

Algorithms and Calculation Scheme for Planning the Way of Movement of Trajectory Point During Maneuvering for Anchoring

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ABSTRACT: The analysis of the historical aspect of the development of the maneuvering during anchoring shows that during the movement there is no time to control the position by technical means, due to the speed of the process of changing the parameters of movement. The main purpose of this research is to modify the methodological basis for the preparation of flight planning during anchoring with increased accuracy to determine the coordinates along which the ship will move. The methodology of this work is based on the calculation of trajectory points of the path in combination with the method of segments on the map using the characteristics of the maneuverability of the vessel. The method is based on determining the coordinate matrices of rectilinear and curvilinear sections through which the vessel passes during maneuvering for anchoring. The calculation program is developed in Excel, and allows without the help of a micro calculator that takes into account the maneuverability of the vessel in the automatic system. Thus, the control of the center of gravity of the vessel relative to a given path line is performed.

A high-precision system for automatic determination of planned coordinates by trajectory points on track and traffic control during anchoring has been developed, which is based on recently developed algorithms, calculation schemes and methods at the Maritime University, which are based on the latest meaningful models of high-precision planning movement on them. This approach automates the process of controlling safe traffic, including the use of decision support systems, including stranding prevention and collisions with other vessels. The results of the research can be used on a ship for automated planning of coordinates on waypoints and control of traffic on them for safe maneuvering, as well as for training navigators on specialized simulators to perform trajectory planning, including limited conditions.

1 INTRODUCTION

Analysis of the voyage cycle of sea vessels shows that they spend about 20% of the sailing time in confined waters, but it accounts for about 80% of all emergency events.

Turning a ship in the open ocean, when sailing away from navigational hazards, is not difficult, and when using maps 1: 50,000 and smaller, its details are not expressed on the map at all. In confined waters,

the water area for maneuvering is commensurate with the geometrical dimensions of the vessel and planning the trajectory of movement, and especially its curvilinear section, becomes of paramount importance.

The most dangerous section of the track, which determines the safety of the vessel's movement, is the curved one. The reasons for this are the speed of the process of moving the vessel when turning, the absence of the planned coordinates of the curved path

and the necessary data on the turnability, which are required for their planning.

To eliminate such reasons, it is necessary: to carry out preliminary planning of the coordinates of curved track sections or to automate the process of their calculation, which can be performed while sailing; perform automated control of lateral displacement, relative to the planned coordinates, select a maneuver for divergence and use the maneuver in a timely manner to correct movement; use high-precision methods of determining the position of the vessel, including geodetic ones. Therefore, the purpose of this work is a method for planning the specified coordinates of trajectory by waypoints (WP), based on determining the matrixes of coordinates of trajectory points (TP) of rectilinear and curved track sections through which the ship passes when maneuvering for anchoring. Another aspect of the problem is the lack of the necessary data on the maneuvering properties of braking and turnability of the vessel for all modes of using control actions. Therefore, such tasks are highly relevant.

2 ANALYSIS OF RECENT STUDIES AND PUBLICATIONS, WHICH BEGAN TO SOLVE THIS PROBLEM AND HIGHLIGHT THE PREVIOUSLY UNSOLVED PARTS OF THE GENERAL PROBLEM

There are three ways to plan a turn - manual, semi-automatic and automatic.

When planning a turn manually, the required initial data [5] is determined by the Master according to the turnability characteristics before the start of the turn. They include the coordinates of the points of the beginning and end of the turn, bearings and distances to noticeable landmarks at these moments. A sailor controls the steering wheel during the turn. Turn control consists in determining the position of the vessel at the moments of its beginning and end. Movement on a curved path is not controlled due to the fact that location determination takes a long time, and such information is delayed by the time a control decision is made. In order to control the position when turning, use the accelerated methods of determining the place.

With semi-automatic, part of the turn planning functions [2, 9] is performed manually, then part of the motion control functions are performed automatically.

Currently, there are navigation devices [3, 5], which make it possible to quickly determine the position of the pivot point (PP) and the width of the maneuvering lane during movement, which significantly increases the speed of the process of obtaining parameter values and making decisions on control.

Using the method of control of the abscissa of the position of the centre of gravity (CG) [8], PP, recalculation of the coordinates of the satellite dish to the CG and the method of planning a given path using coordinate matrixes [4] of trajectory points (TP) allow automating the process of high-precision planning

and control along the trajectories including curved sections. Methods for solving these problems, developed at the National University "Odessa Maritime Academy" recently [1-5, 8, 9], make it possible to propose algorithms and calculation schemes and develop a navigation system for automatic planning of coordinates of the path of movement and control along it.

3 FORMATION OF THE GOAL OF THE WORK AND THE FORMULATION OF RESEARCH OBJECTIVES

Algorithms and computational schemes determine the procedure for increasing the accuracy of planning the route of movement to anchorage area, taking into account the water area for maneuvering, characteristics of braking and turnability and the use of methods for planning the route of movement by trajectory points, including curved sections. To achieve this goal, we will perform the inverse route planning when anchored in *m/v "MSC Canaberra"* on the roadstead of the Chernomorsk Port, as shown in Fig.1.

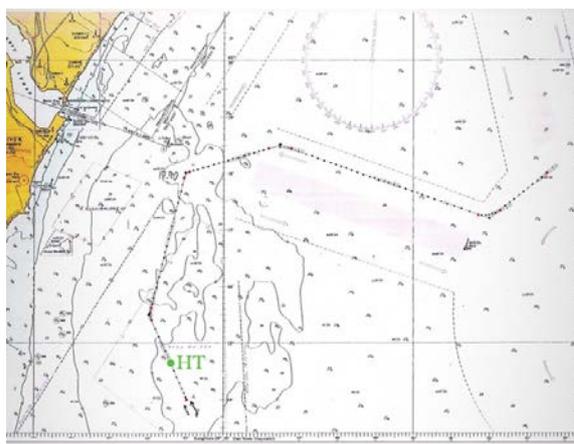


Figure 1. Planning of the TP maneuvering route when the vessel is proceeding to anchored area No.351 on the roadstead of the port of Chernomorsk

4 PRESENTATION OF THE MAIN RESEARCH MATERIAL

To perform route planning, the following vessel data are required: permanent vessel data; two tables of characteristics of braking and turning ability [2, 9]; a map with an area for maneuvering and recommended paths of movement, determined by geodetic methods.

The further algorithm of the meaningful model will be as follows:

1. The coordinates of the anchoring point are plotted, which are agreed with the VTS.
2. The total vector of the wind and current direction is determined and the approach line is drawn in its direction for releasing the anchor until it intersects the recommended path line on the map or the water area of the beginning of maneuvering, free from hazards and suitable in depth, and determine the coordinates of the penultimate maneuvering

point, as shown in Fig. 1.

For this, the navigator must set the initial data in the computer, namely, the coordinates of the waypoints and the maneuvering characteristics of the vessel, which must be available on the vessel in electronic form in the form of tables. After that, the trajectory point's matrices will be automatically given to the skipper, along which the vessel will follow every 2 cables.

3. Make a table of waypoints and calculate the TC, the distance from the previous WP to the next one, the angle of rotation at each waypoint and the required rudder shift angle as follows.

The procedure for calculating these points is as follows: using formula (1) from a spherical triangle, taking latitude and longitude as the basis, we determine the true course that the ship will follow.

$$TC = \arctan\left(\sin|DLon| \div (\tan \phi_2 \sin \phi_1 - \sin \phi_1 \cos DLON)\right) \quad (1)$$

where TC - true heading from the previous point to the next; DLon - the difference between the longitudes of the end and start points; ϕ_1 - latitude of the starting point; ϕ_2 - latitude of the end point.

These calculations were performed in Excel. The results of calculating the initial data and calculating the course to follow to each of the previous to the next point are shown in table. 1. In this case, calculations are performed in radians. Therefore, it is necessary to convert the coordinates of points from degrees to radians in advance.

Table 1. Calculation of true courses to follow between points

WP	LAT	LON	Course
0	46°18,0' N	30°53,5' E	
1	46°17,2' N	30°52,0' E	233
2	46°18,5' N	30°46,5' E	289
3	46°18,0' N	30°44,0' E	265,7
4	46°15,5' N	30°43,0' E	204,1
5	46°14,0' N	30°44,0' E	164

After the TC value is determined, you can proceed to the automatic calculation of the distance between the specified WPs using the following formulas:

$$DLon = \lambda_{i-1} - \lambda_i \quad (2)$$

$$DLat = \phi_{i-1} - \phi_i \quad (3)$$

The value of the meridional parts in equatorial minutes for the Krasovsky's ellipsoid can be calculated by the formula:

$$MP = 3437.7468 \cdot \ln \left\{ \tan \left(45^\circ + \frac{\phi}{2} \right) \left(\frac{1 - e \cdot \sin \phi}{1 + e \cdot \sin \phi} \right)^{\frac{e}{2}} \right\} \quad (4)$$

where MP - is the meridional part of the parallel ϕ , eq. min.; ϕ - geographic latitude; e - the eccentricity of the terrestrial ellipsoid.

The name of the MP coincides with the name of the latitude. To obtain the difference in the meridional

parts (DMP), it is necessary to calculate the MP_i, then the MP_{i-1}, and after that the algebraic difference:

$$DMP_i = MP_i - MP_{i-1} \quad (5)$$

The name DMP_i is indicated from MP_i to MP_{i-1}, that is, it corresponds to the DLat name. The direction of TC_i is calculated by the formula:

$$\tan TC_i = \frac{\lambda_i - \lambda_{i-1}}{DMP_i} \quad (6)$$

The direction is obtained in a quarter count and for recalculation in a circular one it is necessary to take into account that the first letter of the quarter corresponds to the name of the DLat, and the second to the DLon.

The distance traveled between the WPs is determined by the formula:

$$S_i = DLat \cdot \sec TC_i \quad (7)$$

The calculation results are summarized in table 2.

Table 2. Calculation of distances to follow between points

WP	LAT	LON	Distance S, cables
0	46°18,0' N	30°53,5' E	
1	46°17,2' N	30°52,0' E	13,2
2	46°18,5' N	30°46,5' E	40,0
3	46°18,0' N	30°44,0' E	18,5
4	46°15,5' N	30°43,0' E	15,8
5	46°14,0' N	30°44,0' E	16,9

After receiving the TC, it is necessary to determine the angle of rotation θ . To do this, it is necessary to subtract the course that was before the commence of the turn from the course that the ship will follow after the turn, as shown in formula (8).

$$\theta = TC_i - TC_{i-1} \quad (8)$$

Rotation angle data between points are given in table. 3. All calculations are performed in degrees.

Table 3. Calculation of distances to follow between points

WP	LAT	LON	Course	θ
0	46°18,0' N	30°53,5' E		
1	46°17,2' N	30°52,0' E	233	56
2	46°18,5' N	30°46,5' E	289	23,3
3	46°18,0' N	30°44,0' E	265,7	61,6
4	46°15,5' N	30°43,0' E	204,1	40,1
5	46°14,0' N	30°44,0' E	164	

It should also be remembered that the circulation parameters depend on the rudder shift. The rudder shift, in turn, depends on the steering angle. The formula (9) gives recommendations for choosing the rudder shift.

$$\delta = \begin{cases} 5^\circ & \text{if } \Delta\theta \text{ less than } 30^\circ \\ 10^\circ & \text{if } \Delta\theta = 30^\circ - 60^\circ \\ 15^\circ & \text{if } \Delta\theta \text{ more than } 60^\circ \end{cases} \quad (9)$$

Table 4 shows the definition of the recommended rudder shift for each steering angle, according to formula (9).

After the main parameters of the track lines are obtained, you can commence calculating the points of the beginning and end of the turn.

Table 4. Steering angle depending on the steering angle

WP	LAT	LON	Course	θ	δ
0	46°18,0' N	30°53,5' E			
1	46°17,2' N	30°52,0' E	233	56	10
2	46°18,5' N	30°46,5' E	289	23,3	5
3	46°18,0' N	30°44,0' E	265,7	61,6	15
4	46°15,5' N	30°43,0' E	204,1	40,1	10
5	46°14,0' N	30°44,0' E	164		

When performing a turn automatically, the routine work of calculating the necessary data - the moment of the beginning of the turn, choosing an angle rudder shifting, determination of the coordinates of the current position, the onset of the moment of holding the vessel is performed by a computer. The navigator gives the necessary commands to the helmsman and controls on the computer screen the actual position of the vessel relative to the planned one and corrects its movement.

All the calculations performed are summarized in one table 5, which are necessary for planning the coordinates of the planned path by trajectory points (TP) and navigation control of control along it, including curved sections of the path, when anchored.

With the automatic execution of the turn, the process of movement is planned and carried out by a computer without the participation of the navigator and the helmsman. The navigator exercises control over the normal operation of the control system and, if possible, visually evaluates the position of the vessel relative to the signs of the navigational situation.

Table 5. Summary table of turnability parameters

WP	LAT	LON	Course	Distance, S, cables	θ	δ
0	46°18,0' N	30°53,5' E				
1	46°17,2' N	30°52,0' E	233	13,2	56	10
2	46°18,5' N	30°46,5' E	289	40,0	23,3	5
3	46°18,0' N	30°44,0' E	265,7	18,5	61,6	15
4	46°15,5' N	30°43,0' E	204,1	15,8	40,1	10
5	46°14,0' N	30°44,0' E	164	16,9		

Currently, there are two ways of planning the planned coordinates of the trajectory points of the beginning and end of the turn, which differ in the method of taking into account the characteristics of turnability when planning a given path and control of steering. The first is based on the choice of the rudder shift angle according to the value of the course change, the calculation or transfer of the corresponding section of the turnability characteristics curve to the map with the subsequent determination of the coordinates of the beginning and end of the circulation. At the same time, the moment of giving the command to shift the rudder is taken as the beginning of the turn, as in the performance of full-scale tests to determine the characteristics of

turnability. The turning process is controlled by a gyrocompass.

The second method is based on the choice of the transfer angle in accordance with the value of the steady-state radius of curvature of the trajectory. It involves maintaining the angular rate of rotation constant during the entire circulation time by variable rudder masses. Rotation control is carried out by an angular velocity sensor and a gyrocompass. The disadvantage of this method is that it does not allow you to establish a correspondence between the current and valid locations. The control is carried out according to the steady-state value of the angular velocity while the vessel is moving in maneuvering mode. Variable rudder angles, which are used, increase the width of the maneuvering lane. The latter in hazardous areas of confined waters is of paramount importance. Both methods do not provide for the formalization of the process of movement and control.

When planning the coordinates of movement, the path is usually used in the form of straight-line segments with their intersection at waypoints. This planning method is suitable for use on the high seas. Turn planning is not expressed in terms of the scale of the map used at the crossing, so it does not make sense.

When sailing in confined waters, when the geometrical dimensions of the vessel are commensurate with the distance to hazards, it becomes necessary to carefully plan safe coordinates of movement and ensure their passage using the vessel's movement controls.

Since the process of movement in cramped conditions and when making turns is fast, planning, and when making turns, and controlling the parameters of maneuvering is not always possible.

To take into account the characteristics of turnability when planning a curvilinear movement, we will use the method of segments [6, 7].

When planning a curved trajectory, it is necessary to transfer the corresponding section from the turnability data presented in the ship's documents in graphic form to the map. For a more convenient performance of such work, it is recommended to graphically plot the circulation curves, which are available in the ship's documents, on a maneuverable tablet, as shown in Fig. 2.

To explain the essence of the method of segments, let us consider the circulation curves of the m / v "MSC Canaberra".

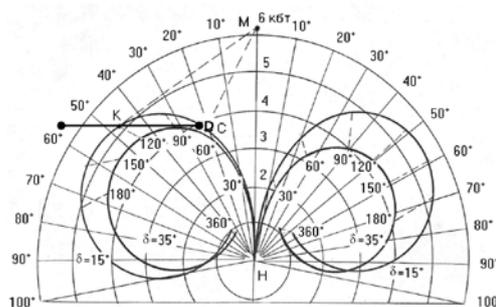


Figure 2. Circulation curves of m / v "MSC Canaberra" in ballast

The following procedure is recommended for calculating rotation elements.

1. By the value of the angle of rotation, the side of the rotation and the angle of rotation, mark the end point of the rotation E with a pencil.
2. Apply a parallel ruler to the center of the tablet and a point on its circumference corresponding to the angle of rotation 120° . Move the ruler to point E and draw a straight line from it until it intersects with the initial radius of the tablet, get the point M of intersection with the path line before turning.
3. On the scale of the tablet, the values of the segments MC and ME are taken, which are plotted accordingly from point M on the map, which gives the points of the beginning and end of the ship's trajectory when turning as shown in Fig. 3.
4. The bisector of the CME angle is drawn on the tablet, the MS segment is removed and transferred to the card. Connect points C, S and E with a smooth curve. Get the trajectory of the ship at the turn. The coordinates of points H and K are taken, data is obtained for turning (bearing and distance).
5. The duration of the turn is determined according to the table, which is usually available in the ship's documents.

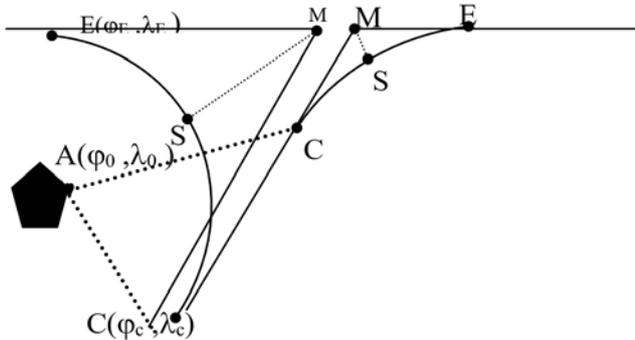


Figure 3. Plotting a turn using line segments on the map

6. The coordinates of the trajectory points are analytically calculated for certain segments, the known coordinates of the waypoint M and the coordinates of the turning point, as shown in Fig. 4, for turning at the entrance to the channel of the Yuzhny Port.

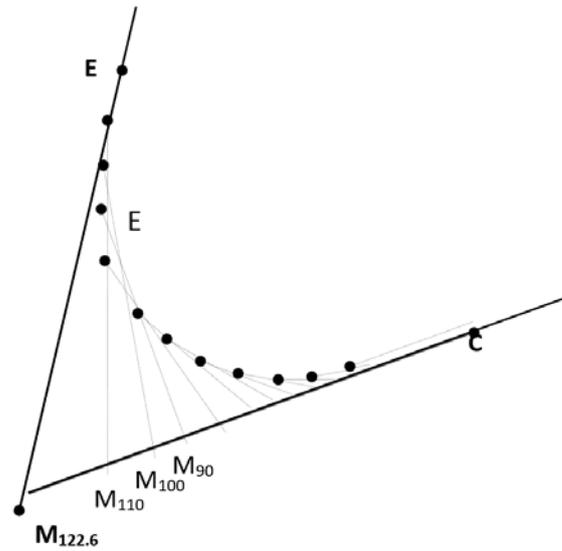


Figure 4. Construction of a curved by TP path graphically

When calculating the coordinates, the distance should be taken in miles, calculations are made to the fourth decimal place of a minute, and rounding to the third.

A detailed calculation is made in the following sequence for the selected vessel "MSC Canaberra".

1. Using the formulas (2, 3), we calculate the parameters of circulation in the cargo, give them in the form of Table 6 and convert them into miles after the corresponding calculations.

Table 6. Calculated circulation parameters

Rudder Parament Shift		Legend	Laden	In ballast
15°	Advance, cables	l1	3.32	3.19
	Direct displacement, cables	l2	2.11	2.02
	Tactical diameter, cables	D _T	4.73	4.53
	Constant diameter, cables	D _γ	4.86	4.53

We calculate the coefficients for the MC in cargo:

$$a = l_1 - \frac{D_T}{2} = 3.32 - 2.37 = 0.95 \text{ cables} = 0.095 \text{ miles}$$

$$b = \frac{D_T}{2} = 2.37 = 0.237 \text{ miles}$$

Coefficient for ME in laden
 $a = l_2 = 2.11 \text{ cables} = 0.211 \text{ miles}$

2. We calculate the segments for the angle of rotation $\theta = 122.6^\circ$, and after 10° within the limits of rotation according to the formulas:
 $MC = a + b \cdot \tan \frac{\theta}{2} = 0.095 + 0.237 \cdot \tan \frac{122.6}{2} = 0.528 \text{ miles}$

Table 7. Results of calculating turning segments

Angle of rotation	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	122,6°
MC, cables	1,373	1,600	1,833	2,078	2,339	2,622	2,936	3,290	3,7	4,189	4,792	5,808
ME, cables	0,227	0,458	0,697	0,946	1,212	1,501	1,821	2,182	2,6	3,099	3,713	4,749

Table 8. Results of calculation by segments of perpendiculars

Angle of rotation	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	122,6°
HP, cables	1,597	2,03	2,437	2,803	3,118	3,373	3,559	3,669	3,7	3,651	3,522	3,249
KP, cables	0,039	0,157	0,349	0,608	0,928	1,3	1,711	2,149	2,6	3,052	3,489	4,001

$$ME = l_2 + \tan \frac{\theta}{2} = 0.211 \cdot \tan \frac{122.6}{2} = 0.211 \cdot 1.827 = 0.386 \text{ miles}$$

The calculation results are summarized in Table 7.

We calculate the perpendiculars by the formulas $HP = HM + ME \cos \theta$ $KP = ME \sin \theta$ and summarize in table. 8.

3. We plot the circulation curve graphically in the following sequence, Fig. 4:

- On the map, using navigational tools, we build a waypoint M of intersection of the recommended courses, and determine its coordinates.
- From point M with segments MC and ME, from Table 7 for a rotation angle of 122.6°, on a scale we plot the points of the beginning and end of the rotation H₁₁ and K₁₁ and determine the coordinates of these points analytically by the coordinates of the waypoint and the direction of TC before and after the rotation.
- From point E we postpone the MC segment along the line of the original path and from its end we draw a line, at an angle of 10° at which we set aside the segment ME10 and obtain the trajectory point when turning by 10°. For analytical calculation according to the coordinates of the point H₁₁, the direction and size of the segments EM10° and M10°K10°, the coordinates of TP K10° are calculated according to the data in Table 7.
- Similarly, for all values of the turning angles from Table 7, we construct the trajectory points (TP) and obtain the planned path at the turn. If necessary, we connect the TP with the help of a template and get a turn plan.
- The results of calculating trajectory points using the "Rotate" program, given in work [7], is shown in Fig. 5.

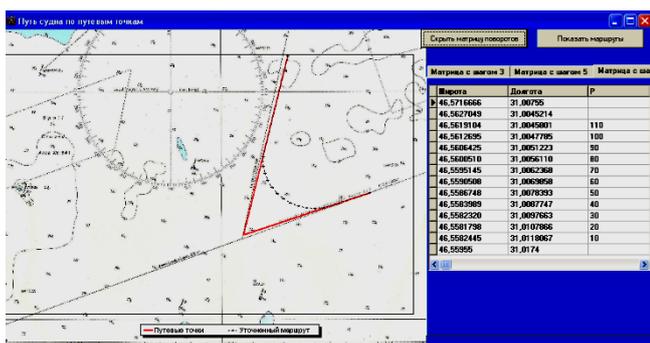


Figure 5. Turn when entering the port of Yuzhny TP in increments of 5°

In order not to perform graphic constructions every time when it becomes necessary to determine the point of the beginning and end of the rotation, it is advisable to perform all the described actions on the tablet once, for rotation angles through 5° or 10°, and the results are summarized in a table. When working with a programmable micro calculator, as well as taking into account the characteristics of turnability in automated systems, it is advisable, instead of using a tabular form, to program the calculations of all two necessary values of MC and ME which we denote by

the letter d according to the general approximating formula 10 [2, 9].

$$d = a + b \cdot \tan \frac{\theta}{2} \quad (10)$$

where a and b are the turnability coefficients; θ - angle of rotation.

The coefficients a and b included in formula (10) can be determined by the method of least squares, or more simply, and with sufficient accuracy for practical purposes of navigation, by the method of selected points. For this, the graphs of the dependence of d on θ are plotted from the table of segments. Two further spaced points are selected on the graph and the corresponding values of d and θ are written out.

Substituting these values into formula (10), a system of two linear equations with two unknowns a and b is obtained, from which they are determined. The values of the thus calculated segments are given in table. 9.

For an approximate calculation, you can use the following formulas:

$$\begin{cases} MC : a = l_1 - \frac{D_T}{2} & b = \frac{D_T}{2} \\ ME : a = 0 & b = l_2 \end{cases}$$

Taking into account all the above parameters, we determine the points of the beginning and end of the turn and bring this to Table 9.

Table 9. Elements of turns in the form of segments when maneuvering for anchoring in the roadstead of the port of Chornomorsk

WP	LAT	LON	C	θ	MC	ME
0	46°18,0' N	30°53,5' E				
1	46°17,2' N	30°52,0' E	233	56	2,7166907	1,9939104
2	46°18,5' N	30°46,5' E	289	23,3	1,8351734	1,2927493
3	46°18,0' N	30°44,0' E	265,7	61,6	1,379717	1,5677947
4	46°15,5' N	30°43,0' E	204,1	40,1	2,1030485	1,3685956
5	46°14,0' N	30°44,0' E	164			

C - Course

The next task is to calculate the coordinates of the rotation matrices every 10 degrees by the method of segments. To do this, it is necessary, according to the method described above, to determine for each section the beginning, end of the turn and TP with a step of 10 degrees. These data for each turning angle when anchored in the port of Chornomorsk are given in Tables 10-13. It should be emphasized that the calculation takes place for small sections of the path. Therefore, in order to increase accuracy, it is necessary to leave 10 decimal places.

Having received the data of the lines for each parcel, you can determine the geographic points in which they will be located. These calculations are best done in tabular form. To do this, it is necessary to initially find the difference in latitude (DLat) and the difference in longitude (DLon) between each point, using formulas (12) and (13).

Table 10. Rotation elements of angle of rotation 1 as line segments

Angle	10°	20°	30°	40°	50°	56°
MC	1,081958282	1,408883289	1,746053028	2,099410462	2,476012182	2,71669
ME	0,328082488	0,661226178	1,004809472	1,364888378	1,748653718	1,99391

Table 12. Rotation elements of angle of rotation 3 as line segments

Angle	10°	20°	30°	40°	50°	61,6°
MC	0,031844958	0,267266499	0,51006536	0,764521121	1,035715294	1,37972
ME	0,230095185	0,463739959	0,704706376	0,957241716	1,226389141	1,56779

Table 13. Rotation elements of angle of rotation 4 as line segments

Angle	10°	20°	30°	40,1°
MC	1,081958282	1,408883289	1,746053028	2,103048453
ME	0,328082488	0,661226178	1,004809472	1,368595571

Table 11. Rotation elements of angle of rotation 2 as line segments

Angle	10°	23,3°
MC	1,121244311	1,835173414
ME	0,54855392	1,292749344

$$DLat = MC \cdot \cos TC \quad (12)$$

where TC is the heading before the turn.

$$DLon = DMP \cdot \tan TC \quad (13)$$

The difference between the meridional parts can be determined by the formula (14).

$$DMP = 3437.75 \cdot \ln \left[\frac{\tan \left(45^\circ + \frac{\varphi_E}{2} \right)}{\tan \left(45^\circ + \frac{\varphi_C}{2} \right)} \right] \quad (14)$$

It must be remembered that for the calculation of the first section, it is the coordinate of the turning point. For each section of the turn, the data of the difference in latitude and longitude between each segment of the MC and ME were calculated. Having received the segments of the difference in latitude and the difference in longitude, using simple navigation formulas (15) and (16), we determine the coordinates of these points.

$$\varphi_C = \varphi_M + DLat \quad (15)$$

where φ_C is the latitude of the turning point.

$$\lambda_C = \lambda_M + DLon \quad (16)$$

where λ_M is the longitude of the turning point.

Thus, having determined its coordinates for each point of the turning section, it is possible to construct the rotation matrices, which are given in Tables 14-17.

The next task is to determine the matrices of straight sections. It should be noted that the matrix for the first segment will start from the zero point and end with the turn start point 1. The second straight segment matrix will start from the turn end point 1 calculated above. It will end as the starting point of the turn at WP 2. Subsequent matrices of straight

sections, except for the final one, will have the same construction principle. For the last leg, the straight matrix will start at turn end point 4 and end with waypoint 5.

Table 14. Matrix of trajectory point for turning angle 1

Mt1	φ_{c1}	46°17,29810' N	λ_{E1}	30°52,3879' E
	φ_{E11}	46°17,26745' N	λ_{E11}	30°52,3532' E
	φ_{E12}	46°17,23683' N	λ_{E12}	30°52,3528' E
	φ_{E13}	46°17,21277' N	λ_{E13}	30°52,2773' E
	φ_{E14}	46°17,20443' N	λ_{E14}	30°51,9039' E
	φ_{E15}	46°17,21461' N	λ_{E15}	30°51,8827' E
	φ_{E1}	46°17,23895' N	λ_{E1}	30°51,7195' E

Table 15. Matrix of trajectory point for turning angle 2

Mt2	φ_{C2}	46°18,46415' N	λ_{C2}	30°46,8146' E
	φ_{E21}	46°18,46738' N	λ_{E21}	30°46,5507' E
	φ_{E2}	46°18,44780' N	λ_{E2}	30°46,313' E

Table 16. Matrix of trajectory point for turning angle 3

Mt3	φ_{C3}	46°18,00621' N	λ_{C3}	30°44,0808' E
	φ_{E31}	46°17,98465' N	λ_{E31}	30°44,0734' E
	φ_{E32}	46°17,98112' N	λ_{E32}	30°44,0678' E
	φ_{E33}	46°17,98275' N	λ_{E33}	30°44,0207' E
	φ_{E34}	46°17,95989' N	λ_{E34}	30°43,7965' E
	φ_{E35}	46°17,94024' N	λ_{E35}	30°43,7916' E
	φ_{E3}	46°17,91413' N	λ_{E3}	30°43,7229' E

Table 17. Matrix of trajectory point for turning angle 4

Mt4	φ_{C4}	46°15,61518' N	λ_{C4}	30°43,04254' E
	φ_{E41}	46°15,60160' N	λ_{E41}	30°43,02962' E
	φ_{E42}	46°15,58431' N	λ_{E42}	30°43,01078' E
	φ_{E43}	46°15,43542' N	λ_{E43}	30°43,01337' E
	φ_{E4}	46°15,42106' N	λ_{E4}	30°43,03575' E

Well-known navigation formulas are used to construct matrices of straight-line segments. The formula for determining the difference in latitude will have a different form. The section MC for rectilinear matrices is replaced with a step κ , which for the first point is 2, for the next 4, and so on. The formula for calculating the DLat of a straight section is given below.

$$DLat = \kappa \cdot \cos TC \quad (17)$$

Calculations are carried out up to the point where the pivot starts.

Table 18. Straight leg matrix between waypoint 0 and turn start point 1

M ₀₁	φ ₀	46°18,0' N	λ ₀	30°53,5' E
	φ ₀₁	46°17,92778' N	λ ₀₁	30°53,3811' E
	φ ₀₂	46°17,85556' N	λ ₀₂	30°53,2622' E
	φ ₀₃	46°17,78335' N	λ ₀₃	30°53,1433' E
	φ ₀₄	46°17,71113' N	λ ₀₄	30°53,0244' E
	φ ₀₅	46°17,63891' N	λ ₀₅	30°52,9055' E
	φ ₀₆	46°17,56669' N	λ ₀₆	30°52,7867' E
	φ ₀₇	46°17,49448' N	λ ₀₇	30°52,6678' E
	φ ₀₈	46°17,42226' N	λ ₀₈	30°52,5489' E
	φ ₀₉	46°17,35004' N	λ ₀₉	30°52,43' E
	φ _{C1}	46°17,29810' N	λ _{C1}	30°52,3879' E

Table 19. Matrix of the straight segment between the end of turn 1 point and the start point of turn 2

M ₁₂	φ _{E1}	46°17,23895' N	λ _{E1}	30°51,7195' E
	φ ₁₁	46°17,27802' N	λ ₁₁	30°51,5631' E
	φ ₁₂	46°17,31709' N	λ ₁₂	30°51,4068' E
	φ ₁₃	46°17,35616' N	λ ₁₃	30°51,2504' E
	φ ₁₄	46°17,39522' N	λ ₁₄	30°51,094' E
	φ ₁₅	46°17,43429' N	λ ₁₅	30°50,9376' E
	φ ₁₆	46°17,47336' N	λ ₁₆	30°50,7812' E
	φ ₁₇	46°17,51243' N	λ ₁₇	30°50,6249' E
	φ ₁₈	46°17,55150' N	λ ₁₈	30°50,4685' E
	φ ₁₉	46°17,59056' N	λ ₁₉	30°50,3121' E
	φ ₁₁₀	46°17,52963' N	λ ₁₁₀	30°50,1557' E
	φ ₁₁₁	46°17,66870' N	λ ₁₁₁	30°49,9993' E
	φ ₁₁₂	46°17,70777' N	λ ₁₁₂	30°49,8429' E
	φ ₁₁₃	46°17,74684' N	λ ₁₁₃	30°49,6865' E
	φ ₁₁₄	46°17,78591' N	λ ₁₁₄	30°49,5301' E
	φ ₁₁₅	46°17,82497' N	λ ₁₁₅	30°49,3737' E
	φ ₁₁₆	46°17,86404' N	λ ₁₁₆	30°49,2173' E
	φ ₁₁₇	46°17,90311' N	λ ₁₁₇	30°49,0609' E
	φ ₁₁₈	46°17,94218' N	λ ₁₁₈	30°48,9045' E
	φ ₁₁₉	46°17,98125' N	λ ₁₁₉	30°48,7481' E
	φ ₁₂₀	46°18,02031' N	λ ₁₂₀	30°48,5917' E
	φ ₁₂₁	46°18,05938' N	λ ₁₂₁	30°48,4353' E
	φ ₁₂₂	46°18,09845' N	λ ₁₂₂	30°48,2789' E
	φ ₁₂₃	46°18,13752' N	λ ₁₂₃	30°48,1225' E
	φ ₁₂₄	46°18,17659' N	λ ₁₂₄	30°47,9661' E
	φ ₁₂₅	46°18,21566' N	λ ₁₂₅	30°47,8096' E
	φ ₁₂₆	46°18,25472' N	λ ₁₂₆	30°47,6532' E
	φ ₁₂₇	46°18,29379' N	λ ₁₂₇	30°47,4968' E
	φ ₁₂₈	46°18,33286' N	λ ₁₂₈	30°47,3404' E
	φ ₁₂₉	46°18,37193' N	λ ₁₂₉	30°47,1839' E
	φ ₁₃₀	46°18,41100' N	λ ₁₃₀	30°47,0275' E
	φ ₁₃₁	46°18,45006' N	λ ₁₃₁	30°46,8711' E
	φ _{C2}	46°18,46415' N	λ _{C2}	30°46,8147' E

Table 20. Matrix of the straight segment between the end of turn 2 point and the start point of turn 3

M ₂₃	φ _{E2}	46°18,44780' N	λ _{E2}	30°46,313' E
	φ ₂₁	46°18,43880' N	λ ₂₁	30°46,2675' E
	φ ₂₂	46°18,42980' N	λ ₂₂	30°46,2221' E
	φ ₂₃	46°18,42080' N	λ ₂₃	30°46,1766' E
	φ ₂₄	46°18,41181' N	λ ₂₄	30°46,1311' E
	φ ₂₅	46°18,40281' N	λ ₂₅	30°46,0856' E
	φ ₂₆	46°18,39381' N	λ ₂₆	30°46,0401' E
	φ ₂₇	46°18,38481' N	λ ₂₇	30°45,9946' E
	φ ₂₈	46°18,37582' N	λ ₂₈	30°45,9491' E
	φ ₂₉	46°18,36682' N	λ ₂₉	30°45,9037' E
	φ ₂₁₀	46°18,35782' N	λ ₂₁₀	30°45,8582' E
	φ ₂₁₁	46°18,34882' N	λ ₂₁₁	30°45,8127' E
	φ ₂₁₂	46°18,33983' N	λ ₂₁₂	30°45,7672' E
	φ ₂₁₃	46°18,33083' N	λ ₂₁₃	30°45,7217' E
	φ ₂₁₄	46°18,32183' N	λ ₂₁₄	30°45,6762' E
	φ ₂₁₅	46°18,31283' N	λ ₂₁₅	30°45,6308' E
	φ ₂₁₆	46°18,30384' N	λ ₂₁₆	30°45,5853' E
	φ ₂₁₇	46°18,29484' N	λ ₂₁₇	30°45,5398' E
	φ ₂₁₈	46°18,28584' N	λ ₂₁₈	30°45,4943' E
	φ ₂₁₉	46°18,26785' N	λ ₂₁₉	30°45,4033' E

φ ₂₂₀	46°18,25885' N	λ ₂₂₀	30°45,3579' E
φ ₂₂₁	46°18,24985' N	λ ₂₂₁	30°45,3124' E
φ ₂₂₂	46°18,24085' N	λ ₂₂₂	30°45,2669' E
φ ₂₂₃	46°18,23186' N	λ ₂₂₃	30°45,2214' E
φ ₂₂₄	46°18,22286' N	λ ₂₂₄	30°45,1759' E
φ ₂₂₅	46°18,21386' N	λ ₂₂₅	30°45,1304' E
φ ₂₂₆	46°18,20486' N	λ ₂₂₆	30°45,0850' E
φ ₂₂₇	46°18,19587' N	λ ₂₂₇	30°45,0395' E
φ ₂₂₈	46°18,18687' N	λ ₂₂₈	30°44,994' E
φ ₂₂₉	46°18,17787' N	λ ₂₂₉	30°44,9485' E
φ ₂₃₀	46°18,16887' N	λ ₂₃₀	30°44,9030' E
φ ₂₃₁	46°18,15988' N	λ ₂₃₁	30°44,8575' E
φ ₂₃₂	46°18,15088' N	λ ₂₃₂	30°44,8121' E
φ ₂₃₃	46°18,14188' N	λ ₂₃₃	30°44,7666' E
φ ₂₃₄	46°18,13289' N	λ ₂₃₄	30°44,7211' E
φ ₂₃₅	46°18,12389' N	λ ₂₃₅	30°44,6756' E
φ ₂₃₆	46°18,11489' N	λ ₂₃₆	30°44,6301' E
φ ₂₃₇	46°18,10589' N	λ ₂₃₇	30°44,5847' E
φ ₂₃₈	46°18,09690' N	λ ₂₃₈	30°44,5392' E
φ ₂₃₉	46°18,08790' N	λ ₂₃₉	30°44,4937' E
φ ₂₄₀	46°18,07890' N	λ ₂₄₀	30°44,4482' E
φ ₂₄₁	46°18,06990' N	λ ₂₄₁	30°44,4027' E
φ ₂₄₂	46°18,06091' N	λ ₂₄₂	30°44,3573' E
φ ₂₄₃	46°18,05191' N	λ ₂₄₃	30°44,3118' E
φ ₂₄₄	46°18,04291' N	λ ₂₄₄	30°44,2663' E
φ ₂₄₅	46°18,03391' N	λ ₂₄₅	30°44,2208' E
φ ₂₄₆	46°18,02492' N	λ ₂₄₆	30°44,1753' E
φ ₂₄₇	46°18,01592' N	λ ₂₄₇	30°44,1299' E
φ _{C3}	46°18,00621' N	λ _{C3}	30°44,0808' E

Table 21. Matrix of the straight segment between the end of turn 3 point and the start point of turn 4

M ₃₄	φ _{E3}	46°17,91413' N	λ _{E3}	30°43,7229' E
	φ ₃₁	46°17,80459' N	λ ₃₁	30°43,6905' E
	φ ₃₂	46°17,69505' N	λ ₃₂	30°43,6581' E
	φ ₃₃	46°17,58551' N	λ ₃₃	30°43,6256' E
	φ ₃₄	46°17,47597' N	λ ₃₄	30°43,5932' E
	φ ₃₅	46°17,36643' N	λ ₃₅	30°43,5608' E
	φ ₃₆	46°17,25689' N	λ ₃₆	30°43,5283' E
	φ ₃₇	46°17,14735' N	λ ₃₇	30°43,4959' E
	φ ₃₈	46°17,03781' N	λ ₃₈	30°43,4635' E
	φ ₃₉	46°16,92827' N	λ ₃₉	30°43,4311' E
	φ ₃₁₀	46°16,81873' N	λ ₃₁₀	30°43,3986' E
	φ ₃₁₁	46°16,70919' N	λ ₃₁₁	30°43,3662' E
	φ ₃₁₂	46°16,59965' N	λ ₃₁₂	30°43,3338' E
	φ ₃₁₃	46°16,49011' N	λ ₃₁₃	30°43,3014' E
	φ ₃₁₄	46°16,38057' N	λ ₃₁₄	30°43,2690' E
	φ ₃₁₅	46°16,27103' N	λ ₃₁₅	30°43,2365' E
	φ ₃₁₆	46°16,16149' N	λ ₃₁₆	30°43,2041' E
	φ ₃₁₇	46°16,05195' N	λ ₃₁₇	30°43,1717' E
	φ ₃₁₈	46°15,94241' N	λ ₃₁₈	30°43,1393' E
	φ ₃₁₉	46°15,83287' N	λ ₃₁₉	30°43,1069' E
	φ ₃₂₀	46°15,72333' N	λ ₃₂₀	30°43,0745' E
	φ _{K4}	46°15,61518' N	λ _{K4}	30°43,0425' E

Table 22. Straight leg matrix between turn end point 4 and waypoint 5

M ₄₅	φ _{E4}	46°15,42106' N	λ _{E4}	30°43,03575' E
	φ ₄₁	46°15,30571' N	λ ₄₁	30°43,1141' E
	φ ₄₂	46°15,19036' N	λ ₄₂	30°43,1924' E
	φ ₄₃	46°15,07501' N	λ ₄₃	30°43,2707' E
	φ ₄₄	46°14,95966' N	λ ₄₄	30°43,349' E
	φ ₄₅	46°14,84431' N	λ ₄₅	30°43,4273' E
	φ ₄₆	46°14,72895' N	λ ₄₆	30°43,5056' E
	φ ₄₇	46°14,61360' N	λ ₄₇	30°43,5839' E
	φ ₄₈	46°14,49825' N	λ ₄₈	30°43,6622' E
	φ ₄₉	46°14,38290' N	λ ₄₉	30°43,7405' E
	φ ₄₁₀	46°14,26755' N	λ ₄₁₀	30°43,8188' E
	φ ₄₁₁	46°14,15220' N	λ ₄₁₁	30°43,8971' E
	φ ₄₁₂	46°14,03685' N	λ ₄₁₂	30°43,9754' E
	φ ₅	46°14,00000' N	λ ₅	30°44,0004' E

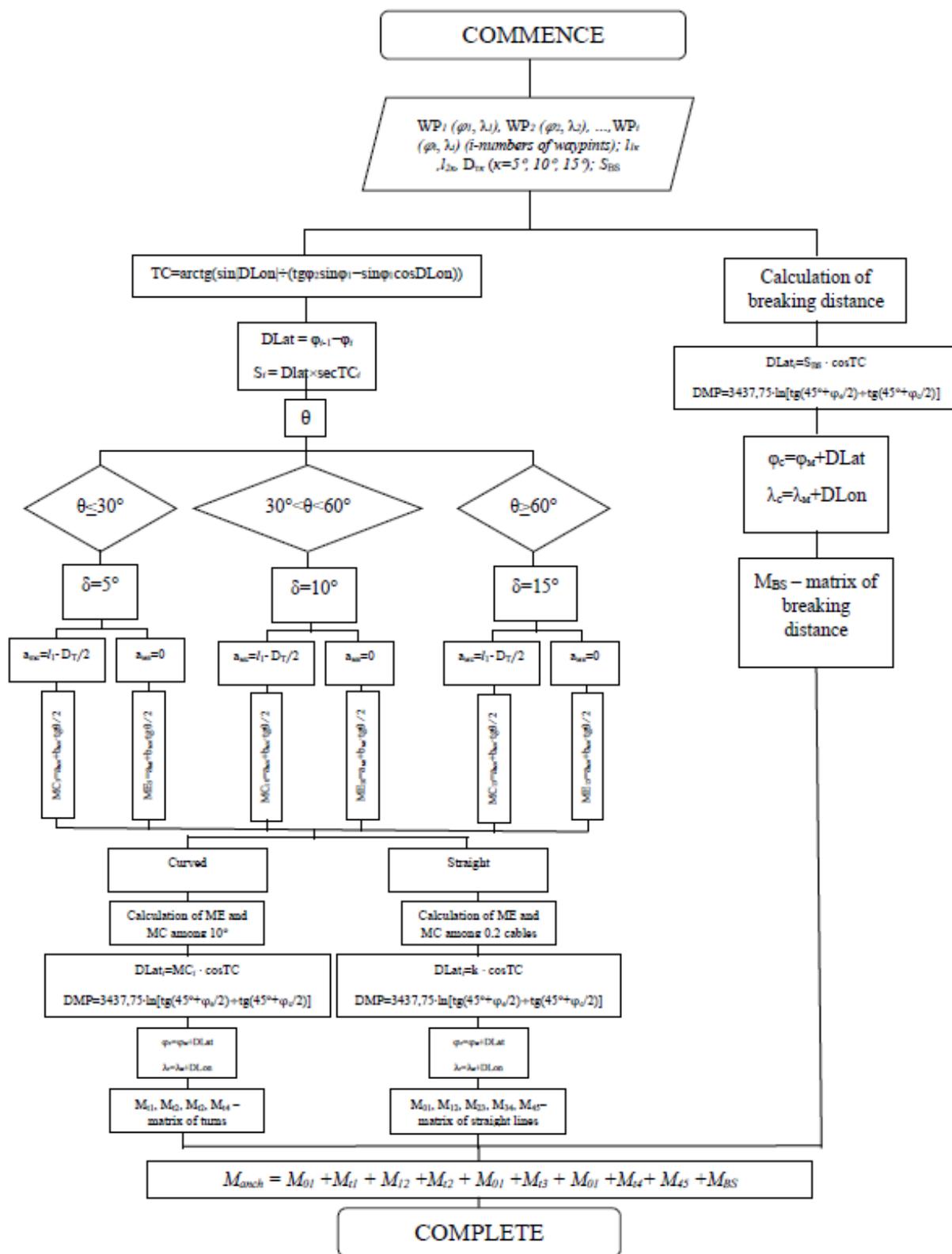


Figure 5. Block diagram of the automation of calculations of a given algorithm for the operation of the control system in the form of an algorithm for calculating the coordinates of the trajectory points of anchoring, presented in the form of coordinate matrices of straight and curved track sections

Having received the DLat and DLon points for each trajectory point with a step of 2 cables, it is not difficult to construct matrices of straight sections using the segment method, remembered that the course remains unchanged. The matrices of these areas for anchoring in the port of Chornomorsk are shown in Tables 18-22.

Thus, in the presence of only the coordinates of the waypoints taken from the electronic map, and the maneuvering characteristics of the vessel, given in electronic format, it is possible to determine the matrices of the vessel's track section. This will allow you to control the movement of the center of the vessel along the planned track line with an accuracy of 2 cables.

Having determined the matrix of the final straight-line section of the path, it is necessary to find the braking start point. Let us resort to the assumption that the entire segment of the way to the approach to anchor, the vessel was moving at an average forward speed (the HA (half ahead) speed for this vessel is 10.3 knots). According to the maneuvering characteristics of the vessel, the active braking distance for HA is 14.59 cables.

We start the calculation from the final fifth point. The distance from it to the turning point will be 14.59 cables. To do this, replace the MC segment with a number equal to the active braking segment and then calculate using the formulas as usual. The calculation results are shown in Table 23.

Table 23. Braking start point coordinates

M_{BS}	φ_{BS}	46°14,84149' N	λ_{BS}	30°43,42921' E
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The resulting calculations of the matrices of curvilinear and straight track sections, as well as the coordinates of the braking point can be displayed on the navigation map in the form of trajectory points and track lines, as shown in Fig. 1. This will increase the control over the movement of the center of gravity of the vessel relative to a given path.

Then the given algorithm for maneuvering control during anchoring Manoh can be represented as a sum of matrices of straight and curved track sections:

$$M_{anch} = M_{01} + M_{t1} + M_{t2} + M_{t3} + M_{t4} + M_{t5} + M_{t6} + M_{t7} + M_{t8} + M_{t9} + M_{t10} + M_{t11} + M_{t12} + M_{t13} + M_{t14} + M_{t15} + M_{t16} + M_{t17} + M_{t18} + M_{t19} + M_{t20} + M_{t21} + M_{t22} + M_{t23} + M_{t24} + M_{t25} + M_{t26} + M_{t27} + M_{t28} + M_{t29} + M_{t30} + M_{t31} + M_{t32} + M_{t33} + M_{t34} + M_{t35} + M_{t36} + M_{t37} + M_{t38} + M_{t39} + M_{t40} + M_{t41} + M_{t42} + M_{t43} + M_{t44} + M_{t45} + M_{BS} \quad (18)$$

5 CONCLUSIONS

The results of this calculation algorithm can be summarized in one flowchart for automating the calculations of a given algorithm for the functioning of the control system in the form of an algorithm for calculating the coordinates of the trajectory points of anchoring, presented in the form of coordinate matrices of straight and curved track sections, which is shown in Figure 6.

The developed navigation information and analytical complex "Planning the path trajectory using the waypoint matrices" contains modernized methods and techniques for creating a given algorithm for the operation of the ship control system and control over the process of moving along the trajectories, including curved and straight sections of the track when anchored. It automates the anchorage route planning process and controls safe maneuvering, including the use of motion control techniques using dynamic positioning.

The results of the developed navigation information-analytical complex can be used on unmanned ships, as well as on commercial and passenger ships during practical work, in order to accurately control the place of the vessel; in maritime educational institutions in the preparation of senior cadets for work on ships and in refresher courses.

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