DESIGN OF AN AUTONOMOUS MONITORING SYSTEM APPLYING IoT AND SOLAR ENERGY FOR AQUACULTURE

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ABSTRACT

Reliable and continuous water-quality monitoring is critical for sustaining modern aquaculture systems. This paper presents the design and implementation of a solar-powered autonomous monitoring platform based on Internet-of-Things (IoT) technologies. The proposed system integrates an ESP32 microcontroller with pH, temperature, total dissolved solids (TDS), and turbidity sensors, while autonomous navigation is achieved using a NEO-8M GPS receiver and a digital compass to follow predefined survey paths. A LoRa communication module enables long-range data transmission to a central monitoring station, where measurements are visualized through an Android application that supports real-time tracking and manual control. Experimental evaluations indicate stable performance, with measurement errors below 5% for temperature, 2.5-6% for pH, and 0.066% for TDS. The GPS subsystem exhibits a positional deviation of 2-3 m which is acceptable for pond-scale aquaculture monitoring applications, and LoRa communication remains reliable within a 15-m range under the tested environmental conditions. The system provides an average off-sunlight operating duration of 1.87 h with the current battery capacity and motor operating configuration. The results confirm the feasibility of the proposed platform and demonstrate its potential for scalable, energy-efficient, and automated water-quality monitoring in aquaculture applications.

1. INTRODUCTION

Aquaculture plays a crucial role in Vietnam's economic development, yet productivity and product quality depend heavily on water environmental conditions. According to Clause 25, Article 3 of the 2020 Environmental Protection Law, environmental monitoring is defined as the continuous, periodic, irregular, and systematic observation of environmental components, influencing factors, and pollutants to provide information for assessing environmental status, trends, and impacts [1]. In practice, water-quality inspection in aquaculture remains largely manual, labor-intensive, inconsistent, and insufficient for modern high-tech farming requirements.

In recent years, domestic and international research has explored the use of the Internet of Things (IoT) to automate environmental monitoring in aquaculture by integrating wireless communication and sensor networks.

An overview of smart agriculture using internet of things (IoT) and web services in India [2]; Freshwater shrimp farm monitoring system for Bangladesh based on internet of things [3]; Development of an automatic paddle wheel aerator and re-mote movement water quality monitoring for use in a marine

shrimp farm in Thailand [4]; Portable Filtration with Solar Photovoltaic-Powered IoT-Based Water Quality Monitoring System for Aquaponics in Malaysia [5]. These studies demonstrate advanced integration of IoT, automation, and data analytics but often involve substantial upfront costs, making them unsuitable for small-scale farms in developing countries.

Domestic studies include water-quality measurement systems for industrial shrimp ponds (Can Tho University) [6]; advanced monitoring and forecasting systems for lobster farming in Phu Yen (Hanoi University of Science and Technology) [7]; autonomous monitoring boats for aquaculture (Industrial University of Ho Chi Minh City) [8]; and IoT-based environmental management solutions for rice-shrimp farming models in Kien Giang [9]. These works offer practical and cost-effective approaches suitable for local conditions but remain limited in scale, durability, automation capability, and data analytics features.

Given these observations, future research should integrate the strengths of IoT technologies with renewable energy while ensuring affordability and practicality for Vietnamese aquaculture. This study addresses the need for a mobile, solar-powered, autonomous water-monitoring platform. The novelty of this research lies in developing an autonomous monitoring boat capable of predefined navigation, equipped with multiple environmental sensors, LoRa-based long-range communication, and Android-based data visualization. The objective is to design, fabricate, and evaluate the system in terms of measurement accuracy, operational stability, and energy efficiency, thereby demonstrating its feasibility and practical potential for sustainable aquaculture monitoring.
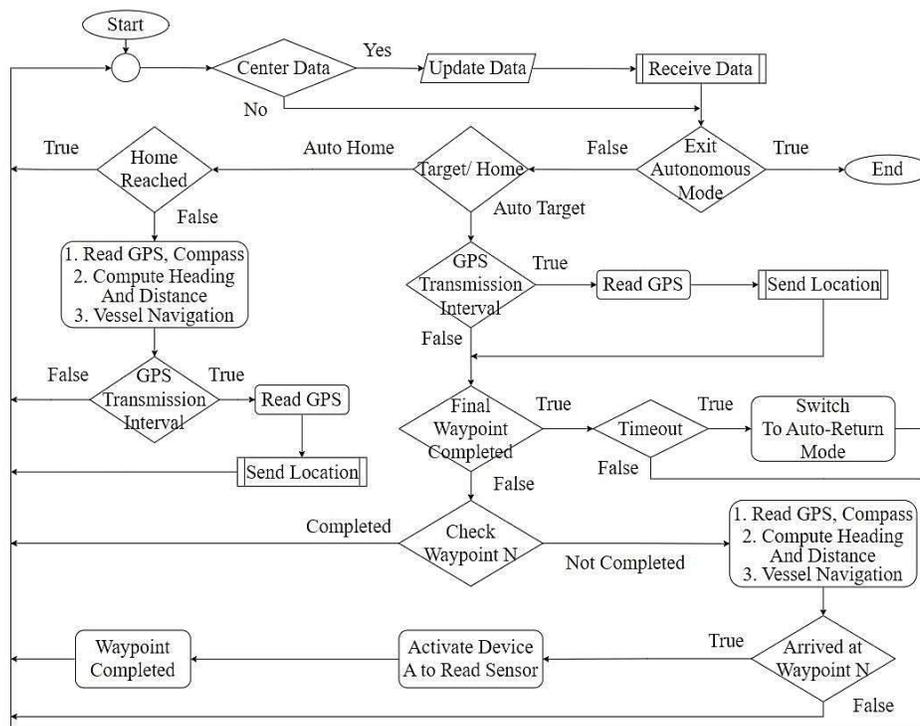
2. METHODOLOGY

2.1. System Architectur

Figure 1. Flowchart of the autonomous navigation mode

The autonomous monitoring system consists of four main functional modules operating in an integrated manner to ensure continuous and stable environmental data acquisition, transmission, and visualization.

Central Control Station: An ESP32 microcontroller receives and manages all incoming data. It communicates with the monitoring boat via a LoRa module, displays sensor readings on a TFT touchscreen, and synchronizes collected data with Firebase via Wi-Fi.

Autonomous Monitoring Boat: An ESP32 serves as the central controller, integrating the NEO-8M GPS for positioning and the HMC5883L digital compass for orientation. Together, they enable precise navigation toward predefined measurement points. Data are transmitted to the central station via LoRa. Two DC motors controlled through an L298N H-bridge provide propulsion and steering, while an N20 motor actuates the sensor-lowering mechanism. Power is supplied by a 6 V, 10 W solar panel combined with a 3.6 Ah Li-ion battery pack.

Water-Quality Sensor Module: This module includes an NTC temperature sensor, pH sensor, TDS sensor, and turbidity sensor for accurate assessment of water conditions.

Mobile Management Application: Developed on Firebase, the Android application supports real-time monitoring, historical data retrieval, position tracking, configuration of measurement cycles, QR-code login, and bilingual support (Vietnamese/English).

2.2. System Algorithm

The autonomous navigation algorithm illustrated in Figure 1 begins with system initialization, which includes configuring the GPS, digital compass, LoRa transceiver, environmental sensors, and motor drivers. Once the system becomes operational, the ESP32 continuously acquires the current GPS coordinates and compares them with the target coordinates preconfigured via the mobile application. Based on compass data, the controller computes the heading deviation relative to the desired trajectory and issues commands to adjust the speed of the two propulsion motors through the L298N H-bridge module. This enables the boat to move forward, reverse, or change direction as required to accurately reach each designated measurement point.

The procedure for computing the current distance to the target and determining the appropriate turning direction is performed as follows:

Step 1: Read the boat's current position and the target position, then convert both longitude and latitude values from degrees to radians.

Step 2: Once the current and target coordinates are obtained, calculate the present distance to the target. Using the Haversine formula [10], the distance is computed as follows:

The difference in latitude between the target and the boat:

$$\Delta_{lat} = \varphi_B - \varphi_A \quad (radian) \quad (1)$$

The difference in longitude between the target and the boat:

$$\Delta_{lon} = \lambda_B - \lambda_A \quad (radian) \quad (2)$$

Intermediate variable representing the great-circle distance component using the sine function:

$$a = \sin^2\left(\varphi_B - \frac{\varphi_A}{2}\right) + \cos\varphi_A \cdot \cos\varphi_B \cdot \sin^2\left(\lambda_B - \frac{\lambda_A}{2}\right)$$

$$(3)$$

Central angle between the two points on the spherical surface:

Distance from the boat to the target:

$$c = 2 \cdot \text{atan2}\left(\sqrt{a}, \sqrt{1-a}\right) \quad (4)$$

$$d = R \cdot c \quad (m) \quad (5)$$

where:

φ_A, φ_B: latitudes of the boat's current position and the target point, respectively.

λ_A, λ_B: longitudes of the boat's current position and the target point, respectively.

R: Earth's radius, R = 6,371,000 (m).

Step 3: Calculation of the geographic bearing (azimuth), defined as the directional angle between true North and the line connecting the boat to the target.

East-West coordinate component:

$$x = \cos(\lambda_A).\sin(\lambda_B) - \sin(\lambda_A).\cos(\lambda_B) \quad (6)$$

North-South coordinate component:

$$y = \sin(\Delta_{lon}).\cos(\varphi_B) \quad (7)$$

Geographic bearing angle:

$$b = atan2(y,x) \quad (8)$$

Step 4: Heading correction based on digital compass data.

The boat's turning direction is determined by the difference between the computed bearing angle and the heading angle A measured by the digital compass:

$$\Delta_\theta = b - A \quad (9)$$

After calibrating Δ_θ into the ranges $0°$ to $180°$ and $-180°$ to $0°$, the controller determines whether the boat should turn left or right to align itself with the target direction.

When the boat approaches the target point, the system activates the sensor-lowering mechanism to immerse the probes into the water and measure parameters including temperature, pH, TDS, and turbidity. After measurement and data transmission are completed, the sensors are retracted. The boat then either proceeds to the next predefined waypoint or returns to the starting location, depending on the assigned mission. This cycle continues until all sampling points are completed or a stop command is issued by the operator.

In the data-receiving algorithm illustrated in Figure 2, the LoRa module at the central control station continuously remains in listening mode to receive data packets from the boat. Upon receiving a packet, the ESP32 verifies its integrity through checksum validation, discards corrupted packets, and requests retransmission when necessary. Valid data packets are decoded and processed simultaneously for two tasks: (i) displaying real-time information on the TFT touchscreen, and (ii) synchronizing data to Firebase via Wi-Fi for storage and visualization on the mobile application. The application automatically fetches updated data and renders real-time charts as well as the boat's location.
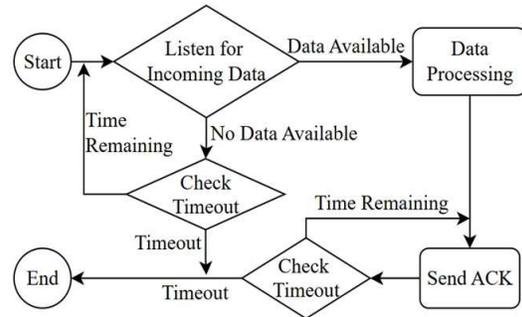

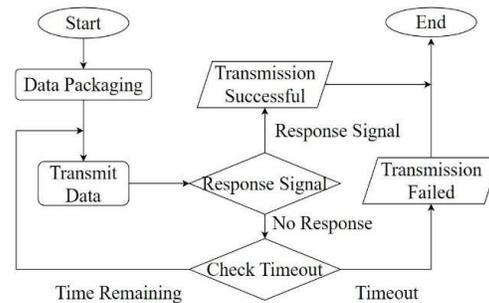**Figure 2. Flowchart of the data-reception**

Figure 3. Flowchart of the data-transmission process

Regarding the data-transmission algorithm shown in Figure 3, once the sensors complete data acquisition, the ESP32 filters and conditions the signals to ensure stability. Sensor outputs are converted from voltage values to physical units and encapsulated into a LoRa packet containing a header, payload (temperature, pH, TDS, turbidity, GPS coordinates), and checksum. The LoRa transmitter then sends the packet to the control station. An acknowledgment mechanism is implemented: if no acknowledgment is received, the packet is retransmitted to prevent data loss.

3. RESULTS AND DISCUSSION

3.1. Evaluation

3.1.1. Monitoring Boat Design

The prototype illustrated in Figure 4 features a compact and lightweight structure, allowing easy movement across aquaculture ponds while providing sufficient internal space for sensors, control electronics, and power components. The system is powered by a 6 V-10 W solar panel combined with a Li-ion backup battery, enabling continuous, grid-independent operation suitable for outdoor environments and remote aquaculture sites. The propulsion system employs two symmetrically arranged rudder-motor assemblies, providing stability, smooth directional control, and reduced vibration during movement. The sensor-lowering mechanism (Fig. 5), driven by an N20 motor and lifting shaft, ensures that the sensor module reaches the required depth and is retracted promptly, protecting the probes from excessive fouling and prolonging service life.
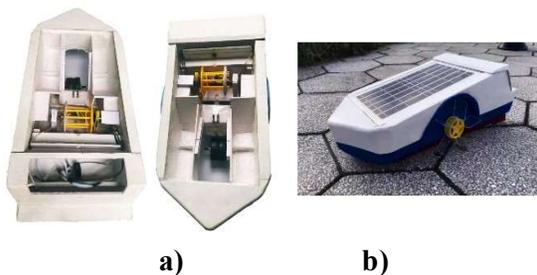

a)   b)

Figure 4. Autonomous water-quality monitoring boat prototype: Inside the boat (waterproofing system removed) (a) and Outside the boat (b)

3.1.2. Management Application

The mobile application (Fig. 6), developed on the Firebase platform, provides real-time monitoring, map-based tracking of boat movement, and full historical data storage. Its user-friendly interface supports QR-code login and flexible configuration of operational parameters such as measurement interval and waypoint coordinates. Bilingual support (Vietnamese and English) enhances accessibility for both domestic and international users. Synchronization between the control station and the application is fast and stable, ensuring timely updates that enable efficient remote supervision and system control under various operational conditions.
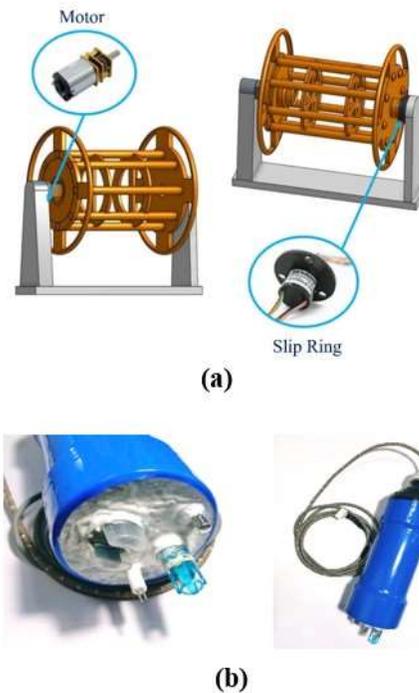
3.1.3. Experimental Results

Figure 5. Components of the sensor-deployment mechanism (a) and sensor module (b)

The central control station operates reliably with stable LoRa communication, despite the transmitter being enclosed inside the boat's body. As shown in Figure 7, all essential interface functions-including sensor dashboard (a), sensor reading mode (b), manual control (c), position setting and cycle configuration (d), position setup (e), and autonomous mode (f)-are fully implemented. Data transmission via LoRa remains consistent within a range of approximately 15 meters under the tested experimental conditions, in which the antenna was installed inside the waterproof hull of the monitoring boat.
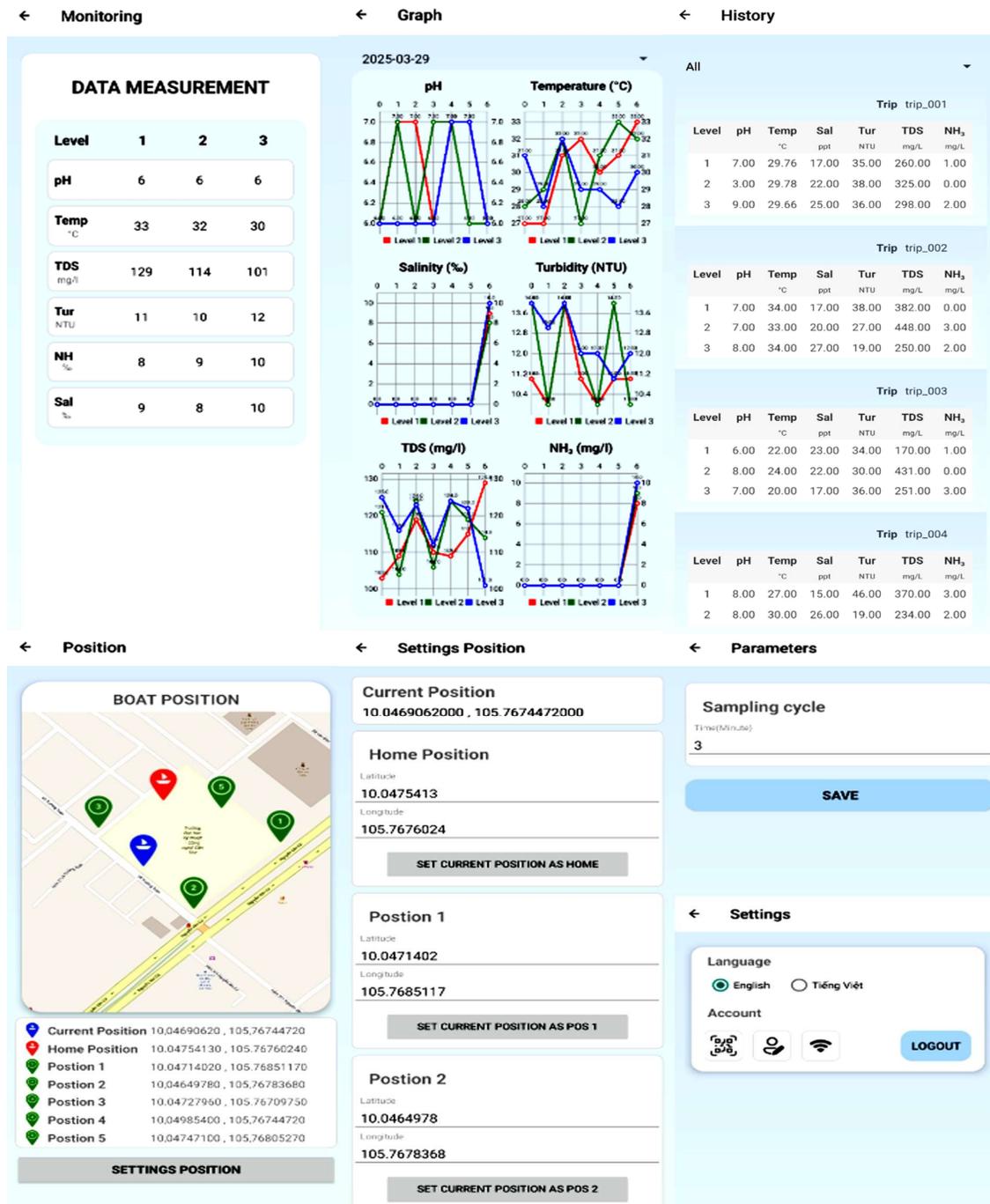
Figure 6. Android application interface

Temperature, pH, TDS, and turbidity sensors demonstrate high accuracy and stable signals throughout the experiments. Temperature error remains under 5%, pH sensor error varies between 2.5% and 6% depending on environmental conditions, and the TDS sensor exhibits superior accuracy with an error of only 0.066%. These results are achieved through multi-sample averaging, which effectively reduces noise

caused by electrical fluctuations and dynamic water conditions.

Regarding navigation performance, the integration of the NEO-8M GPS module and the HMC5883L digital compass enables the boat to autonomously reach the programmed sampling points. Although environmental disturbances such as wind, surface waves, and inertia cause deviations from a perfectly linear trajectory, field experiments (Fig. 8) show that the boat maintains a positional error of approximately 2-3 meters-acceptable for pond-scale applications.
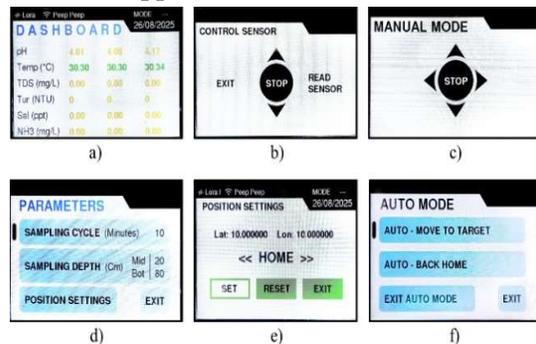

Figure 7. Interface of the central control station: Real-time water quality monitoring dashboard (a), Sensor control interface (b), Manual operation mode interface (c), Sampling and depth configuration interface (d), Position setting and navigation control interface (e), and Automatic operation mode interface (f).

3.2. Discussion

The experimental findings highlight both the strengths and operational constraints of the LoRa-based communication architecture employed in the proposed system. The observed communication stability within a 15-meter radius, despite the antenna being enclosed within the boat's hull, suggests the suitability of LoRa for short-range, low-altitude water-surface propagation in pond-scale aquaculture environments. This behavior is consistent with the known advantages of sub-GHz frequencies-such as the 434 MHz band used in this study-which generally exhibit reduced free-space path loss and improved diffraction over water surfaces compared with higher-frequency wireless standards.

A comparative analysis with Wi-Fi and Bluetooth further underscores the relevance of LoRa for aquaculture applications, particularly in terms of transmission stability over water surfaces and lower power consumption under fluctuating environmental conditions. Wi-Fi typically experiences substantial signal attenuation and multipath distortion near water surfaces, while Bluetooth is constrained by limited transmission range and susceptibility to interference from co-located electronic devices. In contrast, LoRa's chirp-spread spectrum modulation provides improved link robustness under such conditions and enables reliable data transmission at low power levels. These characteristics effectively complement the solar-powered system design, allowing prolonged autonomous operation and reducing the frequency of manual battery maintenance.

Nevertheless, the communication range achieved in this study remains below the nominal capabilities of LoRa technology, primarily due to signal attenuation associated with internal antenna placement within the waterproof enclosure. The dielectric properties of the enclosure material and its proximity to the water surface contribute to additional signal loss. Preliminary testing indicates that relocating the antenna externally or elevating it above the water surface can significantly enhance received signal strength without increasing power consumption. For larger aquaculture ponds, the deployment of relay gateways or multi-hop LoRa nodes may provide an effective means of extending communication coverage while maintaining overall energy efficiency.

These findings suggest several opportunities for improvement. Incorporating an external or elevated antenna module may immediately extend operational range without increasing power consumption. For larger aquaculture facilities, integrating relay gateways or multi-hop LoRa nodes could further enhance network coverage while preserving low energy requirements.

Additionally, optimizing transmission power, bandwidth, and spreading factor within permissible regulatory limits may improve communication reliability under varying environmental conditions. Such enhancements would support scalable deployment of autonomous monitoring systems across diverse aquaculture settings.

To further extend continuous operation under low-irradiance or cloudy conditions, future improvements may include optimizing motor control algorithms, implementing aggressive power-saving modes for the ESP32, adjusting measurement intervals, and upgrading battery capacity while maintaining a compact system design.
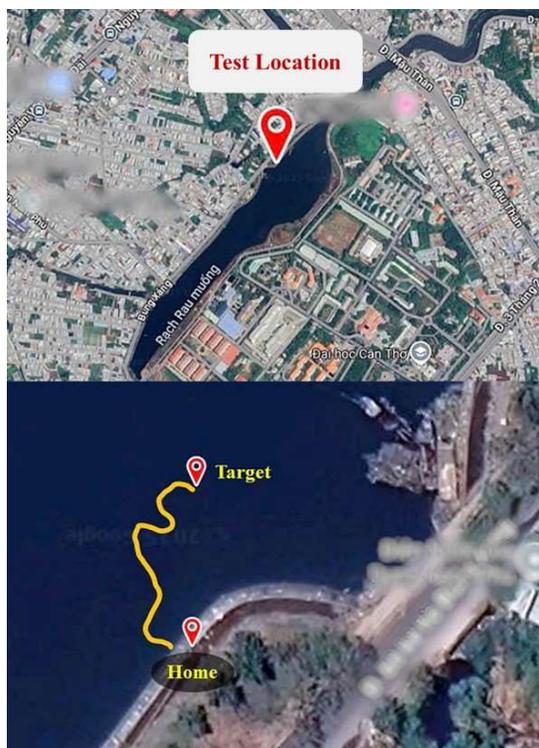

Figure 8. Field experiment conducted at the pond

In high-density or precision aquaculture scenarios, this level of accuracy may become a limiting factor. Potential enhancements include the integration of higher-precision GPS modules, sensor fusion with inertial measurements, or the application of filtering algorithms to improve positional stability in future system versions.

4. CONCLUSION

The proposed autonomous IoT and solar-powered monitoring system for aquaculture has been successfully developed, fulfilling the primary design and research objectives. By integrating hardware components, embedded software, wireless communication, and mobile data visualization, the system provides a comprehensive and sustainable approach to automated water-quality monitoring. The proposed solution is low-cost and energy-efficient, combining autonomous navigation, multi-parameter water-quality sensing, LoRa-based communication, and mobile visualization for practical pond-scale applications. GPS-compass-based navigation, LoRa communication, Android visualization, and Firebase synchronization all demonstrate stable operation. Sensor measurements (pH, TDS, turbidity, temperature) fall within acceptable accuracy ranges, confirming system feasibility and reliability.

The solar-powered architecture enables continuous off-grid operation, making the system suitable for diverse aquaculture environments. Although limitations remain -such as the number of sensors, LoRa range, and GPS accuracy in complex field conditions - the system establishes a robust foundation for future large-scale, energy-efficient, and intelligent environmental-monitoring platforms.

Future developments may focus on enhancing software functionality, including early-warning mechanisms, data analytics, and multi-device synchronization. Sensor modularity may also be expanded, with dissolved oxygen (DO) prioritized due to its critical role in early detection of hypoxia and sudden water-quality deterioration, while COD and ORP sensors are considered for subsequent research phases. Additional improvements may include enhancing mechanical durability for long-term field

deployment and developing coordination algorithms for multi-vehicle monitoring systems.

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THIẾT KẾ THUYỀN QUAN TRẮC TỰ HÀNH ỨNG DỤNG IOT VÀ NĂNG LƯỢNG MẶT TRỜI CHO NUÔI TRỒNG THỦY SẢN

TÓM TẮT

Việc giám sát chất lượng nước liên tục và đáng tin cậy là yêu cầu thiết yếu trong nuôi trồng thủy sản hiện đại. Nghiên cứu này giới thiệu một hệ thống quan trắc tự hành sử dụng năng lượng mặt trời, phát triển trên nền tảng IoT. Hệ thống tích hợp vi điều khiển ESP32 với các cảm biến pH, nhiệt độ, TDS và độ đục, đồng thời sử dụng GPS NEO-8M và la bàn số để dẫn hướng theo lộ trình định sẵn. Dữ liệu được truyền đến trạm giám sát qua LoRa và hiển thị trên ứng dụng Android theo thời gian thực. Thực nghiệm cho thấy sai số đo dưới 5% đối với nhiệt độ, 2,5-6% đối với pH, 0,066% đối với TDS; sai lệch GPS 2-3 m; và liên lạc LoRa ổn định trong phạm vi 15 m. Hệ thống hoạt động trung bình 1,87 giờ khi không có ánh sáng mặt trời. Các kết quả khẳng định tính khả thi và tiềm năng mở rộng của giải pháp cho quan trắc chất lượng nước tự động và tiết kiệm năng lượng.

Từ khóa: Cảm biến, internet vạn vật, LoRa, nuôi trồng thủy sản, quan trắc tự hành