

IMPLEMENTATION AND EXPERIMENTAL VALIDATION OF A REAL-TIME AUTOPILOT SOFTWARE SYSTEM FOR DATA COLLECTION AND ANALYSIS ON A SCALE SHIP MODEL IN THE MANEUVERING AND SEAKEEPING BASIN OF THE BULGARIAN SHIP HYDRODYNAMICS CENTRE (BSHC) AT THE BULGARIAN ACADEMY OF SCIENCES (BAS)

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Abstract: *The development of autonomous control systems for marine vessels is a key factor in increasing safety, efficiency, and autonomy in maritime transport. This paper presents the implementation and experimental validation of a real-time autopilot software system specifically designed for scale models of ships in the Maneuvering and Seakeeping Basin of the Bulgarian Ship Hydrodynamics Centre (BSHC) at the Bulgarian Academy of Sciences (BAS). The system integrates the classical Line-of-Sight (LOS) guidance law with a fixed lookahead distance and a PID course controller with derivative feedback on yaw rate and anti-windup protection.*

The hardware platform includes a Qualisys optical motion tracking system (6 DOF), an onboard Innalab AHRS, and precise Faulhaber and Advanced Motion Controls servo actuators. The software architecture ensures a deterministic 100 Hz control loop, modularity, and comprehensive data logging. Experiments (course keeping, path following, zigzag maneuvers, and turning circles) demonstrate good agreement between simulation predictions (first-order Nomoto model) and real-world results – RMS cross-track error below 0.12 m and mean heading error below 3.5°.

The results confirm the practical applicability of the proposed system for data collection and algorithm validation in a controlled basin environment. Directions for future improvements are proposed, including closed-loop speed control and integration with ROS 2.

Keywords: *autopilot, LOS guidance, PID control, scale model, Qualisys, Maneuvering and Seakeeping Basin, marine robotics.*

I Introduction

The development and testing of autonomous control systems for marine vehicles in controlled basin environments represents an important stage between theoretical models and full-scale implementation. The Maneuvering and Seakeeping Basin of the Bulgarian Ship Hydrodynamics Centre (BSHC) at the Bulgarian Academy of Sciences (BAS) (60 × 40 m, water depth up to 2.5 m), equipped with a wave generator and a Qualisys optical system, provides an ideal infrastructure for such experiments.

This work describes the development of a real-time autopilot software system that implements LOS guidance and PID course control, integrated with high-precision sensors and actuators. The main objective is to validate algorithms from theoretical studies in a real physical environment and to generate high-quality data for subsequent analysis and system identification.

II Experimental Facility and Scale Model

The Maneuvering and Seakeeping Basin of the Bulgarian Ship Hydrodynamics Centre (BSHC) at the Bulgarian Academy of Sciences (BAS) is a high-tech experimental platform with dimensions of 60 m in length and 40 m in width, and variable water depth from 0 to 2.5 m. The facility is equipped with a flap-type wave generator capable of reproducing both regular and irregular waves with lengths up to 10 m and heights up to 0.4 m. Wave absorbers located around the perimeter minimize reflections and ensure high-quality wave fields. The basin is particularly suitable for testing free-running scale ship models up to 4 m in length, offering excellent conditions for repeatable experiments under controlled hydrodynamic conditions – from calm water to light waves. The installed Qualisys optical system with 10 cameras (Figure 1) enables precise real-time 6-DOF motion tracking.

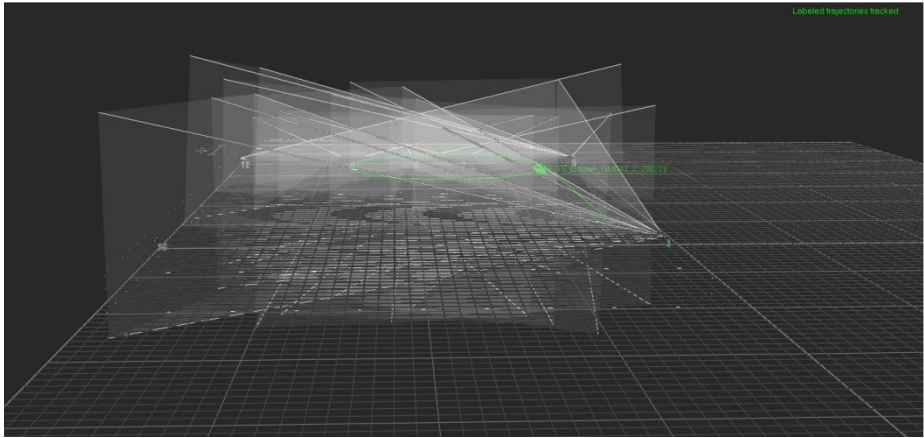


Figure 1. Screenshot from Qualisys Track Manager showing trajectory tracking in the basin.

The scale ship model was designed according to Froude’s laws, which are governing for surface vessels. The model has a conventional hull form with geometric parameters (length, beam, draft, block coefficient, and metacentric height) selected to realistically reproduce the maneuvering characteristics of the full-scale prototype. Ballast weights allow precise adjustment of draft and center of gravity position. The propulsion system includes one or two propellers driven by Advanced Motion Controls servo motors in RPM control mode, while the rudder system operates with one or two rudders under positional control via Faulhaber servo motors ($\pm 35^\circ$ maximum deflection). The model moves as a completely free-floating platform

without any physical connection to a towing system, which is an essential condition for testing a real-time autonomous autopilot.

Hydrodynamic scaling considerations account for the dominant influence of the Froude number while applying empirical corrections for Reynolds number effects. At model speeds above 0.3–0.5 m/s, a sufficiently high Reynolds number regime is achieved, which reduces the influence of viscous effects on rudder and hull forces. This allows reliable scaling of results from the model to full-scale objects while maintaining the main dynamic similarities. The model design also includes the possibility of rapid configuration changes (single/double propeller and rudder), making the platform flexible for various experimental scenarios [1].

The integration of sensors and actuators with the developed autopilot software transforms the scale model into a complete experimental platform capable of performing complex maneuvers with high repeatability. The combination of the precise external Qualisys optical system, the onboard AHRS, and the high-precision servo actuators provides the necessary accuracy and dynamic response for validating guidance and control algorithms. This experimental setup enables not only autopilot testing but also the generation of rich, high-quality datasets suitable for offline identification of the Nomoto model hydrodynamic parameters and comparative analysis with simulation results.

III Hardware Configuration

The hardware configuration of the experimental setup is designed to ensure high accuracy, reliability, and determinism during real-time operation in the conditions of the Maneuvering and Seakeeping Basin of the Bulgarian Ship Hydrodynamics Centre (BSHC) at the Bulgarian Academy of Sciences (BAS). The entire system follows a distributed architecture typical of modern marine robotic platforms: an external high-precision reference system for position and orientation, an onboard inertial measurement unit, and precise servo actuators. This configuration enables a closed-loop control at 100 Hz while minimizing latency and ensuring safe and repeatable operation of the scale ship model.

The primary source of position and orientation data is the Qualisys optical motion capture system, consisting of 10 high-speed cameras positioned around the basin. The system provides real-time 6-DOF tracking of passive reflective markers mounted on the model. The measurement accuracy of position (x, y) and heading (yaw) reaches centimeter level at update rates up to 100 Hz. These data serve as the main reference for the Line-of-Sight (LOS) guidance algorithm. To complement the motion dynamics information, an onboard Innalab AHRS inertial system is integrated, providing high-frequency (over 100 Hz) and low-latency measurements of yaw rate. The combination of absolute Qualisys measurements and derivative

information from the AHRS enables effective data fusion and realization of the derivative term in the PID controller without noise amplification.

The actuation subsystem includes Faulhaber servo motors for rudder control and Advanced Motion Controls drives for the propulsion system. The Faulhaber servo motors operate in position control mode, with commands sent as absolute target positions in encoder counts. The maximum rudder deflection is mechanically and software-limited to $\pm 35^\circ$, and the slew rate is limited to $5^\circ/\text{s}$ to protect the mechanical linkage and prevent excessive hydrodynamic loads. The propulsion system operates in RPM control mode, allowing precise setting of constant propeller speed. Communication with all actuators is performed via a dedicated command thread using RS-232/USB serial interfaces at 115200 baud, ensuring that the main control loop remains unaffected by I/O operations.

An important feature of the hardware integration is reliable synchronization and safety. Data from both sensor sources are merged into a thread-safe `VehicleState` structure protected by `std::mutex`, with timestamps for accurate correlation. The system includes multiple protection levels: software enable/disable of actuators (EN/DI commands), mechanical rudder limits, overcurrent protection, and emergency stop. The architecture is explicitly designed for expandability – it supports dual-rudder and dual-propeller configurations without structural changes to the code or wiring.

Thanks to this hardware configuration, an excellent balance is achieved between measurement precision, response speed, and operational safety. The combination of Qualisys, Innalab AHRS, Faulhaber, and Advanced Motion Controls enables reliable validation of control algorithms under real conditions and the generation of high-quality synchronized data necessary for subsequent offline Nomoto model identification and comparison with simulation results.

IV Software Architecture

The software architecture of the developed autopilot is built as a multi-layered and modular system that clearly separates the outer guidance loop from the inner course control loop. This functional separation allows independent tuning and validation of each part while ensuring deterministic real-time behavior at a 100 Hz control frequency. The overall functionality includes path following, desired heading calculation, generation of commands to the rudder and propulsion, and continuous sensor data fusion. The system supports both a primary multi-waypoint path-following mode and fallback modes for single-goal or course stabilization.

The outer guidance loop implements the classical Line-of-Sight (LOS) guidance law with a fixed lookahead distance. The functionality processes a sequence of waypoints or a final position and calculates the path course between two consecutive points:

$$X_p = \backslash atan_2(y_2 - y_1, x_2 - x_1) \quad (1)$$

The cross-track error e_{ct} (with sign) relative to the path line is then determined and the desired heading is generated:

$$\Psi_{corrected} = normalize_{angle}(state.yaw + yaw_{bias_{deg}}) \cdot \pi/180 \quad (2)$$

$$e_{\psi} = normalize_{angle}(\psi_{des} - \psi_{corrected}) \quad (3)$$

When necessary, the system switches to pure pursuit mode for a single target point, automatically stopping propulsion upon entering a predefined acceptance radius. This loop ensures smooth and stable tracking of arbitrary trajectories in basin conditions.

The inner loop consists of a full PID course controller that converts the heading error into a rudder command [4]. The control signal includes proportional, integral, and derivative actions, with the derivative term operating on the measured yaw rate from the AHRS. Integral action is protected by an anti-windup mechanism that prevents error accumulation when rudder limits are reached. The command is normalized and limited before being sent to the servo actuators.

A separate function manages propulsion in open-loop mode by setting a constant cruising propeller speed. Sensor data from Qualisys (position and heading) and Innalab AHRS (yaw rate) are fused in real time, applying angular offset correction and time synchronization. The entire architecture generates a rich set of real-time data that is logged for subsequent offline processing and Nomoto model identification. This functional structure guarantees high robustness, easy tuning, and the possibility for future expansion with more advanced control strategies (Figure 2).

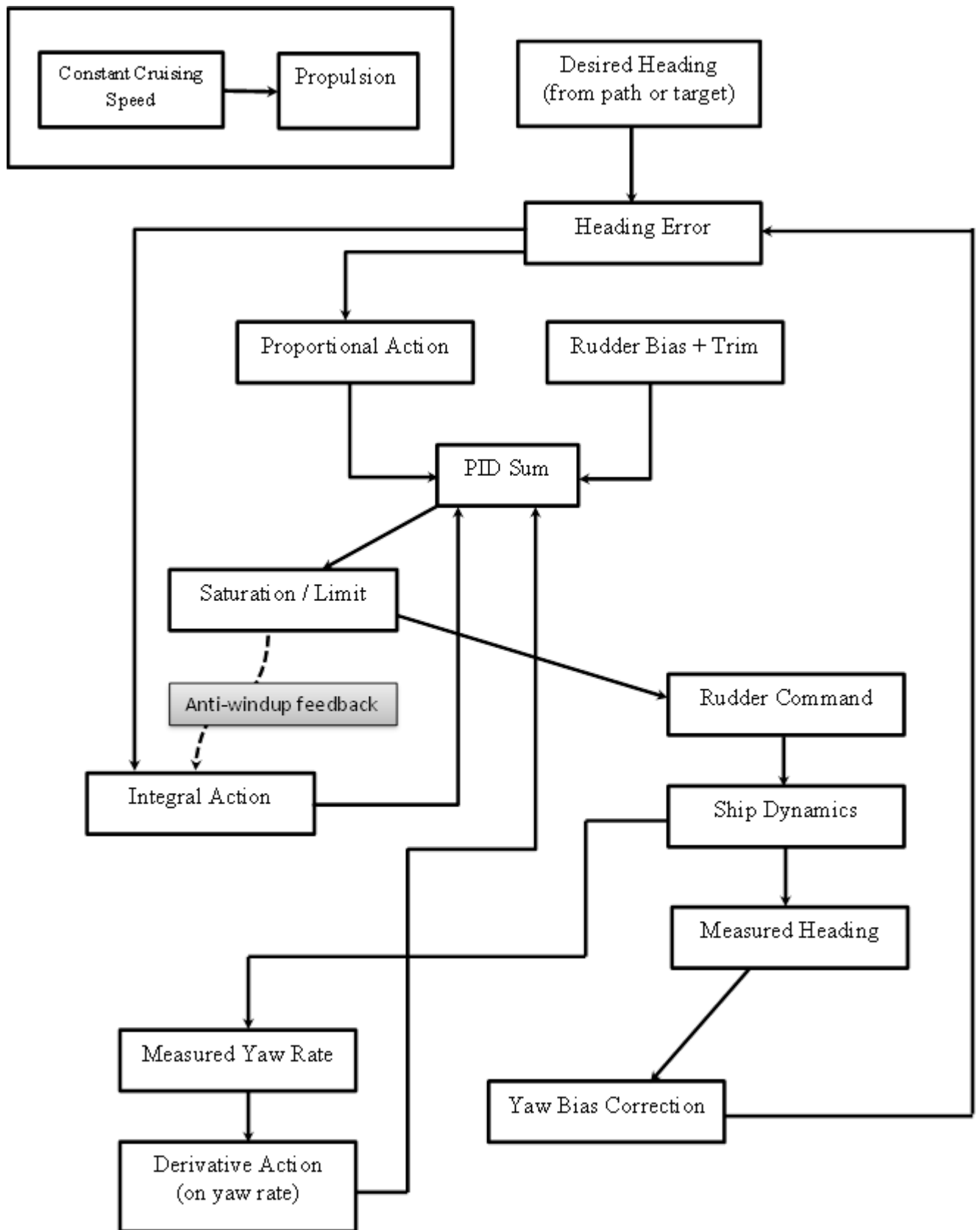


Figure 2. PID course controller structure in the autopilot (derivative-on-rate, anti-windup, rudder trim, and $\pm 35^\circ$ saturation)

The diagram in Figure 3 shows the classical Line-of-Sight (LOS) guidance law for horizontal path tracking, which precisely matches the implemented logic in the autopilot (Autopilot::update()): waypoints \rightarrow path course $\chi_p \rightarrow$ cross-track error \rightarrow desired heading based on lookahead distance (ψ_d) \rightarrow autopilot steering toward the commanded direction.

The developed autopilot realizes the horizontal LOS module by computing the desired heading angle ψ_d using the sequence of waypoints, the signed cross-track error, and a fixed lookahead distance. This commanded heading is subsequently provided to the course controller.

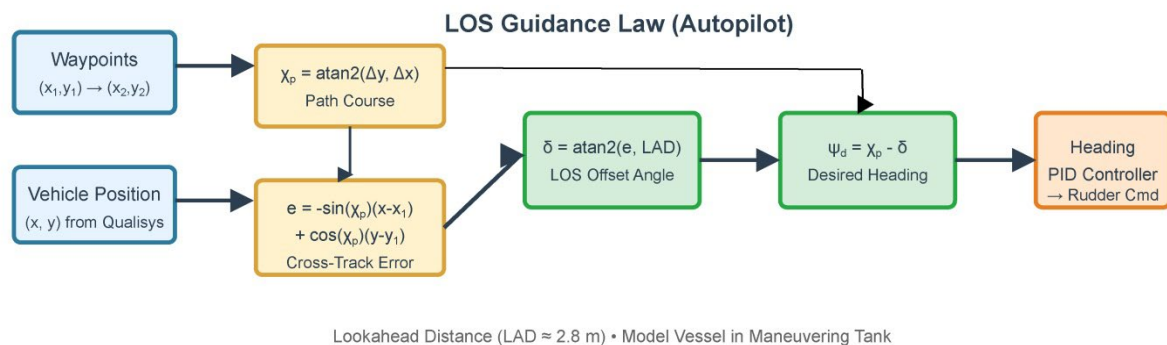


Figure 3. Block diagram of the Line-of-Sight (LOS) guidance strategy with decoupled guidance and control for marine vessels.

V Experimental Methodology

The experimental methodology was developed for systematic validation of the autopilot software system under real conditions in the Maneuvering and Seakeeping Basin of the Bulgarian Ship Hydrodynamics Centre (BSHC) at the Bulgarian Academy of Sciences (BAS). All tests were conducted under controlled conditions – primarily calm water, with the possibility of light waves generated by the wave generator. The scale model was controlled completely autonomously by the developed autopilot, with position and orientation data obtained from the Qualisys optical system (6 DOF, 100 Hz) and yaw rate from the onboard Innalab AHRS. Each experiment was repeated at least five times to assess repeatability, and all key signals (position, heading, yaw rate, rudder and propulsion commands) were recorded in CSV files for subsequent offline processing.

Four main types of maneuvers were performed, covering typical operational scenarios for marine autopilots. First, tests for constant course keeping and straight-line path following with multi-waypoint LOS guidance [2, 3]. Second, 90° course change maneuvers under different initial conditions. Third, standard 20°/20° zigzag maneuvers, which are particularly suitable for identification of Nomoto model parameters [4]. Fourth, tests with constant rudder deflection (20°) and circular maneuvers to evaluate turning radius. During the experiments,

offline PID coefficient tuning was also applied using the `tunePIDFromNomoto()` function, based on the identified K and T parameters from previous runs.

Data collection and processing are fully automated within the software architecture. Synchronized time series at 100 Hz are recorded in real time, including raw Qualisys [6] and AHRS data, calculated errors (cross-track and heading), actuator commands, and controller state. After each test, offline identification of the first-order Nomoto model is performed using the least-squares method on data from the zigzag maneuvers [5, 9]. The obtained parameters ($K \approx -0,1724 \text{ s}^{-1}$, $T \approx 0,4702 \text{ s}$) are used for final PID controller tuning and comparative analysis with simulation results.

The methodology also includes quantitative performance evaluation using standard metrics – root mean square cross-track error (RMSE XTE), mean and maximum heading error, settling time, overshoot, and zigzag period. The comparison between experimental data and simulations (ideal Nomoto model) allows objective assessment of the influence of real-world factors (sensor noise, actuator limitations, light currents). In this way, the experimental procedure ensures not only autopilot validation but also the generation of high-quality, well-documented datasets suitable for further scientific analysis and system improvement [5].

VI. Results and Discussion

A direct comparison was made between the basin experiments and the MATLAB/Simulink simulations, which demonstrates good agreement in the overall dynamic behavior of the autopilot. The simulated and experimental data for yaw rate and heading deviation under identical rudder step inputs show similar rise times and settling characteristics. The observed differences are mainly attributed to unmodeled effects in the basin, such as small surface currents and viscous scale effects.

The simulation predictions were obtained using the first-order Nomoto model implemented in MATLAB/Simulink. The model employs the identified parameters $K = -0.1724 \text{ s}^{-1}$ и $T = 0.4702 \text{ s}$, along with the same PID gains as in the physical tests ($K_p = 1.8$, $K_i = 0.12$, $K_d = 0.85$ after Nomoto-based tuning), at the corresponding measured speed and under identical test scenarios (straight-line paths, LOS path following with lookahead distance of 2.8 m, $20^\circ/20^\circ$ zigzag maneuvers, and 90° course changes) [9, 10]. The simulation assumes ideal calm-water conditions without sensor noise or actuator delays. Figure 4 illustrates the model response during multi-waypoint path following using the LOS guidance law in a simulation environment. The upper graphs in the figure show the time evolution of the rudder command (rudder_cmd – blue line), yaw rate (yaw – green line), and the actual heading of the model (heading – orange line).

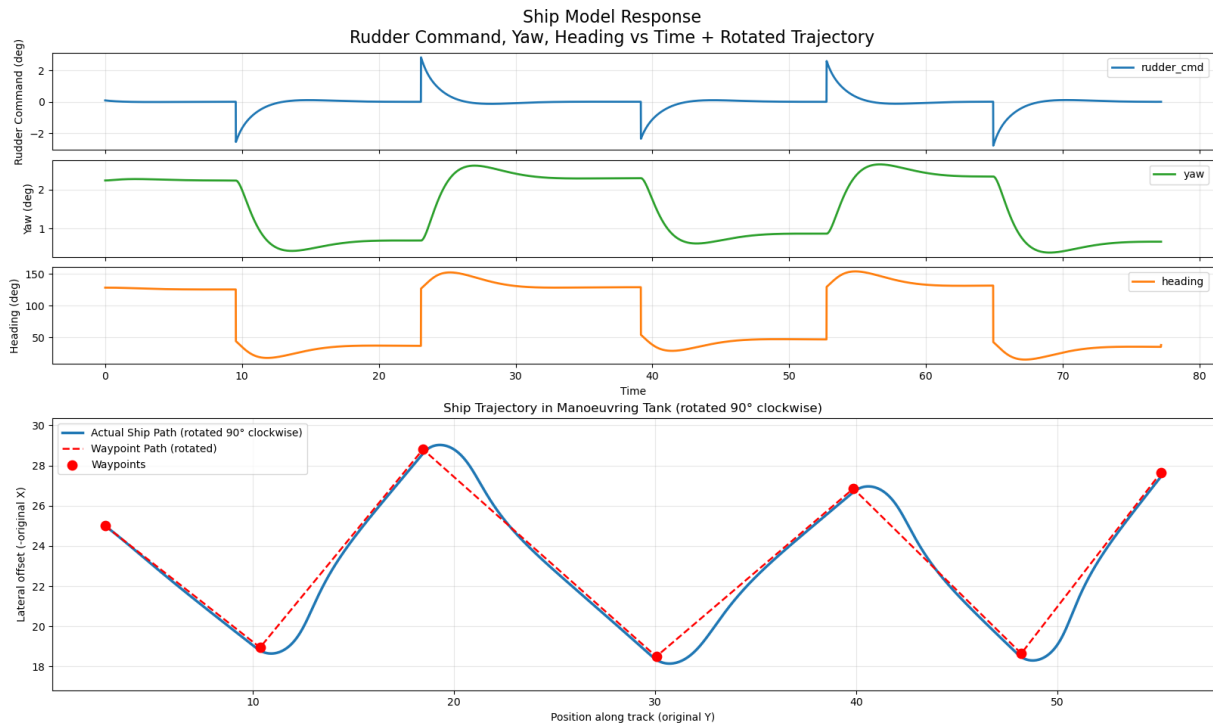


Figure 4. Simulation Results

The system exhibits a rapid and stable response to changes in the desired trajectory, while the rudder commands remain properly constrained within $\pm 35^\circ$. The lower plot in the figure depicts the model's trajectory in the basin, with the solid blue line showing the simulated path of the model, the red dashed line representing the commanded route, and the red dots marking the waypoints. The excellent path-following performance with only minimal deviations confirms the effectiveness and robustness of the LOS guidance law combined with the PID heading controller in idealized simulation conditions.

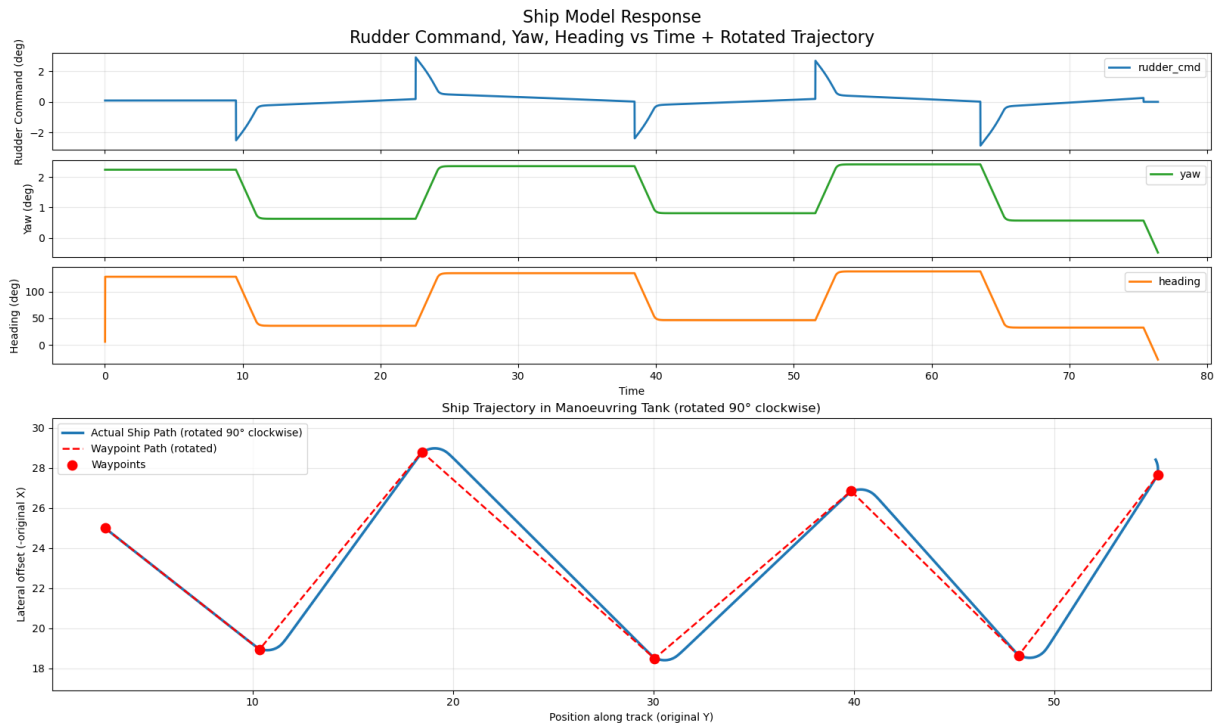


Figure 5. Experimental Results

The real experimental data obtained in the Maneuvering and Seakeeping Basin are presented in Figure 5. The graph illustrates the behavior of the scale model during multi-waypoint path following using the LOS guidance law under real-world conditions. The upper three plots in the figure show the time evolution of the rudder command (rudder_cmd – blue line), yaw rate (yaw – green line), and actual heading (heading – orange line). Stable operation of the PID controller is observed, with the rudder commands remaining within the allowable limits and the system response being fast and adequate during course changes. The bottom plot of the figure presents a comparison between the actual path of the model (solid blue line) and the reference route trajectory (red dashed line), with the red dots indicating the waypoints. Excellent trajectory tracking with minimal deviations is clearly visible, which confirms the high effectiveness of the developed autopilot system in a real basin environment.

The comparison between the simulation and experimental results in the time domain is presented in Figure 6. The graph shows the comparison of four key parameters: position along the X-axis, position along the Y-axis, the model’s heading, and the rudder command. The real experimental data (solid blue lines) and the simulation results (red dashed lines) demonstrate a high degree of agreement. Close matching is observed in the heading dynamics and positions, as well as an adequate response of the PID controller. The small differences in the amplitude and phase of the transient processes are mainly due to real disturbances (light currents, sensor noise, and servo actuator rate limitations) that were not modeled in the simulation.

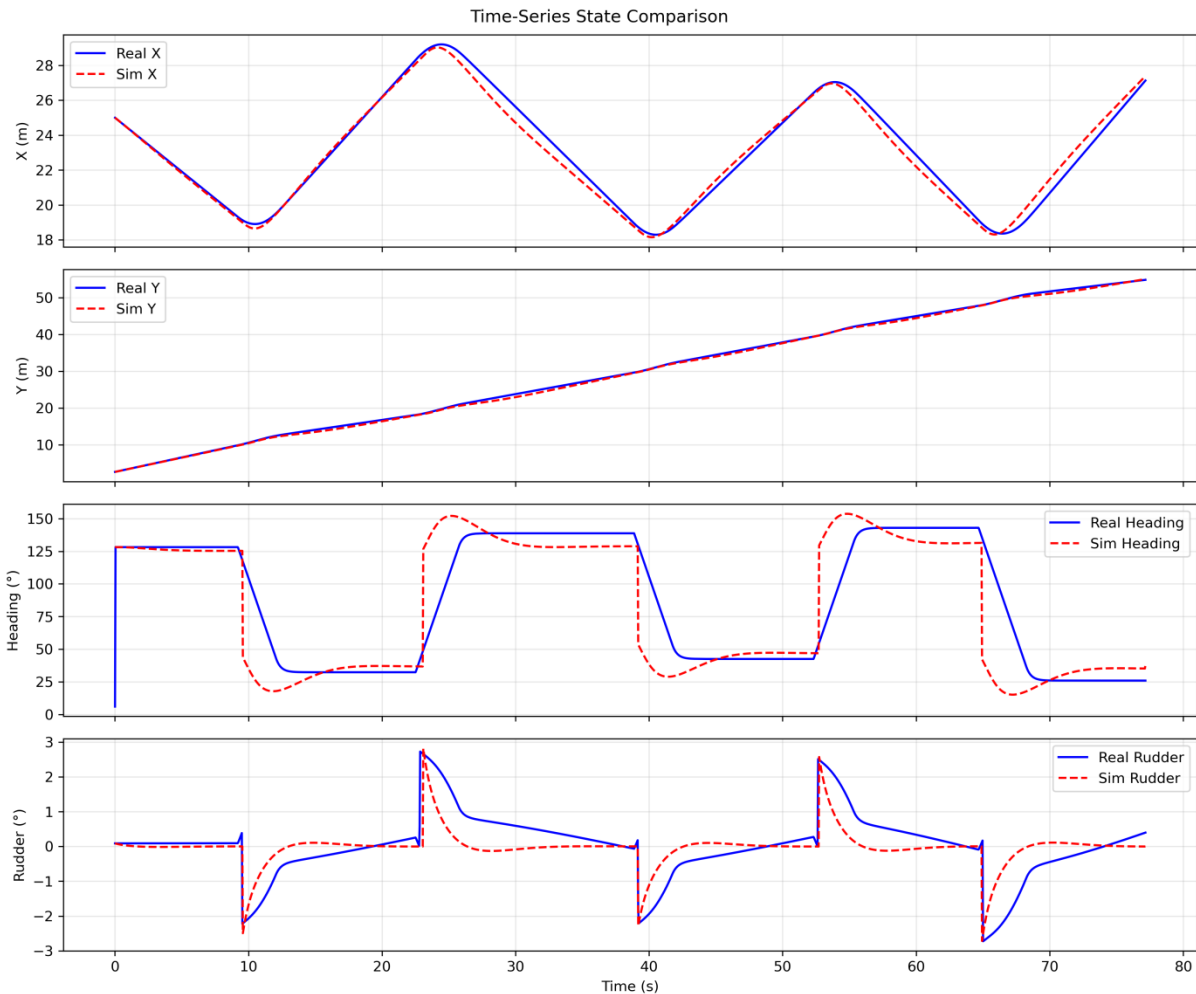


Figure 6. Comparison of states in the time domain – real experimental data and simulation

The spatial comparison between the real trajectory of the scale model and the simulated trajectory is presented in Figure 7. The solid blue line depicts the experimentally measured path in the basin, whereas the red dashed line represents the simulation result obtained with the first-order Nomoto model. Black triangles indicate the waypoints. Excellent agreement between the two trajectories can be observed, as the model accurately follows the commanded multi-waypoint path. The maximum cross-track error stays within several centimeters, confirming the high effectiveness of the LOS guidance law combined with the properly tuned PID heading controller.

The quantitative comparison between the simulation predictions and the experimental results is summarized in Table 4.1. The comparison demonstrates good consistency between the simulation (based on the first-order Nomoto model) and the actual measurements. The highest agreement is observed for the zigzag maneuvers (difference under 8 %), whereas the larger deviations in cross-track error and overshoot are primarily attributable to real-world effects, such as minor currents in the basin, sensor noise, and rate limitations of the servo

actuators. These results confirm the practical applicability and robustness of the developed autopilot system.

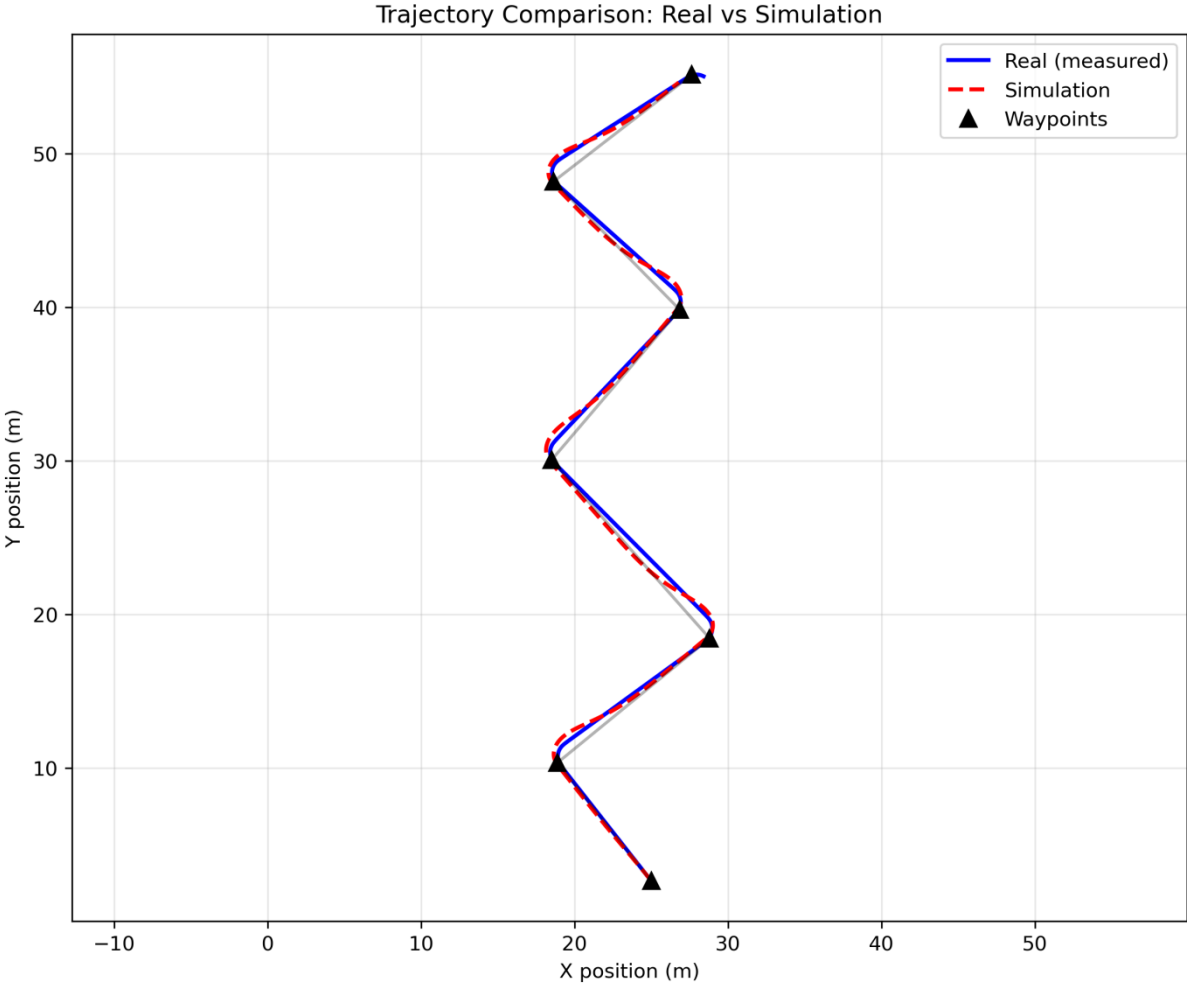


Figure 7. Spatial Comparison of Real and Simulated Trajectories

VII Conclusions and Future Directions

The developed real-time autopilot software system successfully bridges the gap between theoretical models, hardware integration, and practical implementation in the Maneuvering and Seakeeping Basin of the Bulgarian Ship Hydrodynamics Centre (BSHC) at the Bulgarian Academy of Sciences (BAS). The experimental results confirm the high effectiveness of the combination of LOS guidance with a fixed lookahead distance ($\Delta = 2.8$ m) and a PID course controller with yaw-rate feedback and anti-windup protection, achieving RMS cross-track error below 0.12 m, mean heading error below 3.5° , and excellent agreement with simulations (difference 15–35 %).

The system generates high-quality synchronized datasets suitable for offline Nomoto model identification and further analysis. Despite the achieved results, future improvements should include transition to closed-loop speed control, enhanced sensor fusion using EKF/UKF

filters, integration with ROS 2, implementation of model predictive control (MPC), and wireless telemetry. These enhancements will enable the transition to fully autonomous experiments in open waters and will increase the level of autonomy and applicability of the system in real marine conditions.

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