparative tests in deep water and in shallow water at mathematical model m/v "Mykola Bajan" were conducted.

In carrying out these comparative tests, characteristics of braking, turning capacity and steady in the helm of turning in deep water and in shallow water H / T = 1.2; 1.4; 1.6; 1.8; 2.0 were determined [8]. The results of these tests to determine the turning capacity characteristics are shown in Table. 2

To make practical calculations of maneuvering in shallow water, coefficients for each element must be taken into account:
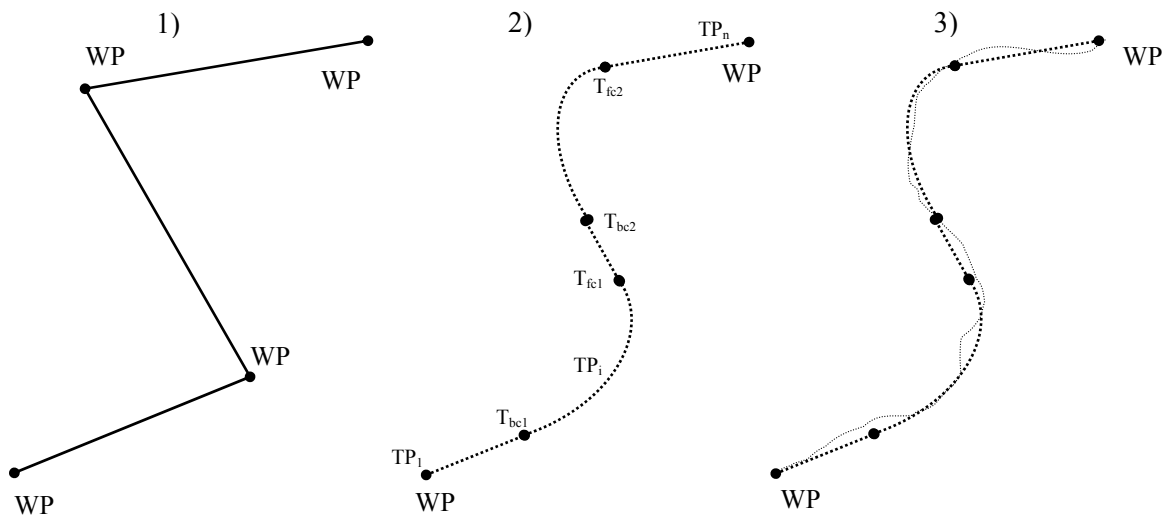
Fig. 2. – The Graphic image transformation of set and actual path: 1) on data from block 9; 2) on data from block 14; 3) on indicator 15.

$$\ell_1^{H/T} = \ell_1^{\mathfrak{p}} \cdot k_{\ell_1}; \ell_2^{H/T} = \ell_2^{\mathfrak{p}} \cdot k_{\ell_2};$$

$$D_T^{H/T} = D_T^{\mathfrak{p}} \cdot k_{D_T}; D_y^{H/T} = D_y^{\mathfrak{p}} \cdot k_{Dy} \qquad (1)$$

Table 2 - Comparison tests of turning capacity characteristics m / v "Mykola Bajan" under cargo for $\delta = 35^0$ at Vr = 12.4 kt

The results of the research are used to represent the coefficients of the shallow water in the form of a linear regression:

$$K = b_o + b_1 \cdot X_1 + b_2 \cdot X_2 , \qquad (2)$$

where $X_1 = (T/H)$, and $X_2 = (T/H)^2$.

Influence of shallow water on the characteristics of turning capacity is proposed it approximately in the form of coefficients calculated by the formula:

$$K_{\ell 1} = 1.55 - 1.81 \cdot (T/H) + 1.84 \cdot (T/H)^2 . \quad (3)$$

$$K_{\ell 2} = 2.35 - 4.63 \cdot (T/H) + 4.84 \cdot (T/H)^2 . \quad (4)$$

$$K_{D_T} = 1.60 - 2.77 \cdot (T/H) + 3.51 \cdot (T/H)^2 . \quad (5)$$

$$K_{D_Y} = 0.27 - 0.42 \cdot (T/H) + 2.09 \cdot (T/H)^2 . \quad (6)$$

Also taking into account shallow water on the accuracy of route planning two factors affect - the conversion of the coordinates of the antenna in the center of gravity of the SNA vessel and control the deviation from the center of gravity of the line of the planned path defined by the CT.

The coordinates of the center of gravity X' и Y' are calculated using detection by satellite system X и Y read on definite by satellite system with $0^0 \le K \le 90^0$ by the following relationships: [6,7], fig.3:

$$X' = X - \Delta X_1 + \Delta X_2 \text{ и } Y' = Y + \Delta Y_1 + \Delta Y_2 , \quad (7)$$

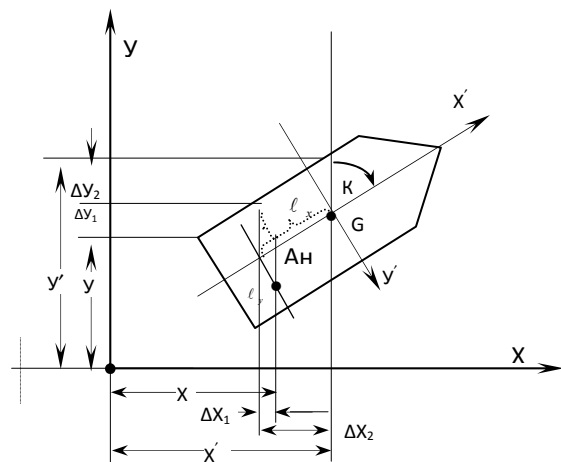| H/T	ℓ_1, cbt	ℓ_2 cbt	$D_\text{т}$, cbt	D_y, cbt
1.2	4.58	2.56	5.83	5.73
1.4	4.17	2.04	4.62	4.37
1.6	4.00	1.84	3.98	3.62
1.8	3.89	1.75	3.68	3.07
2.0	3.84	1.67	3.54	2.75
∞	3.48	1.36	3.23	2.67

Fig. 3 Reduction of observation to the center of gravity

where ΔX_1 - the distance projection of the point of antenna reception $A_{\text{н}}$ from the center plane ℓ_y in the X-axis; ΔX_2 – distance projection of the point of the antenna from the center of gravity of the DP in the X-axis; ΔY_1 - The distance projection distance of the point of antenna reception $A_{\text{н}}$ from center line on the axis Y; ΔY_2 – distance projection of the point of the antenna ℓ_x from the center of gravity of the DP on the Y axis.

The expanded form of the equation (7) can be written as:

$$\Delta X_1 = \ell_y \cos K; \ \Delta X_2 = \ell_x \sin K$$

$$\Delta Y_1 = \ell_y \sin K; \ \Delta Y_2 = \ell_x \cos K$$

$$X' = X - \ell_y \cdot \cos K + \ell_x \cdot \sin K \qquad (8)$$

$$Y' = Y + \ell_y \cdot \sin K + \ell_x \cdot \cos K \qquad (9$$

The central link in the system for prevention of vessel stranding is calculating the distance from the current position to the plan [8].

On entering the coordinates of the observe point from navigation system is necessary to calculate the distance and bearing from observe points to the trajectory points of plane coordinates, using the known formulas shown in Fig. 4:

$$TB_i = arc\left[(\lambda_0 - \lambda_i) \cdot \cos \varphi_0 / (\varphi_0 - \varphi_i)\right], \quad (10)$$

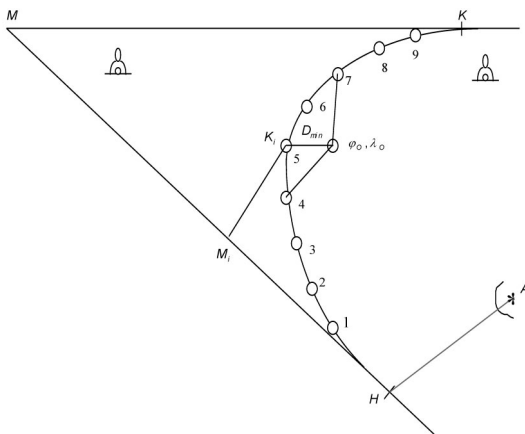$$d_{\text{cur}i} = 1852(\varphi_0 - \varphi_i) / \cos TB_i. \quad (11)$$

Fig. 4 Control of traffic on the trajectory points

Then, they define the minimum value d_{cur} and if it is less than d_{per}, the rudder angle remains unchanged until the next observation. If the deviation is greater than specified, depending on the position of an observation point relative to planned one, rudder angle is increased or decreased to enter the planned trajectory. This method can also be used to control movement on the straight sections. If the deviation is larger than allowed, visual and audible alarm automatically triggers.

Application of this method to prevent the grounding of the ship aground will allow avoiding an accident, which is caused by the incorrect management of the vessel when maneuvering in areas of heavy traffic, narrow waters and difficult navigational conditions. This will significantly reduce accidents and incidents related to marine pollution and the loss of property.

A working model of the navigation program for path planning was developed, in accordance with the data from block diagram shown in Fig. 1. It contains the following subsystems; calculation of maneuvering characteristics, taking into account of shallow water; coordinate system conversion from space with a satellite antenna on the center of gravity; a system of high-precision calculation of the path of the TP with the curved portions and the current system of calculating deviations from DH track and assess values.

The model allows you to modify the original data when the ship to change its load. Appearance panel is shown in Fig. 5.
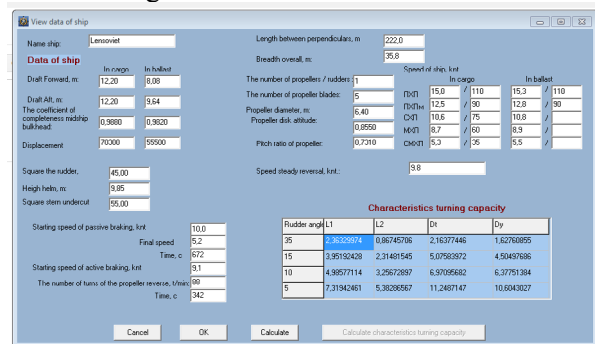

Fig. 5. Input data panel

After calculating the path of TP; results are placed in a matrix and displayed in graphical form as shown in Fig. 6.
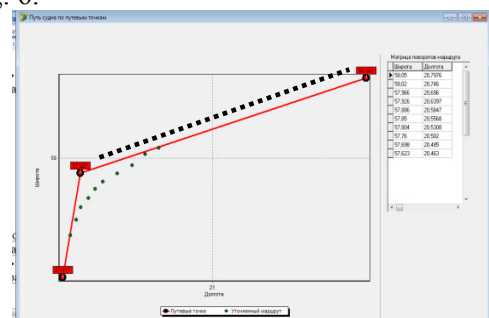

Fig. 6. The results of the calculation of path

As an example, on fig. 7 it is shown a fragment of the path when turning on the entrance to the port of Yujniy.

The developed system "path planning" contains for the first time developed methods and techniques for developing a predetermined algorithm for the system control of the vessel and control over the processes of moving the motion paths, including curved portions. It automates the process of planning the motion path based on turning ability and control of safe maneuvering.

4. Conclusions

The results can be used on vessels with automatic transition planning, part of the pilot individual devices and the information to create a simulator for training navigators on maneuvering in restricted area and conditions.

In order to perform this work, 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 refresher training courses for navigators and during pilotage planning.

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Система високоточного планування переходу морського судна

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У роботі розглянуто навігаційний комплекс планування шляху, який містить уперше запропоновані способи, методики розробки заданого алгоритму функціонування системи управління судном та контролю над процесом переміщення по траєкторіях руху, включаючи криволінійні ділянки. Наведено алгоритми контролю над процесом руху і способи високоточного контролю місця судна при управлінні. Створено автоматичні системи планування і контролю місця при криволінійному русі. Запропонована концепція дає новий напрям для забезпечення безпечного плавання суден у будь-яких умовах руху. Це дає можливість автоматизувати процес планування та управління судном при русі по траєкторіях довільної кривизни.

Зазначені переваги досягаються за рахунок: розробки високоточних методів планування траєкторії руху, які враховують маневрені властивості судна; вдосконалення алгоритмів керування, котрі використовують системи підтримки прийняття рішення в режимі реального часу; використання автоматичного контролю відхилення центру ваги від заданого шляху високоточними способами; перерахунку високоточних координат місця супутникової антени визначення місця судна на центр ваги; використання високоточних способів розрахунку маневрених характеристик; візуалізації процесу руху і підвищення оперативності його коригування з єдиного пульту управління.

Результати можуть бути використані на судах при створенні навігаційного пристрою плануванні переходу, в складі лоцманського індивідуального інформаційного пристрою і в тренажерах для підготовки судноводіїв до управління в умовах обмеженого простору.

Ключові слова: криволінійний рух; навігаційний комплекс; планування шляху; система; траєкторні точки; управління.

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В работе рассмотрен навигационный комплекс планирования пути, который содержит впервые предложенные способы, методики разработки заданного алгоритма функционирования системы управления судном и контроля над процессом перемещения по траекториям движения, включая криволинейные участки. Приведены алгоритмы контроля над процессом движения и способы высокоточного контроля места судна при управлении. Созданы автоматические системы планирования и контроля места при криволинейном движении. Предложенная концепция дает новое направление для обеспечения безопасного плавания судов в любых условиях движения. Это дает возможность автоматизировать процесс планирования и управления судном при движении по траекториям произвольной кривизны. Указанные преимущества достигаются за счет: разработки высокоточных способов планирования траектории движения, которые учитывают маневренные свойства судна; совершенствования алгоритмов управления, использующих системы поддержки принятия решения в режиме реального времени; использования автоматического контроля отклонения центра тяжести от заданного пути высокоточными способами; пересчета высокоточных координат места спутниковой антенны определения места судна на центр тяжести; использования высокоточных способов расчета маневренных характеристик; визуализации процесса движения и повышение оперативности корректировки движения с единого пульта управления.

Результаты могут быть использованы на судах при создании навигационного устройства планировании перехода, в составе лоцманского индивидуального информационного устройства и в тренажерах для подготовки судоводителей к управлению в стесненных условиях.

Ключевые слова: криволинейное движение; навигационный комплекс; планирование пути; система; траекторные точки; управление.

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