DESIGN AND DEVELOPMENT OF AN AUTONOMOUS MARITIME RESCUE VEHICLE USING POINT-TO-POINT NAVIGATION METHOD

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Abstract

Survival rates during Man Overboard (MOB) incidents depend heavily on the time required to initiate rescue evacuations. Conventional life-saving equipment, such as life buoys, can only provide flotation support, they lack the ability to autonomously navigate to the victim's location due to the absence of auxiliary propulsion components. Consequently, these conventional rescue methods rely strictly on manual interventions performed by the ship's crew. This study focuses on designing and evaluating the performance of an autonomous maritime rescue vehicle named Varuna Buoy, utilizing the Point-to-Point navigation method. The developed onboard platform consists of an ESP32 microcontroller unit, a Neo-6M GPS module, an HW127 digital compass, a BTS7960 motor driver, modified bilge-pump thrusters, and a LoRa Communication Module to achieve autonomous navigation functions. Integrating the haversine calculation function, azimuth bearing, and differential thrust control successfully created a prototype capable of moving toward predefined coordinates. Results obtained from autonomous navigation testing comprising 10 trials under 2 different scenarios at Ketintang Lake, Universitas Negeri Surabaya demonstrated successful arrival at the target, with a final position error ranging between 1.27 m and 2.62 m. By establishing a stopping threshold of 2 meters, the system achieved a navigation success rate of 70%. Additionally, the performance of the LoRa network for data communication yielded an average latency of 1.06 seconds, enabling consistent, near-real-time telemetry. This study proves that the implementation of this navigation type can be utilized to develop autonomous marine rescue systems.

Keyword: *autonomous maritime rescue, Haversine, LoRa communication, Man Overboard, Point-to-Point Navigation.*

I. INTRODUCTION

Indonesia is an archipelagic country that relies heavily on maritime transportation to support the mobility of people and goods between islands. According to Statistics Indonesia (BPS), the number of domestic sea transportation passengers reached 19.38 million during the January–September 2024 period, representing a 27.17% increase compared with the same period in the previous year (Badan Pusat Statistik, 2024). This continuous growth in maritime transportation activity increases the urgency and importance of maritime safety systems, as higher shipping intensity will be accompanied by greater risks of accidents caused by human error, environmental conditions, and limitations of existing onboard safety equipment (Wahyuni, Widodo, & Rubiyanto, 2025).

Among various maritime accidents, Man Overboard (MOB) incidents remain one of the most critical emergency situations because the probability of successful rescue decreases rapidly as rescue time increases (Integrated Man Overboard Search and Rescue System, 2018). A MOB incident occurs when a person accidentally falls from a vessel into the sea, where waves, ocean currents, and limited visibility continuously alter the victim's position and complicate rescue operations (Integrated Man Overboard Search and Rescue System, 2018). Under these conditions, rapid response becomes the most important factor for improving survival probability, particularly during adverse weather or nighttime operations (Zhang, Tao, & Yin, 2024).

Conventional maritime rescue equipment is still primarily based on passive tools such as trailing lines, rescue buoys, and life rings, which are effective only in limited situations and cannot actively approach the victim (V. Jain, et al., 2021). Consequently, rescue operations continue to depend heavily on the crew's manual response and situational judgment, and human error remains a major contributing factor during emergency response procedures, including man overboard drills (S.I. Ahn, et al., 2022). Previous studies have demonstrated that autonomous rescue platforms can reduce the risk and workload placed on human responders while accelerating emergency response, indicating significant potential for improving maritime rescue effectiveness (V. Jain, et al., 2021).

Recent advances in embedded systems, satellite positioning, digital navigation sensors, and wireless communication technologies have enabled the development of autonomous maritime vehicles capable of performing navigation tasks without continuous human intervention (Sadraey, 2024). One of the most widely implemented navigation approaches is Point-to-Point Navigation, which guides an autonomous vehicle from its current position toward predetermined target coordinates using navigation parameters such as heading, bearing, and distance (Sadraey, 2024). In this approach, the target distance can be estimated using the Haversine formula (Farid & Yunus, 2017; Rahayu, Fanni, & Bima, 2022), while the navigation direction is determined from azimuth bearing calculations and corrected continuously using heading information obtained from a digital compass (Zalewski, 2019).

Several previous studies have implemented GPS and compass based autonomous navigation on unmanned surface vehicles for applications such as environmental monitoring, hydrographic surveys, and autonomous patrol (Leksono & Syahrorini, 2021; Kolev et al., 2021; Sotelo Torres et al., 2023). A GPS equipped autonomous surface vessel has also been developed specifically for search and rescue operations, demonstrating the feasibility of GPS-based navigation for locating victims and evidence at sea (H. Mansory, et al., 2021). However, this and other existing rescue-oriented USVs have generally not been evaluated using rescue-specific performance indicators such as heading correction capability, target-reaching accuracy, and autonomous stopping precision near the victim's location — leaving these aspects, particularly for Man Overboard scenarios, still underexplored.

Therefore, this study develops Varuna Buoy, an autonomous maritime rescue vehicle employing the Point-to-Point Navigation method to navigate automatically toward predetermined target coordinates. The proposed system integrates an ESP32 microcontroller, Neo-6M GPS receiver, HW127 digital compass, BTS7960 motor driver, modified bilge pump thrusters, and a LoRa wireless communication module. Navigation is achieved by combining Haversine distance estimation, azimuth bearing calculation, and differential thrust control to continuously minimize heading error during autonomous movement (Farid & Yunus, 2017; Li et al., 2019).

The novelty of this research lies in the integration of Point-to-Point Navigation, Haversine-based distance estimation, azimuth bearing calculation, differential thrust control, and LoRa-based telemetry into a compact autonomous rescue buoy specifically designed for Man Overboard applications. The proposed system is experimentally evaluated through autonomous field navigation tests under different initial heading conditions to assess heading correction capability, navigation accuracy, and target-reaching performance. The results are expected to provide an effective alternative for improving maritime rescue operations while serving as a reference for future development of autonomous maritime rescue vehicles.

II. THEORY

A. Man Overboard Rescue

A Man Overboard (MOB) incident refers to an emergency situation in which an individual accidentally falls from a vessel into the water during maritime operations. MOB accidents are considered among the most critical emergencies because the victim's survival depends heavily on the speed and effectiveness of the rescue operations. Ocean currents, waves, wind, and limited visibility continuously alter the victim's position, making search and rescue efforts increasingly difficult as response time increases. Therefore, international maritime safety regulations emphasize the importance of immediate rescue actions to maximize the probability of survival (Integrated Man Overboard Search and Rescue System, 2018; Zhang, Tao, & Yin, 2024).

Conventional rescue equipment, such as life buoys, primarily functions as flotation devices and cannot actively navigate toward victims. Consequently, rescue operations rely on manual intervention from ship crews, which may introduce delays and increase the likelihood of human error. Recent developments in autonomous rescue technology have demonstrated that unmanned rescue systems can significantly reduce response time while improving operational safety by minimizing direct human involvement during emergency situations (Lygouras et al., 2018).

B. Autonomous Maritime Rescue Vehicle

An autonomous maritime rescue vehicle is an unmanned surface vehicle (USV) designed to perform rescue missions without continuous human control. These vehicles integrate positioning sensors, navigation algorithms, propulsion systems, and communication modules to autonomously reach designated target locations. Compared with manually operated rescue equipment, autonomous rescue vehicles can provide faster response, consistent navigation performance, and improved operational reliability, particularly in hazardous environments where direct human intervention may be difficult (Leksono & Syhrorini, 2021; Kolev et al., 2021). The effectiveness of an autonomous rescue vehicle depends on its ability to estimate its current position, determine the target direction, continuously correct navigation errors, and maintain stable motion under varying environmental conditions. Therefore, navigation accuracy and heading stability become essential performance indicators for evaluating autonomous maritime rescue systems.

C. Point-to-Point Navigation

Point-to-Point Navigation is one of the most widely used navigation methods for autonomous vehicles because of its simplicity and computational efficiency. The method guides a vehicle directly from its current position toward a predetermined destination by continuously calculating the target bearing and the remaining distance. During navigation, the vehicle compares its current heading with the desired bearing to obtain the heading error, which is subsequently used to determine steering corrections (Sadraey, 2024).

In unmanned surface vehicles, heading information is commonly obtained from a digital compass, whereas the target bearing is calculated using GPS coordinates. By continuously minimizing the heading error, the vehicle maintains its trajectory toward the destination while adapting to changes in orientation during movement. Previous studies have shown that Point-to-Point Navigation provides reliable performance for autonomous navigation applications because of its relatively low computational complexity and straightforward implementation (Kolev et al., 2021).

D. Haversine Distance Calculation

The Haversine formula is a mathematical method used to determine the shortest distance between two geographical coordinates on the Earth's surface based on latitude and longitude. Unlike Euclidean distance, the Haversine method considers the Earth's curvature, making it more suitable for navigation and geographic positioning applications (Farid & Yunus, 2017). The Haversine equation is expressed as

$$d = 2.R.\arcsin(\sqrt{sin^2\left(\frac{\Delta\varphi}{2}\right) + cos\varphi1.cos\varphi2.sin^2\left(\frac{\Delta\lambda}{2}\right)} \quad (1)$$

where d represents the distance between two coordinates, R is the Earth's radius, φ denotes latitude, and λ denotes longitude. In autonomous navigation systems, this calculated distance is used to determine the remaining travel distance, trigger speed reduction near the destination, and stop the vehicle when the predefined target threshold has been reached. The implementation of the Haversine method has demonstrated high positional accuracy in various location-based applications, achieving results comparable to measurements obtained from digital mapping services (Rahayu, Fanni, & Bima, 2022).

E. Differential Thrust Control

Differential thrust control is a steering technique in which directional motion is achieved by varying the rotational speeds of the left and right propulsion units. Instead of using a conventional rudder, autonomous surface vehicles equipped with dual thrusters modify the thrust difference between both motors to generate turning moments. When both motors rotate at equal speed, the vehicle moves straight ahead. Increasing the thrust of one motor while decreasing the other causes the vehicle to rotate toward the side with lower thrust (Li et al., 2019).

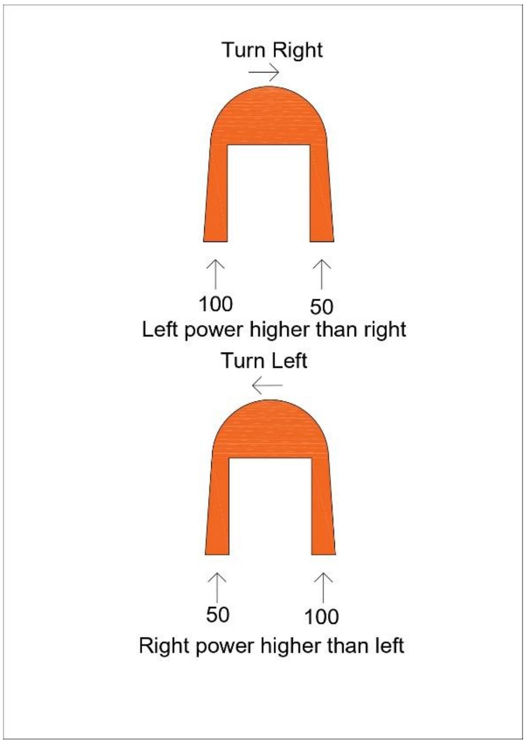

Figure 1. Differential thruster mechanism

In this research, the heading error obtained from the comparison between the target bearing and the compass heading is converted into differential PWM values for the left and right thrusters. This strategy enables the Varuna Buoy to perform gradual steering corrections, sharp turns, and straight-line navigation while continuously reducing heading error throughout the navigation process. Differential thrust control provides a simple yet effective steering mechanism for compact autonomous rescue vehicles because it eliminates the need for additional steering actuators while maintaining maneuverability.

III. METHOD

A. Research Method

This research employed an experimental research method to design, implement, and evaluate an autonomous navigation system for the Varuna Buoy maritime rescue vehicle. The experimental approach was selected because it enables direct evaluation of the proposed Point-to-Point Navigation algorithm under real operating conditions. System performance was assessed based on navigation accuracy, heading correction capability, target-reaching performance, and communication response during field experiments.

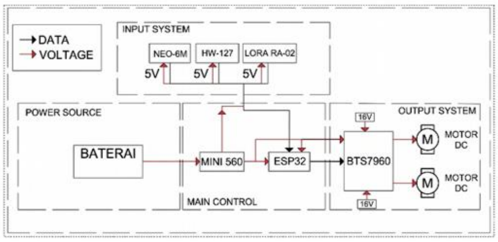

Figure 2. System Block Diagram

The research was conducted through several stages, including problem identification, literature review, system design, hardware integration, software development, field testing, data collection, performance evaluation, and conclusion. These sequential stages ensured that the developed navigation system fulfilled the research objectives and operated according to the intended design.

B. Experimental Setup

Field experiments were conducted at Ketintang Lake, Universitas Negeri Surabaya, where relatively calm water conditions minimized disturbances caused by waves and currents. This study did not include testing under extreme environmental conditions, such as high waves and strong winds, because the vehicle used was a first-stage prototype that still requires further development and refinement. Therefore, the experiments were focused on evaluating the fundamental performance of the autonomous navigation system in a controlled environment. The autonomous navigation system was evaluated through two navigation scenarios, each consisting of five experimental trials, resulting in a total of ten autonomous navigation tests.

In each experiment, the Varuna Buoy started navigation from predetermined initial coordinates and autonomously traveled toward a fixed target coordinate. The use of a fixed target coordinate was intended to evaluate the fundamental capability of the navigation system to accurately reach its destination before being further developed to handle more complex scenarios involving moving targets that drift with ocean currents, as commonly occurs in *man overboard* (MOB) incidents. This approach enabled an objective evaluation of the navigation algorithm because the target position remained constant throughout the experiments.

Each trial began with a different initial heading orientation to evaluate the performance of the navigation algorithm under various initial conditions. The selection of these initial heading variations is consistent with the principle of uncertainty in the position and orientation of objects at sea, which underlies maritime search and rescue theory, considering that environmental forces acting on floating objects are dynamic (Lonin S., et al., 2025). This approach enables a more comprehensive assessment of the system's ability to perform heading correction and maintain navigation accuracy under different initial orientation scenarios.

All experiments were conducted using identical hardware and software configurations to ensure consistent testing conditions. During each trial, the ESP32 continuously recorded GPS coordinates, compass heading, distance to the target, heading error, PWM values of both thrusters, and wireless communication response time as performance evaluation parameters. The collected data were subsequently used to analyze navigation performance, target-reaching accuracy, and the overall response of the autonomous navigation system throughout the experiments.

C. System Architecture

The proposed autonomous rescue system consists of two main subsystems, the autonomous rescue vehicle (Varuna Buoy) and the monitoring station. The Varuna Buoy integrates an ESP32 microcontroller as the central processing unit, a Neo-6M GPS module for positioning, and an HW127 digital compass for heading measurement, which together enable an autonomous navigation system capable of determining vehicle position and guiding the vehicle toward a predetermined waypoint accurately. Motion is actuated by a BTS7960 motor driver and two modified bilge pump motors functioning as thrusters. Navigation and sensor data are transmitted to the monitoring station via a LoRa RA-02 communication module operating at 433 MHz, leveraging LoRa's low-power, long-range wireless data transmission characteristics suitable for real-time remote monitoring applications (Andre et al., 2022). Meanwhile, the monitoring station receives navigation data transmitted by LoRa and displays real-time information through the MQTTX platform.

The navigation system continuously acquires GPS coordinates and heading information from onboard sensors. The ESP32 processes these data to calculate the remaining distance using the Haversine formula and determine the target direction using azimuth bearing calculation. The calculated heading error is subsequently converted into differential PWM signals to regulate the rotational speeds of the left and right thrusters, allowing the vehicle to autonomously navigate toward the designated target coordinate.

D. Navigation Algorithm

The navigation algorithm of the Varuna Buoy is based on the Point-to-Point Navigation method. Initially, the system receives the target coordinates and continuously updates its current position obtained from the GPS module. The distance between the current position and the destination is calculated using the Haversine formula, while the target direction is determined through azimuth bearing calculation. The actual vehicle heading is measured by the digital compass and compared with the desired bearing to obtain the heading error. This error becomes the primary input for the differential thrust controller.

Depending on the magnitude of the heading error, the controller performs one of three navigation maneuvers: straight navigation, gradual heading correction, or pivot turning. Furthermore, the propulsion speed is automatically reduced by 50% when the remaining distance is less than 4 meters, and both motors are stopped once the vehicle reaches a stopping threshold of 2 meters. This control strategy enables continuous heading correction while maintaining stable navigation toward the target. The algorithm utilized by the system is presented in Figure 3.

```
Algorithm Point-to-Point Navigation Control
function NAVIGATION_CONTROL(errorHeading, distance)
    turnRatio ← Map(errorHeading)                  ▷ Heading Mapping
    forwardRatio ← Map(distance)                   ▷ Distance Mapping
    if errorHeading > 60° then
        Set Sharp Right Turn                       ▷ Pivot Turn
    else if errorHeading < -60° then
        Set Sharp Left Turn                        ▷ Pivot Turn
    else if ±10° ≤ |errorHeading| ≤ ±60° then
        Reduce forward and turning speed by 50%    ▷ Gradual Turning
        Calculate Differential Steering
    else
        Move Straight or Differential Steering     ▷ Normal Navigation
    end if
    if distance < 4 m then
        Reduce Motor Speed                         ▷ Slow Down Near Target
    end if
    if distance ≤ 2 m then
        Stop Both Motors                           ▷ Target Reached
    end if
    Convert Motor Output to PWM                    ▷ PWM Conversion
    return rightPWM, leftPWM                       ▷ Motor Command
end function
```

Figure 3. Point-to-point Algorithm Pseucode

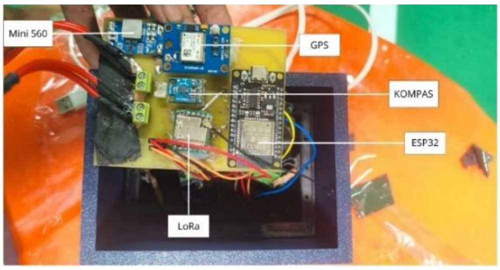

Figure 4. Varuna Buoy Board PCB

E. Perfomance Evaluation

The autonomous navigation system was evaluated using four performance parameters:

1. Communication Delay, representing the time required to transmit navigation data from the Varuna Buoy to the monitoring station through the LoRa communication network.
2. Heading error, representing the angular difference between the desired bearing and the actual heading measured by the digital compass during navigation.
3. Final distance to the target, representing the remaining distance between the vehicle and the destination after the navigation process was terminated.
4. Navigation success rate, representing the percentage of experiments in which the Varuna Buoy successfully reached the predefined stopping threshold.

The navigation process was considered successful when the vehicle autonomously reached the target area while maintaining stable heading correction throughout the navigation process. The collected experimental data were analyzed descriptively to evaluate the effectiveness of the proposed Point-to-Point Navigation algorithm for autonomous maritime rescue applications.

IV. RESULT AND DISCUSION

A. Hardware Implementation

The autonomous maritime rescue system was implemented by integrating all electronic components into the Varuna Buoy platform. The hardware consists of an ESP32 microcontroller, Neo-6M GPS receiver, HW127 digital compass, BTS7960 motor driver, Mini560 voltage regulator, LoRa RA-02 communication module, and two modified bilge pump motors functioning as differential thrusters. The vehicle hull was constructed using resin-coated styrofoam to provide sufficient buoyancy while maintaining lightweight characteristics suitable for autonomous navigation on calm water surfaces.

Figure 5. Varuna Buoy

The complete prototype is presented in Figure 4.

The integration of positioning, heading measurement, wireless communication, and propulsion subsystems enabled the Varuna Buoy to perform autonomous navigation while simultaneously transmitting telemetry data to the monitoring station. The ESP32 continuously processed sensor data and generated PWM commands for both thrusters based on the calculated heading error, allowing the vehicle to maintain directional stability throughout the navigation process.

Figure 5 shows the complete Varuna Buoy prototype with all navigation, communication, and propulsion components integrated into the floating platform. The electronic control board presented in Figure 4 was installed inside the waterproof compartment, while the GPS antenna and LoRa module were positioned to ensure reliable signal reception and wireless communication. Two bilge-pump-based thrusters were mounted symmetrically at the rear of the buoy to generate differential thrust for steering and forward motion. This integrated configuration enabled the Varuna Buoy to autonomously navigate toward the target while maintaining system stability during field experiments.

B. Autonomous Navigation Testing

The autonomous navigation experiments were conducted at Ketintang Lake, Universitas Negeri Surabaya. This location was selected because its relatively calm water conditions minimized the influence of waves and currents, allowing the evaluation to focus primarily on the navigation algorithm.

Figure 6. Testing Location at Ketintang Lake, Universitas Negeri Surabaya

Table 1. Testing Coordinate

Scenario	Initial Coordinate	Target Coordinate
Scenario 1	-7.314402, 112.726006	-7.314462, 112.726059
Scenario 2	-7.314381, 112.726028	

Ten experiments were performed under two navigation scenarios with different initial heading orientations while maintaining identical hardware and software configurations.

The navigation process began by processing the Varuna Buoy current coordinates acquired from the GPS module. The remaining distance to the destination was then calculated using the Haversine formula, while the desired direction was determined through azimuth bearing calculation. The heading error, obtained by comparing the target azimuth and the actual compass heading, was subsequently converted into differential PWM commands for the left and right thrusters until the vehicle reached the predefined stopping threshold (2 m). With this configuration, the proposed Point-to-Point Navigation method can be effectively implemented on a compact autonomous rescue platform without requiring additional steering mechanisms.

C. Communication Performance

Reliable wireless communication is essential for real-time monitoring of autonomous rescue vehicles. Therefore, the communication latency between the Varuna Buoy and the monitoring station was evaluated using the LoRa RA-02 communication module.

Experimental results indicate that the communication delay varied between 0.07 s and 1.4 s, with an average of 1.06 s. The minimum delay occurred during Trial 9, whereas the maximum delay was observed in Trial 7. Despite these variations, the communication remained stable throughout the experiments.

This relatively low latency demonstrates that the LoRa-based telemetry system is capable

Table 2. Communication Response Time

Transmission Timestamp	Reception Timestamp	Delay (s)
22:10:13:.0	22:10:14:.0	1.0 s
22:10:18:.0	22:10:19:.2	1.2 s
22:10:23:.0	22:10:23:.9	0.9 s
22:10:28:.0	22:10:29:.3	1.3 s
22:10:33:.0	22:10:33:.8	0.8 s
22:10:38:.0	22:10:39:.1	1.1 s
22:10:43:.0	22:10:44:.4	1.4 s
22:10:48:.0	22:10:49:.2	1.2 s
22:10:53:.0	22:10:53:.7	0.7 s
22:10:58:.0	22:10:59:.0	1.0 s
Mean		**1.06 s**

of transmitting navigation information in near real-time. Such performance is sufficient for monitoring autonomous rescue missions, as position updates remain consistent while requiring significantly lower power consumption compared to conventional wireless communication technologies.

D. PWM Analysis

To evaluate the performance of the proposed differential thrust controller, the Pulse Width Modulation (PWM) values of the left and right thrusters were analyzed during the autonomous navigation experiments. The controller continuously adjusted the PWM values based on the heading error measured by the digital compass, thereby regulating the thrust generated by each motor to maintain the desired navigation direction. Figures 6 and 7 present the average PWM responses of the left and right thrusters with respect to the remaining distance to the target for Scenarios 1 and 2, respectively

As shown in Figure 6, the control system generated a distinct difference between the left and right PWM values during the initial stage of navigation when the vehicle was approximately 10 m from the target. The left thruster operated at a higher PWM value than the right thruster, producing differential thrust that enabled the Varuna Buoy to rotate toward the target coordinates. As the heading error gradually decreased, the PWM difference between both thrusters also narrowed, indicating that fewer steering corrections were required. At a remaining distance of approximately 5 m, both thrusters reached their maximum PWM values. This indicates that the vehicle had successfully aligned with the target direction, prompting the controller to increase forward propulsion to accelerate the approach. Subsequently, the PWM values gradually decreased as the vehicle entered the deceleration zone (4 m). When the remaining distance reached the predefined stopping threshold of approximately 2 m, the PWM values of both thrusters dropped to 1500, causing the propulsion system to come to a complete stop.

Figure 7 illustrates the PWM values obtained during the second navigation scenario. Compared with Scenario 1, larger fluctuations in PWM were observed during the early stage of navigation in Scenario 2 due to the considerably greater initial heading error. At the beginning of the trial, the generated PWM values created a larger difference between the left and right thrusters to produce a sharp turning movement, allowing the vehicle to rapidly correct its heading toward the target. Once the heading error was reduced, the PWM values of both thrusters gradually converged, indicating the transition from steering maneuvers to straight-line navigation. Similar to the first scenario, the PWM output values decreased as the remaining distance approached the stopping threshold (2 m).

Overall, the PWM values generated in both scenarios demonstrate that the developed differential thrust controller successfully processed heading errors into propulsion commands during the navigation process.

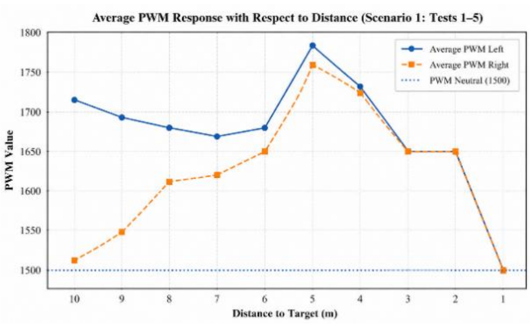

Figure 7. Average PWM Response with Respect to Distance in Scenario 1

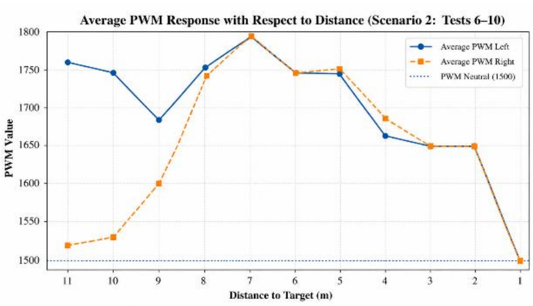

Figure 8. Average PWM Response with Respect to Distance in Scenario 2

A larger heading error resulted in a wider PWM difference to generate stronger steering corrections, whereas a smaller heading error produced nearly identical PWM values for both thrusters to maintain stable forward motion. The gradual reduction of PWM near the destination also indicates that the controller effectively limited the vehicle's speed before reaching the target. This results in a smoother stopping transition while minimizing the potential for overshoot beyond the predefined navigation threshold.

E. Heading Error Analysis

Heading error was analyzed to evaluate the capability of the proposed navigation controller in maintaining the vehicle's orientation toward the target coordinate.

The first navigation scenario generated initial heading errors ranging from 93° to 112°. During autonomous navigation, the average heading error decreased to 27.00°–34.50°, indicating that the navigation system and the differential thrust controller continuously corrected the vehicle's orientation. The final distance achieved by the vehicle ranged between 1.68 m and 2.62 m.

Table 3. Navigation Results in Scenario 1

Initial Heading Error (°)	Average Heading Error (°)	Initial Distance (m)	Final Distance (m)
94	27	9.07	1.7
102	29.56	9.6	1.69
101	29.88	10.57	1.71
112	34.5	10.53	2.62
93	28.87	9.48	1.68

Table 4. Navigation Results in Scenario 2

Initial Heading Error (°)	Average Heading Error (°)	Initial Distance (m)	Final Distance (m)
177	51.87	9.62	1.68
171	44.65	10.72	1.27
142	49.71	10.77	2.52
137	50.26	11.31	2.54
128	34.1	11.41	1.76

Table 5. Final Distance to Target

Trial	Final Distance (m)	Status
1	1.7	Success
2	1.69	Success
3	1.71	Success
4	2.62	Exceeded Threshold
5	1.68	Success
6	1.68	Success
7	1.27	Success
8	2.52	Exceeded Threshold
9	2.54	Exceeded Threshold
10	1.76	Success

The second scenario presented a more challenging condition because the initial orientation of the Varuna Buoy was almost opposite to the target direction, triggering a heading error ranging from 128° to 177°. Although the average heading error increased to 34.10°–51.87°, the navigation system successfully redirected the vehicle toward the target coordinates. The final distance achieved consistently remained within the range of 1.27 m to 2.54 m, proving the system's ability to maintain effective heading correction even when faced with a massive initial error.

A comparison of both scenarios indicates that a larger initial heading deviation requires more corrective maneuvers before the Varuna Buoy achieves a stable trajectory. Nevertheless, the proposed controller is proven capable of executing continuous heading corrections throughout the navigation process. This confirms that the integration of a compass-based estimation system and differential thrust control delivers robust directional performance.

F. Navigation Accuracy

Navigation accuracy was evaluated using the final distance between the Varuna Buoy and the target coordinate.

Experimental results indicate that the final distance achieved by the Varuna Buoy ranged from 1.27 m to 2.62 m. Out of ten trials, seven successfully reached the predefined stopping threshold of 2 m, resulting in a navigation success rate of 70%. The remaining three trials exceeded the threshold, with distance deviations ranging from 0.52 m to 0.62 m.

The observed distance deviations were primarily influenced by three factors. First, the GPS receiver exhibited positioning uncertainty of up to several meters due to satellite geometry, signal multipath effects, and environmental interference. Since the stopping decision was based on the distance calculated from GPS data, fluctuations in the measured position could cause the stopping command to be executed either earlier or later than intended, directly affecting the final distance error. Second, heading measurements obtained from the digital compass were affected by sensor noise and magnetic interference, resulting in orientation errors during navigation. These heading deviations caused the vehicle to follow a slightly longer trajectory than the ideal straight path toward the target, thereby increasing the remaining distance when the stopping threshold was reached. Third, although the controller immediately terminated the propulsion once the measured distance reached the stopping threshold, the Varuna Buoy continued moving due to hydrodynamic inertia. The vehicle retained forward momentum until its kinetic energy was fully dissipated by water resistance, resulting in an overshoot beyond the intended stopping point. This effect became more pronounced when the Varuna Buoy approached the target at a relatively higher speed.

Despite these limitations, the maximum recorded distance deviation was only 0.62 m beyond the predefined 2 m stopping threshold, representing approximately 6.2% of the initial navigation distance of approximately 10 m. These results demonstrate that the proposed Point-to-Point Navigation method provides satisfactory positioning accuracy for autonomous maritime rescue applications. In future work, these distance deviations are expected to be further reduced by employing GPS receivers and digital compasses with higher measurement accuracy. The Neo-6M GPS module used in this study provides a positioning accuracy of approximately ±2 m under ideal operating conditions; therefore, coordinate fluctuations may still affect distance estimation and the timing of the stopping decision. Consequently, the use of higher-accuracy GNSS modules, such as RTK-GNSS or multi-band GNSS receivers, together with industrial-grade digital compasses offering improved heading stability, has the potential to enhance navigation accuracy and further reduce distance deviations in future studies.

V. CONCLUSION

This research successfully designed and implemented a system called Varuna Buoy, an autonomous maritime rescue vehicle that uses the Point-to-Point Navigation technique to assist during Man Overboard (MOB) rescue operations. The proposed system consists of an ESP32 microcontroller, Neo-6M GPS receiver, HW127 digital compass, BTS7960 motor driver, modified bilge pump thrusters, and LoRa wireless communication to enable autonomous navigation and real-time telemetry. Experimental evaluations conducted over ten navigation trials demonstrate the effectiveness of the proposed navigation algorithm in guiding the unmanned surface vehicle (USV) toward predetermined target coordinates under different initial heading conditions. The LoRa communication system achieved an average latency of 1.06 s, enabling reliable real-time monitoring. In terms of autonomous navigation performance, the proposed algorithm achieved a success rate of 70% based on a predefined stopping threshold of 2 m, resulting in final target distances ranging from 1.27 m to 2.62 m, as illustrated in Figure 8. These results indicate that integrating Haversine-based distance estimation, azimuth bearing calculation, and differential thrust control provides an effective approach for achieving robust autonomous maritime rescue missions. Future work should focus on improving navigation accuracy through advanced sensor fusion techniques and adaptive control strategies, as well as implementing obstacle avoidance and evaluating system performance under real maritime environmental conditions involving waves, currents, and wind disturbances.

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