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Development of a Solar Autonomous Boat Navigation Guidance System for Future Swarm Unmanned-Surface-Vehicle Implementation

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Abstract

Changes in the quality of the lake environment due to human activities demand efficient and sustainable monitoring solutions. This research designed a navigation guidance system for the solar autonomous boat that operates independently using solar energy and designed as a modular navigation unit to support future swarm-based cooperation between multiple vessels. The system relies on GPS ATGM336H and GY-271 digital compass sensor as positioning and direction determinants, controlled by a TTGO ESP32 LoRa microcontroller. Navigation data is processed in real-time and sent over the LoRa network to a central or intership gateway. This research focuses on the development and validation of the autonomous navigation core, providing the necessary guidance capabilities for integration into a swarm unmanned surface vehicle (USV) framework. The test results showed that the boat could follow the destination's direction with an accuracy of 92%, where most of the trajectory was within the pre-programmed directional tolerance. The average direction error was recorded at 5.4 degrees, within acceptable tolerance limits. The system can adaptively maintain a stable heading and respond to aquatic environmental conditions. By establishing this stable autonomous navigation baseline, the system provides a scalable platform for future swarm implementations aimed at improving large-scale environmental monitoring. This system is considered successful as an intelligent and sustainable autonomous navigation solution.

Keywords: solar-autonomous-boat, LoRa communication, swarm USV, environmental monitoring.

I. INTRODUCTION

Lakes are a terrestrial aquatic ecosystem with a strategic role in supporting social, economic, and environmental sustainability. In Indonesia, the functions of lakes include the provision of drinking water, irrigation, aquaculture, water transportation, tourism, and power generation, and they are part of the cultural values of local communities. However, pressures from anthropogenic activities such as domestic waste disposal, pollution, and land conversion lead to significant degradation of lake environmental quality. This poses a challenge in maintaining the balance of the lake ecosystem [1],[2].

One of the approaches that has begun to be developed for monitoring the aquatic environment is unmanned surface vehicle (USV) technology. USV is an unmanned vehicle that can operate autonomously on the water's surface without direct human intervention. This system is effectively used by conventional manned vessels to reach narrow, shallow, or inaccessible areas [3], [4], [5]. With its ability to automatically monitor water and air quality, USV can provide real-time and continuous environmental data [6].

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Nevertheless, the successful operation of the USV is highly dependent on the reliability of the integrated navigation system. The navigation system is the main component in ensuring that the boat moves to the predetermined waypoint accurately and can avoid obstacles such as aquatic vegetation or floating objects [7]. This navigation technology generally relies on integrating global positioning system (GPS) sensors and digital compasses. GPS modules, such as ATGM336H, serve as positioning and speed estimators based on the movement of the boat trajectory, while compass sensors, such as the GY-271, are used to determine the direction of the boat face [8].

To improve the system's efficiency, coverage, and durability, the Swarm USV concept began to be implemented. Current research in maritime autonomy emphasizes the transition from single-agent vehicles to modular, hierarchical Swarm USV (SUSV) architectures [9],[10]. This approach ensures that individual navigation guidance systems, like the one proposed in this study, can serve as scalable nodes for future multi-agent cooperation. This technology allows multiple autonomous vessels to work in a coordinated manner on a single mission, thereby accelerating data acquisition and reducing reliance on manual measurement methods [11], [12], [13]. In addition, wireless communication support such as LoRa plays an important role in the efficient and power-efficient exchange of data between boat or with central gateways [14]. Solar energy is also used to support sustainable and environmentally friendly operations, making these systems in line with the principles of water resource conservation.

Based on this background, this research focuses on designing and implementing a navigation system for a solar autonomous boat based on GPS, digital compass, and LoRa communication. The system was also developed with a swarm approach to improve the effectiveness of automatic and continuous monitoring of the lake's environment.

II. METHODS

This chapter describes the modeling and design of navigation systems applied to solar-powered autonomous vessels. The system is designed to allow the boat to move autonomously towards a predetermined waypoint, relying on the integration of various sensors such as GPS and digital compass. The experiments were conducted in a real-world open water environment (local lake) to validate the system's response to actual aquatic disturbances. The overall system architecture, illustrating the link between hardware components, is shown in Figure 1.

A. Navigation System Design

The navigation system is designed to allow the boat to move autonomously towards the waypoint based on position and direction data. The main devices used are the ATGM336H GPS module to determine the boat's geographical coordinates and the GY-271 digital compass sensor to determine the direction of the heading. These two sensors are connected to the TTGO ESP32 LoRa microcontroller, which is a data processing center.

The data processed by TTGO ESP32 is then transmitted via LoRa communication to the LoRa T-Beam V1.1 device, which functions as a receiver (RX). Next, the data is forwarded to the Blynk application as a real-time monitoring interface.

Figure 2 shows a navigation system diagram block that includes the input path from the sensor, processing on the TTGO ESP32, data communication to the receiver via LoRa, and visualization via the Blynk application.

B. Waypoint-Based Navigation

Navigation is based on a list of waypoints containing geographic coordinates. The system calculates the direction of the destination (bearing) from the current position to the next waypoint using data from the GPS and compares it with the actual direction of the GY-271 digital compass sensor.

If the directional deviation exceeds the tolerance threshold (e.g., ±10°), the system will automatically activate the directional correction maneuver to return the boat to its destination precisely.

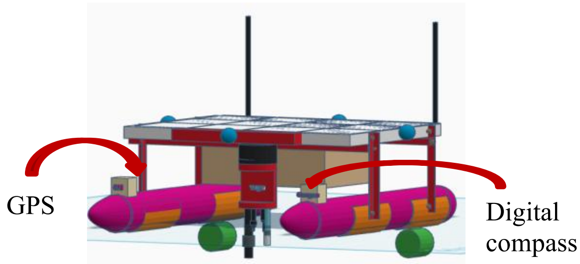

Figure 1. System architecture.

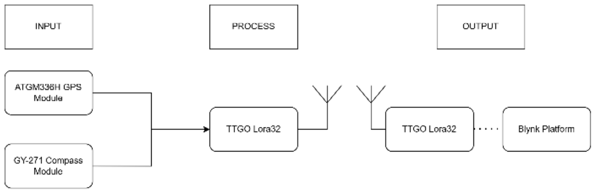

Figure 2. USV navigation system diagram block.

The formula used to calculate heading error is as follows:

$$Heading\ Error = \theta_{destination} - \theta_{current} \quad (1)$$

With:

- $\theta_{destination}$: the directional angle from the current position to the waypoint (calculated from GPS coordinates),
- $\theta_{current}$: the current direction of the boat facing (read from the digital compass).

Formula (1) is a standard method used in autonomous navigation systems to determine directional deviations and activate correction mechanisms. The system will continue to monitor the heading error value in real-time and only make corrections if the value exceeds the predetermined tolerance limit. This approach allows the vessel to stay on the correct trajectory independently without manual intervention.

Figure 3 illustrates the relationship between the direction facing the boat, the direction towards the waypoint, and the heading error.

C. Automatic Direction Correction

The navigation system is equipped with an automatic direction correction mechanism based on heading error values to keep the boat on the right path to the waypoint. Direction correction is done by continuously comparing the directional angle to the waypoint (θdestination) and the direction facing the boat (θcurrent).

If the heading error exceeds a predetermined tolerance threshold, e.g., ±10°, the system automatically activates the steering maneuver control (rudder or motor) to reduce the error. The correction process will continue until the heading error is within the tolerance range.

This direction correction is designed to adapt to changes in the boat's position due to water currents, wind, or other environmental disturbances. Thus, the boat can still move in the direction of the waypoint without deviating significantly from the predetermined path.

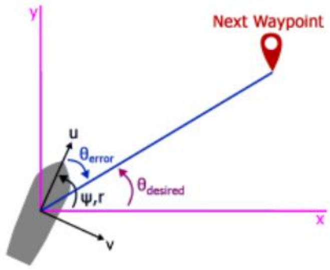

Figure 3. Illustration of directional angle.

This correction mechanism is implemented using simple logic-based control algorithms, such as decision-making:

- If the heading error > +10°, turn left
- If the heading error < -10°, turn right
- If the heading error is in the range of ±10°, keep the direction

With this approach, the boat can navigate the trajectory autonomously with adequate accuracy and remain responsive to changes in direction during the voyage.

D. System Workflow

To ensure data synergy, the TTGO ESP32 utilizes a prioritized polling loop where GPS NMEA sentences are parsed and synchronized with the GY-271 digital compass heading at 10Hz intervals. This ensures that the navigation command (steering) is based on the most recent positioning and orientation data simultaneously. Figure 4 represents the workflow of the GPS and digital compass-based navigation system applied to the solar autonomous boat. This workflow begins with the device initialization stage, namely the activation and configuration of the ATGM336H GPS module, QMC5883L compass sensor, and TTGO ESP32 LoRa microcontroller to ensure all components can function and connect properly. After initialization, the system reads the geographic position data from the GPS module in the form of latitude and longitude coordinates in real-time. On the other hand, the digital compass sensor detects the direction of the boat's face (heading) to magnetic north. A microcontroller then processes the data from these two sensors to determine the boat's orientation to the destination point. The system also tests the consistency between the direction of motion based on GPS and the direction facing from the digital compass to ensure synchronization of navigation data.

Furthermore, the processing results are sent wirelessly over the LoRa network to other receiving devices or vessels. Based on the information received, the boat automatically adjusts its direction of motion towards the predetermined waypoint. This flow allows the vessel to move independently with stable navigation and real-time position monitoring, thus supporting the implementation of a reliable autonomous navigation system.

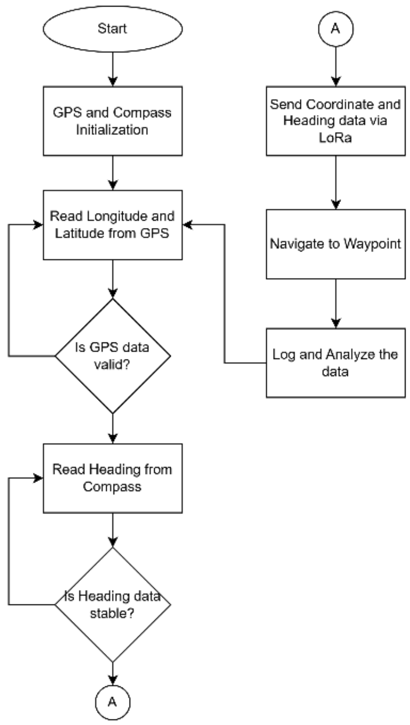

Figure 4. System workflow.

E. Electronic Controller System Design

Figure 5 is a schematic of the printed circuit board (PCB) on the solar autonomous boat that contains the wiring of the navigation system. This schematic shows the logical relationship between the TTGO ESP32 LoRa as the control center and the two main sensors, namely the GPS ATGM336H and the GY-271 digital compass. In this circuit, the GPS module is connected to the TTGO ESP32 LoRa through a UART interface that transmits coordinate data in series from the GPS to the microcontroller. Meanwhile, the GY-271 digital compass sensor uses I2C communication to transmit front-facing data. Both sensors obtain a power supply from a 3.3V line, corresponding to each module's operational voltage specifications. They are connected to the GND line as a shared voltage reference. The specific wiring and pin assignments between the sensors and the TTGO ESP32 are detailed in Table 1.

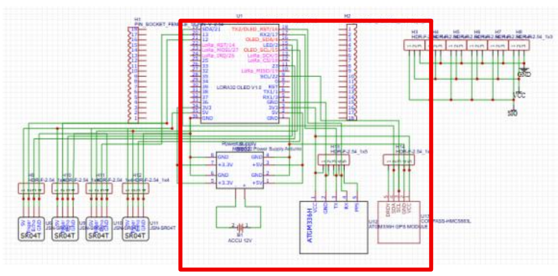
Figure 5. Electronic controller system schematics.

TABLE 1
PIN CONFIGURATION

No	Component	Interface	Pins on Components	Pin on TTGO ESP32
1	GPS ATGM336H	UART	TX	RX (GPIO 16)
			RX	TX (GPIO 17)
2	GY-271 Compass	12C	SDA	GPIO 21
			SCL	GPIO 22

The integration of the ATGM336H GPS and GY-271 digital compass creates a navigational synergy where global positioning is dynamically corrected by real-time heading data to minimize positional drift [15]. Furthermore, the use of LoRa for data transmission addresses the specific constraints of maritime ad-hoc communication, ensuring reliable status updates in low-bandwidth aquatic environments [10].

III. RESULTS AND DISCUSSION

In this system, the GPS module and digital compass sensor are placed at the front of the boat to avoid interference from the magnetic field of other electronic components and ensure that the GPS module has an open view of the sky to obtain satellite signals properly. This placement configuration is shown in Figure 6.

Furthermore, Figure 7 shows the main PCB shape used to lay the LoRa TTGO ESP32 module and the wiring path for the GPS module and digital compass sensor connected directly to the microcontroller. This PCB's design allows for modular, neat, and easy-to-maintain installation of components inside the system's protective box.

Figure 8 shows the sensor wiring scheme on the system, which includes the connection between the TTGO ESP32 module and the GPS sensor, the digital compass, and the communication lines and power supply that support the operation of the overall navigation system. The wiring arrangement is carried out systematically to minimize signal interference and simplify maintenance.

Figure 6. Component placement.

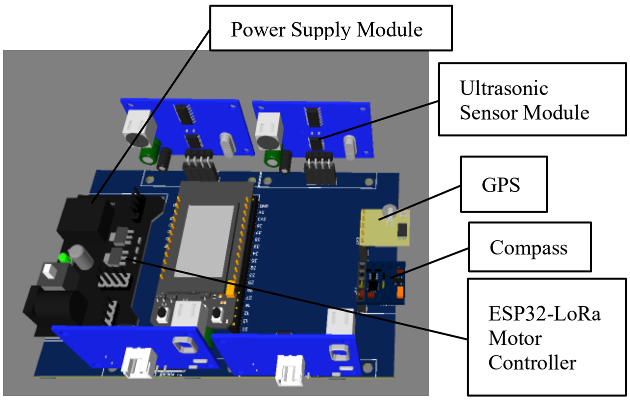

Figure 7. Physical design of boat controller.

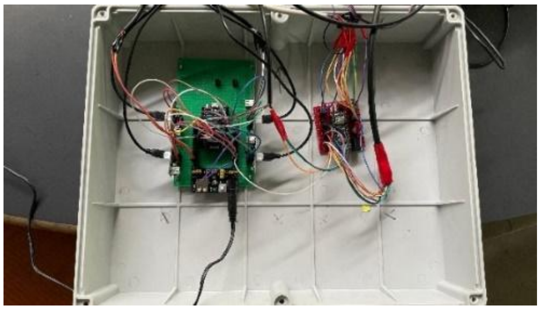
Figure 8. Sensor wiring.

A. Test Scenarios

Several test scenarios were conducted in an open water environment for example at Telkom University's Situ Tekno or Danau Galau to evaluate the navigation and heading correction system's performance on the autonomous boat as describe in Figure 9.

1) Boat Testing Turns Its Back to Waypoint

In Figure 10, the autonomous boat starts its journey from coordinates −6.973021, 107.631863 with the initial facing direction with its back to the Waypoint at the coordinates −6.972987, 107.631489. Since the initial position does not directly lead to the Waypoint, the navigation system makes a slow direction adjustment while still moving forward.


Figure 9. Boat turning back to waypoint test scenario.

Figure 10. Boat turning back to waypoint test on scenario 1.

The boat moves through several points of trajectory, such as −6.973009, 107.631651, and −6.973131, 107.631579, as part of a gradual turning maneuver with a gentle turning radius. This movement aims to change the boat's heading to align with the direction of the Waypoint, which is located in the northwest. Once the direction facing the boat is aligned and the path is declared unobstructed, the boat moves straight to the destination point. Along the course, the system automatically monitors the heading and position of the vessel to ensure the course remains accurate and the vessel can reach the Waypoint with precision.

2) Testing with Obstacles

In Figure 11, the autonomous boat begins its journey from the initial coordinates of -6.972870, 107.631743 to reach the Waypoint at -6.973180, 107.631618. During navigation, the system detected an obstacle at coordinates -6.972930, 107.631639, blocking the straight path to the Waypoint.

In response to these conditions, the boat's navigation control system automatically changes the trajectory direction to avoid obstacles. After successfully passing through the obstacle area, the boat reached a safe point at the coordinates -6.972890, 107.631577. From that point, the boat redirected to the Waypoint according to the navigation command.

The boat's trajectory depicted in the illustration shows how the system dynamically adjusts the direction of the voyage to avoid collision and reach the destination. This proves that the designed navigation system can adapt to non-ideal environmental conditions and maintain the shipping lane autonomously.

Full details of the boat trip can be seen in the Table below, which lists the position of the coordinates per second, the direction facing the boat (direction), the actions of the boat, and relevant navigation information.

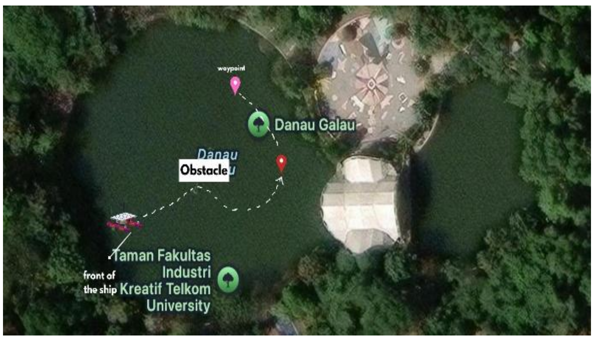

Figure 11. Obstacle tests on scenario 2.

The navigation system was tested under two real-world challenge scenarios: when the boat started by facing away from the Waypoint and encountered an obstacle along its route. These scenarios evaluated the system's ability to perform heading correction and autonomously maintain its path toward the Waypoint.

In the first scenario, the boat initially faced away from the Waypint, with a deviation angle of more than 150°. The system detected the heading error and executed a turning maneuver until the boat's heading aligned with the path toward the Waypoint. The correction process was gradual and stable, demonstrating the system's ability to adjust the boat's direction effectively.

The boat was tested with a floating obstacle on the sailing route in the second scenario. When the obstacle was detected, the system automatically performed an avoidance maneuver and then reoriented the boat back toward the Waypoint. This process demonstrated the system's adaptive capability to respond to environmental disturbances.

The average recorded heading error from both scenarios was 5.4°, which remains within the system's tolerance threshold of ±10°. According to previous studies, autonomous navigation systems are generally considered stable when the heading error is under 10° [11], thus confirming that the system operated within an acceptable performance range. These results indicate that the designed navigation system can maintain course stability and perform well under dynamic field conditions.

B. Platform Blynk

Figure 12 shows the output of all sensors installed on the boat, consisting of latitude and longitude coordinate data, heading, and other information that supports the monitoring and navigation system in indonesian parameter caption. This data is generated in real-time from a GPS module and a digital compass sensor, then processed by the TTGO ESP32 LoRa microcontroller before being displayed through the user interface. With this navigation information, users can monitor the boat's movement directly from a distance and ensure that the boat stays on the predetermined path. In addition, the data sent periodically allows for further analysis of the boat navigation performance while operating in open waters. This feature provides flexibility and ease of surveillance and supports faster and more accurate decision-making in autonomous boat systems.

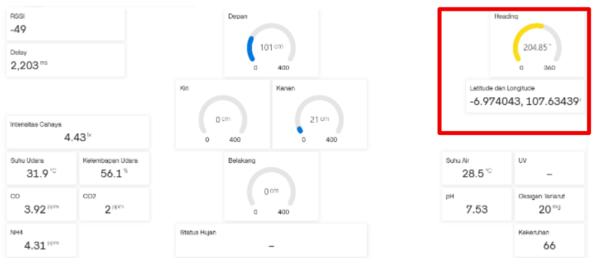

Figure 12. Sensor output on blynk platform.

While this study validates a single-node navigation accuracy of 92%, the underlying IoT-based framework is designed to be sensor-agnostic and extensible [16], providing a robust baseline for future swarm monitoring missions in inland water environments.

IV. CONCLUSION

Based on the design, implementation, and testing, the navigation guidance system for the solar autonomous boat has been successfully developed and can operate autonomously using solar energy. The system comprises the GPS ATGM336H module, GY-271 digital compass sensor, and TTGO ESP32 LoRa microcontroller. Test results show that the boat could follow the trajectory toward the Waypoint with an accuracy of 92% and an average heading error of 5.4°, remaining within the system's tolerance limits. The system also demonstrated real-time directional adjustment and stable performance in dynamic aquatic conditions. The integration of swarm technology enhances collective monitoring efficiency. The system meets the research objectives and demonstrates reliable performance for autonomous environmental monitoring over water bodies.

DECLARATIONS

Conflict of Interest

The authors have declared that no competing interests exist.

Credit Authorship Contribution

Nurul Fahmi Adani Syam: Software, Investigation, Visualization, Writing – Original Draft Preparation; Denny Darlis: Conceptualization, Writing – Review & Editing, Supervision, Funding Acquisition; Aris Hartaman: Methodology, Supervision, Writing – Review & Editing.

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REFERENCES

[1] C. Mammides, “A global assessment of the human pressure on the world’s lakes,” *Glob. Environ. Chang.*, vol. 63, pp. 102084, Jul. 2020, doi: 10.1016/j.gloenvcha.2020.102084.

[2] Y. Han, Q. Lin, S. Huang, C. Du, J. Shen, and K. Zhang, “Human impacts dominate global loss of lake ecosystem resilience,” *Geophys. Res. Lett.*, vol. 51, no. 11, Jun. 2024, doi: 10.1029/2024GL109298.

[3] C. Barrera, I. Padron Armas, F. Luis, O. Llinas, and N. Marichal, “Trends and challenges in unmanned surface vehicles (usv): from survey to shipping,” *TransNav, Int. J. Mar. Navig. Saf. Sea Transp.*, vol. 15, no. 1, pp. 135–142, 2021, doi: 10.12716/1001.15.01.13.

[4] Z. Liu, Y. Zhang, X. Yu, and C. Yuan, “Unmanned surface vehicles: an overview of developments and challenges,” *Annu. Rev. Control*, vol. 41, pp. 71–93, 2016, doi: 10.1016/j.arcontrol.2016.04.018.

[5] E. M. de Andrade, J. S. Sales, and A. C. Fernandes, “Operative unmanned surface vessels (usvs): a review of market-ready solutions,” *Automation*, vol. 6, no. 2, pp. 17, Apr. 2025, doi: 10.3390/automation6020017.

[6] Q. Wu and R. Zhang, “Towards smart and reconfigurable environment: intelligent reflecting surface aided wireless network,” *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2020, doi: 10.1109/MCOM.001.1900107.

[7] M. Specht, C. Specht, H. Lasota, and P. Cywiński, “Assessment of the steering precision of a hydrographic unmanned surface vessel (usv) along sounding profiles using a low-cost multi-global navigation satellite system (gnss) receiver supported autopilot,” *Sensors*, vol. 19, no. 18, pp. 3939, Sep. 2019, doi: 10.3390/s19183939.

[8] A. M. Triezani and D. A. Jatmiko, “Rancang bangun unmanned surface vehicle (usv) dengan sistem navigasi berbasis kompas dan estimasi a-gps,” *Telekontran: Jurnal Ilmiah Telekomunikasi, Kendali dan Elektronika Terapan*, vol. 9, no. 1, pp. 23–36, Oct. 2021, doi: 10.34010/telekontran.v9i1.5607.

[9] H. M. Park, J. H. Sung, H.S. Park, Y.H. Lim, J. Sur, and K. M. Seo,“A Hierarchical, Modular Interface and Verification Architecture for Mission Planning in Swarm Unmanned Surface Vehicles: Simulation and Sea-Trial Validation”, *Journal of Marine Science and Engineering*, vol. 14, no. 3, pp. 302, 2026, doi: 10.3390/jmse14030302.

-[10] J. Zhang, H. Liu, Y. He, W. Gao, N. Xu, and C. Liu, “MCLORA: Maritime ad-hoc communication system based on LORA”, *High-Confidence Computing*. vol. 5, pp. 100275, 2024, doi: 10.1016/j.hcc.2024.100275.

[11] J. Ansary, J. O’Donnell, N. Fyza, and B. Trease, “Swarms of aquatic unmanned surface vehicles (usv), a review from simulation to field implementation,” in *2020 Int. Des. Eng. Tech. Conf. and Comp. and Inform. in Eng. Conf.*, Aug. 2020. doi: 10.1115/DETC2020-22702.

[12] G. Xia and X. Sun, “Swarm control for multiple unmanned surface vehicles with unknown time-varying environmental disturbance and input saturation,” *J. Control Sci. Eng.*, vol. 2022, pp. 1–12, Jul. 2022, doi: 10.1155/2022/8962970.

[13] M. Dorigo, G. Theraulaz, and V. Trianni, “Swarm robotics: past, present, and future [point of view],” *Proc. IEEE*, vol. 109, no. 7, pp. 1152–1165, Jul. 2021, doi: 10.1109/JPROC.2021.3072740.

[14] S. Devalal and A. Karthikeyan, “LoRa technology - an overview,” in *2018 Second Int. Conf. Electron. Commun. Aerosp. Technol.*, pp. 284–290. Mar. 2018, doi: 10.1109/ICECA.2018.8474715.

[15] V. Ušinskis, M. Nowicki, A. Dzedzickis, and V. Bučinskas, “Sensor-Fusion Based Navigation for Autonomous Mobile Robot,” *Sensors*, vol. 25, no. 4, pp. 1248, Feb. 2025, doi: 10.3390/s25041248

[16] A. A. Priadi, T. Cahyadi, L. Barasa, S. A. Sukarno, N. Suranta, M. Yando, " Development of IoT-based monitoring for unmanned surface vessels (USV)", *Journal of Engineering Science and Technology*, vol. 20, no. 5, pp. 1 - 10, 2025, School of Engineering, Taylor’s University