

Global and Local Planning of Ship Route Using MATLAB and Simulink

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ABSTRACT: This article considers a new method of decomposing the ship route into global and local planning using MATLAB and Simulink developed by the authors. The authors propose to create a program code in MATLAB and operate it into Simulink. Wherein, the corrective coefficients were written in MATLAB. Such trajectories are constructed as a set of points, collected into the special matrix. In determining of the angle value of the rudder was used the ship's turning ability such as: high (HG), middle (MD) or low (LW) with regard to passage area. Moreover, in the article were analyzed and calculated the ship rudder effectiveness for Proportional-Integral-Derivative (PID) control. The paper is devoted to the problem of safety navigation. First of all is the task of planning the path: the trajectory of the vessel's movement in the local water area. The purpose of planning the vessel trajectory in the local water area is to ensure navigation safety due to marine traffic and environmental conditions. One of the tasks of the present work is controlling following a desired trajectory. The article notes affect of the vessel motion deviation into control process.

1 INTRODUCTION

Movement along a given trajectory is associated with the solution of the well-known problem of choosing the necessary speed and course of the vessel, taking into account vessel dynamic characteristics [21]. The ordinary task of controlling the movement of the vessel is stabilization on a given course. Keeping the vessel on a given trajectory is carried out by developing in one way or another amendments to a given course, which is supposed to be equal to the heading angle of the trajectory section, and stabilizing on this corrected course. At the same time, a sufficiently accurate knowledge of its model is necessary and the synthesis of a high-quality control system requires the task of parametric identification. Errors in a priori ideas about the model of vessel movement can significantly affect of the vessel motion deviation in the process of control. The accuracy of

such control may not be enough in conditions of high traffic intensity and/or restrictions of the water area. Even if the model of the vessel's movement is well identified on experiments, it's characteristics can change significantly during operation, because of change in the geometry of the hull, change in displacement, etc.

The development of the transport industry in the modern world is characterized by the intensification of the use of Maritime Autonomous Surface Ships (MASS) [9]. The desired route of this ship is usually expressed by the set of way points [6]. This method of explanation is extremely attractive because it is easy to save the route in the memory of the computer on board. Crossings can be marked and planned before or during the voyage, taking into account factors such as weather conditions, obstacle avoidance and path planning [6,15,16,19]. Each way point defined in

Cartesian coordinates (x_i, y_i) is used to create the desired path in the form of a series of straight line segments connecting pairs of consecutive path points. When the vessel reaches the indicated receiving circuit surrounding point i , the route moves to the next part of the line connecting intersections $i+1$. In a more advanced solution, the arcs of the circles connecting the segments to the road lines are identified around each point on the route and then used to determine the desired line at that time [10]. The fourth level of operation it is a fully autonomous ship. The fourth level of operation it is a fully autonomous ship and it involves managing control devices without human intervention [9]. Once the checkpoints have been established, it is recommended to monitor the way points from the sea as closely as possible, even in the presence of unknown environmental circumstances. The works [11,12] explained global and local planning of the trajectory of a ship as a control object. An important feature is the need to increase the capabilities of these vessels and expand the scope of tasks.

In an autonomous vessel, the controls are connected to the control device, which allows to increase the relevant control criteria: centralization, reliability and control capacity [17]. Centralization of control is characterized by the number of control devices using controls. Reliability of management is characterized by the probability of loss of control. The control capacity is characterized by the simplicity of the control algorithm. Centralization of the control of an autonomous vessel is more effective than centralizing the control of a non-autonomous vessel, because an autonomous vessel uses a controlled device that has a direct connection to all controls. The reliability of controlling the electronic control device is more confident than the reliability of manned control, because it depends only on possible programming errors and does not depend on the emotional component, especially when duplicating the control device. The control capacity of the control device of an autonomous vessel is greater than the capacity of non-autonomous control, because the autonomous control algorithm is expressed in the form of mathematical models and does not depend on subjective perception, and the decision is determined objectively for mathematical calculations.

Definitions for this article mentioned below [11,12]:

- path matrix (PM) – an incident matrix that represents the relationship between the vertices of the ship's path [11];
- route matrix (RM) is a matrix consisting of a series of geographic coordinates, coordinates are taken from the database of the control device;
- scenario is a coincidence of certain conditions, under the fulfillment of which actions occur at a set time that lead to a change in the route matrix or movement of the vessel in real time, with the exception of actions of deceleration or acceleration, which do not affect the route of the vessel; at the same time, these scenarios are executed in accordance with the International Rules for the Prevention of Collisions of Ships at Sea [2] and other mandatory international and state regulations, as well as taking into account meteorological data;

- set time is the minimum time before a probable event to determine the scenario and make a decision in a non-emergency mode, changing the global planning task;
- scenario matrix (SM) – a matrix that represents the relationship between the points (vertices) of the ship's route and the corresponding scenarios;
- pilot-operator – a person who remotely downloads input data to the control device using a computer or telephone, which affects the route or movement of the vessel;
- the vessel, from the point of view of the theory of ship's control and automation, is the object of control;
- from the point of view of hydrodynamics, the vessel is a body whose behaviour depends on the landing, stability, measurements, displacement, hydrodynamic coefficients, external factors, stable position, characteristics of engines, thruster devices and other data;
- control device – a device connected to the Internet, programmed into a microcontroller, which can be a computer, smartphone, regulator or navigation robot;
- immediate/emergency scenario is a scenario of emergency active braking with the possibility of changing the direction of movement of the vessel, initiated through a supervising device or pilot-operator, or shipowner, performed in emergency mode, stopping the implementation of the global planning task;
- segment [22] and sector [18] methods are methods that are combined for the construction of turns;
- segment MH is a segment, which comes from wheel over point H to turn vertex M;
- segment MK is a segment, which comes from vertex M to course stabilisation point K.
- alteration course scenario is a scenario, that determined in local planning, not in global planning, as additional arc into the route to avoid some danger.

The purpose of this study is fully implementation global and local planning [11,12] and simulation route passing only with the help of the MATLAB and Simulink environments. It can be used in ports, inland waters and in open waters, which will significantly reduce the cost of water navigation, while increasing its safety, eliminating human errors in the management of the vessel.

MATLAB and Simulink environments are flexible enough for motion simulation tasks and have the necessary tools of built-in functions. These programming environments have more similarities with C++, JAVA and C# than MS Excel, which in the future will facilitate the integration of development into modern electronic systems.

There are a lot of similar functions in MATLAB, C++, JAVA and C# environments and this circumstance has the main role in choice the MATLAB and Simulink environments.

Research tasks:

6. Explain the basic control concept of the proposed autonomous control method;
7. Construct the trajectory of the vessel in global and local planning using only MATLAB environment, analyze the features of trajectory changes in

accordance with the scenarios, conditions and parameters of the vessel;

8. Analyze the features of computer modeling of the hydrodynamics of the vessel;
9. Construction of the path control model for the vessel B-481 in the Simulink environment to keep it on local planning trajectory.

2 BASIC CONTROL CONCEPT AND THE ESSENCE OF THE PROPOSED METHOD OF AUTONOMOUS CONTROL OF VESSELS

Basic control concept of the proposed method is to create such interaction between control device, control sources and vessel, that will eliminate the risks of collisions with other objects or grounding and give opportunities to execute ordinary and critical operations using simple algorithm in accordance to the environment conditions in unmanned mode or almost unmanned mode.

SP1 is a subprogram that creates global planning tasks for SP2 and gives basic information about external circumstances to SP2.

SP2 is a subprogram that creates a smooth trajectory in local planning based on global planning tasks.

SP3 is a subprogram that responses for keeping vessel on local planning trajectory.

The essence of the proposed method of autonomous control of vessels according to the use of a control device equipped with a ship's route planning algorithm and a database, remotely observed or operated by the pilot-operator, using sensors, including position and Global Positioning System (GPS), lies in the fact that: a control device equipped with a microcontroller and subprograms SP1, SP2 and SP3 connected back to:

- an array of sensors and devices monitoring the ship and its surroundings, whose vision systems are arranged on board such that the distances between them are less than or equal to the radii of the circles constituting the fields of view of these systems and are placed on a rotating manipulator in a configuration such that at least two of them are on the bow of the ship, at least two in the stern of the ship and at least one on each side of the ship;
- the engine unit;
- database;
- steering gear through the SP1 subprogram and on the basis of information obtained from the database;
- processes, generates and samples the ship's route from the starting point A1 to the end point B into shorter sections, and the geographical coordinates of the separated points are stored in the form of a matrix, and then
- determines the safe initial speed of the vessel and forms of the path matrix and analyzes the information from the team sensors and devices monitoring the ship and its surroundings and creates a scenario matrix (SM), of which at least one predefined scenario is selected by the pilot-operator or the operator or is automatically loaded

by the subprogram SP1 for a given route from the database, after which

- on the basis of the scenario matrix (SM) modifies the original path matrix (PM) and creates a processed route matrix (RM) containing geographical coordinates and sends it to the subprogram SP2 of the control device,
- at the same time, the control device using the subprogram SP1 determines the turning ability of the ship (TA), creates matrix of a rudder shift selection MRSS (Table 1) and sends it to the subprogram SP2, analyzing hazards and determines a safe speed of the vessel and initial turning mode parameters for the subprogram SP3;
- the control device through the subprogram SP2 generates a local planning (LP) matrix and sends the local planning route matrix to the subprogram SP3, which then converts the information from the subprogram SP1 and SP2 into outgoing signals and sends them to the steering machine and engine unit.

Main advantages of the method:

- the control device is connected back to the autopilot and to the steering gear;
- the control device through the SP2 subprogram generates (LP) local planning trajectory and transmits it to the SP3 subprogram, which then processes the information from the SP1 and SP2 subprograms, creates signals and sends them to the engine assembly and to the autopilot system;
- the control device receives information from the steering gear, autopilot system or engine unit of the failure of any of these components. It generates through the subprogram SP3 an emergency scenario or function slowing down the proceeding of the ship;
- the control device receiving information from a set of sensors and devices monitoring the ship and its surroundings, about the detection of a dangerous object and/or the threat of collision and/or change of depth and/or change of weather conditions, or damage to one of the sensors or devices belonging to the sensor assembly and devices monitoring the ship and its surroundings, generates through the SP3 subprogram an emergency scenario or function that slows down the movement of the ship;
- the control device receiving information from the pilot-operator or the operator through the SP3 subprogram, triggers an emergency scenario or slows down the movement of the ship or accelerates its speed, regardless of the processes and scenarios previously planned by this device;
- when the control device through the SP1 subprogram determines passive braking scenario, it forms a diagonal matrix of the passive braking scenario S1, for example, at point A3 of the ship's route and adds the path matrix PM to it, creates a processed path matrix PM';
- when the control device through the SP1 subprogram determines active braking scenario, it forms a diagonal matrix of the active braking scenario S2, for example, at point A4 of the ship's route and adds the path matrix PM to it, creates a processed path matrix PM';
- the level of turning ability of the TA vessel is determined on the basis of the angular velocity of

the previous turn, or on the basis of weather data and sea currents at a given location;

- the control device, on the basis of information received from the sensor assembly and devices for monitoring the ship and its surroundings about the change in the actual path of the ship relative to the previously planned route, changes the initial manoeuvre ability level TA (turning ability) established to the manoeuvre ability level TA' with a higher rudder shift for the same turn.

It is also advantageous if, in the scenario matrix [11], the active braking and lateral movement scenario S4 of the ship occurs, for example, at point A3, the processed path matrix PM' has the same form as for the active braking scenario S2, whereby in the event of a stop of the ship and a lateral deviation from the specified braking point occurs, the control device sends to the thrusters control signals with the appropriate speed and direction of rotation.

It is also advantageous if, for example, in the scenario matrix SM, the skipping scenario (S3) or S_{An} (in local planning) of point occurs at point A3, using scenario matrix S_{A3}, and the passive braking scenario S1 occurs at point A4, the control device through the subprogram SP1 generates filtration matrices that corrects the path matrix due to the all executed scenarios.

It is also advantageous if, for example, during the generation of local planning trajectory sometimes it is necessary to carry out a course alteration to avoid danger (alteration course scenario), the control device through the SP2 subprogram calculates the route alteration consisting of:

- the wheel over point H, at which the rudder angle is adjusted in accordance with the assumed angle of turn Q;
- the end point of turn K;
- turning matrix between H and K.

Represented below on Figures 1,2 are two variants of the proposed autonomous ship control method. In the first variant, the Autopilot 5 used as control means by Control device 1. In the second variant the autopilot is part of SP3.

There are three subprograms of the control device: SP1, SP2 and SP3. Those subprograms take the roles of executive parts, which receive information and formulate decisions. Therefore, sensors give to the control device all important information about the ship's position, speed, course, depth, wind force and wind direction, and vessel traffic situation around the ship. Global feedback in both variants has packs of information, the first pack is about control meanings work and conditions is sent to SP3, and the second pack is information about ship movement and about her environment (weather, traffic situation) that is read by sensors and sent to SP1. Local feedback in both variants combines all information from the first and the second pack in one pack and sends to Autopilot (in the first variant) or to SP3 (in the second variant).

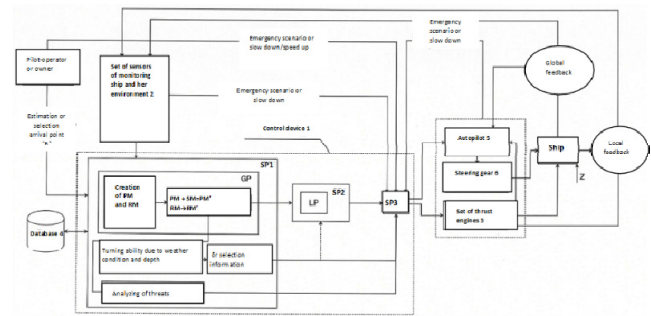


Figure 1. Autonomous ship control method (autopilot works separately)

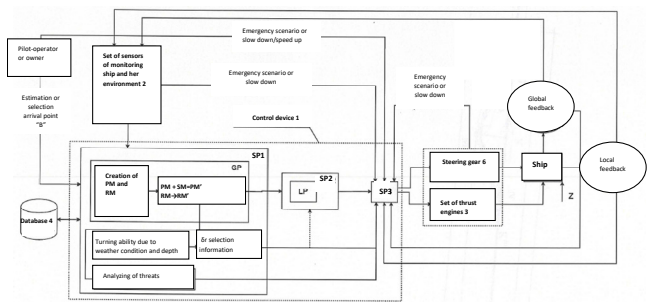


Figure 2. Autonomous ship control method (autopilot is part of SP3)

Thus, according to the Figures 1 and 2 immediate/emergency scenario (emergency braking scenario) can be received from tracking/traffic/environment control sensors (SP1 receives) or from condition control sensors of control means (SP3 receives). This is a scenario that is defined in time less than set time and stops the global planning task execution.

3 CONSTRUCT THE TRAJECTORY OF THE VESSEL IN GLOBAL AND LOCAL PLANNING USING ONLY MATLAB ENVIRONMENT

The construction of the trajectory based on researches [11,12], in these researches were explained how to use theory of graphs [11] to create the global planning task and how to construct a smooth trajectory in local planning using segment method [22] and sector method [18]. So, global planning scenarios connected to vertex, local planning trajectory has segment points (wheel over point and stabilisation point) and turning arcs, which are divided into sectors.

The main advantage of the MATLAB environment is empty value option: $Emp = []$, that is very useful as a filtration instrument, when 2/3 of turning points were calculated, it's time to stop the turning calculation using empty option.

In MATLAB environment was written code that can be used minimal for two degrees sector step up to 180° degrees turn, so it is programmed 60 points in each turn to calculate (maximum 120° is 2/3 of 180°), so empty value option works when the turn is less than 180°.

One of the advantages of this article is the demonstration of skipping scenario matrix of points

A2, A3 and A4. For global planning initial route matrix (RM) was taken as an example:

RM = [40.06616667, 40.10083333, 40.13533333,
40.14900000, 40.19416667; 26.31350000, 26.35316667,
26.38966667, 26.39283333, 26.38716667]

Therefore, when we calculated courses according to algorithm [13] for this example (Dardanelles (Canakkale) Strait) the first turn in initial local planning is 2.2262°, therefore on Figures 3-5 it was simplified to H1 and K1 and not visible.

The global planning trajectory is constructed as a set of five points, therefore there is no reason to skip more than one point. If we need to execute 2 scenarios braking and skipping, it will be summarized as: $S=S_{An}+abs(S2a_{n+i})$ or $S=S_{An}+S1p_{n+i}$, where $S1p$ is the scenario of passive braking (scenario 1 (S1) in global planning), where $S2a$ is the scenario of active braking (scenario 2 (S2) in global planning), S_{An} is skipping scenario (S3 in global planning), see scenario matrix in the article [11]. In addition to what was said in the article [11], we can say that the global planning scenario is a corrective/filtration matrix that changes the path matrix. Therefore, the formula for final path matrix mentioned in such way is:

$$PM' = PM + S \quad (1)$$

or $PM' = PM + S_{An} + abs(S2a_{n+i})$,
or $PM' = PM + S_{An} + S1p_{n+i}$,

where initial path matrix for 5-points route is:

PM = [0 1 0 0 0; -1 0 1 0 0; 0 -1 0 1 0; 0 0 -1 0 1;
0 0 0 -1 0]

As it was written in article [11] "1" is a link between vertex, which shows the directions from one vertex (on matrix row) to another vertex (on matrix column), "-1" means movement can be only in one direction, "0" means that there is no link between vertex.

Skipping scenario matrixes:

$$SA_2 = [0 -1 1 0 0; 1 0 -1 1 0; -1 1 0 -1 1; 0 0 1 0 -1;
0 0 -1 1 0] \quad (\text{skipping p.2}) \quad (2)$$

$$SA_3 = [0 0 0 0 0; 0 0 -1 1 0; 0 1 0 -1 1; 0 -1 1 0 -1;
0 0 0 1 0] \quad (\text{skipping p.3}) \quad (3)$$

$$SA_4 = [0 0 0 0 0; 0 0 0 0 0; 0 0 0 -1 1; 0 0 1 0 -1;
0 0 -1 1 0] \quad (\text{skipping p.4}) \quad (4)$$

In practice, there is no need to skip more than one point in the initial route with 5 points. If we need to combine the braking and skipping scenario, we should just summarize the skipping and braking matrix. In work [12] coordinates of local planning trajectory was calculated in MS Excel, longitude calculation of this work power (e/2) was simplified due to short distances in calculation, but now in MATLAB calculation was used classic formula for

calculation meridional parts (12). Also, a condition filter was added for turns less than 4 degrees, such turns were simplified to points H and K. Formulas for calculation segments [22]:

$$MH = \left(L_1 - \frac{D_T}{2} \right) + \frac{D_T}{2} \cdot \text{tg} \left(\frac{Q}{2} \right) \quad (5)$$

$$MK = L_2 \cdot \text{tg} \left(\frac{Q}{2} \right), \quad (6)$$

where L_1 is advance of turning circle, L_2 is transfer of turning circle for appropriate rudder angle, D_T is turning circle tactical diameter, Q is turning angle.

Formulas for turning circle manoeuvring parameters [3]:

$$L_1 = 6.41 \cdot \frac{\Phi}{\sqrt{\delta}} + 0.7 \cdot \text{trim} - 0.93 \quad (7)$$

$$L_2 = 5.84 \cdot \frac{\Phi}{\sqrt{\delta}} + 0.68 \cdot \text{trim} - 2.15 \quad (8)$$

$$D_T = 11.75 \cdot \frac{\Phi}{\sqrt{\delta}} + 1.35 \cdot \text{trim} - 3.9 \quad (9)$$

where Φ is rudder and hold factor, δ is rudder angle, trim taken in degrees. It is important to say, that δ is ordinarily different for calculation MH and MK of turn. MH is also a minimum safe distance to stop the vessel by vertex in such a way that it will be possible to turn and continue to execute the global planning task. Any other position for stop before point H is calculated from point H with regard to circumstances. Simulation was executed based on the parameters of vessel B-481 [7].

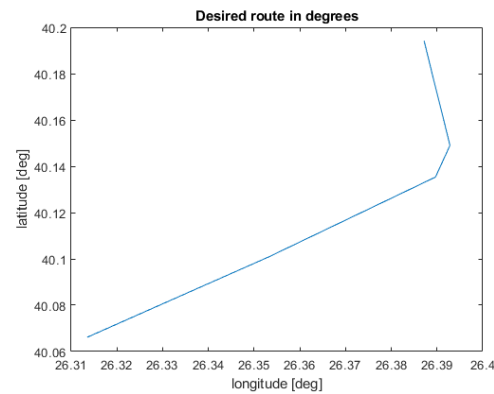


Figure 3. Initial ship route in WGS-84 geographical coordinate system

On figure 4 illustrated selected part of the passage plan on the electronic chart for show the realistic of the research.

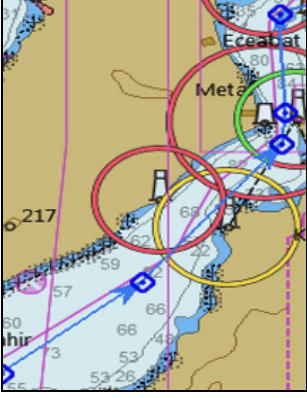


Figure 4. Initial ship route on OpenCPN Ver. 5.0.0. (Dardanelles passing)

Coefficient k_{dis} [12] replaced by coefficient k_{dt} , that determined according to the trajectory conditions: if $D_{on} \leq 3.5 \cdot LOA / 1852$ and the directions of $Turn_{n-1}$ and $Turn_n$ are same, $k_{dt} = 0.3$, if not $k_{dt} = 1$. When the distance between points $D_{on} < MK_{n-1} + MH_n$, it will be necessary to use additional filtration for these two turns by skipping points K_{n-1} , H_n and the first two points of the $Turning_n$ arc.

$$Lat_{(1,2)} = Lat_{(H,1)} + k_h \cdot k_{dt} \cdot k_{turn1} \cdot k_{turn2} \cdot k_{di} \cdot d_0 \cdot \cos(TC_{n+1} \cdot \pi / 180) / 60 \quad (10)$$

$$Lat_{(3,4,\dots,n)} = Lat_{(2,3,\dots,n)} + k_{turn1} \cdot k_{di} \cdot d_0 \cdot \cos(TC_{n+1} \cdot \pi / 180) / 60 \quad (11)$$

where TC_{n+1} is true course that is changing by the size of the sector step. Longitudes were calculated by the formula:

$$Long_{n+1} = Long_n - \left(\begin{array}{c} 7915.70447 \cdot \lg \left(\left(45 + \frac{Lat_n}{2} \right) \cdot \frac{\pi}{180} \right) \cdot \left(\frac{1 - e^{-\sin(Lat_n \cdot \frac{\pi}{180})}}{1 + e^{-\sin(Lat_n \cdot \frac{\pi}{180})}} \right)^{\frac{\delta}{2}} \\ 7915.70447 \cdot \lg \left(\left(45 + \frac{Lat_{n+1}}{2} \right) \cdot \frac{\pi}{180} \right) \cdot \left(\frac{1 - e^{-\sin(Lat_{n+1} \cdot \frac{\pi}{180})}}{1 + e^{-\sin(Lat_{n+1} \cdot \frac{\pi}{180})}} \right)^{\frac{\delta}{2}} \end{array} \right) \cdot \lg(TC_{n+1} \cdot \frac{\pi}{180}) / 60 \quad (12)$$

Derive the formula for converting coordinates in degrees to meters based on rhumb line distance calculation (partly in MATLAB format):

$$Lat_{meters} = Lat \cdot \left(\frac{\pi}{180} \right) \cdot b \quad (13)$$

$$\text{mod}_{Long} = \text{mod} \left(Long, \text{fix}(\min(Long)) \right) \quad (14)$$

$$Long_{meters} = \text{mod}_{long} \cdot \cos \left(Lat \cdot \frac{\pi}{180} \right) \cdot 60 \cdot 1852 + \min_{Long} \quad (15)$$

where

$$\min_{long} = \cos \left(\text{fix}(\min(Lat)) \cdot \frac{\pi}{180} \right) \cdot \left(\text{fix}(\min(Long)) \cdot \frac{\pi}{180} \right) \cdot a$$

Matlab function $\text{fix}()$ rounds down a module of value to integers and then returns an initial sign of this value, function $\text{fix}()$ in the west part of the Earth gives opportunities to calculate the maximum value of

longitude, for example: -5, then it will be determined by function $\text{mod}()$ the remainders, $\text{mod}(-5.6, -5) = -0.6$ & etc. The abbreviation mod_{Long} means remainders of longitude matrix division by the rounded down minimal integer value of longitude for this route, the abbreviation min_{Long} means distance in meters from Greenwich meridian to the rounded down minimal integer value of longitude for this route, which is calculated on rhumb line (not Cartesian scale). In MATLAB operator: $(*)$ - times matrixes; $(*)$ times values; and constant π is written as (pi); $a = 6378137$ meters (semi-major axis); $b = 6356752$ meters (semi-minor axis). Below you can see trajectory in global and local planning (Figures 5 and 6)

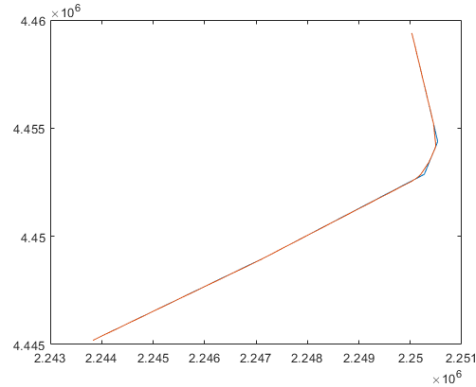


Figure 5. Initial ship route in metrical coordinate system: global and local planning (ordinary view)

On table 1 you can see the rudder shift matrix for different turning ability. Therefore, in accordance with table 1 execute calculation of MH, but δ for MK takes from another matrix:

$$Delta_{mk} = [1 \ 5 \ 10 \ 10 \ 10 \ 10 \ 15] \quad (16)$$

The calculation of MH and MK as it comes from formulas (5,6) depends also on the loading/ballast condition of the vessel.

As mentioned above (16), rudder shift for calculation MK changes not so frequently, because it will be rudder shift to another side for course stabilization and depends only on ship load condition and turning angle. This matrix (16) can be modified according to the calculated vessel (taking from practice). And So, in accordance with the researches of [11,12,13,18,22] trajectory was constructed using only the MATLAB environment.

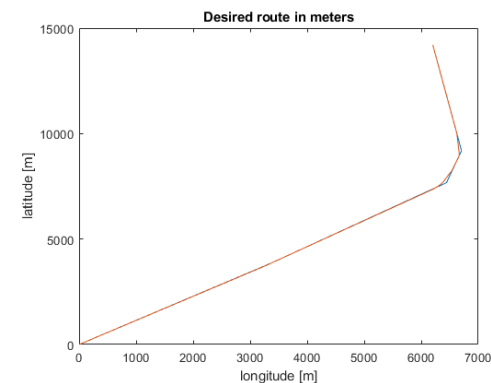


Figure 6. Initial ship route in metrical coordinate system: global and local planning (zero-point centered view)

On Figures 7,8 illustrated execution of the skipping scenario in point A2 and the braking scenario in point A4. So, it is $PM' = PM + SA_2 + S1p_4$, path matrix can be written as:

$$PM' = [0 \ 0 \ 1 \ 0 \ 0; 0 \ 0 \ 0 \ 1 \ 0; -1 \ 0 \ 0 \ 0 \ 1; 0 \ 0 \ 0 \ 1 \ 0; 0 \ 0 \ -1 \ 0 \ 0], \quad (17)$$

as result, the route matrix will be:

$$RM = [40.06616667, 40.13533333, 40.14900000; 26.31350000, 26.38966667, 26.39283333]$$

But for calculating wheel over point H2 in local planning (initial point of second turn) were also used the coordinates of the fifth point of the initial route matrix.

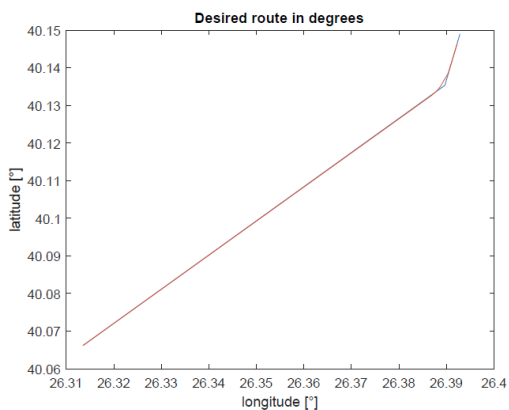


Figure 7. Braking scenario in point 4 + skipping scenario in point 2 without regard to shoreline (WGS-84 format)

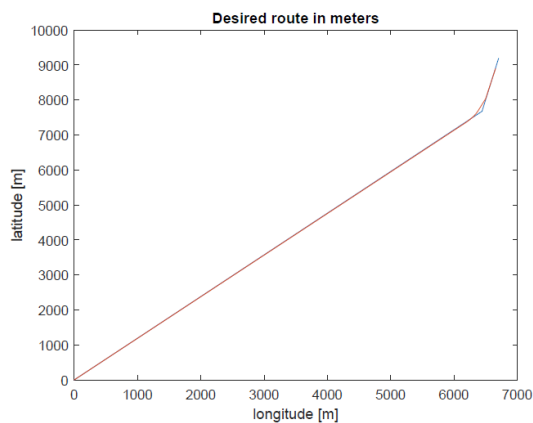


Figure 8. Braking scenario in point 4 + skipping scenario in point 2 (zero-point centered view)

On Figures 7,8 illustrated the execution of two scenarios: passive braking and skipping point, it shows that in MATLAB environment there is an opportunity to process two scenarios for one route in the same time.

Formula (18) explains the basic principle of calculation of initial length of arc between two points [12].

$$d_0 = D_T \cdot \pi / (\Delta\psi'), \quad (\text{in nautical miles}) \quad (18)$$

where $\Delta\psi$ - this is a step,

$\Delta\psi'$ - it's an attitude $360^\circ / \Delta\psi$

Table 1. Rudder angle shift selection table for trajectory construction calculations (MH calculation)

Turning ability	Angle of turn Q	Rudder angle δ
HG (high)	$0^\circ < Q_1 \leq 10^\circ$	$\delta_1 = 5^\circ$
	$20^\circ < Q_2 \leq 30^\circ$	$\delta_2 = 10^\circ$
	$30^\circ < Q_3 \leq 40^\circ$	$\delta_3 = 15^\circ$
	$40^\circ < Q_4 \leq 50^\circ$	$\delta_4 = 20^\circ$
	$50^\circ < Q_5 \leq 55^\circ$	$\delta_5 = 25^\circ$
	$55^\circ < Q_6 \leq 60^\circ$	$\delta_6 = 30^\circ$
	$60^\circ < Q_7$	$\delta_7 = 35^\circ$
MD (middle)	$0^\circ < Q_1 \leq 10^\circ$	$\delta_1 = 5^\circ$
	$10^\circ < Q_2 \leq 20^\circ$	$\delta_2 = 10^\circ$
	$20^\circ < Q_3 \leq 30^\circ$	$\delta_3 = 15^\circ$
	$30^\circ < Q_4 \leq 40^\circ$	$\delta_4 = 20^\circ$
	$40^\circ < Q_5 \leq 45^\circ$	$\delta_5 = 25^\circ$
	$45^\circ < Q_6 \leq 55^\circ$	$\delta_6 = 30^\circ$
	$55^\circ < Q_7$	$\delta_7 = 35^\circ$
LW (low)	$0^\circ < Q_1 \leq 5^\circ$	$\delta_1 = 5^\circ$
	$5^\circ < Q_2 \leq 10^\circ$	$\delta_2 = 10^\circ$
	$10^\circ < Q_3 \leq 20^\circ$	$\delta_3 = 15^\circ$
	$20^\circ < Q_4 \leq 30^\circ$	$\delta_4 = 20^\circ$
	$30^\circ < Q_5 \leq 40^\circ$	$\delta_5 = 25^\circ$
	$40^\circ < Q_6 \leq 45^\circ$	$\delta_6 = 30^\circ$
	$45^\circ < Q_7$	$\delta_7 = 35^\circ$

Figure 9 illustrates the turning set of points from H to K [12]. As mentioned in [14] the sector step is course step and changes at the same time. Thus, global and local planning trajectory construction and changes were executed based on scenario matrixes and path matrix. Route matrix changes were executed due to the logical basis (global planning) and due to the ship parameters and voyage conditions (local planning).

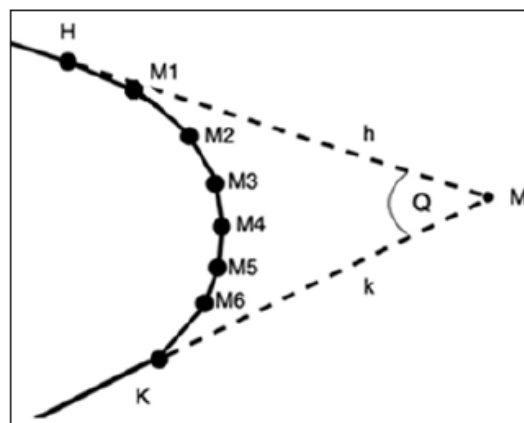


Figure 9. Construction of a turn trajectory [12]

Point calculation of turning matrix executed in such way: first of all, need to calculate points to 2/3 arc of the turn (Fig. 9), then it directed to point K, for this purpose adopted turn step in turning matrix, and using MATLAB function $length(unique(Turning_i))$, turning matrixes are correlated by coefficients 1/3 (starboard side turn, calculation oriented on next course) and 2/3 (port side turn, calculation oriented on previous course), such coefficients come from ordinary practice, when turn executed on 2/3 of course difference, the rudder position starts change to another side, to midships (Bring rudder angle to 0 degrees) and then rudder angle changes the sign; if turn is less than 4 degrees, the trajectory of turn is

simplified to point H and point K of the turn. The next paragraph explains the basic principles of ship hydrodynamics linearization, which is necessary for ship path simulation.

4 ANALYZING THE FEATURES OF COMPUTER MODELING OF THE MODEL OF VESSEL

4.1 Kinematics

In kinematics, only the geometric aspect of motion is considered. Kinematic relationships are established only between different types of coordinate systems [20]. To describe the ship motion in three degrees of freedom, two reference frames are used in simplified versions limited to two dimensions: the fixed coordinate system (X_N, Y_N) associated with the water map, and the reference frame (X_B, Y_B) attached to the moving ship (Figure 10).

The state variables describing the ship motion are collected in two vectors $\eta = [x, y, \psi]^T$ and $v = [u, v, r]^T$, where (x, y) are the ship position coordinates, ψ is the ship heading, (u, v) are the linear body-fixed velocities (surge, sway), and r is the yaw rate. The Earth-fixed velocity vector defined in the inertial frame (X_N, Y_N) is related to the body-fixed velocity vector determined in the reference frame (X_B, Y_B) through the following kinematic relationship [6],

$$\dot{\eta} = R(\psi)v \quad (19)$$

where $R(\psi)$ is the matrix of rotation around Z_N axis by angle ψ , calculated from the formula:

$$R(\psi) = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (20)$$

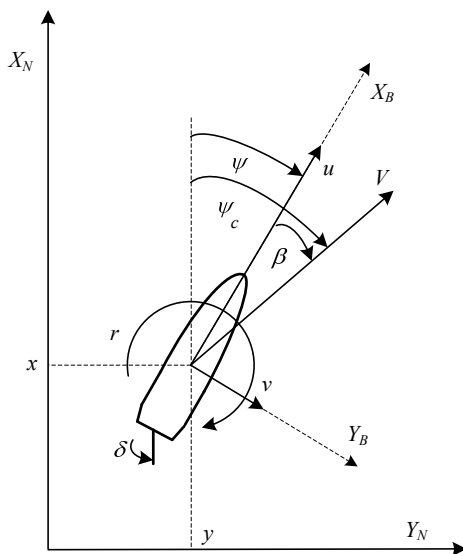


Figure 10. Reference frames, used to describe the motion of the ship

4.2 Hydrodynamics

When determining the mathematical model of ship dynamics, the following shall be considered: the hull of the ship as a moving rigid body immersed in a liquid and the forces of the liquid acting on that moving rigid body [20]. In hydrodynamics, it is generally accepted that hydrodynamic forces and moments acting on a rigid body can be linearly superimposed [4]. The τ_H vector is a superposition of several hydrodynamic interactions, which include the problems of energy dissipation on the waves produced by a ship moving on the surface of the water and the problem of diffraction of these waves. The forces and moments caused by propagating waves are the sum of three components [5]:

- added mass associated with the inertia of the surrounding fluid;
- potential attenuation associated with the dissipation of energy generated by waves on the surface of the water;
- restorative forces associated with Archimedes' law (weight and buoyancy).

Based on works [14,23] use following system:

$$\dot{V}_x = \ddot{x} = \frac{1.8T_v - X_H - X_R + m(1 - k_{22})V_y r + F_x}{m(1 + k_{11})} \quad (21)$$

$$\dot{V}_y = \ddot{y} = \frac{Y_H + Y_R + T_B + F_y}{m(1 + k_{22})} \quad (22)$$

$$\dot{r} = \ddot{\psi} = \frac{M_H + M_R + M_B + M_z}{Y_{zz}(1 + k_{66})} \quad (23)$$

where: V_x is the longitudinal component of ship speed, V_y is the transversal component of ship speed, r is yaw rate, T_v is propeller thrust, T_B is bow thrust, X_R is longitudinal component of rudder force, Y_R is transversal component of rudder force, steering forces, M_R is moment of rudder force, M_b is moment of bow thrust, X_H is longitudinal component of hydrodynamic force, Y_H is transversal component of hydrodynamic force, M_H is moment of hydrodynamic force, F_x, F_y, M_z are external forces and moments that act on the hull (wind and sea waves), \dot{V}_x, \dot{V}_y are longitudinal and transversal components of ship acceleration. Make linearization for simulation, write initial data: $V(t) \equiv V$ (for this rpm), $y(t) \equiv 0, \psi \equiv 0, r_0(t) \equiv 0, \delta \equiv 0$ (rudder angle), $F_x \equiv 0, F_y \equiv 0, M_z \equiv 0$.

Simulation was executed for ship model B-481. The most important parameters that were used for simulation research are in Table 2, which were used for calculating kinematics and hydrodynamics using formulas and parameters, mentioned above in the text.

Table 2. The main parameters of the ship B-481 for full loading [7]

No.	Variable	Unit	Description	Value
1.	L_{OA}	m	Overall length	181
2.	L_{PP}	m	Length between perpendiculars	165
3.	L_w	m	Length on water line	173.15
4.	B	m	Breadth	28.2
5.	T_d	m	Draft on the bow	9.64
6.	T_r	m	Stern draft	9.64
7.	T	m	Overage draft	9.64
8.	Q	-	Conductivity coefficient	0.626
9.	B_{md}	-	Fullness coefficient	0.965
10.	x_G	m	Longitudinal position of the center of gravity	-5.6
11.	K_1	-	Main propeller coeff.	-0.05
12.	K_2	m	Main propeller coeff.	4.5
13.	dH_{max}	1/s	Max increment of the propeller angle	0.08
14.	H_{max}	-	Max propeller angle	1.0
15.	n_{max}	rpm	Max speed rotation of main propeller	2.33
16.	dn_{max}	rps	Max increment of the speed rotation of prop.	0.1
17.	D	m	Propeller diameter	5.6
18.	T_{SG}	s	Time constant	4
19.	S_p	m ²	Rudder blade surface	23.5
20.	c	-	Rudder coefficient	0.74
21.	δ_{max}	deg	Max deflection of the rudder blade	35
22.	$\dot{\delta}_{max}$	deg/s	Maximum increment of rudder blade deflection	2.5

5 CONSTRUCTION OF THE PATH CONTROL MODEL FOR THE VESSEL B-481 IN THE SIMULINK ENVIRONMENT TO KEEP IT ON LOCAL PLANNING TRAJECTORY

Using control means managed by subprogram 3 of electronic control device (Figures 1 and 2). Determining ship trajectory control algorithms and their positioning on the basis of a mathematical model has become a common practice since the use of LQG (*Linear Quadratic Gaussian*) regulator and similar techniques based on the description in space of states that were introduced in the 1960s [20]. Successes with LQG regulators in autopilots and dynamic positioning systems, as well as the emergence of accurate positioning systems such as GPS, have resulted in increased interest in control systems along a given trajectory, consisting of sections connecting successive turning points. The process of analyzing ship steering systems along a given trajectory began in the early eighties of the last century [20]. Problem solutions were based on the classic autopilot mounted on board the ship, which was the heading regulator. Control cascade systems were created by adding an additional, external control loop, which, based on the known position of the ship, determined a given course for the internal loop in which the course regulator was located [1]. This method of control along a given trajectory is now commonly known as LOS (*Line-of-Sight*) [8]. The advantage of the LOS algorithm is that conventional autopilot systems with one degree of freedom can be used in the trajectory tracking algorithm. The nearest turning point to which the ship is going, together with its current position, is converted to a smooth set course of the vessel. In many cases, it is important to minimize the

lateral deviation of the ship from the set trajectory. Steering along a present trajectory means that lateral deviation from the set trajectory should be minimized. Further solutions of trajectory regulators involved the use of lateral deviation, which was the input value taken into account when determining the rudder shift angle. The problem of maneuvering control along a given trajectory is defined by two control objectives and two related tasks that need to be solved. The first of these is to reach and follow the given route, expressed in the stationary coordinate system associated with the water area map (geometric task). The second purpose of control are the requirements related to the speeds and accelerations of the ship's movement, expressed in the Cartesian coordinate system (X_B, Y_B), associated with the moving ship (dynamic task).

Depending on whether the vessel is moving at low or high speeds, different steering settings are used. All operations can be divided as ordinary and critical.

Ordinary operations:

1. proceeding from port to port in open sea;
2. lie down in a drift;
3. anchorage without excessive convergence to other vessels;

Critical operations:

1. proceeding in narrow channels or canals;
2. maneuvering in the port water area;
3. mooring to the berth, bank or other vessel;
4. anchorage with excessive convergence to other vessels;
5. bunkering in open sea;
6. maneuvering in shallow water;
7. tugging of the ship;
8. maneuvering in storm condition;

For the realization of those operations, it is necessary to create a useful model of ship path control system which will execute the scenarios of global and local planning. The control of the movement of the ship on the surface of the water is considered, the description of the movement of the ship has been limited to three degrees of freedom: in the longitudinal directions x , transverse y and angular rotation r . Assuming movement only in the horizontal plane, other values are negligible.

Simulation studies were carried out for the model of the control system shown in Fig. 13. The determination of the set trajectory was made in MATLAB with global and local path planning, while the entire model of the control system was made in Simulink in the system shown in Fig. 11.

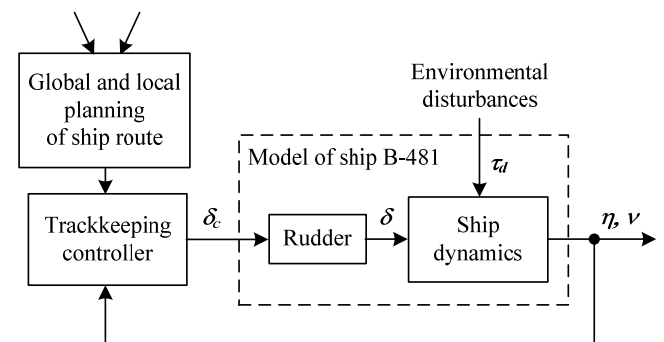


Figure 11. Block diagram of the control system model

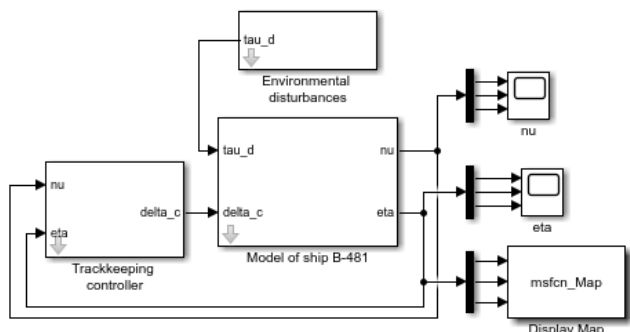


Figure 12. Block diagram of the control system modelled in Simulink

In this system, the controller was used to control along the given trajectory described in [21], whose parameters were manually selected for the model of the B-481 ship. As a result of all mentioned above, the path control model executes local planning trajectory based on hydrodynamic parameters of ship B-481 and regulator settings (Fig. 11). On figure 12 shown block diagram of the control system modelled in Simulink, which purpose is to execute the ship path control. Thus, scenarios will be global task scenarios which will be executed in local planning as trajectory construction and steering on the trajectory by proposed path control model, that can be used as part of subprogram 3.

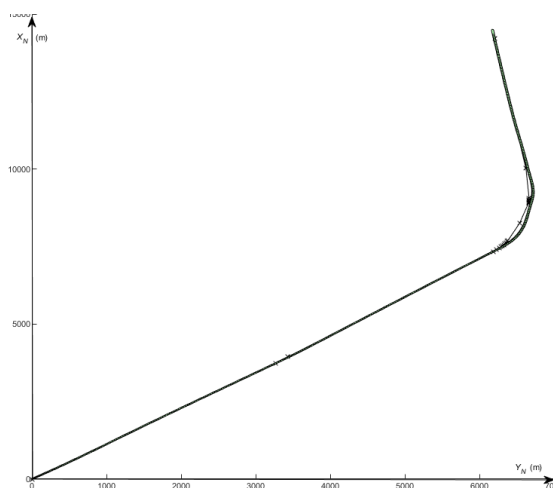


Figure 13. Ship trajectory analyzed in this article – simulation studies

6 CONCLUSIONS

1. Based on the explanation of the basic control concept of the proposed autonomous control method founded on the two parts: planning and execution. Figures 1 and 2 show the electronic control devices and their collaboration with control means. So, the main purpose of the electronic control device is to construct the trajectory in subprogram SP1 and SP2 and to control passage execution by subprogram SP3, that can contain autopilot as part of itself or send orders to autopilot as a result of information procession.
2. The construction of the trajectory of the vessel in global and local planning using only the MATLAB environment takes to account executed scenarios,

vessel condition, turning ability, value of turning angle, distance to next point, and direction of next turn. The rudder shift angles for MH and MK ordinary are different for the same turn, because the rudder shift for MK is shifted to another side.

3. The main features of computer modeling ship hydrodynamics are the calculation of ship conditions only in full load condition, in reality it can be another picture of trajectory, especially if the vessel has different trim/draughts.
4. Construction of the path control model for the vessel B-481 in the Simulink environment illustrated can be used as part of subprogram SP3 of the electronic device.

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