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Computer simulator of a model ship's unmanned movement

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Abstract

As part of this research, an experimental model of an unmanned ship equipped with an ecological electric drive was built. Ultimately, the ship model was equipped with an on-board computer with appropriate software for autonomous control. A computer simulator was used to test the control software. This article presents the concept of such a simulator, a general mathematical model of the movement dynamics of an unmanned vehicle, a description of the propulsion system, and the tasks planned for implementation in a computer simulator.

Introduction

To begin the research, design, and construction of unmanned – and ultimately autonomously controlled – ships, it is necessary to develop algorithms and specialized software. The installation of an on-board computer with control software on a ship will require significant research and trials to determine the correct operation of the automation system. However, before the control software is installed, many tests must be performed on a land-based computer simulator.

Computer simulators are important and useful tools for studying the properties of vessels before they are built. They are also used to research and test ship systems or algorithms and control software, e.g., in dynamic systems (DPS) or anchor positioning (MPS). There are many publications concerning computer simulators or simulations of various types of measurement and control software. The results or conclusions of this type of research can be used to build a computer simulator to test unmanned ships.

Some of these publications include:

- (Szelangiewicz & Żelazny, 1999) ship movement parameters were simulated and studied during anchoring operations using an anchor positioning system;
- (Mei & Arshad, 2015) the possibility of using artificial neural networks and potential fields to control an autonomous surface ship were explored;
- (Jenssen, 1997) the accuracy of the measuring sensors and their influence on the accuracy of maintaining the position using DP were investigated;
- (Cadet, 2003) the effects of applying the Kalman filter to the dynamic positioning system were studied;
- (Hamamatsu, 2002) non-linear mathematical models of the DP control system were studied;
- (Zwierzewicz, 2018), an adaptive mathematical model of traffic control on a movement trajectory was studied.

This brief literature review shows that many publications have built a mathematical model, a control system, and a computer simulator to study the movement dynamics of an unmanned ship.

Purpose of research

The construction of an autonomously controlled unmanned ship will require many tests of the control software. Before the ship is built, the software must be studied and tested in a land-based computer simulator (such a simulator can be used to monitor and eventually control the movement of a real ship).

The computer simulator will use test software to accomplish tasks performed on a manned ship during its operation, including:

- manoeuvers associated with leaving the port after loading the ship;
- selection and implementation of the shipping route to the destination port, Figure 1 (for long-distance routes through seas and oceans, this will mean optimizing the shipping route using weather information);
- implementation of anti-collision manoeuvers (avoiding permanent and mobile obstacles – other ships or floating objects), Figure 2;
- manoeuvers related to entering the destination port and mooring to the quay, Figure 3.

The implementation of these tasks requires the development of a computer simulator and a mathematical model of the ship's movement with appropriate control criteria. The mathematical model includes the ship's hydrodynamic characteristics and its propulsion system (i.e., the hydrodynamic characteristics of all propulsors installed in the ship's hull and the characteristics of the propulsion engines). To test the algorithms and determine the appropriate program to control an unmanned ship, a computer simulator based on a mathematical model is needed.

The aim of this research is therefore to:

- develop the concept of a computer simulator to model and study the movement dynamics of an unmanned vehicle;
- develop a mathematical model of a ship containing all the factors affecting the movement dynamics of the ship;
- develop a vessel traffic monitoring system and operating parameters of the propulsion system.

Figure 1. Selection and implementation of the unmanned navigating route (PMK, 2017)

Figure 2. Anti-collision manoeuvers of an unmanned ship – phot. DNV GL (PC, 2017)

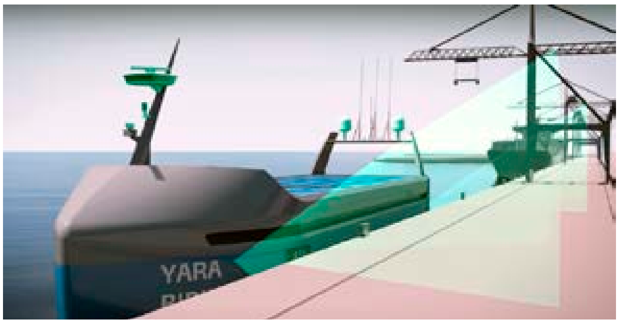

Figure 3. Autonomous mooring to the quay of an unmanned ship (PMK, 2017)

In the first stage of research, computer simulations will be carried out to model the constructed unmanned ship. Ultimately, the computer simulator will be equipped with simulation software for a real autonomously controlled unmanned ship.

Experimental model of an unmanned ship

In 2018, a design of an unmanned container ship was created (Figure 4). The control and propulsion systems of the unmanned vehicle model were built on a 1:25 scale (Figure 5).

The experimental model of the unmanned ship was equipped with an ecological propulsion system of the same construction expected to be used on a real unmanned ship. The drive system (Figures 5 and 6) consists of:

- 2 stern azimuthal propellers (APL and APR) with electric motors,
- 2 bow tunnel thrusters (BT1 and BT2) with electric motors.

Each electric motor has its own power supply (accumulators) and a controller to regulate the propulsors revolution.

The model's drive control system has been built so that:

- each propulsor can be individually controlled,
- the entire drive can be controlled by setting the resultant thrust force in any direction.

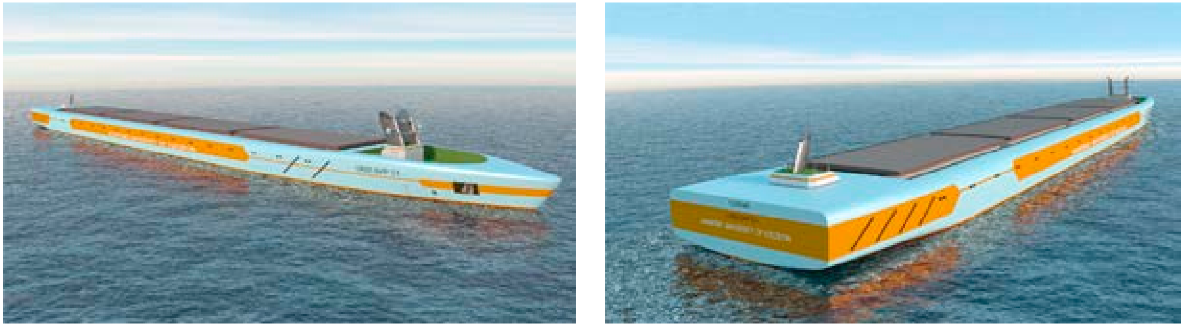

Figure 4. Visualization of the unmanned container, autonomously controlled (L_C = 78.75 m, B = 11.10 m, T = 4.33 m, ∇ = 2500 m^3)

Figure 5. The propulsion system of the autonomous ship model

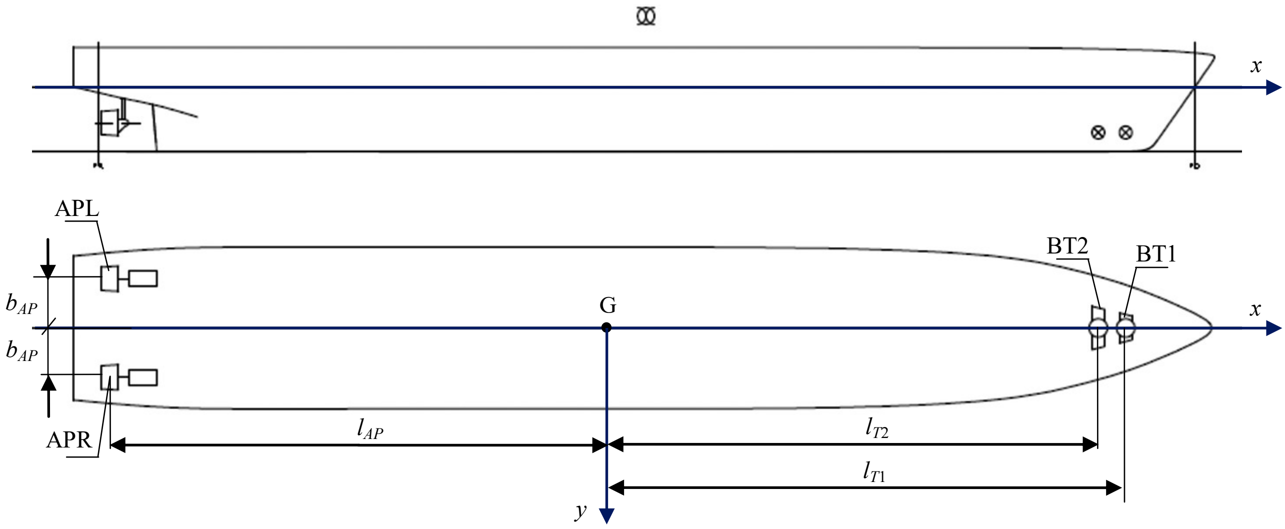

Figure 6. Propulsion vessel's system location

The control can be:

- remote wireless,
- autonomous – the model is controlled by an on-board computer with the appropriate software.

Mathematical movement model of an uncontroller

General movement equations

When controlling a ship's propeller, movement in the horizontal plane is considered during its operation. The equations of movement are the same as when manoeuvring a ship. The ship's movement is described by three non-linear differential equations, in accordance with Newton's Second Law, written in a coordinate system related to the centre of the ship's mass ($Gxyz$) (Figure 7):

$$
\begin{aligned}
M_s(\ddot{x} - \dot{y}\dot{\psi}) &= F_x \\
M_s(\ddot{y} + \dot{x}\dot{\psi}) &= F_y \\
I_{zz}\ddot{\psi} &= M_z
\end{aligned}
\tag{1}
$$

where:

M_s – mass of the ship;

I_{zz} – the moment of inertia of the ship's mass relative to the axis "z";

$x, \dot{x}, \ddot{x}$ – displacement, speed, and acceleration of longitudinal movement (along the axis "x");
$y, \dot{y}, \ddot{y}$ – displacement, speed, and acceleration of lateral movement (along the axis "y");
$\psi, \dot{\psi}, \ddot{\psi}$ – displacement, speed, and acceleration of rotational motion (around the axis "z");
F_x, F_y, M_z – forces and external moment acting on the ship.

The solution of the system of Equations (1) is the position (x_0, y_0, ψ_0) stored in the Earth-fixed reference system $O_0x_0y_0z_0$ (Figure 7) and the speed ($\dot{x} = V_x$, $\dot{y} = V_y$, $\dot{\psi} = \omega$) stored in a system related to the ship ($Gxyz$).

The external forces F_x, F_y and the moment M_z can be divided into:

- inertia forces (F_I),
- damping forces and water effects (R_D),
- forces induced on the thrusters of the propulsion system:
  - thrust forces of azimuthal propellers (R_{AP}),
  - thrust forces of bow thruster tunnel rudders (R_{BT}),
- air (wind) and wave effects (R_A, R_W).

Generalized inertial forces

Generalized inertial forces F_I result from the transfer of momentum (and moment of momentum) that occurs due to the variable speed of the ship on water. For the system of Equations (1) describing horizontal plane movement, these forces are as follows:

$$\begin{aligned} F_{Ix} &= -m_{11}\ddot{x} + m_{22}\dot{y}\dot{\psi} + m_{16}\dot{\psi}^2 \\ F_{Iy} &= -m_{22}\ddot{y} - m_{11}\dot{x}\dot{\psi} - m_{26}\ddot{\psi} \\ M_{Iz} &= -m_{66}\ddot{\psi} - m_{62}\ddot{y} + (m_{11} - m_{22})\dot{x}\dot{y} - m_{62}\dot{x}\dot{\psi} \end{aligned} \tag{2}$$

where: m_{11}, m_{22}, m_{16}, m_{26}, m_{62}, m_{66} are the generalized hydrodynamic masses and moments.

Hydrodynamic masses and moments are most often calculated using numerical methods, assuming a potential flow around the ship's hull or using approximate dependencies, developed for simplified shapes (e.g., three-axis ellipsoids).

Substituting Equation (2) into (1), a non-linear, differential system of equations is obtained which describes the ship's horizontal plane movement:

$$\begin{aligned} (M_s + m_{11})\ddot{x} - (M_s + m_{22})\dot{y}\dot{\psi} - m_{16}\dot{\psi}^2 &= R_x \\ (M_s + m_{22})\ddot{y} + m_{26}\ddot{\psi} + (M_s + m_{11})\dot{x}\dot{\psi} &= R_y \\ (I_{zz} + m_{66})\ddot{\psi} + m_{62}(\ddot{y} + \dot{x}\dot{\psi}) + (m_{22} - m_{11})\dot{x}\dot{y} &= M_z \end{aligned} \tag{3}$$

Generalized, external damping forces

Generalized, external damping forces come from the interaction of water (and surface water current) with the sailing ship. These forces, for the ship model, can be presented in the form of equations:

$$\begin{aligned} R_{xD} &= \frac{1}{2}\rho_w S V_{RC}^2 C_x(\beta_{RC}) \\ R_{yD} &= \frac{1}{2}\rho_w S V_{RC}^2 C_y(\beta_{RC}) \\ M_{zD} &= \frac{1}{2}\rho_w L S V_{RC}^2 C_m(\beta_{RC}) \end{aligned} \tag{4}$$

where:
V_{RC} – speed of the ship model relative to water (including surface current), (Figure 7);
S – wetted surface of the hull of the ship model;
C_x, C_y, C_m – coefficients of resistance of the underwater part of the ship's hull;
β_{RC} – relative drift angle of the ship's model (including current direction), (Figure 7);
ρ_w – water density;
L – length of the ship model.

The speed of the ship model on the water relative to the current and drift angle (Figure 7):

$$V_{RC} = \sqrt{(V_{RCx})^2 + (V_{RCy})^2} \tag{5}$$

$$\beta_{RC} = \text{arc tg}\frac{-V_{RCy}}{V_{RCx}} \tag{6}$$

$$\begin{aligned} V_{RCx} &= V_x - V_C \cos\beta_C \\ V_{RCy} &= V_y - V_C \sin\beta_C \end{aligned} \tag{7}$$

where:
$V_x = V\cos\beta$, $V_y = -V\sin\beta$ – components of the ship's absolute speed,
V_C – surface current speed,

$$\beta_C = \gamma_C - \psi \tag{8}$$

β_C – the current direction relative to the ship model, Figure 7;
γ_C – geographical current direction, Figure 7;
ψ – the geographic course of the ship model, Figure 7.

If the current velocity $V_C = 0$ then the Equations (4) describe the resistance components of the ship model on calm water during movement with a drift angle β. If the drift angle $\beta = 0$ (straight line movement of the ship model) then R_{xD} is the longitudinal resistance, and R_{yD} and $M_{zD} = 0$. To determine the components of the impact of water on the hull of the

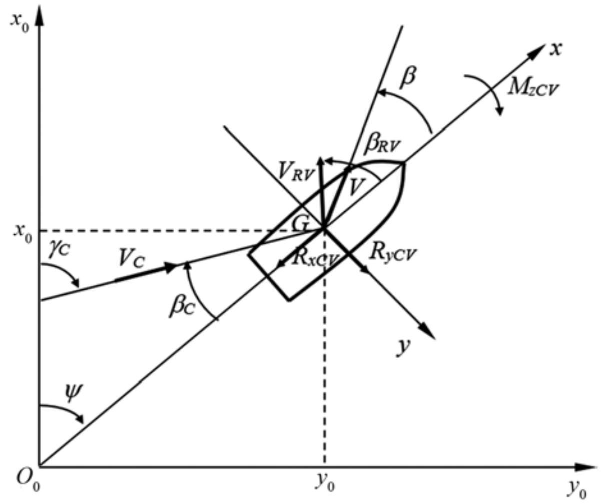

Figure 7. Position and course as well as current direction and speed of the ship's model with drift angle

ship model, the drag coefficients C_x, C_y, C_m and the wet surface of the hull S must be known.

Generalized forces induced on the thrusters of the ship's propulsion system

Forces of azimuthal propellers (AP)

In the azimuthal propellers used in ship propulsion, (Figures 5 and 6), the thrust force is regulated by changing the rotational speed of the propellers. The value of the thrust force also depends on the angle of the propellers' position relative to the vertical axis (with certain propeller settings – rotation relative to the vertical axis – thrust drop may occur due to the impact of the model's hull and also due to possible propeller thrust from the opposite side).

Therefore, the propeller thrust can be determined experimentally in the form of:

$$T_{AP} = f(G_P, n_P, C_P) \tag{9}$$

where:

G_P – geometric parameters of the propeller,
n_P – rotational speed of the propeller,
C_P – correction factor taking into account the thrust drop from the impact of the model's hull and the adjacent propeller.

The components of the resultant thrust force and the moment relative to the axis "z" azimuthal propellers are as follows:

$$\begin{aligned} R_{xAP} &= T_{APL}\cos\varphi_{APL} + T_{APR}\cos\varphi_{APR} \\ R_{yAP} &= T_{APL}\sin\varphi_{APL} + T_{APR}\sin\varphi_{APR} \\ M_{zAP} &= T_{APL}\left(\cos\varphi_{APR} b_{AP} - \sin\varphi_{APL} l_{AP}\right) + \\ &\quad - T_{APR}\left(\cos\varphi_{APR} b_{AP} + \sin\varphi_{APR} l_{AP}\right) \end{aligned} \tag{10}$$

where:

T_{APL}, T_{APR} – thrust of the left and right propeller,
φ_{APL}, φ_{APR} – the angle of the azimuthal propeller: left and right,
l_{AP} – distance of the propeller from the centre of mass of the ship model, Figure 5.

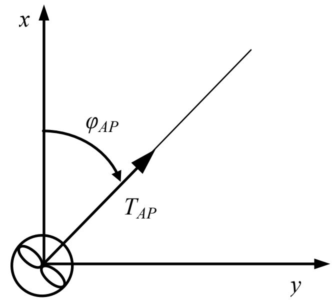

Figure 8. The angle of the azimuthal propeller's setting

Forces of bow tunnel thrusters (BT)

The thrust of the bow tunnel thruster is regulated by changing the rotational speed and is determined from the dependence:

$$T_{BT} = f(A_T, n_T, C_T) \tag{11}$$

where:

A_T – geometrical parameters of the thruster screw;
n_T – rotation speed of the thruster screw;
C_T – correction factor including the length of the tunnel, the shape of the hole in the hull, the speed of the ship model.

The components of the resultant thrust force of the bow tunnel thruster are as follows:

$$\begin{aligned} R_{xBT} &= 0 \\ R_{yBT} &= T_{BT1} + T_{BT2} \\ M_{zBT} &= T_{BT1} l_{T1} + T_{BT2} l_{T2} \end{aligned} \tag{12}$$

where:

T_{BT1}, T_{BT2} – thrust of bow tunnel thruster No. 1 and 2;
l_{T1}, l_{T2} – the coordinates of the position of the thruster No. 1 and 2 from the centre of mass of the ship model, (Figure 5).

Generalized, external wind, and wave forces

The constructed experimental model of the unmanned ship is designed to test the propulsion system and the autonomous control program. The tests are performed on calm water, hence mathematical model (1) does not take into account the external wind forces (the model has no superstructure) or the wave action forces. Another ship model (larger than the current one) or an unmanned ship that will be sailing on the water in real weather conditions will be equipped with control software containing modules regarding the impact of wind and waves.

Concept of a computer simulation movement for an unmanned model ship

The computer simulator of the unmanned ship model's movement was designed to meet the assumed objectives (simulating a ship's movement and the parameters of its propulsion system), and also be extended to carry out additional research tasks in the future.

The simulator will be equipped with:

- a computer program to solve a system of non-linear differential Equations (3) including equations describing generalized external forces (4), (10), and (12);
- a module for determining hydrodynamic characteristics of propulsors, Equations (9) and (11), propulsion system of the ship and optimization of propulsion power (system of Equations (3) for given movement parameters – the speed and course of the ship – can have many solutions for various propulsor settings; the solution for the minimum power of the drive is selected);
- module simulating the work of measurement sensors (position, speed, and course of the ship);
- wireless communication system – during tests on the water, current operational parameters (speed, position, and course of the ship, and propulsion system parameters) are recorded on the ship model and transmitted via radio to the computer simulator.

During simulation in the field of movement time of the unmanned ship model, all preset parameters, simulated or measured, are displayed on the graphic page (Figure 9).

Conclusions

Work on the propulsion system and control of unmanned ships requires many tests to be carried out on a special computer simulator. The presented design concept of such a simulator meets all the requirements – the simulator can be extended and equipped with additional elements in accordance with the needs resulting from the subsequent stages of the experimental model of the unmanned ship.

In order to conduct simulation studies of the movement of a constructed experimental model of

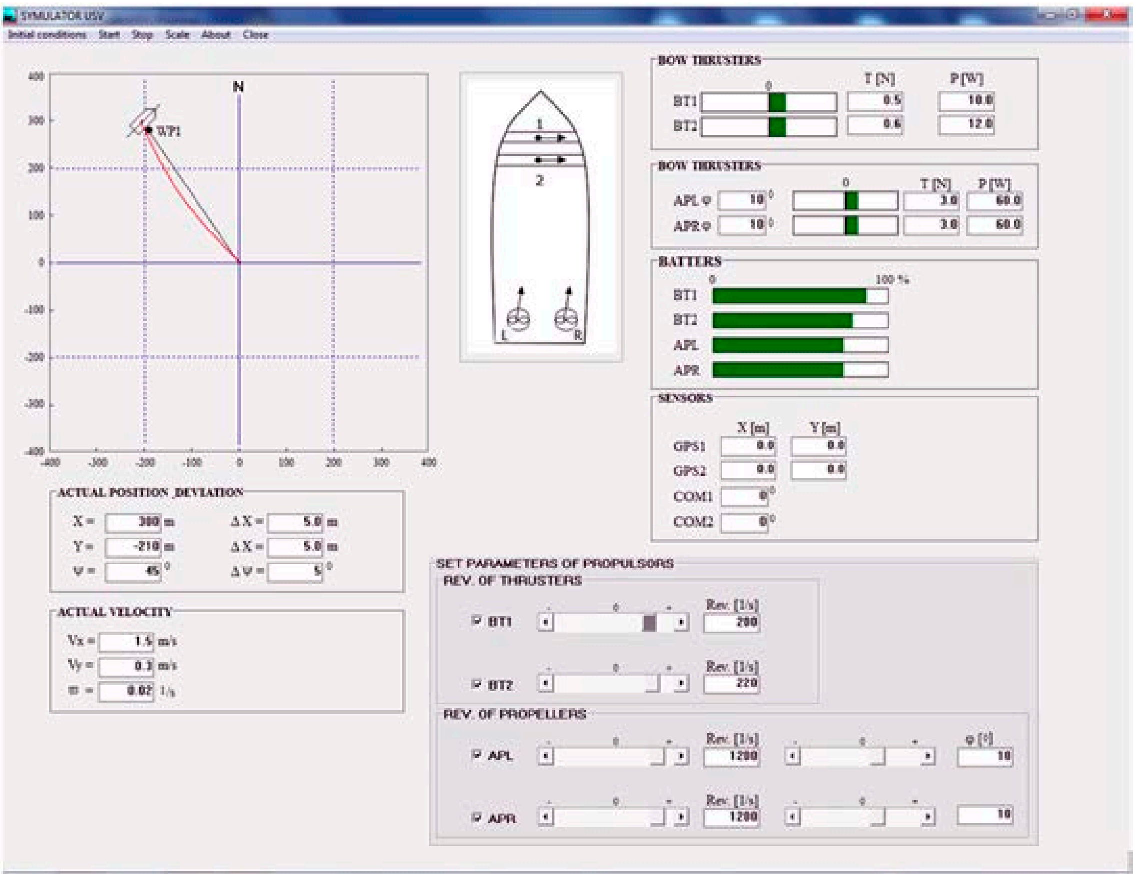

Figure 9. Visualization of a computer simulator

an unmanned ship, the following must still be determined (calculated):

- generalized hydrodynamic masses and moments – the values of these coefficients will be calculated from approximate formulas and CFD methods;
- generalized, external damping forces – calculated by CFD method;
- hydrodynamic characteristics of bow thrusters T_{BT} and stern azimuthal propellers – T_{AP} – will be measured on the ship model in the model basin.

The results of all the abovementioned calculations of the values of individual coefficients, as well as propeller characteristic measurements will be presented in subsequent publications, as well as the full simulation movement results of the unmanned ship model.

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