International Journal of Marine Engineering Innovation and Research, Vol. 11(3), Sept. 2026. 887-897
(pISSN: 2541-5972, eISSN: 2548-1479)

Performance Evaluation of Autonomous Waypoint Navigation on a Catamaran-Type Unmanned Surface Vehicle

Dzikri Ibnu Fadhilah[1*], Setyawan Ajie Sukarno[2], Wahyudi Purnomo [3], Noer Fajrin [4], Riky Adhiharto [5]

(Received: 1 June 2026 / Revised: 12 June 2026 / Accepted: 27 June 2026 / Available Online: 1 September 2026)

***Abstract* —** Autonomous Unmanned Surface Vehicles (USVs) are increasingly used for maritime applications such as environmental monitoring and coastal inspection, where reliable waypoint navigation is essential. However, many existing USV navigation systems remain tightly dependent on built-in autopilot firmware, which limits the flexibility to develop custom navigation algorithms. This study develops and evaluates an autonomous waypoint navigation system for a catamaran-type USV using a modular ROS 2-based architecture that separates the high-level navigation control from the low-level control. The system performs waypoint-following through real-time position monitoring, heading control, and telemetry communication, and was implemented on a catamaran-type USV platform with a companion computer, GPS, inertial sensors, and dual-thruster propulsion. Navigation performance was evaluated in both simulation and real-world environments using waypoint error and heading error as the primary metrics. Simulation recorded a mean waypoint error of 0.49 m and a mean heading error of 4.21°, whereas field trials yielded errors of 1.15 m and 10.8° respectively. The increased field errors are attributed to GPS noise, water surface disturbances, and vessel dynamics, yet all assigned missions were completed without failure. These results indicate that the proposed modular architecture provides sufficient reliability for autonomous waypoint-following while offering greater flexibility for navigation development in maritime monitoring and coastal inspection applications.

Keywords— Performance Evaluation, Autonomous, Waypoint Navigation, USV, Catamaran.

**Corresponding Author: dzikriibnuf@gmail.com*

I. INTRODUCTION

The advancement of autonomous maritime technology has significantly increased the implementation of Unmanned Surface Vehicles (USVs) in various marine applications such as hydrographic surveys, bathymetric mapping, environmental monitoring, and maritime surveillance [1][2]. Compared to conventional manned vessels, USVs provide higher operational flexibility and lower safety risks because missions can be performed without direct onboard human involvement [3][4]. In recent years, autonomous USVs have also been increasingly utilized for intelligent water quality monitoring and long-duration marine observation systems due to their capability to operate continuously in dynamic aquatic environments [5][6]. These developments have encouraged extensive research on autonomous navigation systems capable of improving trajectory tracking performance and navigation reliability during autonomous maritime operations [7][8].

Various navigation and guidance approaches have been proposed to improve waypoint-following performance for USVs operating in complex marine environments [9][10]. Other studies investigated vector-field guidance methods, adaptive sliding mode control, and trajectory reconstruction algorithms to improve path-following consistency under environmental disturbances such as currents and waves [11]–[13]. In addition, collision avoidance and global path planning strategies have also been integrated into autonomous navigation systems to improve operational safety in dynamic maritime environments [14][15]. Although these approaches successfully improved autonomous navigation capability, many systems still rely heavily on the built-in autopilot navigation mechanism, limiting the flexibility of implementing and modifying high-level navigation algorithms [16].

Recent advancements in autonomous robotic systems have increased the adoption of Robot Operating System (ROS) as a modular middleware framework for navigation, communication, and distributed robotic processing [17][18]. Several studies integrated ROS into autonomous navigation architectures for robotic systems and USVs because ROS provides flexible communication and modular software integration [19], [20]. However, in many implementations, ROS is mainly utilized for communication and sensor integration, while the navigation computation and waypoint control processes remain dependent on the autopilot firmware architecture [21]. Consequently, the navigation system becomes less modular and more difficult for implementing waypoint navigation strategies. Furthermore, previous studies generally evaluated navigation performance qualitatively based on mission completion without comprehensive quantitative trajectory tracking analysis [22].

Dzikri Ibnu Fadhilah. Department of Automation Engineering, Politeknik Manufaktur Bandung, Bandung, 40135, Indonesia. E-mail: dzikriibnuf@gmail.com
Setyawan Ajie Sukarno. Department of Automation Engineering, Politeknik Manufaktur Bandung, Bandung, 40135, Indonesia. E-mail: ajie@ae.polman-bandung.ac.id
Wahyudi Purnomo. Department of Automation Engineering, Politeknik Manufaktur Bandung, Bandung, 40135, Indonesia. E-mail: wahyudi@ae.polman-bandung.ac.id
Noer Fajrin. Department of Automation Engineering, Politeknik Manufaktur Bandung, Bandung, 40135, Indonesia. E-mail: noer.fajrin@polman-bandung.ac.id
Riky Adhiharto. Department of Design Engineering, Politeknik Manufaktur Bandung, Bandung, 40135, Indonesia. E-mail: riky@de.polman-bandung.ac.id

Based on these limitations, this study develops an autonomous waypoint navigation system for a catamaran-type Unmanned Surface Vehicle (USV). The proposed system enables autonomous waypoint-following missions through real-time position monitoring, heading computation, and navigation control. The navigation framework is implemented on a USV platform equipped with GPS, IMU, companion computer, and autopilot hardware. To evaluate navigation performance, autonomous waypoint-following experiments were conducted in both simulation and real-world environments using waypoint error and heading error as the primary performance metrics. The proposed system aims to provide a reliable and practical navigation solution for autonomous USV operations.

II. Method

This section describes the proposed system architecture, operational workflow, and navigation process of the developed autonomous waypoint navigation system, supported by the corresponding system and flowchart diagrams.

A. System Design

The proposed autonomous navigation system adopts a layered architecture to support modular and flexible waypoint-navigation development for Unmanned Surface Vehicles (USVs) [23], [24]. The high-level control handles mission planning, waypoint management, navigation monitoring, and telemetry processing, while the low-level control handles vehicle stabilization and propulsion through the autopilot system. This separation allows the navigation functions to be developed and modified independently of the low-level control, improving system modularity and enabling the navigation algorithms to be tested without affecting the underlying vehicle-control architecture [24].

This layered approach improves system modularity and enables autonomous navigation functions to be developed and tested without affecting the underlying vehicle-control architecture. The navigation system is implemented on a catamaran-type USV platform equipped with a companion computer, autopilot controller, GPS module, IMU sensors, and a dual-thruster propulsion system. During autonomous operation, the system continuously acquires vehicle-position and heading information to determine the active waypoint and generate navigation commands. Telemetry information, including vehicle position, heading orientation, mission status, and waypoint progress, is exchanged continuously to support autonomous mission execution and real-time navigation monitoring [24], [25].

Navigation performance is evaluated through autonomous waypoint-following experiments conducted in both simulation and real-world environments. The evaluation focuses on waypoint-following accuracy and heading-tracking performance using waypoint error and heading error as the primary performance metrics. These parameters are utilized to assess the capability of the proposed navigation system in guiding the USV toward predefined waypoint locations during autonomous operation [25], [26].

Figure 1 illustrates the overall architecture of the proposed autonomous USV system in both simulation and real-world environments. The simulation environment is utilized to validate navigation functionality and mission execution before deployment to the physical platform. Following simulation validation, the same navigation framework is implemented on the developed catamaran-type USV platform to evaluate autonomous waypoint-navigation performance under actual operating conditions.

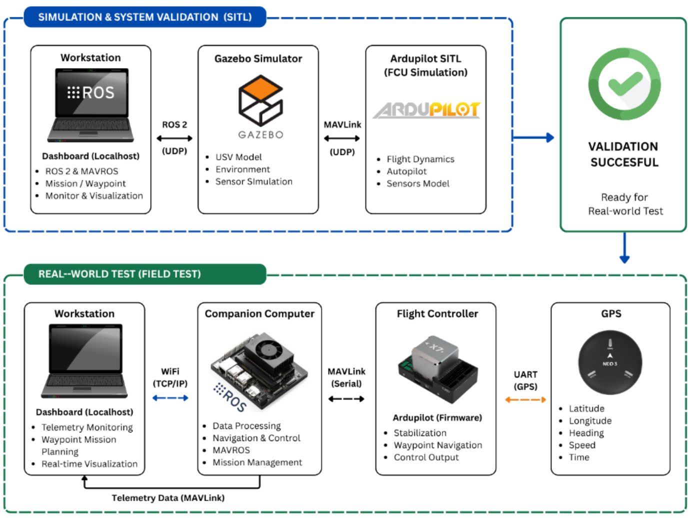

Figure 1. System Overview

B. Hardware Design

The proposed autonomous navigation system was implemented on a catamaran-type USV platform designed to support stable autonomous navigation and differential-thrust maneuvering in aquatic environments. The catamaran configuration was selected because it provides improved balance and stability during autonomous operation compared to monohull platforms. The propulsion system utilizes dual electric thrusters to perform steering and heading control during waypoint-following missions.

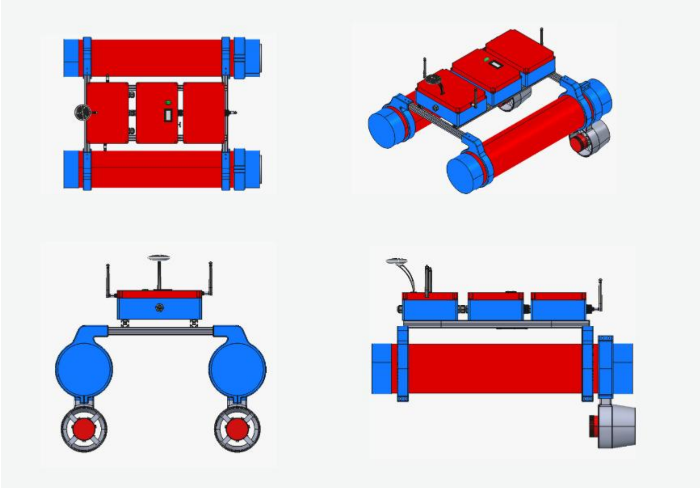

Figure 2. USV Platform

Onboard the USV, a Jetson Nano running Ubuntu 22.04 and ROS 2 Humble took on tasks like navigation processing, telemetry monitoring, and mission execution. A CUAV X7+ with ArduPilot firmware sat at the lower control level, responsible for vehicle stabilization and actuator output. For localization and navigation sensing, the system integrates a CUAV NEO 3 GPS module and onboard IMU sensors to obtain position, heading, and motion information during autonomous operation. Communication between the companion computer and autopilot system is established using MAVLink serial communication through UART interface, enabling real-time telemetry exchange and navigation-command transmission. Table 1 presents the main hardware specifications used in the proposed autonomous USV platform.

TABLE 1.
HARDWARE SPECIFICATION

Component	Specification
Usv Platform	Catamaran
Companion Computer	Nvidia Jetson Nano
Operating System	Ubuntu 22.04
Middleware	Ros 2 Humble
Flight Controller	Cuav X7+
Gps Module	Cuav Neo 3
Autopilot Firmware	Ardupilot
Simulator	Gazebo Sim
Communication Protocol	Mavlink
Propulsion System	Differential Thruster

C. Software Architecture

The proposed navigation framework was developed using ROS 2 middleware because it provides modular communication architecture and real-time data exchange suitable for autonomous robotic applications. The software architecture integrates telemetry acquisition, waypoint management, mission execution, heading computation, and autonomous navigation control within a unified framework capable of operating in both simulation and real-hardware environments. In Simulation Mode, Gazebo Sim and ArduPilot SITL are utilized to emulate USV dynamics and autonomous mission execution. Data exchange between ROS 2 and Gazebo runs through DDS middleware, with MAVROS serving as the link between ROS 2 and ArduPilot SITL over MAVLink. This simulation framework enables autonomous mission validation and telemetry testing before deployment to the physical platform.

In Hardware Mode, the same ROS 2 framework is connected directly to the onboard hardware system through MAVLink serial communication for real-time telemetry exchange and autonomous mission execution. Figure 3 presents the overall software architecture and operational workflow of the developed navigation system. The diagram shows how the system is organized from the user interface level down to the physical platform, with telemetry feedback flowing continuously across all layers throughout each autonomous mission. At the upper end, the Ground Control Station communicates with the companion computer through HTTP and WebSocket, while at the lower end, MAVLink protocol connects the navigation framework to the ArduPilot autopilot layer for direct thruster control and vehicle stabilization. Navigation performance is then captured at the evaluation layer through waypoint error and heading error measurements.

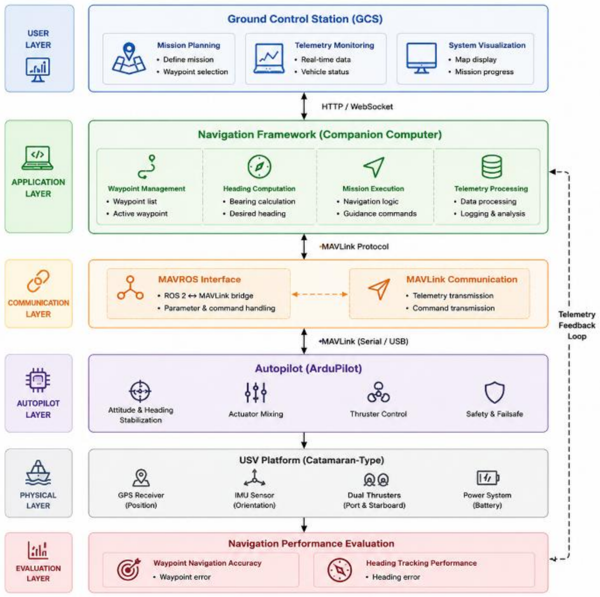

Figure 3. Software Architecture

D. Waypoint Navigation Algorithm

The proposed waypoint navigation algorithm enables the USV to autonomously move toward predefined waypoint coordinates using GPS-based trajectory tracking and heading control. During operation, the navigation system continuously reads the vehicle position from the GPS sensor and determines the active waypoint target from the mission planner. The desired heading angle toward the target waypoint is calculated using geographic coordinate transformation based on the current vehicle position and target waypoint coordinates. The calculated heading reference is then compared with the actual heading obtained from the onboard compass and IMU sensors to determine the heading error used for navigation correction.

The heading reference is calculated using the $atan2$ function because it provides accurate directional computation over all coordinate quadrants. The heading reference toward the target waypoint is defined as:

$$\psi_{ref,i} = atan2(y_{i+1} - y_i, x_{i+1} - x_i) \quad (1)$$

In this equation, $\psi_{ref,i}$ represents the reference heading angle used to direct the USV toward the target waypoint. The variables (x_i, y_i) denote the current waypoint coordinates, while (x_{i+1}, y_{i+1}) represent the target waypoint coordinates.

To evaluate orientation deviation during autonomous navigation, the heading error is calculated from the difference between the reference heading and the actual vehicle heading obtained from the onboard compass and IMU sensors. The heading error is formulated as:

$$e_{\psi,i} = atan2\left(sin(\psi_{ref,i} - \psi), cos(\psi_{ref,i} - \psi)\right) \quad (2)$$

In this formulation, $e_{\psi,i}$ represents the heading error, $\psi_{ref,i}$ denotes the reference heading angle, and ψ represents the actual heading of the USV. The use of the $atan2$ function ensures that the heading error remains within the angular range of $[-\pi, \pi]$. This approach prevents discontinuity in angular calculation and enables the controller to generate stable directional correction when the vehicle crosses heading boundaries during waypoint-following operation.

The Haversine distance formula is employed to determine the geographic distance between the target waypoint and the actual position reached by the USV during autonomous navigation. The calculated waypoint error indicates the positional deviation of the vehicle from the desired waypoint. A smaller waypoint error signifies that the USV reaches the target waypoint with higher accuracy, resulting in better autonomous waypoint-following performance.

$$e_{\wp} = 2Rarcsin(\sqrt{a}) \quad (3)$$

$$a = sin^2\left(\frac{\Delta\phi}{2}\right) + cos(\phi_1)cos(\phi_2)sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (4)$$

In equations (3) and (4), $e_{\wp}$ represents the waypoint error expressed in meters, while R denotes the Earth's radius. The variables ϕ_1 and ϕ_2 represent the latitude coordinates of the target waypoint and the actual USV position, respectively, whereas λ_1 and λ_2 denote the corresponding longitude coordinates. The terms $\Delta\phi$ and $\Delta\lambda$ indicate the latitude and longitude differences between the target waypoint and the actual vehicle position.

During mission execution, the navigation system continuously monitors both heading error and waypoint error to evaluate navigation performance. When the waypoint error falls below the predefined waypoint acceptance threshold, the active waypoint is considered reached and the navigation system automatically proceeds to the next waypoint. This process is repeated until all mission waypoints have been successfully completed.

E. Communication Framework

The proposed autonomous navigation system employs the MAVLink protocol to enable communication between the navigation framework and the ArduPilot autopilot system. In the simulation environment, communication is established between the navigation software and

ArduPilot SITL, while in the hardware implementation, data exchange is performed between the companion computer and the CUAV X7+ flight controller through a serial communication interface. This communication framework enables continuous transmission of telemetry information, including GPS position, heading orientation, vehicle status, and mission progress, to support autonomous waypoint navigation and real-time mission monitoring.

F. Experimental Procedure

The proposed autonomous waypoint navigation system was evaluated through both simulation and real-world experiments to assess its performance under different operating conditions. Simulation testing was conducted in a virtual environment to validate waypoint-following functionality before deployment, while real-world experiments were performed using the developed catamaran-type USV platform. During autonomous waypoint missions, telemetry data including GPS position, heading orientation, vehicle trajectory, and mission status were recorded and analyzed using waypoint error and heading error to assess navigation performance.

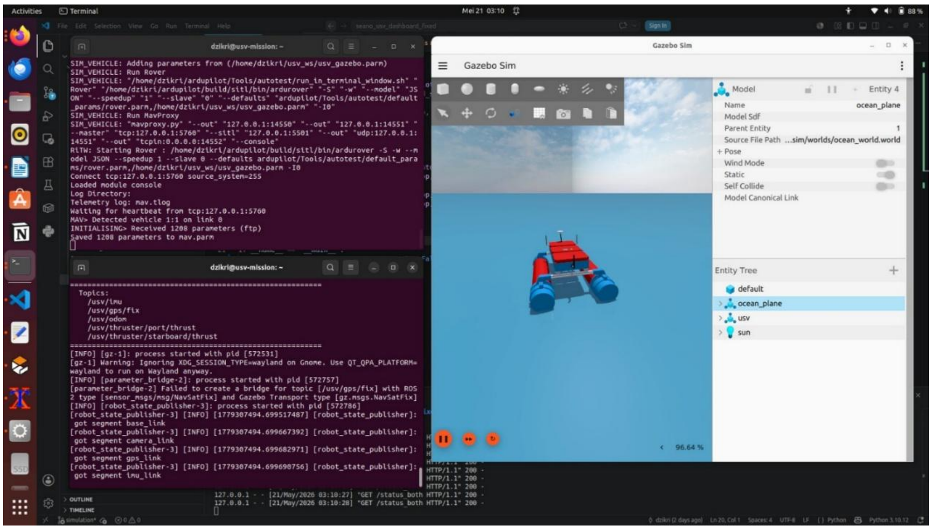

Figure 4. Gazebo Simulation

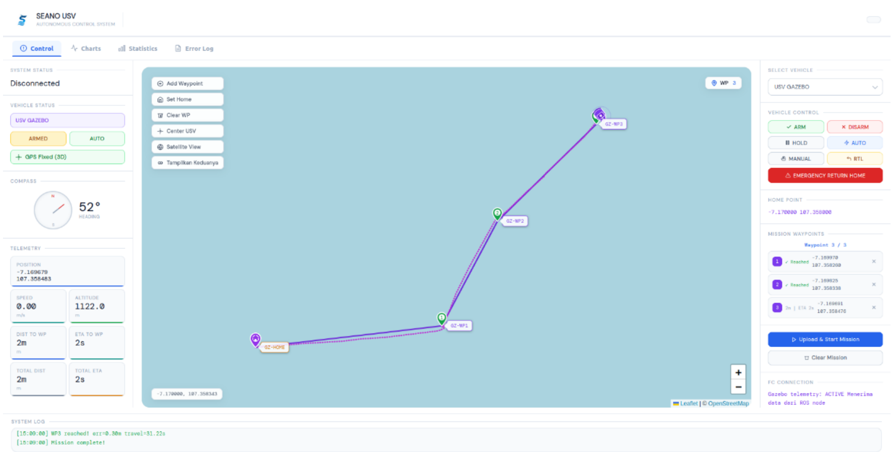

Figure 5. Dashboard Simulation Mode

III. RESULT AND DISCUSSION

This section presents the experimental results and performance analysis of the proposed ROS 2-based autonomous waypoint navigation system in both simulation and real-hardware environments. The evaluation was conducted to analyze telemetry communication, waypoint-navigation capability, and trajectory-tracking performance during autonomous operation.

A. Simulation Environment Validation

The proposed autonomous waypoint navigation system was initially validated in a simulation environment prior to deployment on the physical USV platform. The simulation experiment was conducted to verify autonomous waypoint-following functionality, mission execution capability, and navigation-system integration under controlled conditions. During testing, the virtual USV successfully executed predefined waypoint missions while maintaining continuous telemetry monitoring throughout the navigation process. Figure 4 illustrates the developed simulation environment used for autonomous navigation validation. The simulation platform enables mission planning, vehicle-state monitoring, and trajectory visualization, allowing the navigation system to be evaluated before real-world implementation. Through this environment, the functionality of waypoint navigation, mission execution, and telemetry monitoring can be assessed in a safe and repeatable manner.

During simulation testing, operators could generate waypoints, upload missions, observe vehicle status, and monitor the trajectory in real time through the Ground Control Station dashboard, as shown in Figure 5. Across the simulation runs, the navigation system consistently followed the assigned waypoint trajectory and completed each mission without manual intervention, confirming that the simulation environment provided a reliable validation stage prior to real-world deployment.

B. Hardware Implementation

Following successful simulation validation, the autonomous waypoint navigation system was implemented on the developed catamaran-type USV platform to evaluate navigation performance under real operating conditions. Mounted on this platform are a Jetson Nano, a CUAV X7+ autopilot, a NEO 3 GPS module, IMU sensors, and a dual-thruster propulsion system, each contributing to the positioning, orientation, and control needs of autonomous waypoint navigation. The field experiments were conducted using the developed catamaran-type USV platform shown in Figure 6, in which the dual-thruster arrangement enables differential steering while the onboard GPS and IMU continuously feed navigation data into the system during mission execution. During the hardware experiments, vehicle position, heading orientation, waypoint trajectory, mission status, and navigation progress were monitored in real time through the Ground Control Station dashboard, as shown in Figure 7. Throughout the field trials, the USV completed multiple waypoint missions in sequence without failure, and the mission visualization confirmed that each waypoint was reached sequentially, demonstrating the functionality of the proposed autonomous navigation system under real conditions.

Figure 6. Field Experiment USV

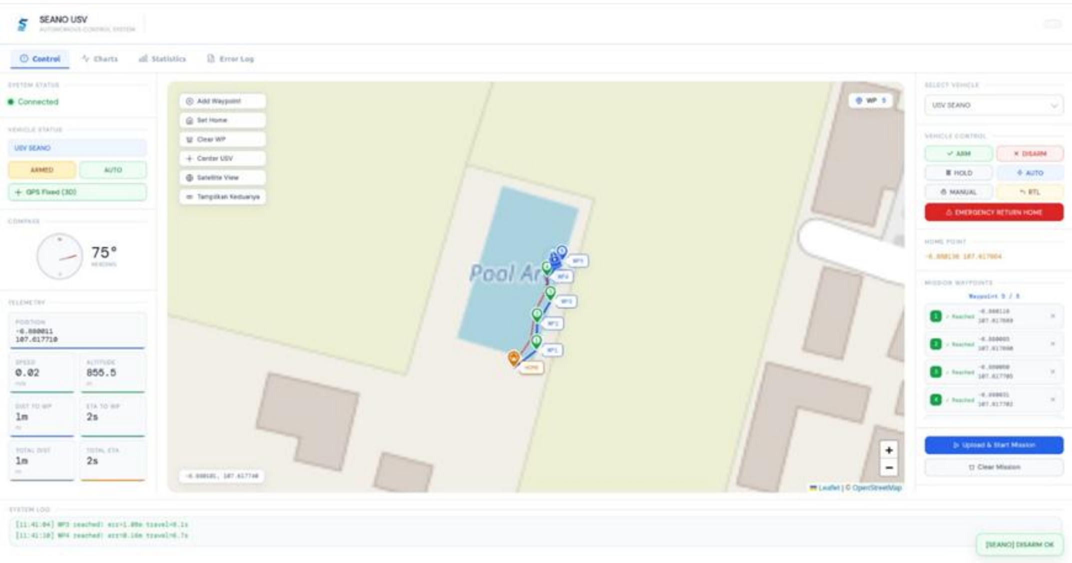

Figure 7. Dashboard Hardware Mode

C. Waypoint Navigation Performance

The waypoint-navigation performance of the proposed autonomous USV system was evaluated through simulation experiments to assess waypoint-following accuracy and heading-tracking capability during autonomous operation. The evaluation was conducted using waypoint error and heading error as the primary performance metrics. The simulation results were obtained from ten autonomous waypoint-navigation trials performed in the Gazebo simulation environment.

The waypoint-navigation results obtained during simulation testing are presented in Table 2, where waypoint error is defined as the distance separating the predefined waypoint coordinates from the actual position attained by the USV upon completion of each mission. This metric directly reflects how closely the USV approached its intended target during autonomous navigation. The recorded errors were generally small, with an average of 0.49 m across the ten trials. Performance was strongest in Trial 2, where the error fell to 0.31 m, and weakest in Trial 4, which reached 0.63 m, yet no trial exceeded the 1 m threshold. These results indicate that the navigation system followed the predefined trajectory accurately and maintained a consistent level of waypoint-following performance throughout simulation conditions.

The consistently low waypoint error across all trials indicates that the navigation algorithm was able to continuously estimate the target direction and refine the vehicle trajectory with sufficient accuracy. As the simulation environment excluded significant disturbances such as wind loads, water currents, and GPS signal degradation, the resulting error may be attributed primarily to the intrinsic behavior of the navigation algorithm and its control framework. The values obtained may therefore be regarded as a baseline that characterizes the navigation capability achievable under ideal operating conditions. Collectively, these results affirm that the proposed navigation architecture is capable of guiding the virtual USV toward its designated waypoint locations with a high degree of positional consistency prior to deployment in real-world environments.

The heading-tracking performance during simulation testing is presented in Table 3, where the heading error was evaluated by comparing the target heading generated by the navigation system with the actual heading of the simulated vehicle. The heading error varied between 3.5° and 5.1°, with an average of 4.21°, and this relatively small deviation indicates that the vehicle maintained its orientation toward the target waypoint accurately throughout the navigation process.

TABLE 2.
NAVIGATION WAYPOINT SIMULATION PERFORMANCE

TRIAL	WAYPOINT LATITUDE	WAYPOINT LONGITUDE	ACTUAL LATITUDE	ACTUAL LONGITUDE	ERROR (m)
1	-35.3632894	149.1648155	-35.3632861	149.1648192	0.42 m
2	-35.3635278	149.1648812	-35.3635249	149.1648785	0.31 m
3	-35.3634764	149.1652795	-35.3634721	149.1652836	0.56 m
4	-35.3632839	149.1647927	-35.3632794	149.1647981	0.63 m
5	-35.3635508	149.1648799	-35.3635475	149.1648842	0.48 m
6	-35.3635103	149.1652473	-35.3635078	149.1652504	0.39 m
7	-35.3634764	149.1652795	-35.3634726	149.1652837	0.57 m
8	-35.3632839	149.1647927	-35.3632791	149.1647985	0.61 m
9	-35.3635508	149.1648799	-35.3635472	149.1648845	0.52 m
10	-35.3634764	149.1652795	-35.3634729	149.1652832	0.44 m
		Mean			0.49 m

TABLE 3.
HEADING SIMULATION PERFORMANCE

TRIAL	TARGET HEADING (°)	ACTUAL HEADING (°)	ERROR (°)
1	-35.3632894	149.1648155	-35.3632861
2	-35.3635278	149.1648812	-35.3635249
3	-35.3634764	149.1652795	-35.3634721
4	-35.3632839	149.1647927	-35.3632794
5	-35.3635508	149.1648799	-35.3635475
6	-35.3635103	149.1652473	-35.3635078
7	-35.3634764	149.1652795	-35.3634726
8	-35.3632839	149.1647927	-35.3632791
9	-35.3635508	149.1648799	-35.3635472
10	-35.3634764	149.1652795	-35.3634729
	Mean		4.21°

An interesting observation is that trials with relatively larger heading errors generally exhibited higher waypoint errors. For example, Trial 4 produced the highest heading error of 5.1° and also recorded the largest waypoint error of 0.63 m. This tendency suggests a direct relationship between vehicle orientation accuracy and waypoint-reaching performance. When the vehicle heading deviates from the desired direction, additional trajectory corrections are required, potentially increasing the final positional error. Nevertheless, the magnitude of the observed errors remained relatively small, indicating that the proposed navigation framework was able to compensate for directional deviations and maintain satisfactory waypoint-following performance.

The simulation results also indicate that the navigation algorithm is capable of maintaining stable waypoint-following performance under ideal operating conditions where environmental disturbances are not present. This condition represents the expected navigation performance that can be achieved when external factors such as wind, water currents, and GPS signal fluctuations have minimal influence on vehicle movement. Therefore, the simulation environment serves as an important baseline for evaluating the impact of real-world maritime conditions on navigation accuracy.

Figure 8 presents the comparison between the target waypoint coordinates and the actual coordinates reached by the USV during simulation testing. Figure 8(a) shows the latitude comparison, while Figure 8(b) presents the longitude comparison for all waypoint-navigation trials. The results indicate that the actual vehicle coordinates closely followed the predefined waypoint coordinates, with only minor deviations observed across the trials. The close agreement between the waypoint and actual positions demonstrates the capability of the proposed navigation system to accurately follow the assigned waypoint trajectory in the simulation environment.

The close agreement between the target and actual coordinate profiles shown in Figure 8 further confirms the consistency of the navigation system throughout the simulation experiments. Only minor deviations can be observed between the planned and achieved positions, indicating that the generated navigation commands were executed effectively by the vehicle model. Furthermore, no significant drift pattern was observed across the trials, suggesting that the navigation algorithm maintained stable trajectory-tracking performance during repeated waypoint-following missions. This consistency is important because it demonstrates that the proposed system can repeatedly achieve similar navigation accuracy under identical operating conditions.

Figure 9 illustrates the navigation-performance metrics obtained during simulation testing. Figure 9(a) shows the heading error for each trial, with values ranging from 3.5° to 5.1° and an average heading error of 4.21°. Figure 9(b) presents the waypoint error, which ranged from 0.31 m to 0.63 m with an average value of 0.49 m. The relatively small variation observed in both metrics indicates that the navigation system maintained stable performance throughout all simulation trials. The real-world navigation performance of the proposed autonomous USV system was evaluated through field experiments using the developed catamaran-type platform. The objective of the experiment was to assess waypoint-following accuracy and heading-tracking performance under actual operating conditions. Similar to the simulation evaluation, waypoint error and heading error were used as the primary performance metrics, and ten autonomous waypoint-navigation trials were conducted during testing.

The waypoint-navigation performance obtained during real-world experiments is presented in Table 4, where the waypoint error ranged from 0.473 m to 1.837 m, with an average of 1.15 m. This error was larger than in the simulation results, reflecting the influence of GPS positioning uncertainty, sensor noise, water-surface disturbances, and vehicle dynamics that are not fully represented in the simulation environment. During field testing, these factors affected the vehicle trajectory and contributed to deviations between the target and actual waypoint positions, as such conditions are commonly encountered in practical maritime operations. Nevertheless, all waypoint missions were successfully completed, indicating that the proposed navigation system maintained sufficient accuracy to guide the USV toward the predefined waypoint locations and to operate reliably under realistic aquatic conditions.

The heading-tracking performance during real-world testing is presented in Table 5, where the heading error varied between 0.4° and 17.4°, with an average of 10.8°. This larger deviation compared with the simulation results reflects the influence of environmental disturbances and vehicle maneuvering dynamics during operation. Despite these deviations, the USV consistently followed the assigned waypoint sequence and completed the autonomous mission successfully, demonstrating that the proposed navigation system remained effective for autonomous waypoint navigation in real-world environments. From an operational perspective, the achieved navigation accuracy is considered adequate for several practical USV applications, including environmental monitoring, water-quality assessment, infrastructure inspection, and autonomous surface patrol, which generally require reliable waypoint-following capability rather than centimeter-level positioning accuracy. The obtained performance therefore demonstrates the practical usability of the proposed system for routine maritime operations.

TABLE 4.
NAVIGATION WAYPOINT REAL-WORLD TESTING

TRIAL	WAYPOINT LATITUDE	WAYPOINT LONGITUDE	ACTUAL LATITUDE	ACTUAL LONGITUDE	ERROR (m)
1	-6.880026844	107.6176751	-6.8800204	107.6176727	0.765 m
2	-6.880046483	107.6176929	-6.8800365	107.6177062	1.837 m
3	-6.880063459	107.6176771	-6.8800571	107.6176706	1.014 m
4	-6.88003416	107.6176932	-6.8800301	107.617683	1.223 m
5	-6.88001153	107.6176989	-6.8800096	107.6176857	1.481 m
6	-6.880114387	107.6176979	-6.8801176	107.6177008	0.473 m
7	-6.88005879	107.6176768	-6.8800561	107.6176895	1.427 m
8	-6.88002684	107.6176862	-6.8800264	107.6176958	1.054 m
9	-6.880063459	107.6176771	-6.8800571	107.6176706	1.014 m
10	-6.88003416	107.6176932	-6.8800301	107.617683	1.223 m
		Mean			0.49 m

The comparison between the target waypoint coordinates and the actual coordinates reached by the USV during real-world experiments is presented in Figure 10, where Figure 10(a) shows the latitude comparison and Figure 10(b) presents the longitude comparison for all waypoint-navigation trials. In both plots, the actual coordinate profiles closely follow the target profiles across the ten trials, with slightly larger deviations in the longitude comparison due to GPS positioning uncertainty and environmental disturbances. These deviations remained small and did not prevent the USV from reaching each predefined waypoint during the missions. This close agreement confirms that the navigation system maintained accurate waypoint-following performance under real operating conditions.

TABLE 5.

HEADING REAL-WORLD TESTING

TRIAL	TARGET HEADING (°)	ACTUAL HEADING (°)	ERROR (°)
1	-35.3632894	149.1648155	-35.3632861
2	-35.3635278	149.1648812	-35.3635249
3	-35.3634764	149.1652795	-35.3634721
4	-35.3632839	149.1647927	-35.3632794
5	-35.3635508	149.1648799	-35.3635475
6	-35.3635103	149.1652473	-35.3635078
7	-35.3634764	149.1652795	-35.3634726
8	-35.3632839	149.1647927	-35.3632791
9	-35.3635508	149.1648799	-35.3635472
10	-35.3634764	149.1652795	-35.3634729
	Mean		4.21°

The heading-tracking performance during real-world testing is presented in Table 5, where the heading error varied between 0.4° and 17.4°, with an average of 10.8°. This larger deviation compared with the simulation results reflects the influence of environmental disturbances and vehicle maneuvering dynamics during operation. Despite these deviations, the USV consistently followed the assigned waypoint sequence and completed the autonomous mission successfully, demonstrating that the proposed navigation system remained effective for autonomous waypoint navigation in real-world environments. From an operational perspective, the achieved navigation accuracy is considered adequate for several practical USV applications, including environmental monitoring, water-quality assessment, infrastructure inspection, and autonomous surface patrol, which generally require reliable waypoint-following capability rather than centimeter-level positioning accuracy. The obtained performance therefore demonstrates the practical usability of the proposed system for routine maritime operations.

The comparison between the target waypoint coordinates and the actual coordinates reached by the USV during real-world experiments is presented in Figure 10, where Figure 10(a) shows the latitude comparison and Figure 10(b) presents the longitude comparison for all waypoint-navigation trials. In both plots, the actual coordinate profiles closely follow the target profiles across the ten trials, with slightly larger deviations in the longitude comparison due to GPS positioning uncertainty and environmental disturbances. These deviations remained small and did not prevent the USV from reaching each predefined waypoint during the missions. This close agreement confirms that the navigation system maintained accurate waypoint-following performance under real operating conditions.

(a) (b)

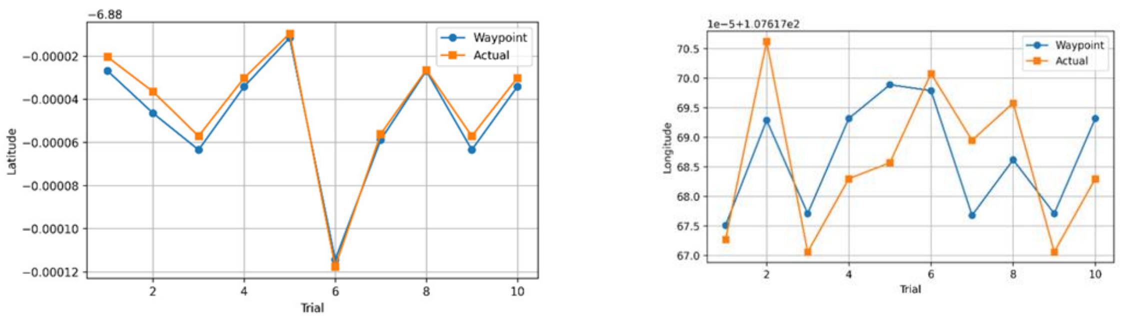

Figure 10. Comparison of Target and Actual Position Coordinates during Real-World Waypoint Navigation: (a) Latitude Comparison and (b) Longitude Comparison

(a) (b)

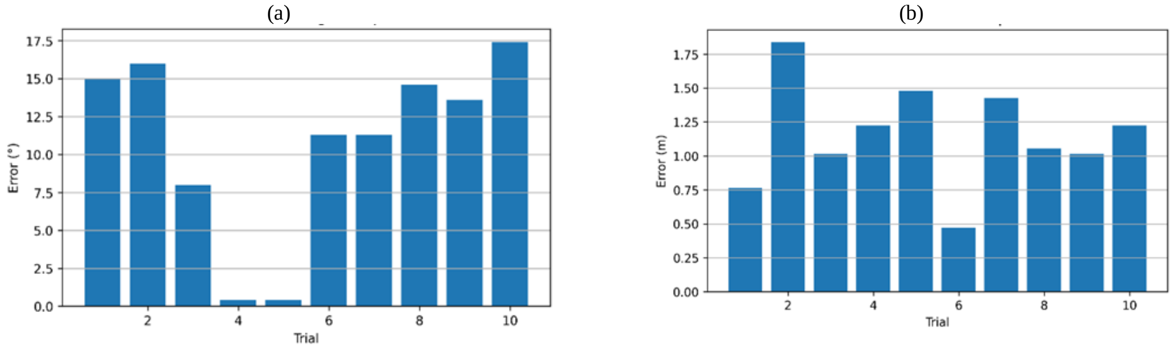

Figure 11. Real-World Navigation Performance: (a) Heading Error and (b) Waypoint Error

Compared with the simulation results, larger deviations can be observed between the waypoint and actual coordinates due to GPS positioning uncertainty, sensor noise, and vehicle dynamics during operation. Nevertheless, the actual trajectory remained relatively close to the target waypoint coordinates, indicating that the proposed navigation system was able to successfully guide the USV toward the predefined waypoint locations throughout the mission.

The navigation-performance metrics obtained during real-world testing are illustrated in Figure 11, which presents the heading error for each waypoint-navigation trial in Figure 11(a) and the corresponding waypoint error in Figure 11(b). The heading error varied between 0.4° and 17.4°, with an average of 10.8°, whereas the waypoint error ranged from 0.473 m to 1.837 m, with an average of 1.15 m. The variations observed in both metrics reflect the influence of real-world operating conditions, including GPS measurement uncertainty, sensor disturbances, and vehicle maneuvering dynamics. Despite these deviations, the proposed navigation system maintained autonomous waypoint-following performance and successfully completed all assigned waypoint missions, indicating that it remained effective in guiding the USV toward the predefined waypoint locations under actual conditions.

The experimental findings further indicate that the proposed navigation framework is particularly suitable for operations in relatively calm aquatic environments such as reservoirs, lakes, and inland waterways. In these environments, the observed navigation errors are unlikely to significantly affect mission objectives. However, deployment in coastal waters or open-sea environments may require additional compensation strategies to address stronger currents, wave disturbances, and more dynamic operating conditions.

D. Telemetry Monitoring and Data Communication

The telemetry communication performance of the proposed navigation system was evaluated by analyzing the communication delay recorded during the autonomous navigation experiments. This evaluation aimed to assess the capability of the telemetry framework to support real-time data exchange among the navigation system, the dashboard interface, and the autopilot platform throughout mission execution. Communication delay was selected as the primary indicator because reliable autonomous operation depends on the timely transmission of navigation and mission data between the onboard system and the ground control station. The delay was measured for each telemetry endpoint based on the time difference between the moment data were received and the moment they were transmitted, allowing the responsiveness of the communication framework to be quantified directly during autonomous waypoint missions.

Across the measured telemetry endpoints, the communication delay ranged from 0.64 ms to 456.97 ms, averaging 73.14 ms during autonomous navigation, as summarized in Table 6. The lowest delay occurred on the /wp_accuracy endpoint, which handled lightweight accuracy-monitoring data, whereas the /waypoint endpoint recorded the highest delay. This higher delay on the waypoint endpoint is attributed to the additional processing required for waypoint handling and mission-data updates, which involve larger data payloads than routine telemetry requests. Even so, most telemetry requests were processed within a short delay, indicating that the dashboard and navigation framework were able to exchange mission-related information efficiently throughout autonomous operation.

TABLE 6
TELEMETRY COMMUNICATION DELAY

METHOD	ENDPOINT	DATA RECEIVED	DATA SENT	DELAY (Ms)	METHOD
GET	/errorlog	10:49:01.980	10:49:01.982	2.08 ms	GET
GET	/wp_accuracy	10:47:43.033	10:47:43.034	0.64 ms	GET
GET	/errorlog	10:47:42.762	10:47:42.765	2.36 ms	GET
GET	/wp_accuracy	10:46:30.398	10:46:30.400	1.43 ms	GET
GET	/errorlog	10:46:29.832	10:46:29.834	2.3 ms	GET
POST	/cmd	10:45:38.760	10:45:38.815	54.79 ms	POST
POST	/cmd	10:45:30.625	10:45:30.626	1.06 ms	POST
POST	/waypoint	10:45:30.425	10:45:30.581	155.3 ms	POST
POST	/waypoint	10:45:17.923	10:45:18.380	456.97 ms	POST
POST	/cmd	10:45:16.174	10:45:16.229	54.47 ms	POST
		AVERAGE DELAY			73.14 ms

The average communication delay remained below 100 ms, indicating that telemetry information such as vehicle position, heading orientation, waypoint status, and mission progress could be transmitted and monitored with minimal delay during waypoint navigation. Reliable telemetry communication is essential in maritime operations, as operators must continuously supervise vehicle position, mission progress, and system status throughout autonomous deployment. The low communication delay observed in this study demonstrates that operational information can be delivered to the ground control station in near real time, supporting safe mission supervision and enabling timely intervention when required during field operations. These results confirm that the telemetry framework of the proposed navigation system provides sufficient communication responsiveness to support reliable autonomous waypoint navigation under real operating conditions.

IV. CONCLUSION

This study developed and evaluated an autonomous waypoint navigation system for a catamaran-type Unmanned Surface Vehicle (USV), and the results confirm that this objective was achieved. The proposed system enabled autonomous waypoint-following through a modular ROS 2-based architecture that separates the high-level navigation control from the low-level control, allowing navigation functions to be developed and evaluated independently of the underlying vehicle-control firmware. Evaluation in both simulation and real-world environments demonstrated that the system successfully executed all assigned waypoint missions while maintaining continuous autonomous navigation capability throughout the experiments. The achieved navigation performance provides quantitative evidence that the objective was met. In simulation, the system attained a mean waypoint error of 0.49 m and a mean heading error of 4.21°, while field trials produced a mean waypoint error of 1.15 m and a mean heading error of 10.8°. The larger deviations observed during field testing are attributed to GPS uncertainty, environmental disturbances, and actual vehicle dynamics. This difference between simulation and field results highlights the influence of real operating conditions on navigation accuracy and emphasizes the importance of validating USV navigation systems under realistic environments rather than simulation alone. The sub-meter to near-meter accuracy maintained across both conditions indicates that the proposed system provides sufficient navigation reliability for practical autonomous operation, with potential applications in environmental monitoring, water-quality assessment, and inland water inspection that require dependable waypoint navigation. Future work will focus on improving navigation accuracy through more advanced guidance and control strategies, evaluating system performance under more diverse maritime conditions, and integrating obstacle-avoidance capabilities to support safer and more complex autonomous maritime operations.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia (Kemdiktisaintek) for the financial support provided for this research. The authors also thank the Department of Automation Engineering, Politeknik Manufaktur Bandung, and all parties who contributed to the development, testing, and completion of this study.

REFERENCES

[1] H. Zheng and C. Liu, "An Overview of Unmanned Surface Vehicles: Methods, Practices, and Applications," Control Engineering Practice, vol. 164, Nov. 2025, doi: 10.1016/j.conengprac.2025.106479.

[2] M. A. Norazuddin, Z. Z. Abidin, and M. I. Hamza, "Unmanned Surface Vessels in Hydrographic Surveying: Exploring Technological Progressions and Development Challenges," National Institute of Science Communication and Policy Research, Jul. 2024, doi: 10.56042/ijms.v53i07.10419.

[3] C. Spicht and D. Śliwińska, "Hydrographic Inspection Using a USV of a Harbour Bottom Deepened by the Periodic Actuation of SAR Vessel Propellers," Remote Sensing, vol. 16, no. 14, Jul. 2024, doi: 10.3390/rs16142522.

[4] H. Duran and N. K. Sömez, "Unmanned Surface Vehicles Used for Water Quality Monitoring," Bilge International Journal of Science and Technology Research, vol. 9, no. 2, pp. 190–206, Sep. 2025, doi: 10.30516/bijgesci.1637877.

[5] H. D. Tran et al., "Unmanned Surface Vehicle for Automatic Water Quality Monitoring," E3S Web of Conferences, Mar. 2024, doi: 10.1051/e3sconf/202449603005.

[6] Z. Lv, X. Wang, G. Wang, X. Xing, C. Lv, and F. Yu, "Unmanned Surface Vessels in Marine Surveillance and Management: Advances in Communication, Navigation, Control, and Data-Driven Research," Journal of Marine Science and Engineering, vol. 13, no. 5, 2025, doi: 10.3390/jmse13050969.

[7] S. Mahmoud Zadeh and A. Yazdani, "A Cooperative Fault-Tolerant Mission Planner System for Unmanned Surface Vehicles in Ocean Sensor Network Monitoring and Inspection," IEEE Transactions on Vehicular Technology, vol. 72, no. 1, pp. 1101–1115, Jan. 2023, doi: 10.1109/TVT.2022.3204949.

[8] L. F. Constantinoiu, M. Bernardino, and E. Rusu, "Autonomous Shallow Water Hydrographic Survey Using a Proto-Type USV," Journal of Marine Science and Engineering, vol. 11, no. 4, Apr. 2023, doi: 10.3390/jmse11040799.

[9] K. Liu et al., "COLREGs-Compliant Autonomous Collision Avoidance and Improved Adaptive LOS-Based Motion Control for USVs in Complex Waters," Ocean Engineering, vol. 318, Feb. 2025, doi: 10.1016/j.oceaneng.2024.120127.

[10] W. Dong, Y. Zhu, J. Xing, S. Wang, and Z. Xin, "Line-of-Sight Guidance Law Design for Path Following of USVs with Sideslip Angle Compensation," Ocean Engineering, vol. 342, Dec. 2025, doi: 10.1016/j.oceaneng.2025.123015.

[11] M. Wang et al., "Vector Field-Based Integral LOS Path Following and Target Tracking for Underactuated Unmanned Surface Vehicle," Ocean Engineering, vol. 285, Oct. 2023, doi: 10.1016/j.oceaneng.2023.115462.

[12] Z. Dong, W. Liu, Y. Ding, S. Lu, Z. Hu, and Y. Liu, "Time-Varying Formation Trajectory Tracking Scheme for Underactuated USVs Based on Adaptive Sliding Mode Control with Improved Guidance Strategy," Ocean Engineering, vol. 331, Jul. 2025, doi: 10.1016/j.oceaneng.2025.121340.

[13] S. Han, J. Sun, L. Yan, S. Ding, and L. Zhou, "Research on Effective Trajectory Planning, Tracking, and Reconstruction for USV Formation in Complex Environments," Ocean Engineering, vol. 341, Dec. 2025, doi: 10.1016/j.oceaneng.2025.122488.

[14] Y. Tao and J. Du, "Time-Optimal Global Path Planning and Collision-Avoidance Local Path Planning for USVs in Traffic Separation Scheme-Implemented Coastal Waters," ISA Transactions, Oct. 2025, doi: 10.1016/j.isatra.2025.06.030.

[15] D. Hasli, S. Yang, and X. Xiang, "Route Planning Algorithms for Unmanned Surface Vehicles (USVs): A Comprehensive Analysis," 2024.

[16] C. Liu et al., "Development of USV Autonomy: Architecture, Implementation and Sea Trials," Brodogradnja, vol. 73, no. 1, pp. 89–107, 2022, doi: 10.21278/brod73105.

[17] D. Portugal, R. Rocha, and J. P. Castilho, "Inquiring the Robot Operating System Community on the State of Adoption of the ROS 2 Robotics Middleware," International Journal of Advanced Robotic Systems, vol. 9, no. 2, pp. 454–479, Jun. 2025, doi: 10.1007/s41315-024-00393-4.

[18] Z. Wei, S. Wang, K. Chen, and F. Wang, "ROS-Based Navigation and Obstacle Avoidance: A Study of Architectures, Methods, and Trends," Sensors, 2025, doi: 10.3390/s25144306.

[19] J. P. Mendoza-Mendoza, J. J. Roldán, and A. Barrientos, Advanced Robotic Vehicles Programming. Switzerland: Springer, 2020.

[20] D. Heath and D. Stonge, Foundations of Robotics: A Multidisciplinary Approach with Python and ROS. Singapore: Springer, 2022.

[21] W. Meng, A. Hume, R. Bucknall, B. Englot, and Y. Liu, "A Fully-Autonomous Framework of Unmanned Surface Vehicles in Maritime Environments Using Gaussian Process Motion Planning," IEEE Journal of Oceanic Engineering, vol. 48, no. 1, pp. 59–79, 2023.

[22] L. Zhao, Y. Bai, and J. K. Paik, "Global Path Planning and Waypoint Following for Heterogeneous Unmanned Surface Vehicles Assisting Inland Water Monitoring," Journal of Ocean Engineering and Science, vol. 10, no. 1, pp. 88–108, Feb. 2025, doi: 10.1016/j.joes.2023.07.002.

[23] A. Koubaa, A. Allouch, M. Alajlan, Y. Javed, A. Belghith, and M. Khalgui, "Micro Air Vehicle Link (MAVLink) in a Nutshell: A Survey," IEEE Access, vol. 7, pp. 87658–87680, 2019, doi: 10.1109/ACCESS.2019.2924410.

[24] N. A. Khan, N. Z. Janjih, S. R. Brohi, A. A. Almazroi, and A. A. Almazroi, "A Secure Communication Protocol for Unmanned Aerial Vehicles," Computers, Materials and Continua, vol. 70, no. 1, pp. 601–618, 2021, doi: 10.32604/cmc.2022.019419.

[25] K. Tanakitkorn, S. Phoemsapthawee, N. Thaweewat, and S. Jungrungruengtaworn, "Unified Line-of-Sight: A Guidance Algorithm with Integral Wind-Up Mitigation and Turning Assist for USVs," Ocean Engineering, vol. 314, Dec. 2024.

[26] C. Shi, G. Zhang, and J. Li, "Integrated Collision Avoidance and Path Following Control for USVs with Adaptive Prescribed Transient Performance," Ocean Engineering, vol. 342, Dec. 2025, doi: 10.1016/j.oceaneng.2025.122897