Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 8, No.2, April 2026, pp. 0260206-01 ~ 0260204-08
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v8i2.2739

Design and Experimental Evaluation o`f a PID Based Ship Rudder Control Prototype Referenced to SOLAS

Arif Rakhman Suharso[1], Ario Hendartono[2*], Amthori Anwar[3], Slamet Supriyadi[4]

[1]Department of Engineering, Politeknik Maritim Negeri Indonesia, Wringin Putih Village, Bergas District, Semarang Regency 50552, Central Java, Indonesia

[2]Department of Nautical, Politeknik Maritim Negeri Indonesia, Wringin Putih Village, Bergas District, Semarang Regency 50552, Central Java, Indonesia

[3]Department of Nautical, Politeknik Maritim Negeri Indonesia, Wringin Putih Village, Bergas District, Semarang Regency 50552, Central Java, Indonesia

[4]Faculty of Engineering and Informatics, University of PGRI Semarang, East Sidodadi, Dr. Cipto Street 24, Karangtempel, East Semarang District, Semarang City 50232, Central Java, Indonesia

*ariohend@polimarin.ac.id

Abstract. The Proportional–Integral–Derivative (PID)-based ship rudder control system is an effective method for maintaining a vessel's heading automatically. This study aims to design and evaluate a ship rudder control prototype in accordance with SOLAS safety standards. The research method employed is Research and Development (R&D), which includes needs analysis, system design, prototype development, and model testing. The cargo ship prototype is equipped with an HMC5883L compass sensor, an Arduino microcontroller, and a servo motor as the rudder actuator. Data processing and PID algorithm implementation are carried out using Visual Basic software. The PID parameters used are Kp = 0.001, Ki = 0.001, and Kd = 0.2, obtained through a tuning process. Testing was conducted in a controlled pool under calm water conditions. The results show that the system achieves a steady-state condition in an average time of 21 seconds with minimal overshoot and small deviation from the setpoint, while complying with the SOLAS requirement of a maximum rudder angle of 35°.

Keywords: PID controller, HMC5883L, rudder control, SOLAS, Arduino.

(Received 2025-09-15, Revised 2025-11-04, Accepted 2026-01-29, Available Online by 2026-03-31)

1. Introduction

Ships are indeed a vital mode of transportation, and they are now increasingly equipped with automated control systems that incorporate technologies such as navigation systems, sensors, and artificial intelligence to enhance efficiency, safety, and autonomy. These systems monitor and regulate parameters such as temperature, pressure, and fluid flow, while also providing precise navigation capabilities to avoid obstacles and determine positioning. Automation contributes to reducing operational costs, minimizing fuel consumption, and optimizing sailing routes [1]. One of the most established and effective approaches for regulating a system's response to input variations is the Proportional–Integral–Derivative (PID) control system. PID control is widely used in automatic control applications due to its robustness and simple implementation. The PID algorithm maintains the system at a specified setpoint by adjusting the output variable based on the error value, defined as the difference between the setpoint and the measured input [2].

This research involves testing a ship's rudder control system using a cargo-ship prototype [3]. According to SOLAS Regulation 29, Section 3.2 concerning steering gear requirements, the steering system must be capable of "putting the rudder over from 35° on one side to 35° on the other side with the ship at its deepest seagoing draught and running ahead at maximum ahead service speed and, under the same conditions, from 35° on either side to 30° on the other side in not more than 28 seconds [4]. This study expands upon previous work conducted by the research team in 2022, which compared the performance of potentiometer and rotary encoder sensors for rudder position measurement in a ship steering simulation [5]. Further research in 2024 examined the mechanical capability of the MG995 servo motor to actuate the rudder under varying load conditions, confirming that the servo motor can handle a rudder load of up to 9 kg, making it suitable for use in this study [6]. The ship steering control system using the PID method has been investigated in previous studies, including mathematical simulations of PID parameter calculations for ship autopilot control employing two PID controllers [7]. MATLAB/Simulink simulations were conducted to compare and verify the disturbance rejection and harmonic suppression capabilities of the improved control strategy to address the control performance and harmonic suppression issues in maritime vessel rudder permanent magnet servo systems, a fractional-order PID controller was introduced into the existing improved repetitive control strategy [8]. The application of PID control to servo motors for heading control on Autonomous Surface Vehicles (ASVs) for surveillance purposes [9], and the implementation of microcontrollers for zig-zag rudder actuation during fast-boat testing [10]. The implementation of a PID controller in ship simulation employs the Maneuvering Modeling Group (MMG) method based on hydrodynamic derivatives, as well as autonomous navigation simulation using Computational Fluid Dynamics (CFD), to simulate ship navigation under wave conditions [11]. Despite the extensive research on PID-based ship control systems, there is still a need to incorporate SOLAS steering safety regulations to ensure compliance with international maritime safety standards.

2. Methods

In this research methodology section, the content includes needs analysis, product design, system and model development, and product testing. The research method applied research and development (R&D), which consisted of designing the product, developing the ship prototype and PID control system, and conducting prototype testing to obtain research data. The first stage was the needs analysis, where the cargo ship model was required to have an autopilot steering system that allowed the vessel to follow a predetermined route. Therefore, research was needed to evaluate the PID control performance using a cargo ship prototype while referring to the SOLAS regulations. To establish a strong theoretical foundation for the PID-based ship steering control system, a literature review and analysis of previous related studies were conducted. The second stage was product design. This stage involved analyzing and designing the maneuvering control model using the PID method. It also served as the initial step in determining the product design of the cargo ship steering control system using PID control.

The third stage involves system and model design, in which the development of the ship maneuvering model using the PID method consists of the Visual Basic and Arduino IDE software. The Visual Basic software is utilized for the PID controller, while the Arduino IDE software is employed to program the Arduino. The microcontroller used in this study to operate the servo for rudder actuation is an Arduino, which can be easily programmed, erased, and reprogrammed, making it highly suitable for control system development [12]. A servo motor is an electromechanical device commonly used in intelligent industrial systems to push or rotate objects with high precision in terms of angular position, acceleration, and speed capabilities that conventional motors do not possess. The servo motor used in this research is a DC servo motor connected directly to the ship's rudder [13].The HMC5883L compass sensor and the Proportional–Integral–Derivative (PID) control method are utilized simultaneously to automatically guide the vessel along a predefined route by using directional data for continuous course correction [14]. The software used to develop the control interface is Visual Basic. Visual Basic provides a graphical interface that displays vessel movement, rudder position, and servo operation in real time [15]. The PID algorithm is employed in this automatic steering system to maintain a stable heading based on compass readings [16]. As a result, the ship's rudder adjusts automatically toward the desired heading through PID control executed via the Visual Basic interface [17].

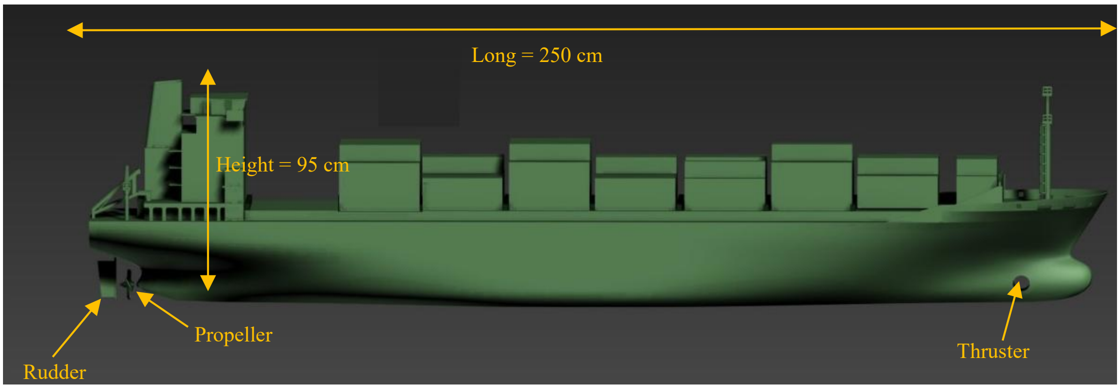

Figure 1. Ship Prototype

The prototype used in this study was a cargo ship model, representing a vessel designed to transport goods and cargo from one port to another. The prototype was equipped with an autopilot system that enables vessel operation with minimal human intervention. Several key components were integrated into the prototype, including an Arduino microcontroller, a digital compass sensor, a 12-volt battery, a 12-volt DC motor for propeller actuation, and an MG995 servo motor to drive the rudder. The DC motor used for propulsion operates at a rated speed of 12,000 rpm. The prototype has a length of approximately 250 cm and a height of 60 cm, built at a 1:160 scale relative to the actual vessel size. The model is designed to float and operate similarly to a real ship. The prototype operates at a moderate speed, reflecting the characteristics of a cargo vessel, which typically travels at slow speeds due to cargo load, with a maximum velocity of approximately 4 knots. The dimensions were adjusted to maintain proportionality with a real cargo vessel while enabling experimental evaluation in a test basin. The use of this ship prototype was essential for evaluating the autonomous steering system, allowing observation of how the PID-based autopilot adjusts rudder movement according to compass readings. The prototype enables real-world testing of the automatic steering mechanism using a scaled cargo ship model. The final stage is the model testing phase, in which hhe data collection technique used in this research involves recording and observing the test results of the ship maneuvering model using the PID method. The testing was conducted in a towing tank, where data were collected from the prototype ship operating under PID control along a predetermined path in calm water and wind conditions.

3. Results and Discussion

The Proportional–Integral–Derivative (PID) controller implemented in this study processes data using Visual Basic software. The controller continuously calculates an error value, which is defined as the difference between the desired setpoint and the actual heading obtained from the compass sensor [18]. For the hardware configuration, the monitoring and control system consists of a computer that executes the PID algorithm through Visual Basic, an Arduino microcontroller that functions as the interface between the computer and the servo motor, and a servo motor that actuates the rudder automatically based on control signals received from the computer according to compass sensor readings [19]. The expected output of this system is a PID-based control model applied to the cargo ship prototype, operating in compliance with SOLAS steering regulations. The conceptual model of the system can be illustrated as follows:

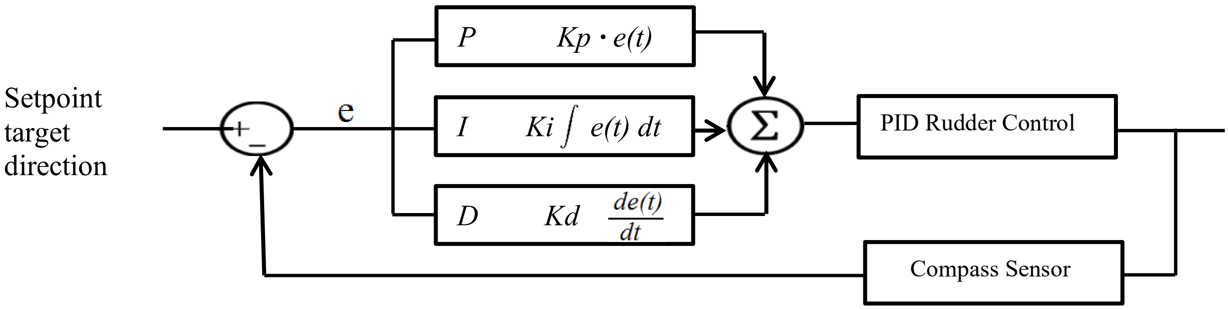

Figure 2. System Design and Model

The computer-based control system is developed using Visual Basic software, where the PID control logic is designed based on heading data obtained from the HMC5883L compass sensor. The sensor data is transmitted through an Arduino microcontroller to the computer via a USB connection. During testing, data communication occurs bidirectionally: Visual Basic sends control signals to the Arduino to drive the servo motor, and the Arduino sends real-time compass sensor data back to the Visual Basic interface. The compass sensor produces an output value ranging from 0° to 360°, representing the vessel's heading. Prior to implementation, calibration is performed by comparing the digital compass reading with a manual compass to ensure directional accuracy. Within the Visual Basic interface, parameter fields are provided for displaying the compass heading, setpoint, PID constants (Kp, Ki, Kd), as well as calculated values for error, error accumulation (integral), and error change rate (derivative) [20]. These parameters are processed using the PID control formula to generate a final control output, which determines the rudder angle. To comply with steering gear safety requirements, the rudder correction angle is constrained to a maximum of 35°.

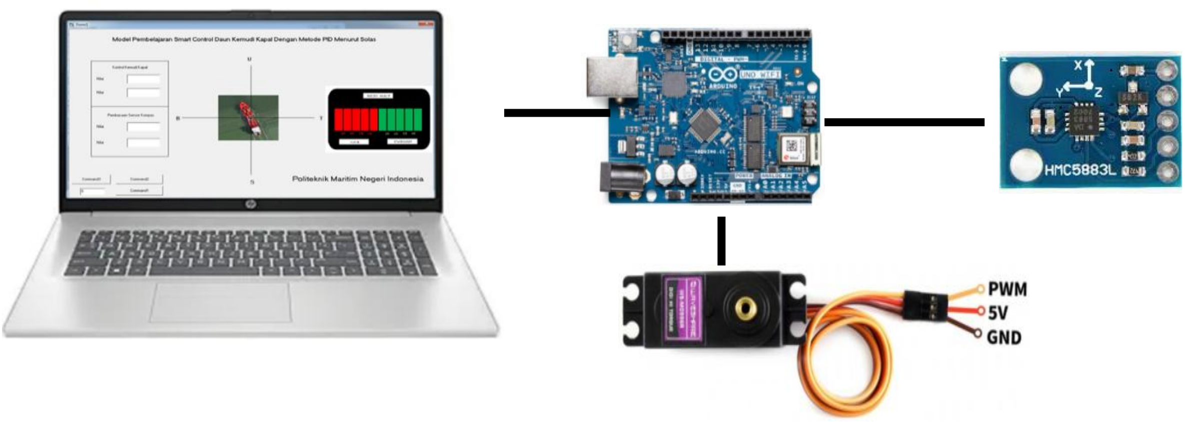

Figure 3. Hardware Design

The equipment testing was carried out by navigating the ship along a predetermined trajectory in a testing pool [21]. This experiment aimed to ensure that the controller developed in the computer software was capable of controlling the ship's motion according to the predetermined set point using the PID method, at a maximum ship speed of 4 knots and under the maximum depth condition. The term deepest draught refers to the maximum depth of the ship, measured from the keel (the bottom of the ship) to the water surface.

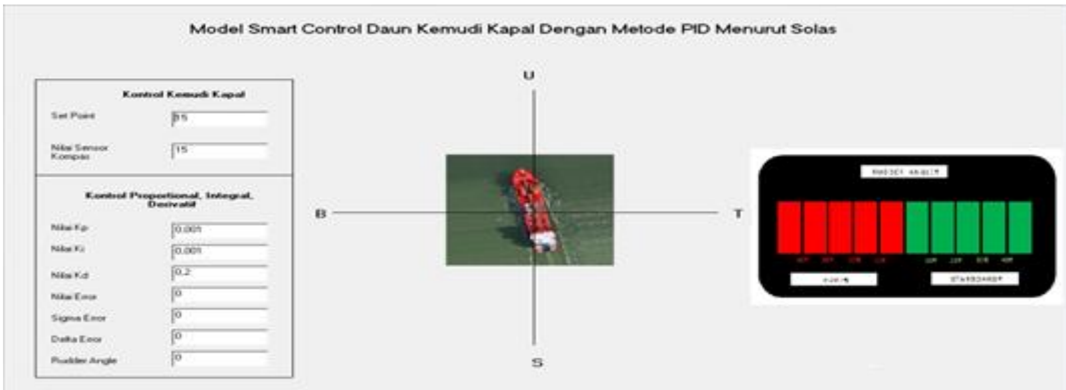

Figure 4. Software Design

This parameter indicates how deeply the ship is submerged, which increases as the vessel carries more cargo. The cargo ship prototype was tested in a towing tank using PID control parameters of Kp = 0.001, Ki = 0.001, and Kd = 0.2, with reference to SOLAS Regulation 29, Section 3.2 regarding steering gear performance, under maximum speed and maximum loading conditions. These PID values were determined through iterative tuning, ensuring that when the maximum error of 360° occurs (derived from the difference between the setpoint and the compass sensor reading), the resulting PID output approaches 35°, which corresponds to the maximum allowable rudder angle based on SOLAS requirements. Compared to previous studies, this research incorporates safety regulations into the PID steering control test. Earlier works applied PID for ship steering simulation and introduced algorithms to limit the rudder angle [22]. PID-based actuator control on an unmanned vessel prototype was also tested under dynamic environmental conditions [23]. Mathematical simulation using Particle Swarm Optimization (PSO) was applied to design an optimal PID controller while considering system constraints such as rudder angle saturation [24]. Furthermore, intelligent rudder optimization using a genetic algorithm has been implemented on a PID controller, with simulation results presented for multiple ship speeds [25].

Figure 5. Equipment Testing

Compass sensor testing was performed to compare the directional readings between a manual magnetic compass and the HMC5883L digital compass sensor. The test was conducted using the serial monitor feature in the Arduino IDE software by comparing the readings from the manual compass with the numerical output generated by the HMC5883L sensor. In the Arduino IDE, the sensor outputs values ranging from 0 to 360 degrees when rotated through a full 360 degree turn. These values were then aligned with the manual compass readings to determine the correct angle for each cardinal direction. After calibration, the compass sensor was connected to the Arduino and laptop for testing on the ship prototype in the test basin. During the navigation test with a target heading toward the south, the PID control parameters used were Kp = 0.001, Ki = 0.001, and Kd = 0.2. When the compass sensor indicated a heading of 105 degrees (north), the set point was assigned with a value of 105 as the desired target heading. This resulted in a heading error of 180 degrees, producing a PID rudder output of 72 degrees from the proportional component (Kp). Since the maximum rudder angle is limited to 35 degrees in both starboard (right) and port (left) directions, any PID output exceeding this value was constrained to the maximum allowable rudder angle. A positive rudder output indicates motion toward the starboard side, while a negative value indicates movement toward the port side. The servo motor (MG995, 9 kg torque) requires approximately 1 second to move the rudder from the neutral position to the maximum angle of 35 degrees in either direction.

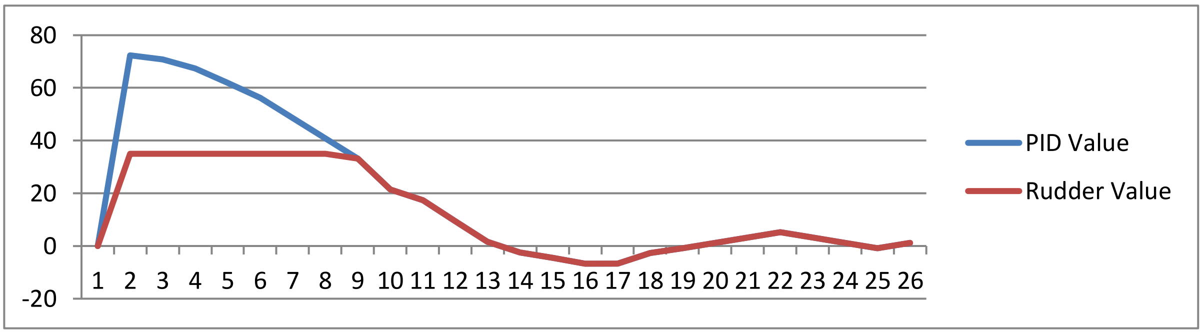

Figure 6. Rudder Test Results

The actual heading value from the compass sensor initially shifts from 105° toward the desired setpoint of 285°, resulting in a maximum overshoot of 7°. The vessel reaches a stable condition (steady state) at 21 seconds. In the Visual Basic program, the control algorithm is designed to determine the shortest rotation path: if the error value (setpoint minus the compass heading) is less than 180°, the vessel turns to starboard; if the error value exceeds 180°, the vessel turns to port. Based on five experimental trials, the system achieved an average time of 21 seconds to reach steady state with a small error margin, even under the maximum error condition of 180°.

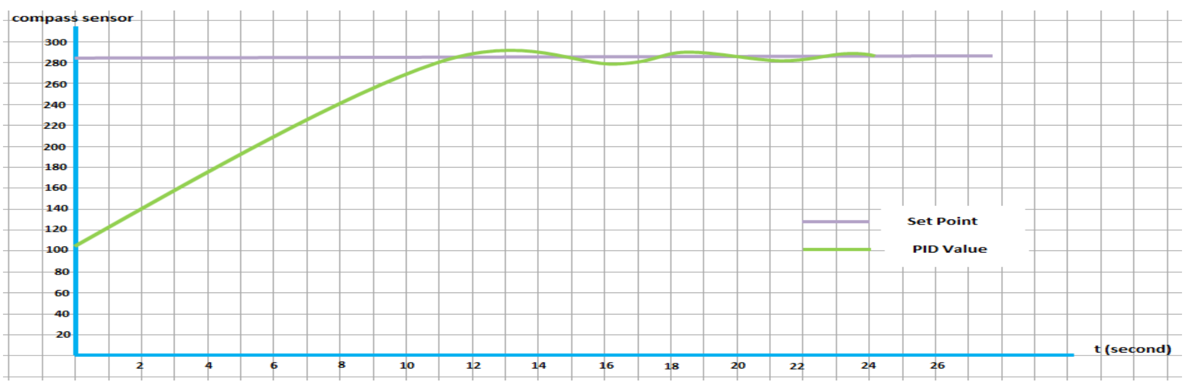

Figure 7. Ship Direction Test Results

4. **Conclusion**

Based on the results and analysis of the rudder movement response using PID control with parameters Kp = 0.001, Ki = 0.001, and Kd = 0.2, it can be concluded that the vessel is able to adjust its heading to the designated setpoint using feedback from the compass sensor. The system reads the compass sensor value and the vessel's heading through the Visual Basic interface, achieving the desired heading at the 13th iteration step with an average time of 21 seconds. The PID steering test meets the requirements of SOLAS Regulation 29, Section 3.2 regarding steering gear performance at a maximum speed of 4 knots and under maximum load conditions, with the rudder deflection limited to 35 degrees and a maximum actuation time of 1 second. The experiment was conducted in a controlled test basin with calm water and minimal wind disturbance. Future experiments will include variations in current direction and wind influence to evaluate the system's performance under more dynamic environmental conditions.

Declaration of AI and AI assisted technologies in the writing process

The authors declare that no artificial intelligence (AI) tools were used in the writing, editing, analysis, or preparation of this manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their sincere appreciation to the Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology, for supporting this research on the development of a PID-based ship steering model. The authors also extend their gratitude to the Politeknik Maritim Negeri Indonesia for providing the facilities and testing area for the ship prototype experiments. We hope that the results of this study contribute to advancing knowledge in the field of autonomous ship steering systems.

References

[1] Lin B, Zheng M, Han B, Chu X, Zhang M, Zhou H, Ding S, Wu H, Zhang K. PSO-based predictive PID-backstepping controller design for the course-keeping of ships. J Mar Sci Eng. 2024;12(2):1–20. https://doi.org/10.3390/jmse12020202.

[2] Zhang Q, Ding Z, Zhang M. Adaptive self-regulation PID control of course-keeping for ships. Pol Marit Res. 2020;27(1):39–45. https://doi.org/10.2478/pomr-2020-0004.

[3] Peeters G, Kotzé M, Afzal MR, Catoor T, Van Baelen S, Geenen P, et al. An unmanned inland cargo vessel: Design, build, and experiments. Ocean Eng. 2020;201:1-17. https://doi.org/10.1016/j.oceaneng.2020.107056.

[4] International Maritime Organization. SOLAS 2018 Consolidated Edition [Internet]. 2018 [cited 2025 Oct 20]. Available from: https://www.samgongustofa.is/media/english/SOLAS-Consolidated-Edition-2018.docx.pdf.

[5] Suharso AR, Santoso GB, Hendartono A, Kumara RB. Perbandingan sensor incremental rotary encoder dan potensiometer pada simulasi kemudi kapal berbasis Arduino. ELKOMIKA. 2023;11(1):155–166. https://doi.org/10.26760/elkomika.v11i1.155.

[6] Suharso AR, Hendartono A, Susanto. Simulasi daun kemudi kapal dengan variasi beban. ARMATUR. 2024;5(2):126–133. https://doi.org/10.24127/armatur.v5i2.6367.

[7] Świder Z, Trybus L, Stec A. Consistent design of PID controllers for an autopilot. Pol Marit Res. 2023;30(1):78–85. https://doi.org/10.2478/pomr-2023-0008.

[8] Yuan T, Wang T, Fan J, Bai J. Current harmonic suppression in maritime vessel rudder PMSM drive system based on composite fractional-order PID repetitive controller. J Mar Sci Eng. 2024;12(7):1–

15. https://doi.org/10.3390/jmse12071108.
[9] Ahmada AI, Wahyudi, Handoyo E. Implementasi pengendali PID untuk navigasi autonomous berbasis global positioning system pada purwarupa autonomous surface vehicle. TRANSIENT. 2020;9(4):574–580. https://doi.org/10.14710/transient.v9i4.574-580.
[10] Rahayu LP, Perdana AR, Permana C, Priananda CW, Adhim FI. Penggunaan metode PID untuk sistem kontrol gerak zig-zag pada pengujian seakeeping miniatur kapal cepat. JAEE. 2022;6(2):89–93. https://doi.org/10.30871/jaee.v6i2.4848.
[11] Li Y, Tang Z, Gong J. The effect of PID control scheme on the course-keeping of ship in oblique stern waves. Brodogradnja. 2023;74(4):155–178. https://doi.org/10.21278/brod74408.
[12] Murra D, Bollanti S, Lazzaro PD, Flora F, Mezi L. Interfacing Arduino boards with optical sensor arrays: Overview and realization of an accurate solar compass. Sensors. 2023;23(24):1–21. https://doi.org/10.3390/s23249787.
[13] Andrian A, Rahmadewi R, Bangsa I. Arm robot pemindah barang (AtwoR) menggunakan motor servo MG995 sebagai penggerak arm berbasis Arduino. JELEKN. 2020;6(2):142–155. https://doi.org/10.32531/jelekn.v6i2.226.
[14] Putri AR, Nurrahayu P, Anas A. Robot navigation control system using HMC5883L. JAREE. 2019;3(1). https://doi.org/10.12962/j25796216.v3.i1.76.
[15] Nurjaman A, Juandi D, Supriyadi E, Hidayat W, Darhim. Research trends about Visual Basic as a programming language in the learning process: a bibliometric analysis. IJECE. 2024;14(6):6498–6507. https://doi.org/10.11591/ijece.v14i6.pp6498-6507.
[16] Suryadhi, Subur J. Pengaturan kecepatan motor penggerak propeller pada kapal menggunakan metode PID dan MA filter. ZETROEM. 2022;4(2):1–6. https://doi.org/10.36526/ztr.v4i2.2158.
[17] Shi X, Chen P, Chen L. An integrated method for ship heading control using motion model prediction and fractional order proportion integration differentiation controller. J Mar Sci Eng. 2023;11(12):1–24. https://doi.org/10.3390/jmse11122294.
[18] An JH, Kim HS, Paik KJ. Development of a systematic method for tuning PID control gains in free-running ship simulations. J Mar Sci Eng. 2025;13(9):1–26. https://doi.org/10.3390/jmse13091813.
[19] Chang H-C, Hsu Y-L, Hung S-S, Ou G-R, Wu J-R, Hsu C. Autonomous water quality monitoring and water surface cleaning for unmanned surface vehicle. Sensors. 2021;21(4):1102. https://doi.org/10.3390/s21041102.
[20] Duran H, Sonmez NK. Design and implementation of the AquaMIB unmanned surface vehicle for real-time GIS-based spatial interpolation and autonomous water quality monitoring. Appl Sci. 2026;16(3):1209. https://doi.org/10.3390/app16031209.
[21] Saputra RE, Aulia S, Rangkuti S. Desain prototype sistem kendali dan pelacakan pada mesin boat. J Rekayasa Elektr. 2021;17(2):79–85. https://doi.org/10.17529/jre.v17i2.19900.
[22] Wang L, Wu Q, Liu J, Li S, Negenborn R. Ship motion control based on AMBPS-PID algorithm. IEEE Access. 2019;7:183656–183671. https://doi.org/10.1109/ACCESS.2019.2960098.
[23] Larrazabala J, Santos M. Intelligent rudder control of an unmanned surface vessel. Expert Syst Appl. 2016;55:106–117. https://doi.org/10.1016/j.eswa.2016.01.057.
[24] Dlabač T, Ćalasan M, Krčum M, Marvučić N. PSO-based PID controller design for ship coursekeeping autopilot. Brodogradnja. 2019;70(4):1–15. https://doi.org/10.21278/brod70401.
[25] Tanguy H, Lebret G, Doucy O. Multi-objective optimisation of PID and H∞ fin/rudder roll controllers. Conference on Manoeuvring and Control of Marine Crafts; 2003; Girona, Spain. p. 179–184. https://doi.org/10.1016/S1474-6670(17)37798-4.