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Dynamic positioning system design for "Blue Lady". Simulation tests

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ABSTRACT

The dynamical positioning system is a complex control consisting of a number of components, including: filters, observers, controllers, and propeller allocation systems. The design and preliminary analysis of operational quality of system operation are usually done based on numerical simulations performed with the aid of the mathematical model of the ship. The article presents a concept of the dynamic positioning system applied to steering the training ship Blue Lady used for training captains in the ship handling research and training centre owned by the Foundation for Safety of Navigation and Environment Protection in Ilawa/Kamionka. The simulation tests performed in the numerical environment of Matlab/Simulink have proved the usability of the designed system for steering a ship at low speed.

Key words: dynamic positioning system; marine systems; ship control

INTRODUCTION

Automatic control of ships has been studied for over a century. In 1911 Elmer Sperry constructed the first automatic ship steering mechanism called "Metal Mike". Today, the range of marine vessels covers a huge diversity of vehicles such as remotely operated vehicle (ROVs) and semi-submersible rigs. Automatic control systems for heading and depth control, way-point tracking control, fin and rudder-roll damping, dynamic positioning (DP), thruster assisted position mooring (PM) etc. are commercial products [1].

DP systems have traditionally been a low-speed application, where the basic DP functionality is either to keep a fixed position and heading or to move slowly from one location to another. In addition specialized tracking functions for cable and pipe layers, and remote operated vehicle operations have been available [2].

The dynamic positioning system for marine vessels has been divided into a set of dedicated modules with designed tasks. The most important components are shown in Fig. 1 [1].

The guidance system is used for planning the route for ship motion from the starting point to a selected target point. In the DP system the guidance system generates a smooth trajectory with position coordinates and course which lead to the next position.

The unit responsible for signal processing monitors the measured signals and performs quality tests to detect extensively large variations, wild points, frozen signals, and/or signal drifts. Erroneous signals are to be detected and not used for further operations. The signal processor should check and evaluate the signal based on the tests of individual sensors when the measurements done on redundant sensors are available. A typical marine vessel equipped with a DP system has two or three gyrocompasses and the same number of position calculation systems.

The main task of the observer is to provide low-frequency estimates of the vessel's position, heading and velocity. Rapid oscillating movements caused by waves are to be filtered out. The observer should also be able to predict ship movements in the situation when ship heading and position measurements become unavailable (dead reckoning).

In low-speed applications the controller calculates three desired parameters: the surge force, the sway force, and the yaw moment. Depending on the performed operation modes, the controller takes into account the system state estimates, the reference trajectory and the measured environmental conditions in the calculations.

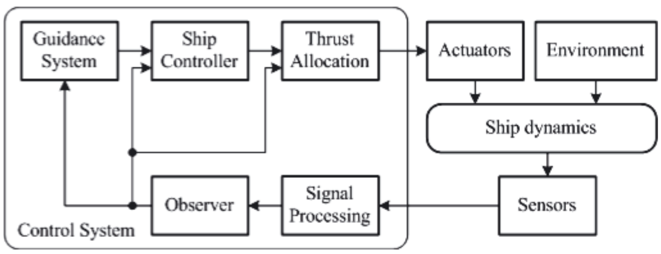

Fig. 1. *The major components of a positioning control system for marine vehicles*

The internal logic of the controller controls the modes of switching between different operation types.

The thrust allocation system maps the desired forces and yaw moment obtained from the controller into the required propeller settings, such as the propeller rotational speed and pitch ratio, the angles of the rudder blade and azimuth thrusters. It is important that these set-points are done in an optimal manner, which most frequently leads to minimisation of energy consumption.

The number of marine vessels with the installed DP systems is continuously growing due to deep-sea gas and oil mining. At present, the DP systems are most frequently used on shuttle tankers which provide services for drilling rigs.

The beginning of the dynamic positioning systems goes as far to the past as to the last century's sixties when the first systems acting on horizontal plane in three directions of ship motion: surge, sway and yaw were introduced. These systems made use of one-dimensional single input/single output (SISO) algorithms of the PID controller, along with low-pass or notch filters. The description of the DP systems which includes early stages of their development was given by Fay [3].

In the last century's seventies, more advanced ship steering methods were introduced which based on multidimensional optimal control and the Kalman filter theory. The first solution of this type was presented by Balchen, Jenssen and Saelid [4] as well as by Balchen, Jenssen, Mathiasen and Saelid [5]. The verification of this solution on a marine ship was later presented by Balchen, Jenssen and Saelid [6]. Later on, this solution was the object of further modifications and extensions, done by Saelid, Jenssen and Balchen [7] who proposed a new algorithm of adaptation to changing frequency in order to improve the quality of system operation within a wide range of changes of environmental conditions.

Grimble, Patton and Wise [8] presented an extended the analysis of the Kalman filter, comparing it to a notch filter which was earlier used in the dynamic positioning systems. Then, Fung and Grimble [9] proposed a self-tuning algorithm for automatic tuning of the Kalman filter matrix, obtaining good results. Despite the improvement in the filtration and estimation algorithms, the operation of the controller still based on the optimal control theory.

However, some problems are observed in cases when linear PD controllers are used in the DP systems. Tuning the gain is a very complicated task which requires time-consuming tests done on sea with the DP system switched on. Unfortunately, the operational quality of the controllers changes following the changes of the level of environmental disturbances and load conditions. The DP operator has to tune manually the controller's gain to adapt to changes of the environmental conditions.

Another important issue is the robustness of the controller. The mathematical model used for modelling the ship motion on the sea, where the ship is subject to the action of wind, sea currents and waves, is strongly nonlinear and some phenomena are extremely difficult for mathematical modelling. The design of the DP controller has to take into account its expected robustness. Since last century's nineties, this issue has been taken into account in designing linear DP systems by using the H_∞ technique. Designs of this type can be found in publications by Katebi, Grimble and Zhang [10], Kijima, Murata and Furukawa [11], Nakamura and Kajiwara [12], Tannuri and Donha [13], Donha and Tannuri [14] as well as Gierusz [15]. This type or controller meets well the robustness requirements in the presence of large changes of environmental conditions. But it is still the linear controller which bases on the linear model of the object; therefore different controllers should be designed for a number of operating points defined in the space of states in the vicinity of the point which the ship reaches during the executed operation.

In order to avoid problems connected with linearization in the DP systems, nonlinear controllers have been introduced. Fuzzy controllers were proposed by Stephens, Burnham and Reeve [16], Broel-Plater [17], as well as by Chang, Chen and Yeh [18]. Nonlinear controllers designed using the backstepping method and proposed by Aarset, Strand and Fossen [19], Strand and Fossen [20], Fossen and Grovlen [21] as well as by Bertin, Bittani, Meroni and Savaresi [22] were also successfully used.

The publications by Fossen and Strand [23], Strand and Fossen [24] as well as Strand [25] present important issues of passive nonlinear observers with adaptive wave filtration. An advantage of the use of the nonlinear theory of passiveness was the reduced complexity of the code packages used for steering. Pettersen and Fossen [26], Pettersen, Mazenc and Nijmeijer [27] as well as Bertin, Bittani, Meroni, and Savaresi [22] have worked out the DP control algorithms for seagoing vessels in which the number of propellers is smaller than the number of freedom degrees (so-called under-actuated vessels). Agostinho, Moratelli, Tannuri and Morishita [28] as well as Tannuri, Agostinho, Morishita and Moratelli [29] have proposed the use of nonlinear sliding control in the DP system.

The application of hybrid control theory proposed by Hespanha [30], Hespanha and Morse [31], Hespanha, Morse and Liberzon [32], as well as the fault-tolerant control proposed by Blanke, Kinnaert, Lunze and Staroswiecki [33] has made it possible to design a correct control architecture for integrating multifunction controllers which link discrete events and continuous steering. The effect of operation of such a controller applied in DP systems was described by Sorensen, Quek and Nguen [34], Nguyen [35], Nguyen and Sorensen [36] who proposed a design of the controller with the superior switching logic to select a proper controller and observer from a set of controller and observers assumed for different environmental conditions.

The applicability of the DP systems on shuttle ships, where such operations as position keeping, sailing along a given trajectory, and unloading with FPSO (floating production storage and offloading) are performed, was analysed by Morishita and Cornet [37], Morishita, Tannuri and Bravin [38], Tannuri and Morishita [39], as well as Tannuri, Saad and Morishita [40].

The article presents a design of the DP system applied to steering the training ship Blue Lady. The investigations performed on the observers which could be hypothetically used in the designed DP system had been done earlier and were presented in the following articles and papers: the discrete Kalman filter [41], the continuous Kalman-Bucy filter [42], and the extended Kalman filter and nonlinear observer [43].

THE MATHEMATICAL MODEL OF BLUE LADY DYNAMICS FOR LOW SPEED

The training ship Blue Lady is owned by the Foundation for Safety of Navigation and Environment Protection in Ilawa and is used for training captains to perform complex and difficult manoeuvres of a large ship. The ship, made of epoxide laminate in the scale of 1:70, is a replica of a tanker used for transporting crude oil. The overall length and breadth of the physical model are, respectively, L_{OA} = 13.75 [m], and B = 2.38 m. In the full-load state its mass is m = 22830 [kg], moment of inertia I_z = 436830.3 [kgm^2], while center of gravity is located at midship, hence x_G = 0 [m]. The model is equipped with a set of actuators with electric motors fed from an accumulator battery, including the main propeller with a conventional plane rudder, and four jet thrusters: two tunnel (the bow thruster and the stern thruster) and two rotational jet propellers with changing rotational speed (the bow propeller and the stern propeller). The distribution of actuators on Blue Lady is presented in Fig. 2.

The presented article takes into account only three actuators, namely the main propeller and two tunnel thrusters: bow and stern.

A complex mathematical model of Blue Lady dynamics, complemented by the modelled actuators which relatively well model its real behaviour, was developed by Gierusz [44].

a) Simplified mathematical model

The mathematical model of ship dynamics is described by the position vector $\boldsymbol{\eta} = [x, y, \psi]$ which comprises the position coordinates: North x, East y, and the heading ψ. These quantities are calculated in the Earth-fixed coordinates fixed to the water region map (n-frame). The velocity components: surge **u** and sway **v** as well as the yaw rate r form the velocity vector $\mathbf{v} = [x, v, r]$ calculated into the body frame fixed to the moving ship (b-frame) and hence moving along with it.

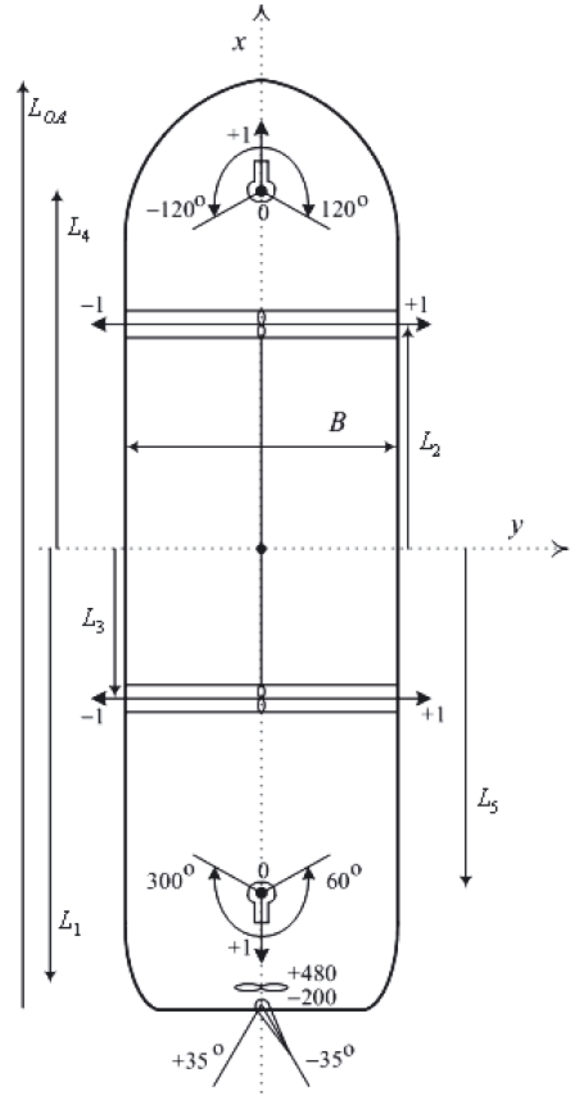

Fig. 2. Distribution of actuators on Blue Lady

The dynamic positioning system is designed for steering the ship at low speed. The proposed multidimensional controller applied in the DP system is determined using the mathematical model of the ship sailing at low speed, given by the following formulas [45]:

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{\nu} \tag{1}$$

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{D}_L\boldsymbol{\nu} = \tau \tag{2}$$

where $\mathbf{R}(\psi)$ is the matrix of rotation calculated from the formula:

$$\mathbf{R}(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

The mass matrix **M** comprises the parameters of inertia of a rigid body, its dimensions, weight, mass distribution, volume, etc., and the added mass coefficients:

$$\mathbf{M} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} \\ 0 & mx_G - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{4}$$

The linear damping matrix D_L is connected with the hydrodynamic damping forces and is calculated for a selected constant small value of the surge speed $\mathbf{v} = \mathbf{v}_0 \approx [u_0, 0, 0]$ [46].

$$\mathbf{D}_L = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix} \tag{5}$$

It is assumed that the both vectors $\boldsymbol{\eta}$ and $\mathbf{v}$ are measured. The parameters of the Blue Lady model motion calculated for the velocity $u_0 = 0.1$ [m/s] are given in Tab. 1.

Tab. 1. *Calculated values of parameters of the simplified mathematical model of Blue Lady*

Parameter	Value	Parameter	Value
$X_{\dot{u}}$	730.5	X_u	21.1
$Y_{\dot{v}}$	1896.2	Y_v	259.8
$Y_{\dot{r}}$	18351.9	Y_r	855.4
$N_{\dot{v}}$	0	N_v	855.4
$N_{\dot{r}}$	0	N_r	6130.5

b) Simplified models of propellers

This section describes the mathematical models of propellers which were used in ship steering. Their operation is analysed for low speed ranges. The thrust force for the propeller screw is:

$$F_1 = k_1|\omega_1|\omega_1 \tag{6}$$

where:
$k_1 = 1.9589$.

The thrust forces for the tunnel thrusters: bow F_2 and stern F_3 are given by the formulas:

$$F_i = k_i\omega_i,\ i \in \{2, 3\} \tag{7}$$

where:
$k_2 = k_3 = 44145$.

The surge and sway forces generated by those thrusters:

$$\mathbf{u} = [F_1\ F_2\ F_3]^T \tag{8}$$

The vector of the forces acting on the ship in relation to the rotational speed of the propellers ω_i:

$$\tau = \mathbf{Tu} \tag{9}$$

$$\begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_N \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & L_2 & -L_3 \end{bmatrix} \cdot \begin{bmatrix} F_1(\omega_1) \\ F_2(\omega_2) \\ F_3(\omega_3) \end{bmatrix} \tag{10}$$

where:
$L_2 = 3.24$ [m],
$L_3 = 2.376$ [m].

The matrix **T** is the thrusters configuration matrix.

GUIDANCE SYSTEM

The ship guidance system was designed for performing two tasks:

- Point stabilisation. The task of the guidance is to keep the vessel at the given point and constant heading;
- Trajectory tracking. The task consists in moving the ship along the time-parameterised reference trajectory.

The mathematical model of the ship moving in the horizontal plane describes the surge dynamics, the sway dynamics and the yaw dynamics and is the model with three degrees of freedom (3 DOF). The description of the ship motion in the dynamic positioning system in which the ship keeps a fixed position or moves slowly from one position to another is done in a very small area and there are no problems with mapping the spherical shape of the Earth onto the plane. Fig. 3 shows schematically an example motion of the vessel from the starting point P to the final point K. This motion was defined using three coordinate systems. The first system is the Cartesian coordinate system $x^n y^n$ fixed to the map of the water region and represents the plane tangential to the surface of the Earth in the region in which the manoeuvre is performed. In this system the x^n axis is directed north, while the y^n axis is directed east. This reference system is related to the navigation on the Earth surface and for simplicity bears the name of the n-frame. The second coordinate system $x^b y^b$ is the relative system fixed to the moving ship. In this system the x^b axis is directed towards the longitudinal axis of the ship (from stern to bow), while the y^b axis is the lateral axis directed towards the starboard side. The ship position (x, y) and heading ψ are calculated with respect to the absolute coordinate system (n-frame) and collected in the position vector $\boldsymbol{\eta} = [x, y, \psi]^T$, while the linear velocity components (u, v) and the angular speed r are calculated in the relative coordinate system $x^b y^b$ and collected in the velocity vector $= [x, \nu, r]^T$. The origin of the relative coordinate system is usually situated in the centre of ship gravity. Moreover, the description of the motion of the ship changing the position makes use of the third coordinate system $x^r y^r$ playing the role of the reference coordinate system and bearing the name of the r-frame. This system is used for describing the ship motion from the starting point P to the final point K. It has the same properties as the n-frame, the only difference is that the x^r axis changes direction and the coordinates of the origin of this system are shifted to the starting point P of the currently passed trajectory segment.

Fig. 3 shows an example situation in which the ship situated at the starting point P has the position coordinates $\eta_P^n = [x_P^n,\ y_P^n,\ \psi_P^n]^T$ and has to change the position moving to the final point K, where it will have the position coordinates $\eta_K^n = [x_K^n,\ y_K^n,\ \psi_K^n]^T$. These position coordinates are written in the n-frame.

During position changes, the movements executed by the ship are governed by the DP controller, the operation of which consists in such ship steering that the ship follows with a satisfying accuracy the positions of the moving reference system $x^d y^d$, fixed to the virtual ship. All this motion from the starting point P to the final point K is described in the r-frame.

To do this, the ship position coordinates at the final point K $\eta_K^n = [x_K^n,\ y_K^n,\ \psi_K^n]^T$, the coordinates of the current ship position $\boldsymbol{\eta} = [x, y, \psi]^T$ and the required ship position

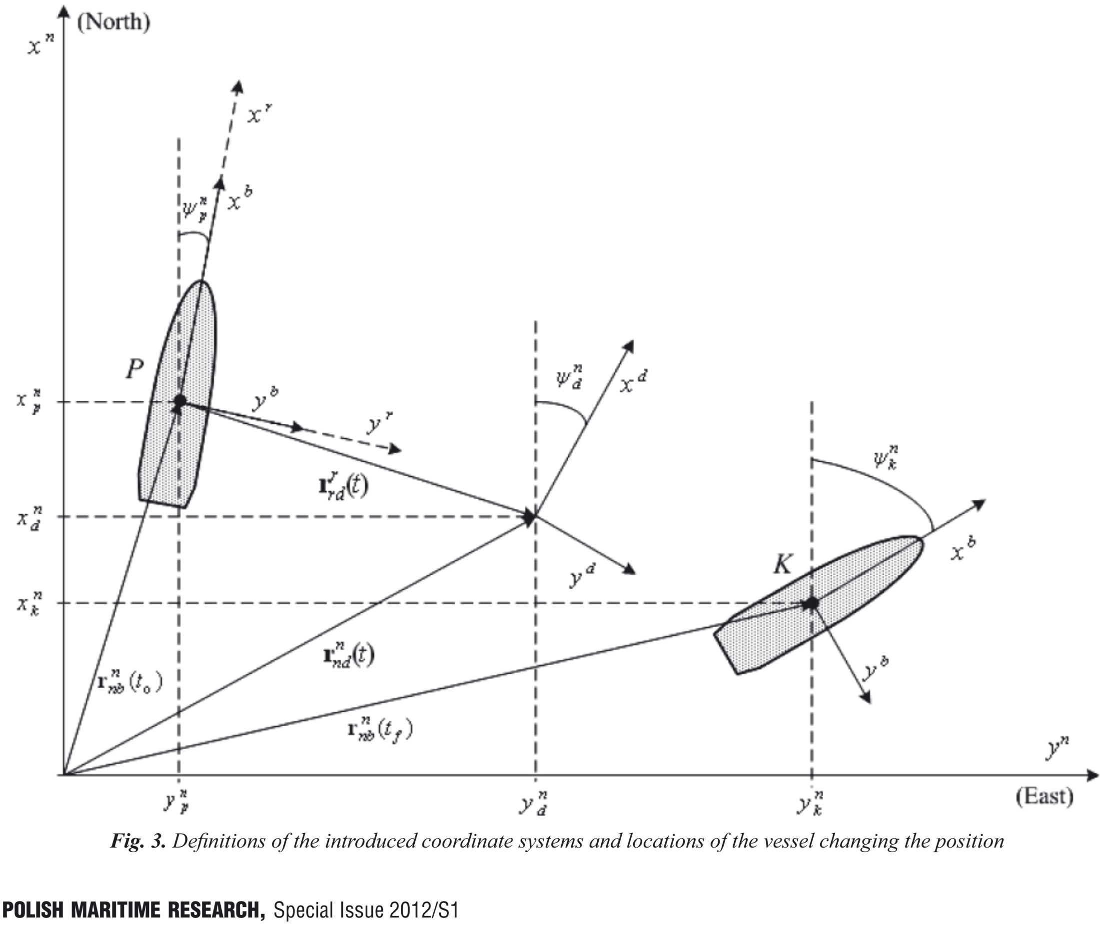

***Fig. 3.** Definitions of the introduced coordinate systems and locations of the vessel changing the position*

$\eta_d^n = [x_d^n, \ y_d^n, \ \psi_d^n]^T$ are recalculated to the r-frame. The starting coordinates and the orientation of the r-frame are identical with the ship position at the starting point P.

The coordinates of the final point toward which the ship moves are calculated in the r-frame from the following relation:

$$\eta_K^r = (\eta_K^n - \eta_P^n) \cdot \mathbf{R}(\phi) \tag{11}$$

where:
R(ϕ) – the rotation matrix defined in the following way:

$$\mathbf{R}(\phi) = \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{12}$$

while the angle of rotation:

$$\phi = -\psi_P^n \tag{13}$$

Let ${}^d\mathbf{r}_{rd}^r = [x_{rd}^r, y_{rd}^r]^T$ be the required position of the ship and ψ_{rd}^r the required course written in the r-frame. The required ship position and course in the r-frame, which control the ship movement from point P to point K is given by the vector $\boldsymbol{\eta}_{rd}^r(t) = \left[({}^d\mathbf{r}_{rd}^r(t))^T, \psi_{rd}^r(t)\right]^T$, shortly written:

$$\boldsymbol{\eta}_d = \boldsymbol{\eta}_{rd}^r \tag{14}$$

The components of the position $\boldsymbol{\eta}_{rd}^r(t)$, velocity $\dot{\boldsymbol{\eta}}_{rd}^r(t)$ and acceleration $\ddot{\boldsymbol{\eta}}_{rd}^r(t)$ of the virtual ship moving from the starting point P to the final point K are calculated in the reference frame shown in Fig. 4. The required input values of the velocity $\dot{\boldsymbol{\eta}}_{rd}^r(t)$ and the acceleration $\ddot{\boldsymbol{\eta}}_{rd}^r(t)$ along the trajectory should not exceed physical limits valid for the ship; therefore relevant limits for the signals were introduced to the system shown in Fig. 4.

The desired velocities calculated in the system presented in Fig. 4. required recalculation from fixed reference coordinate system r-frame to the body frame fixed to the moving vessel (b-frame) according the following formulas:

$$\dot{\boldsymbol{\eta}}_d = \boldsymbol{\nu}_d = \mathbf{R}^T(\psi_e) \cdot \dot{\boldsymbol{\eta}}_{rd}^r \tag{15}$$

$$\ddot{\boldsymbol{\eta}}_d = \dot{\boldsymbol{\nu}}_d = \dot{\psi}_e \mathbf{S}^T \mathbf{R}^T(\psi_e) \cdot \dot{\boldsymbol{\eta}}_{rd}^r - \mathbf{R}^T(\psi_e) \cdot \ddot{\boldsymbol{\eta}}_{rd}^r \tag{16}$$

where:
$\psi_e = \psi - \psi_d$, the matrix of rotation $\mathbf{R}(\psi_e)$ is calculated from equation (3), while the matrix **S** has form

$$\mathbf{S} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{17}$$

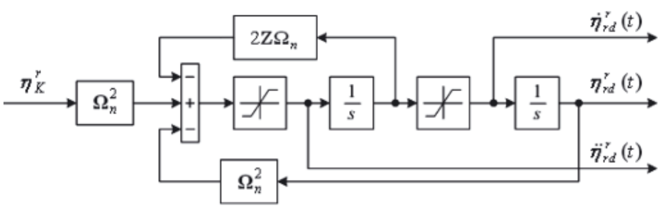

***Fig. 4.** Reference frame for generating input signals for the DP controller*

FULL STATE FEEDBACK PD TRACKING CONTROLLER

The goal of the control is to track the smooth trajectory $(\boldsymbol{\eta}_d(t), \dot{\boldsymbol{\eta}}_d(t), \ddot{\boldsymbol{\eta}}_d(t))$ generated by the ship guidance system. The control system calculates the deviations from the set input values. The position error $\boldsymbol{\eta}_e$ is calculated in the absolute r-frame, while the velocity $\dot{\boldsymbol{\eta}}_e$ and the acceleration $\ddot{\boldsymbol{\eta}}_e$ errors are calculated in the relative b-frame fixed to the moving ship.

$$\boldsymbol{\eta}_e = \boldsymbol{\eta} - \boldsymbol{\eta}_d \tag{18}$$

$$\dot{\boldsymbol{\eta}}_e = \dot{\boldsymbol{\eta}} - \dot{\boldsymbol{\eta}}_d \tag{19}$$

$$\ddot{\boldsymbol{\eta}}_e = \ddot{\boldsymbol{\eta}} - \ddot{\boldsymbol{\eta}}_d \tag{20}$$

The DP control system includes a controller which stabilises the error dynamics, i.e.

$$\ddot{\boldsymbol{\eta}}_e + \mathbf{K}_D \dot{\boldsymbol{\eta}}_e + \mathbf{K}_P \boldsymbol{\eta}_e = 0 \tag{21}$$

After converting the equation (21) to get the ship acceleration $\ddot{\boldsymbol{\eta}}$ we arrive at:

$$\ddot{\boldsymbol{\eta}} = \ddot{\boldsymbol{\eta}}_d - \mathbf{K}_D \dot{\boldsymbol{\eta}}_e - \mathbf{K}_P \boldsymbol{\eta}_e \tag{22}$$

Based on the equation (2), the proposed rule of control is described by the formula:

$$\boldsymbol{\tau} = \mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{D}_L \boldsymbol{\nu} \tag{23}$$

The velocity vector derivative $\dot{\boldsymbol{\nu}}$ in the equation (23) is determined from the kinetic equations (1) differentiated with respect to time, which leads to:

$$\dot{\boldsymbol{\nu}} = \mathbf{R}^{-1}(\psi)[\ddot{\boldsymbol{\eta}} - \dot{\mathbf{R}}(\psi)\boldsymbol{\nu}] \tag{24}$$

The derivative of the rotation matrix $\mathbf{R}(\psi)$ is determined from the formula:

$$\dot{\mathbf{R}}(\psi) = r\mathbf{R}(\psi)\mathbf{S} \tag{25}$$

where:
$r = \dot{\psi}$.

After placing the relation (22) into equation (24), and then into the proposed rule of control (23), we arrive at the formula describing the algorithm of operation of the proposed DP controller:

$$\boldsymbol{\tau} = \mathbf{M}\mathbf{R}^{-1}(\psi)[\ddot{\boldsymbol{\eta}}_d - \mathbf{K}_D \dot{\boldsymbol{\eta}}_e - \mathbf{K}_P \boldsymbol{\eta}_e - \dot{\mathbf{R}}(\psi)\boldsymbol{\nu}] + \mathbf{D}_L \boldsymbol{\nu} \tag{26}$$

CONTROL ALLOCATION

The problem with control allocation can appear when the number of actuators is larger than the number of the controlled degrees of freedom. The algorithm can be realised in two steps, as shown in Fig. 5.

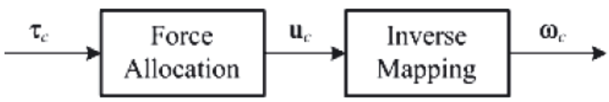

***Fig. 5.** The thrust allocation problem*

In the first step, bearing the name of force allocation, the desired generalised force τ_c is decomposed into all propellers under consideration. The quality of the decisions made in this step depends on how good the force allocation algorithm is. The second step consists in finding such settings in the actuators which generate the required forces **F**. This step is referred to as the inverse transformation as it consists in finding the inverse characteristics of the devices.

In the examined DP system three propellers are used for controlling the ship motion. Their configuration is given in Fig. 2. In this case the force allocation consists in solving the equation:

$$\mathbf{u} = \mathbf{T}^{-1}\boldsymbol{\tau} \tag{27}$$

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & L_2 & -L_3 \end{bmatrix}^{-1} \begin{bmatrix} \tau_X \\ \tau_Y \\ \tau_N \end{bmatrix} \tag{28}$$

Since the number of actuators is equal to the number of the controlled degrees of freedom, there is no problem with calculating the matrix $\mathbf{T}^{-1}$. In case the number of actuators is greater than the number of the number of the controller degrees of freedom, the propeller configuration matrix $\mathbf{T}^{-1}$ does not exist and we cannot find a direct solution. In this case the optimisation methods are to be used [47].

After decomposing the forces into particular propellers, from the transformed formulas (6) and (7) we obtain the desired values for the main screw propeller:

$$\omega_1 = \mathrm{sgn}(F_1)\sqrt{F_1/k_1} \tag{29}$$

and for the tunnel thrusters:

$$\omega_i = F_i/k_i\,, \quad i \in \{2,3\} \tag{30}$$

The desired rotational speed for the main propeller is limited to ±200 [rev/min], while for the bow and stern tunnel thrusters the limits are within the range of ±1 [-].

NUMERICAL SIMULATION RESULTS

The simulation tests were performed in the mathematical environment Matlab/Simulink. Particular components of the control system shown in Fig. 1 were modelled as blocks, while the algorithms describing the action of those blocks have been written in the form of S-functions in the Matlab code. Finally, the algorithms of the DP control system block components were translated into S-functions written in the code C++.

The operational quality of the designed positioning control system was tested on a complex mathematical model of the training ship Blue Lady worked out by Gierusz [15, 44]. Based on the complex mathematical model, a simplified model of ship dynamics was worked out and then used for the synthesis of the controller (26). In the simulation tests the following parameters of the controller were assumed:

$$\mathbf{K}_P = \mathrm{diag}(1\ 1\ 1) \tag{31}$$

$$\mathbf{K}_D = \mathrm{diag}(100\ 100\ 100) \tag{32}$$

The values of the parameters in the superior system were the following:

$$\mathbf{Z} = \mathrm{diag}(1\ 1\ 1) \tag{33}$$

$$\mathbf{\Omega}_n = \mathrm{diag}(0.012\ 0.01\ 0.015) \tag{34}$$

The DP controller applied for determining the desired forces, $\boldsymbol{\tau}$, requires the information about six state variables describing the motion of the ship, out of which the coordinates of ship position (x, y) and course $\boldsymbol{\psi}$ are measured and collected in the position vector $\boldsymbol{\eta} = [x, y, \psi]$, while the velocity components: surge u, and sway v, as well as the yaw rate r, which are not measured, are estimated by the nonlinear observer described in detail by Tomera [43] and collected in the velocity vector $\boldsymbol{\nu} = [x, \nu, r]$.

An example case of ship motion at low speed, shown in Fig. 6, consisted in moving the ship from one quay to another. In that time the ship got away from the first quay moving in the lateral direction and stopped at the first stopping point. Then it sailed in longitudinal direction to the other stopping point at which it performed the rotating manoeuvre. When it took a proper position with respect to the second quay, the ship sailed astern along a distance and finally performed the manoeuvre of touching the land at the second quay. The entire trajectory covered by the ship was divided into five manoeuvres. Each manoeuvre consisted in changing the parameters of the ship position vector $\boldsymbol{\eta}$ from one steady state to another.

The set values for the changing components of the ship position vector $\boldsymbol{\eta}$ were generated in the guidance system. The recorded time-histories of particular vector components are shown in Fig. 7. The ship position coordinates $\boldsymbol{\eta}$ are expressed in the fixed coordinate system, the r-frame, moved to a new position for each manoeuvre.

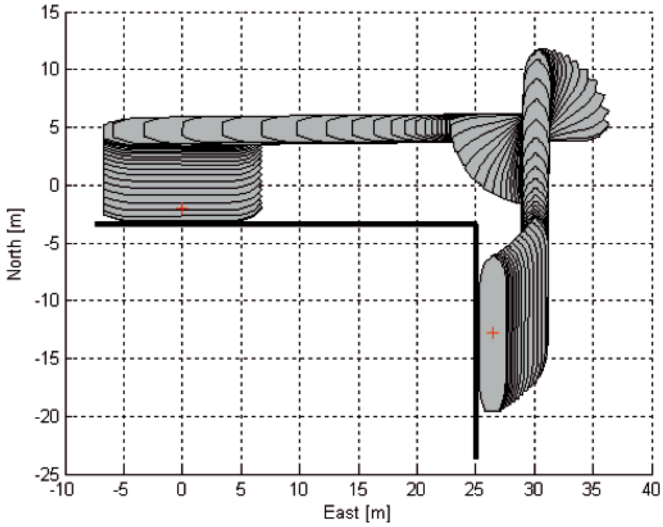

Fig. 6. *Simulation results - example ship motion trajectory*

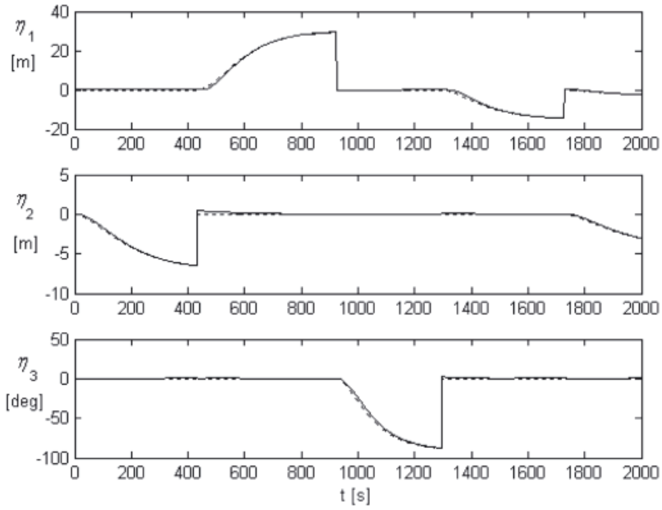

Fig. 7. *Simulation results – the solid lines represent positions while the dashed lines represent reference (r-frame) $\eta_1 = x$ - position x, $\eta_2 = y$ - position y, $\eta_3 = \psi$ - heading*

In transient states, when the ship moved from one fixed point to another, its motion was executed at some speed which was also set by the guidance system. The recorded time-histories of the velocity components: both the set ones and those executed by the ship are shown in Fig. 8. These velocities are expressed in the relative coordinate system, the b-frame, fixed to the moving ship.

The components of the desired forces which are determined by the DP controller and then should be executed by the propellers are shown in Fig. 10. The ship's DP controller calculated these forces based on the errors between the desired and measured values of the position and velocity vectors and the desired acceleration vector values (Fig. 8).

In the force allocation system the desired values of the force vector $\boldsymbol{\tau}$ were recalculated to the desired parameters of the thrusters used for the steering. The time-histories of the desired values calculated for the thrusters are shown in Fig. 11.

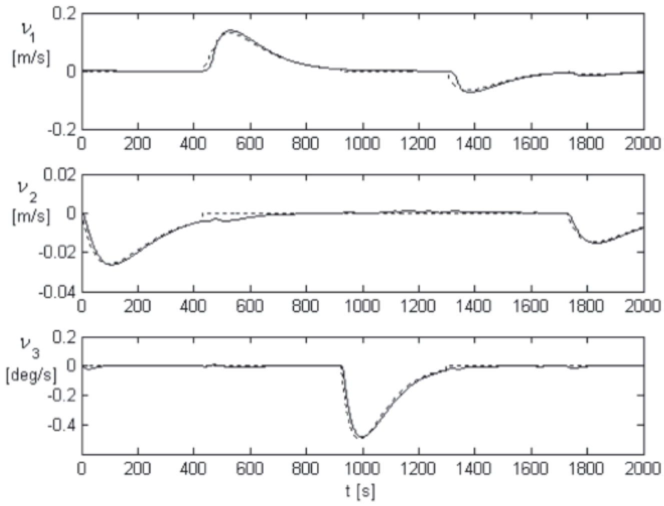

Fig. 8. Simulation results – the solid lines represent velocities while the dashed lines represent references (b-frame) $v_1 = u$ - surge, $v_2 = v$ - sway, $v_3 = r$ - yaw rate

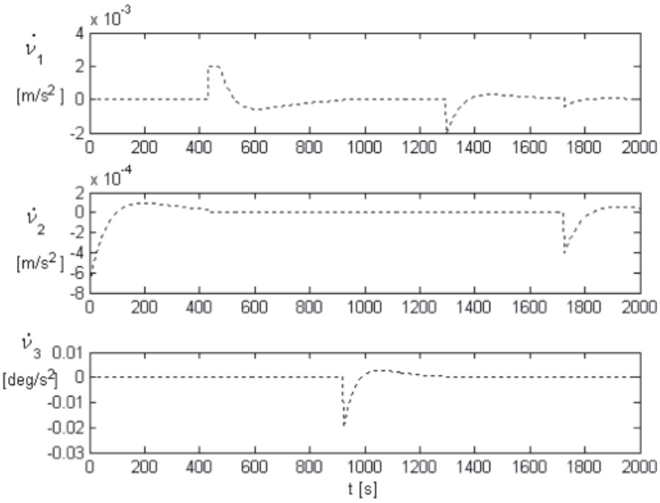

Fig. 9. Simulation results – the doted lines represent set accelerations (b-frame) $\dot{v}_1 = \dot{u}$ - surge, $\dot{v}_2 = \dot{v}$ - sway, $\dot{v}_3 = \dot{r}$ - yaw

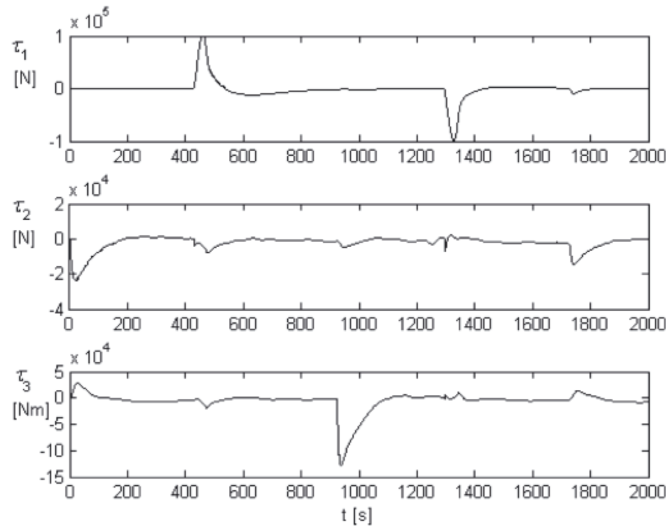

Fig. 10. Simulation results – virtual forces generated by the control law τ_1 - surge force, τ_2 - sway force, τ_3 - yaw moment

The figure does not include current values of these thrusters, because they cannot be measured in the real system. The rotational velocity ω_1 of the main screw propeller is expressed in revolutions per minute, while the desired rotational velocities ω_2 and ω_3 for the bow and stern tunnel thrusters, respectively, are expressed in the normalised numbers ranging between [-1, +1].

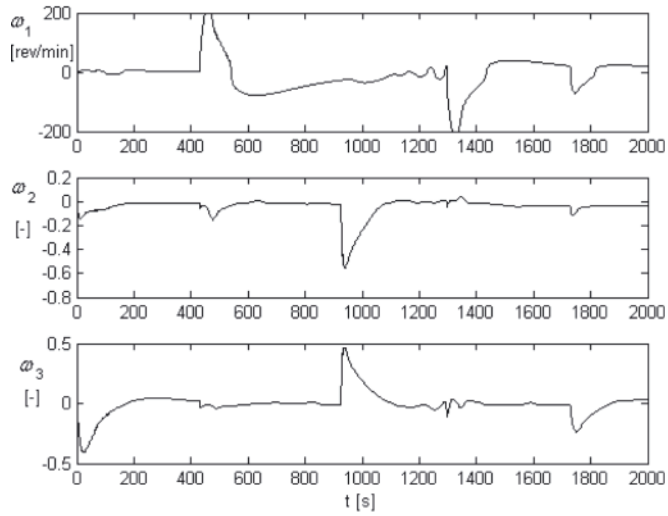

Fig. 11. Simulation results – computed propeller angular velocities by the allocation algorithm ω_1 - desired rotational velocity of the main propeller, ω_2 - desired rotational velocity of the tunnel thruster mounted at the bow, ω_3 - desired rotational velocity of the tunnel thruster mounted at the stern

CONCLUSIONS

The article presents a general concept and the design of the ship motion control at low speed. The operational quality of the designed system was tested using simulation calculations. The training ship "Blue Lady" was selected as the object of control, as it provides opportunities for future experiments in the ship handling research and training centre in Ilawa Kamionka to verify the results of the simulation tests. The performed simulation tests did not take into account the environmental disturbances which normally act on the ship. The planned future experiments will make it possible to determine the level of disturbances acting on the training ship "Blue Lady" when it sails on the lake and take them into account in the mathematical model of the control system.

The article is a first proposal of the multidimensional control algorithm applied to steering the training ship „Blue Lady", which in the future will be improved by introducing the effect of environmental disturbances. Other analysed directions of system development include the use of the multidimensional PID controller instead of the presently used PD controller and the development of the propeller allocation system by including the rotational jet propellers installed on the training ship „Blue Lady". The presently used propeller allocation system does not require optimisation as the number of the used propeller is equal to the number of degrees of freedom in which the steering takes place. The use of two additional thrusters and jet propellers: one at the bow and one at the stern, will introduce four additional set values, as each additional rotational jet propeller requires the set values of the setting angle and the rotational speed.

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