

Control System of Training Ship Keeping the Desired Path Consisting of Straight-lines and Circular Arcs

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ABSTRACT: Presented in this paper is a new, expanded approach to setting the planned route within restricted sea areas where there are permanent obstacles or other vessels, and then tracking it by the ship. In this project the desired path is represented using a combination of straight-lines and arcs. For this purpose a cascade control system of the ship motion has been designed. The task of the outer loop controller to prepare the reference signal is executed by the reference signal generator. The control of angular velocity takes place in an inner loop using IMC approach. Numerical simulation studies of control algorithms that have been developed for lake trials of the training ship are also carried out to demonstrate the effectiveness of the proposed tracking control system.

1 INTRODUCTION

The route of a ship is planned roughly from some starting point (x_0, y_0) to the terminal point (x_k, y_k) . It is usually specified in terms of so called way-points that are defined using Cartesian coordinates (x_i, y_i) for $i=1, \dots, k-1$ [8]. Usually the successive points of the planned route are joint by straight-lines, form a desired trajectory to be covered by the ship. In order to complete the journey along the planned route one may approach the problem in different ways: trajectory tracking and maneuvering control (Skjetne & Fossen 2002).

Sometimes during the journey the need arises to change a part of assumed path then some fragments of the trajectory require updating or further refinement. At such instance the exact trajectory tracking is not always justified. This is because it will result in such control of the ship, taking into account either the dynamic factor or the static factor only, that seeks to minimize the deviation $e(t)$ from the

designated path. This obviously leads to lengthening the route and increasing the cost of the ship control. Therefore, a much more flexible approach is to refrain from the trajectory tracking, if for some reason the ship was outside it, and to abandon the desire to return to its closest point, and instead to steer towards the nearest way-point. It involves the construction of such control system of the ship motion that could cover the planned route along its designated points, which can be reached either along a straight line or a curve of the designated radius. In this approach the way-points are part of the planned route but have a higher priority than the points situated in between, the ones complementing the aggregate of points of the assigned route.

The proposed method of trajectory planning together with system proper to control nonlinear processes provides maneuvers that the ship will be able to perform with minor deviations. This can be of great importance for optimizing the desired path especially in restricted sea areas. The paper is

organized as follows. In Chapter 2 is presented an overview of the proposed system. The subsection 2.1 includes the description of the plant that is a training ship "Blue Lady". 2.2 shows the most important assumptions of the new system, including a new method of creating a trajectory using straight-lines and arcs of a set turning radius connecting predetermined way-points. The control system of a ship moving along such trajectory, which must meet the requirements of quality in a wide range of operating conditions (changes in vessel speed, load condition) is described in subsection 2.3. The next part 3 contains the results of simulation trials. Determination of the planned route with the small time horizon and directing the ship along the trajectory designated in a new way has been tested by means of a computer simulation. The last section summarizes the results and also contains some suggestions regarding the use of this method of control in maritime transport.

2 SYSTEM OVERVIEW

It is assumed that the ship cannot get past the nodal points and has to track desired trajectory using forward thrust T for speed control and a single rudder to minimize the cross-track error. The desired path can be generated by specifying the desired route way-points. Each way-point is defined using Cartesian coordinates (Fig.5). For surface vessel only two coordinates (x_i, y_i) are used. The selected way-points are stored in a WP database and used for generation of trajectory or a path for the moving vessel to follow.

In this work were prepared some algorithms to control the ship motion along the desired path consisting of straight-lines and circular arcs. The structure of the considered system is presented in Figure 1.

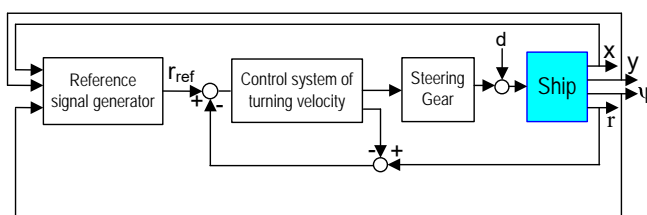


Figure 1. Schema of the control system of the ship motion.

It resembles a cascade control system in which the reference signal generator acts as a master controller. Thus there is an additional loop for the control of the turning rate whose function is keeping the desired angular speed of the ship. During the course maneuver changes the surge and sway velocity, heeling and drift angle, which have a very significant impact on the dynamic properties of the ship.

2.1 Description of the plant

The plant is a small training ship "Blue Lady", belonging to the Foundation for Safety Navigation and Environmental Protection in Hlawa that provides training for masters and merchant navy officers to

practice and progress their skills through trial manoeuvres in a safe environment. It has been inspected very carefully with reference to testing of the allocation system of the thrusters. The ship is made in 1:24 scale from the original model and floats on a small lake Silm, where the training center is located (Fig. 2).



Figure 2. Training ship "Blue Lady" on the Silm Lake.

Blue Lady is equipped with a set of thrusters with electric motors powered by rechargeable cells. It has a double control stand for traffic control which is located at the stern (Fig. 3.).

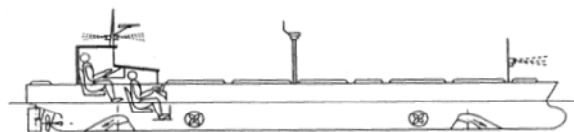


Figure 3. Longitudinal section of „Blue Lady“.

Table 1. The principal particulars of tanker and its model - the training ship [12]

		ship	model
Length overall	LOA [m]	330.65	13.75
Length	L _{pp} [m]	324.00	13.50
Breadth	[m]	47.00	2.38
Max Displacement	T [m]	20.60	0.86
Draught	Δ [T]	315 000	22.83
Maximum Speed	V [m/s]	7.82	1.59

The mathematical model of the object including all types of thrusters installed on it, such as tubular rudders, Voight-Schneider thrusters, was presented by Gierusz & Tomera (2006).

2.2 Reference Signal Generator (RSB)

In RSB is generated a reference signal for the turning rate. The objective of this device is to designate the desired course of the ship or a set turning radius. The block diagram of the set point device is presented in Figure 4. Control of the ship motion along the straight-lines and along the arc takes place through different channels, so it requires switching between them.

The signal of the set turning rate is determined automatically on the basis of the measured variables of the state vector such as course, surge and sway velocity, taking into account the parameters of a specified maneuver which have been calculated in Reference Signal Builder (RSB). The leading signal is a desired path that can be generated using a route management system. This route can be performed in a mode of fixed set course or using a line-of-sight (LOS) guidance technique (McGookin & Murray-Smith 2006). Certain parts of the roughly designed path may be planned entirely differently after enlargement.

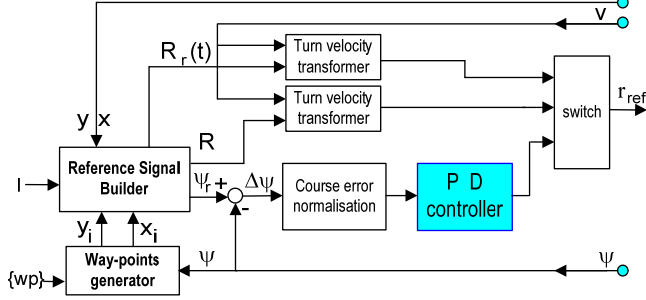


Figure 4. Block schema of Reference Signal Generator.

2.2.1 Path generation using straight-lines and circular arcs

After roughly planning a sea voyage it can be used to change, add or update in more detail new nodes. These adjustments may be introduced to regard to changing weather conditions for collision avoidance, or of the occurrence of deviations from this route or simply because of the need to provide details of the more precise maneuvers.

The operator on the basis of the electronic map, by guiding the cursor to the point, gives it higher priority among the points of representation of the planned route. Such a point, in contrast to the rough route way-points or 3D-Decision Support System for Navigators (Łebkowski, 2015) should not be omitted. Additionally, the operator defines the way of arriving at the next set point and selects the algorithm to determine the parameters of this maneuver. RSB on the basis of the data uploaded into the coordinate system of way-points pinned (i, x_i, y_i, f, s) (i -point number, x, y - the coordinates in Cartesian coordinates, f -flag-specifying the selected operating mode, s - sagitta) and the measured signals such as speed, the ship's course and previously declared constant values such as a route of overtaking which can differ for different maneuvers calculates the parameters of the planned maneuvers. On their basis the Ship Path Generator (SPG) displays a planned route on the background of the map of this body of water which allows the operator to assess if the given part of the route was planned well.

The proposed system of ship control in the sea journey is meant to operate in 4 working modes of steering:

- by a specified fixed course
- towards a specified point along the straight line
- towards a specified point along a specified arc
- along an arc with a limited turning radius with embarking onto a specified course

One of above non mentioned working modes is capable of ensuring the movement of the ship along an arc at a specified constant angular velocity. This maneuver with its advantages, was presented in (Kula 2016).

The course-keeping is usually situational in its character and often stems from the spontaneous pursuit of the visible object. However, if the ship deviates from the set route, for example due to the impact of the sea current, and maintains a specified course, then, before its correction comes into effect, the distance to be covered by the ship will be unnecessarily lengthened. Such a delay in the case presented above, the case of directing the ship to the next way-point, can be avoided when the ship's specified course towards the next way-point will be determined on an ongoing basis as a reference course ψ_{ref} varying depending on the position of the center of gravity of the vessel in relation to the next way-point.

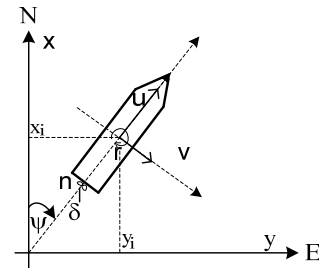


Figure 5. Cartesian coordinate system.

Let us assume that the center of gravity in a fixed coordinates system has the coordinates $G(x, y, z)$ and the offset from the next way-point is at the moment t in the meridian line $\Delta x_i(t) = x_i - x(t)$ and in the parallel line $\Delta y_i(t) = y_i - y(t)$. Then the reference course can be determined from the relationship:

$$\psi_{ref}(t) = \frac{180}{\pi} \cdot \arctg \frac{\Delta y_i}{\Delta x_i} + n \cdot 180 \quad [\text{deg}] \quad (1)$$

where:

- x, y - coordinates of the center of gravity of the ship
- x_{k+1}, y_{k+1} - specified coordinates for the successive turning point
- $n=0$ if $\Delta x_i > 0$ and $\Delta y_i > 0$,
- $n=1$ if $\Delta x_i < 0$,
- $n=2$ if $\Delta x_i > 0$ and $\Delta y_i < 0$

The third of these operating modes, that is the movement of the ship in an arc which is a fragment of a circle, requires a more detailed discussion. It can be an element of the roughly planned route of the ship, but it attains greater importance at the stage of refinement e.g. when planning the maneuver of avoiding permanent obstacles or avoiding a collision with other vessels (Lisowski & Lazarowska, 2013). Preparation for its implementation requires determination of

- the coordinates of the planned begin of the turn $wp_i(x_i, y_i)$ and the end point of the maneuver at the exit from an arc
- the course angle ψ_{i+2} on the next straight-line sector with wp_{i+1} on wp_{i+2} according to (6), taking into account that i increases by 1

– the angle α , that is half of the so-called central angle corresponding to the change of the course angle by $\Delta\psi$ from ψ_i into ψ_{i+2} and the selection of a flag f denoting the mode of moving between the setpoints (if $f=0$ the choice of straight line, $f=\pm 1$ the choice of circle arc, where the negative sign means the change of the direction of calculated rotation). Preparing a maneuver along an arc can be made at the pass from one straight-line sector to a next straight-line sector, to a turn of a different radius or of a different spin direction. Other kind of maneuver is a cross from a turn along an arc to a turn along a different arc.

The task of RSG is to determine the parameters of the selected maneuver and to draft, according to the results of calculations, a parameterized path which will lead to successive set point. The algorithm of determining the radius of the arc, along which the ship is to move from point wp_i and finishing in way-point wp_{i+1} stems from the relationships shown in Figure 6.

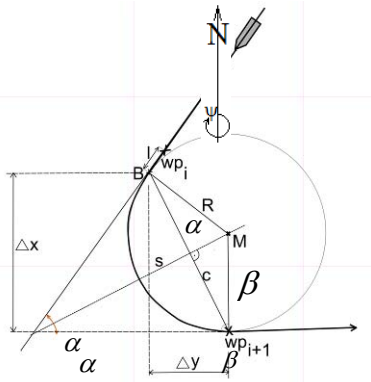


Figure 6. Turning along the set arc to fixed way-point. c -chord, s -sagitta, R -radius, M -middle of the circle, l -advance section

Assume that the turn is made by an angle of no more than 180 degrees. There is only one arc whose slope of tangents in points common to neighboring straight lines will coincide with the slope of these sections. The radius of this arc can be determined as follows:

$$R = 0.5c / \cos\alpha \quad (2)$$

where c means the chord, it's the length of a straight line joining the ends of a desired arc and can be developed from the equation

$$c = \sqrt{\Delta x^2 + \Delta y^2} \quad (3)$$

where:

$$\Delta x = (x_{i+1} - x_i)^2 \quad \Delta y = (y_{i+1} - y_i)^2$$

$x_i, y_i, x_{i+1}, y_{i+1}$ - coordinates of the begin wp_i and the end of the planned turn wp_{i+1} respectively

The angle α , that is half of the so-called central angle corresponding to the change of the course angle $\Delta\psi$ from ψ_i into ψ_{i+2} can be calculated from following equations:

$$\begin{cases} 2\alpha = 180^\circ + \psi_{i+2} - \psi_i \\ \alpha = 0.5 \cdot (\Delta\psi + 180^\circ) & \Delta\psi < 0 \\ \alpha = 0.5 \cdot \Delta\psi & \Delta\psi > 0 \end{cases} \quad (4)$$

If the course ψ_{i+2} leading the vessel to the way-point wp_{i+1} is not previously known then the angle α will be evaluated from following expressions

$$\beta = \psi_i - \psi_{i \rightarrow i+1} \quad \alpha = 90^\circ - \beta \quad (5)$$

where: $\psi_{i \rightarrow i+1}$ is the course angle from wp_i to wp_{i+1}

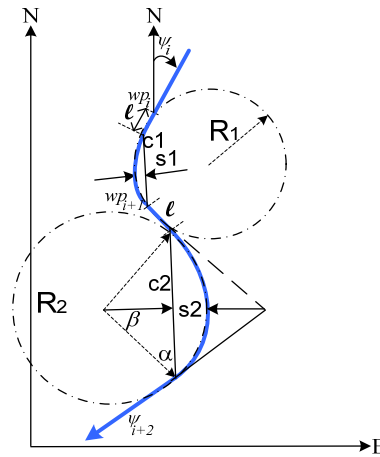


Figure 6. Turning along two arcs sequence

By determining the sequence of more slight turns it may be more convenient to give a sagitta s (Fig.6) Then the radius of the arc can be calculated from the expression:

$$R = s + 0.5c \cdot \tan\alpha \quad (6)$$

After the rudder is turned a ship does not immediately adopt a circular, due to the inertia related to the mass of the vessel. In order to increase the accuracy of path keeping it is necessary to define the point B constituting the beginning of the new maneuver, the rudder will be deflected by a set angle whereas the ship will start turning with its bow to the inside of the turn.

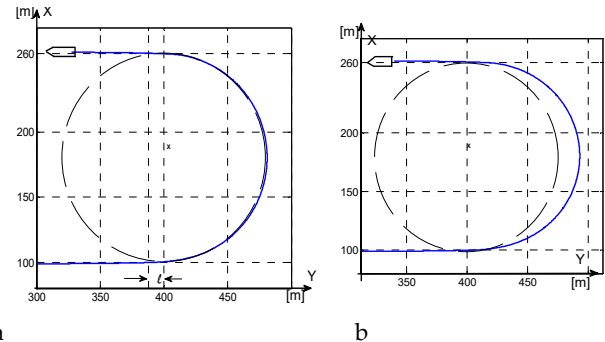


Figure 8. The route of the ship without (a) and with (b) a shift of the beginning of the maneuver.

When planning a maneuver, also along the desired arc, it should be noted that the command of rudder deflection must precede the way-point by a certain distance l . It depends on the inertia of the ship. The

control system estimates the length of this route ahead of the maneuver begin l based on the formula

$$l = u(t) \cdot T(u) \quad (7)$$

where T - the resultant time constant of the Nomoto model $T=T_1+T_2-T_3$ that depends on the ship velocity and rudder deflection.

The coordinates of the point of starting turn $B(x'_i, y'_i)$ that goes beyond the way-point wp_i can be estimated as

$$x'_i = x_i + l \cdot \cos \psi_i \quad y'_i = y_i + l \cdot \sin \psi_i \quad (8)$$

where: ψ_i – course to wp_i

In Figures 8a,b are illustrated two maneuvers of the ship that were planned from $wp_i(100,400)$ to $wp_{i+1}(260,400)$. During the first one, the command of the rudder was given when the ship reached wp_i and the other one by l meters earlier ($l=11.9$ m), that allowed the vessel in absence of disturbances to pass the planned trajectory along the arc of a circle with radius $R = 80$ m. The transition to the next way-point occurs when one of the following conditions is met

$$\psi(t) = \psi_{i+2} \pm 2^\circ \quad \text{or} \quad \sqrt{\Delta x^2 + \Delta y^2} < r_t \quad (9)$$

where r_t - the radius of the circle with center in wp_{i+1} representing acceptable deviation from route node

2.3 The control system of turning rate

Most of the autohelm systems are mainly formulated to follow a desired course under constant speed settings. This is due to the fact that every vessel is a highly nonlinear object and its dynamic varies with the change of the longitudinal velocity. Therefore we can use a control systems designed to control nonlinear objects, such as sliding mode control (SMC) (Faeng & Luo, 2007), predictive control (Velasco & Lopez 2000), fuzzy control (Yang & Ren, 2003). Although the proposed control system must perform the task of course-keeping and control of the ship motion along a predetermined arc, the basis for the execution of maneuvering, mentioned in the previous chapter is the control system of angular velocity, which uses the IMC structure (Morari & Zafiriou 1998). The advantages of IMC to control the motion of the ship have been presented in (Tzeng 1999, Kula 2015). The diagram of the control system is shown in Figure 6.

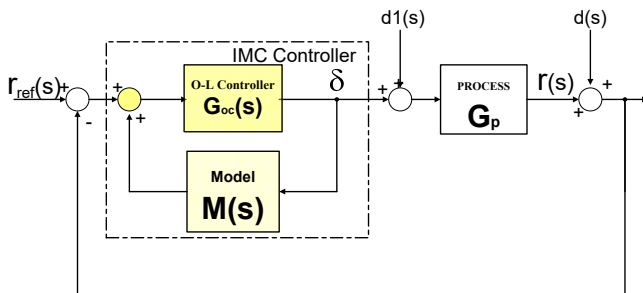


Figure 9. Structure of Internal Model Control IMC.

The starting point for the synthesis of this control system is to design a controller of ship angular velocity $G_{oc}(s)$ having to work in an open-loop system. Let us assume that the dynamics of the linearized object is presented in the form of transfer function $G_p(s)$. Then, the transfer function of an open-loop system can be expressed as:

$$\frac{r(s)}{r_{ref}(s)} = G_{oc}(s) \cdot G_p(s) \quad (10)$$

The controller which should ensure the perfect control in this system should have transfer function equal to the inverse of the object

$$G_{oc}(s) = \frac{1}{G_p(s)} = G_{inv}(s) \quad (11)$$

To make this controller feasible, the transfer function $G_{oc}(s)$ should be proper. For this reason, the transfer function of the object cannot contain zeros in the right plain and potential delays must be omitted in the inverse model. It is also necessary to add to the forming filter with the transfer function $F(s)$. Then it will have the following form

$$G_{oc}(s) = F(s) \cdot M_{inv}(s) \quad (12)$$

where

$M_{inv}(s)$ is inverse model of the process and $F(s)$ –the transfer function of the filter

$$F(s) = (T_f s + 1)^{-n} \quad (13)$$

n - integer number, can be obtained as a difference between the order of the numerator and the order of the denominator of the inverse model

Therefore if we managed to get compliance between the plant and the model, than according to (12) we could achieve in the system a set value with the speed, which can be shaped using the time constant of the transfer function of the filter T_f . In general IMC is an open-loop control system in which the input signal is corrected according to the difference between the response of the plant and the model

$$G(s) = \frac{r(s)}{r_{ref}(s)} = \frac{G_p(s)G_{oc}(s)}{1 - M(s)G_{oc}(s) + G_p(s)G_{oc}(s)} \quad (14)$$

It can be seen (14) that in the absence of uncertainties and plant modeling errors, the control system is working as a open-loop system. The error signal is able to adjust the setpoint in such a way that the value, adjustable in the steady state was equal to the desired value, even when the model differs from the object. The performance of the control system will depend on the accuracy of the model.

The signal of mistuning of the model and the object may be the result of influence of disturbances, model uncertainty or model incorrectness. It should be noted at this point that such approach as IMC cause that the arbitrary determination of the parameter T_f may limit the system's ability to use the

full power of actuators. However, it is extremely useful in implementation of the harmonious control of nonlinear systems.

2.3.1 Nonlinear model of the ship

The motion of a ship can be described by using six nonlinear differential equations. Hence, ship maneuvering is treated as a horizontal plane motion and only the surge, sway and yaw modes are considered.

The following approximations (Saari & Djemai 2012) are set up:

$$\begin{bmatrix} m & 0 & 0 \\ 0 & m & mx_G \\ 0 & mx_G & I_{zz} \end{bmatrix} \cdot \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ N \end{bmatrix} + \begin{bmatrix} m(vr + x_G r^2) \\ -mur \\ -mx_G ur \end{bmatrix} \quad (15)$$

$$\dot{\psi} = r$$

where m is the mass of the ship, I_{zz} is the inertia along the z axis, and x_G is the x co-ordinate of the center of gravity.

X , Y and N denote the hydrodynamic forces and the momentum. They result from the movement of the ship on the surface and depend on speed, weight and a profile of the hull and also on the effect of waves.

Based on (15) after linearization around a selected point of work and after elimination of the sway velocity we have a following simplified linear differential equation

$$\ddot{r}(t) + \left(\frac{1}{T_1} + \frac{1}{T_2}\right)\dot{r}(t) + \frac{1}{T_1 T_2} r = \frac{k}{T_1 T_2} \cdot [T_3 \dot{\delta}(t) + \delta(t)] \quad (16)$$

where time constants T_1 , T_2 , T_3 and gain k depend on derivatives of the hydrodynamic forces and momentums with respect to the sway and surge velocity and yaw rate r .

However, the change of longitudinal and lateral velocities during the maneuver leads to changes in the dynamics of the ship and thus increases the incorrectness of the linear model.

To prevent this, in the proposed control structure such a model was introduced which parameters depending on shaft velocity n and the rudder angle δ . This will ensure better quality of the model in a wider range of changes of the state variables of a system.

The equation (16) after rearranging to the new form

$$\ddot{r}(t) = \frac{k(n, \delta)}{T_1 T_2(n, \delta)} \cdot [T_3(n, \delta) \cdot \dot{\delta}(t) + \delta(t)] - \left(\frac{1}{T_1(n, \delta)} + \frac{1}{T_2(n, \delta)}\right)\dot{r}(t) - \frac{1}{T_1 T_2(n, \delta)} r \quad (17)$$

can be directly used to create a nonlinear model of the ship.

2.3.2 Nonlinear inverse model of the ship

IMC controller includes in its structure an inverse model of the plant. The greater is the accuracy of the model and the inverse model, the better control performance can be achieved in this system. For the purpose of steering of the ship it was prepared a linear and nonlinear training model. Both models have been created based on the Nomoto model (Nomoto 1981). Assuming constant speed of the ship, the transfer function of the model is equal to

$$M(s) = \frac{r(s)}{\delta(s)} = \frac{k(1+T_3s)}{(T_1s+1)(T_2s+1)} \quad (18)$$

Rearranging (19) it takes the form

$$M(s) = \frac{kT_3s/T_1T_2 + k/T_1T_2}{s^2 + s(T_1+T_2)/T_1T_2 + 1/T_1T_2} = \frac{b_1s+b_0}{s^2 + a_1s + a_0} \quad (19)$$

Determination of the parameters of the transfer function enables to predict of response of the ship to deflection of the ship rudder at a constant speed. Then the transfer function of the controller of the open-loop system (12) using a filter (13) of the first order ($n=1$) will be equal

$$G_{oc}(s) = \frac{(T_1s+1)(T_2s+1)}{k(1+T_3s)(T_1s+1)} \quad (21)$$

The use of a linear model for the control of nonlinear plant is acceptable, however, to improve the quality of the control it could be included a nonlinear model in the structure of the IMC controller, causing the better reflection of the behavior of the actual controlled object than a simple linear model. The use of such models of the ship have been presented in (Kula 2015).

A simplified nonlinear model of the training ship "Blue Lady" was constructed on the basis of the transfer function model but its parameters, i.e. the steady state gain k and time constants T_1 , T_2 , T_3 are dependent on the deflection of the rudder and indirect of the ship velocity.

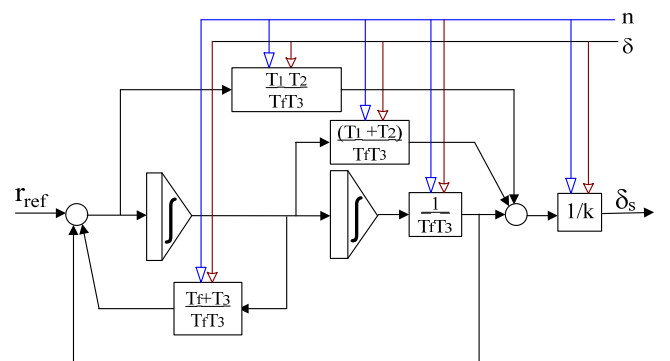


Figure 10. Schema of nonlinear inverse model of the plant.

The simplified ship model was created for only one full loading condition. The block diagram of the inverse model is shown in Figure 9. In a similar way an inverse model is constructed, except that it has been additionally extended by taking into account the zeros in feedforward.. Step responses of the plant and

model $r(t) = f(\delta, n)$ for different values of rudder angle and propeller rotation are presented in Figures 11,12.

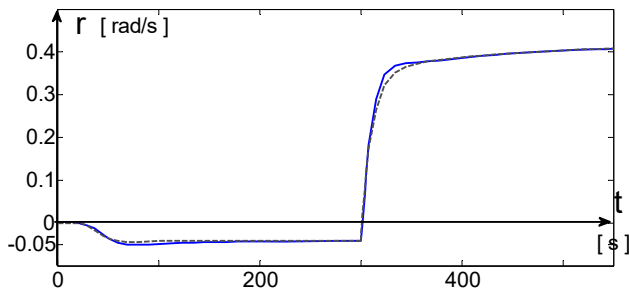


Figure 11. Step responses of ship and model, $\delta=12^\circ, n=240$

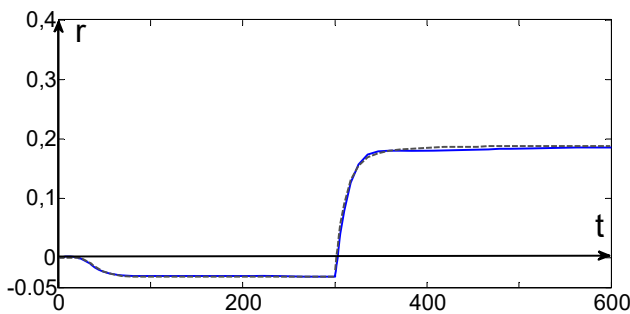


Figure 12. Step responses of ship and model, $\delta=8^\circ, n=180$ —ship, ----model

The nonlinear functions $T_1=f_1(\delta, n)$, $T_2=f_2(\delta, n)$, $T_3=f_3(\delta, n)$, $k=f_4(\delta, n)$ are prepared in form of low order polynomial of rudder angle. The coefficients of this polynomial are calculated using the LS Method.

3 SIMULATION RESULTS

The test of presented control system of the ship motion was performed in two stages. In the first step, we have defined in a proposed form a desired route which the training ship was supposed to sail on the Lake Silm. Two variants of the route have been tested using Matlab/Simulink/C++. For the simulation we assumed that the ship was fully loaded and for control used only main rudder. The specified propeller revolution n was equal to 200 rpm.

3.1 Example 1

The ship from the starting point $wp_0(380,160)$ was going with the course $\psi=170^\circ$ and after 400 s it changed the course in the LOS mode with the average value $\psi_1=143^\circ$ to way-point $wp_1(90,320)$. It was adopted radius tolerance $r_t=2$ m, so reaching wp_1 ended at the point $(92,318.2)$.

In the point B that is located from a way-point at a distance l starts the path-keeping along the arc which radius is up to date calculating on the basis of (2). In this phase until the ship adopts a circular motion in predetermined direction the reaction of the rudder deflection is poor. For first moment at the beginning of the turn because $\Delta x=39.6$, $\Delta y=110.6$ m, $\psi_{1 \rightarrow 2}=70.3^\circ$, $\beta=72.7^\circ$, $\alpha=17.3^\circ$ and $c=117.5$ m the radius will be

equal to 61.5 m. After reaching the way-point $wp_2(130,430)$, the turning radius will be changed to fixed value equal to 90 m. The way that the ship traveled during this maneuver and the heading, is plotted in Figure 13 on the contour of the lake, where the training of navigators takes place.

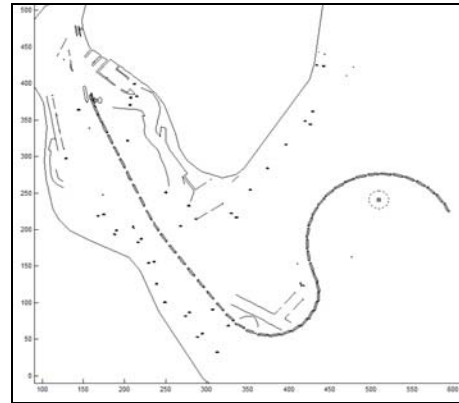


Figure 13. The position and heading trace of the ship maneuver.

Other time histories of surge velocity, drift and rudder angle measured during the test are presented in Figure 14.

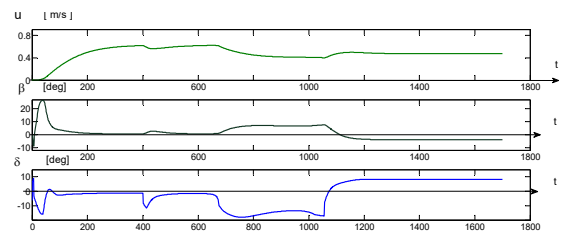


Figure 14. Time histories of surge velocity $u(t)$, drift $\beta(t)$ and rudder angle $\delta(t)$ during the tested maneuver.

3.2 Example 2

The starting point was situated in $wp_0(100,420)$ and the course in first straight-line section $\psi=20$. After 500 s the training ship reached the point $(286,493)$, and then the autopilot controlled in the LOS mode in $wp_1(610,670)$, which at first meant the change of the given course at $\psi=28.6$. From this point the ship reached on the arch the next way-point $wp_{i+2}(720,515)$, and then sailed further at $(550, 420)$. The course was calculated as $\psi_{i+2}=192^\circ$.

$$2\alpha = \psi_{i+2} - \psi_i - 180^\circ = 192^\circ - 29^\circ - 180^\circ = -17^\circ$$

The forecasted place of starting of the turn B had coordinates $x'_{i+1}=599.3$, $y'_{i+1}=664$. The way that the ship traveled during this maneuver and the heading, has been marked in Figure 15.

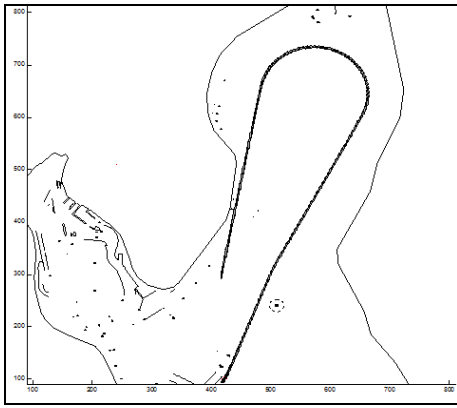


Figure 15. The position and heading trace

3.3 Maneuvering to prevent collisions at sea

Modification of the route may also be required in case of meeting other ships. Figure 16 shows the picture taken by the anti-collision system from the radar screen in the seagoing ship together with a hint how to avoid collisions (Mohamed-Seghir,2016). After scaling for the tested model, the passage of this section of the ship route was planned on the basis of projection after the next steps of monitoring of the anti-collision system. After signaled collision situation and getting some hints from the system to turn to the right, it was changed a given course with the minimum required value 10° .

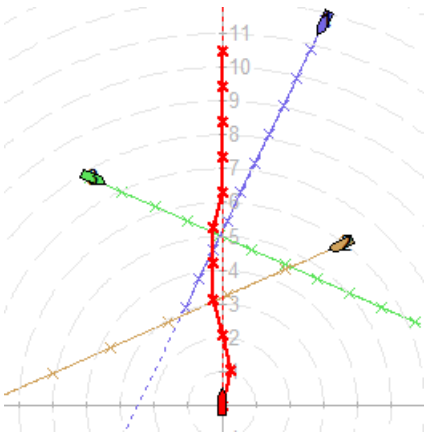
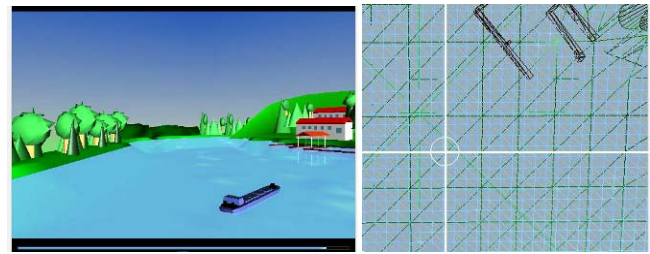


Figure 16. Comparison between game trajectory of own ship in a situation of passing 3 encountered ships from anti-collision system and the path planned using proposed method

After it was reached the next way- point wp_1 was put the first cross and then it was determined a maneuver with a curve 1 with an access to the new course 350° . After reaching wp_1 the course was maintained, to signal the crew of the ship 3, that it is respected its right of priority and after going ~ 30 m it was started the maneuver at wp_2 with coordinates (895,-8).

Indeed, during these maneuvers resulting from the necessity of overtaking ships which are met on the route it was not required a large deflection of the rudder, after planned new trajectory of passage, the extension of the route was 10% shorter and a drop of speed was 16% less than using a original variant



a) b)
Figure 17. Print screen during the visualization of conducted maneuvers.

The effectiveness of the presented route planning method also depends on the interface between the operator and the computational system. The next way-points the crew can apply to the e-map from where they are scanned to the way-points data base. In Figures 16a,b are presented print screens of the visualization of maneuvering and specifying of way-point on the e-map.

The results obtained by a computer simulation of considered training ship compared with similar maneuvers carried out by PID controller show that the overshoot can be eliminated. In addition the settling time can be shortened. It is worth remark that by adjusting the turn radius according to the needs, the mean drift angle is smaller, which results to a lower decrease in the surge velocity.

4 SUMMARY

The most important contribution of this study is the development of the novel method that allows for fast correction in slight advance of pre-defined route and thanks a control system suitable for steering of a nonlinear plants for relatively precise keeping such determined path. The required conditions for the control system meets nonlinear IMC controller that was designed for this target. The concept of extension the Internal Model Control to a nonlinear form allowed to obtain a more accuracy model what also improved the control performance, which is expressed by reducing the overshoot and settling time for a wide range of operating points. In this study the parametric model of the process was created by means of identification based of an open-loop step response by different rudder angle thereby the different ship velocity. Introducing into desired trajectory of defined circular arcs makes it possible to avoid oversized rudder deflection. Long turns have some additional advantages. They may considerably decrease the hydrodynamic resistance which occurs during the maneuver and thus reduce the velocity decreases that result from it. realize. As a result, deviations occurring the path keeping can be significantly reduced. This can make it easier to optimize the set route that is required to pass other surface vessels. Simulation results indicate that the considered system can be a useful tool for quite precise avoiding of obstacles on the route of the ship. The method of route planning presented in this paper creates wider possibilities for implementation by maritime collisions avoidance. It can also be very useful to carry out planned search operation during SAR actions where the search area must be devised

and patrolled with great accuracy (L.Kasyk & K.Pleskacz, 2015). The results of research justify conducting further trials on the lake and extending the control by other thrusters, especially in the context to reduce drift when making turns along circular arcs with a small radius.

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