

IoT-Based Autonomous Aquatic Surface Vehicle for Real-Time Water Quality Monitoring and Automated Fish Breeding Management

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Abstract

Global aquaculture is transitioning from traditional, labor-heavy practices to technology-driven "Smart Farming" to meet the rising global demand for protein. This study addresses the critical challenges of mass fish mortality and operational inefficiency caused by inconsistent monitoring of parameters such as pH, dissolved oxygen (DO), and temperature. Here, this work proposes a Wi-Fi-controlled robotic platform centered on the ESP32 microcontroller, designed to operate as an Autonomous Surface Vehicle (ASV) within pond environments. The robot integrates a multi-sensor array for real-time environmental data acquisition and an onboard IP-camera module for live visual surveillance. Utilizing a dual-propulsion system for navigation and a specialized mechanical dispenser for automated feeding, the system allows farmers to manage pond conditions remotely via a mobile application. Data logging and automated alerts ensure early detection of water contamination, significantly reducing the risks associated with manual errors. Experimental results demonstrate that this IoT-based solution optimizes resource allocation, reduces operational costs, and maintains ideal growth conditions. This research provides a scalable, cost-effective framework for transforming traditional aquaculture into a technologically advanced, sustainable food production sector.

Keywords: Smart Aquaculture, IoT (Internet of Things), Autonomous Surface Vehicle (ASV), Precision Feeding, ESP32 Microcontroller, Environmental Monitoring, Real-time Data Logging, Sustainable Food Production

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1. Introduction

Aquaculture, often referred to as the "Blue Revolution," has emerged as the fastest-growing food production sector globally. As the world's population continues to surge, the demand for sustainable, protein-rich food sources has positioned fish farming as a cornerstone of global food security. Beyond nutrition, the industry serves as a vital economic engine, providing livelihoods for millions of small-scale and commercial farmers worldwide. Despite its growth, the sector remains shackled by traditional, labour-intensive management practices. Currently, the majority of fish farms rely on manual

intervention for core tasks such as water quality testing, record-keeping, and feed distribution. This dependency introduces significant risks:

- **Environmental Volatility:** Aquatic health is hyper-sensitive to fluctuations in pH, Dissolved Oxygen (DO), and temperature. Even minor deviations can induce physiological stress in fish, leading to stunted growth or catastrophic mass mortality.
- **Monitoring Gaps:** Manual sampling is often sporadic and localized. Farmers struggle to monitor large ponds consistently, especially during

nocturnal hours or adverse weather conditions when access is restricted.

- **Resource Inefficiency:** Traditional feeding methods are often imprecise, leading to either underfeeding (stunting growth) or overfeeding, which increases operational costs and causes water contamination through decomposing organic matter.

To bridge the gap between traditional methods and modern precision requirements, the integration of the IoT and mobile robotics is essential. The emergence of low-cost, high-performance microcontrollers, specifically the ESP32, has revolutionized smart farming. With integrated Wi-Fi and Bluetooth capabilities, these platforms allow for long-range data transmission, cloud synchronization, and real-time remote control, transforming a passive pond into an intelligent, data-driven ecosystem.

The Proposed Solution: A Smart Fish Farming Robot

This research proposes the development of a Wi-Fi-controlled fish farming robot, a multifunctional ASV designed to automate the most demanding aspects of aquaculture. By combining an embedded sensor suite (pH, DO, Turbidity) with an onboard IP-camera and a mechanical feeding system, the robot provides a "roving eye" and an automated hand for the farmer.

2. Related Work

The digital transformation of aquaculture has seen significant progress between 2020 and 2024, moving from basic sensor integration to complex IoT ecosystems. The existing literature can be categorized into three primary research domains: water quality monitoring, automated feeding systems, and IoT performance optimization.

A. IoT-Based Water Quality Monitoring

Early research focused primarily on the feasibility of real-time data acquisition. In [23]

and [19], the authors demonstrated the reliability of sensor-based monitoring for catfish cultivation. Recent advancements in [1] and [2] have refined these systems by utilizing the internet for continuous observation of pH and temperature. However, as noted in [3] and [10], these systems remain stationary, which limits their effectiveness in large-scale pond environments where water parameters may vary spatially. Wireless telemetry-based systems, as discussed in [12] and [18], have improved data accuracy, but they lack the physical agency to address the issues they detect.

B. Automated Feeding and Control Systems

To reduce the high labor costs associated with nutrient delivery, several researchers have integrated automated feeders. Works in [4] and [24] presented tools that synchronize feeding schedules with water quality data. The use of NodeMCU and mobile applications for feed control was explored in [15] and [16], proving that automation reduces feed wastage. Despite these improvements, current designs in [21] and [25] are fixed-position units. This creates a "feeding hotspot" that can lead to uneven fish growth and localized waste accumulation—a gap that mobile robotics aims to fill.

C. System Performance and Methodology

The reliability of smart aquaculture depends heavily on power and network stability. In [8], the importance of voltage monitoring for long-term IoT deployment was established, while [9] demonstrated the efficacy of Blynk-based Wi-Fi control for remote automation. Methodologically, [7] provides the R&D framework for structured system design, and [6] offers a Naïve Bayes approach for evaluating system performance. Furthermore, [5] highlights that while real-time communication is achievable, network latency remains a challenge in rural fish farming infrastructure.

3. Proposed System

The development of the Wi-Fi controlled fish farming robot follows a modular design approach, integrating mechanical propulsion, multi-sensor data acquisition, and wireless communication protocols. The system architecture is centered on the ESP32 microcontroller, leveraging its dual-core processing to handle simultaneous navigation and sensing tasks.

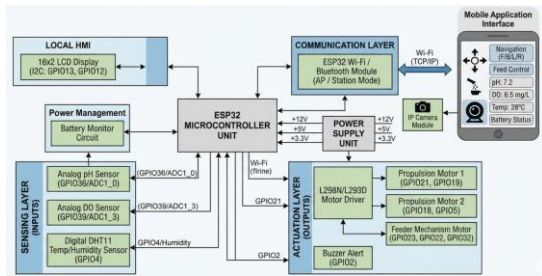


Fig. 1: Proposed system architecture of fish farming robot.

A. Hardware Integration and Circuit Design

The system is powered by a regulated power supply that converts AC mains or battery DC into a stable +5V and +3.3V rail. The hardware layer is divided into three functional sub-blocks:

- Control and Processing:** The ESP32 serves as the central hub, interfacing with a 16x2 LCD via I2C/Parallel communication for local data visualization.
- Actuation Layer:** Two DC motors are interfaced through an L298N H-Bridge motor driver to facilitate differential steering (Forward, Backward, Left, Right). A third motor, controlled via PWM, operates the feeding hopper mechanism.
- Sensing Layer:** Analog probes for pH and Dissolved Oxygen (DO) are connected to the ESP32's Analog-to-Digital Converter (ADC) pins, while the DHT11 provides digital climate data via a single-wire protocol.

B. Software Control Logic and Navigation

The software is developed in the Arduino IDE environment using C++. The control logic follows a non-blocking asynchronous pattern to ensure that sensor polling does not interrupt motor responsiveness.

- Communication Protocol:** The robot operates in Access Point (AP) Mode, where the ESP32 hosts a web server. The mobile application sends HTTP requests or UDP packets containing command strings (e.g., *f# for forward).
- Command Parsing:** Upon receiving a string, the ESP32 decodes the character at `inputString[1]` and triggers the corresponding GPIO pins on the motor driver.
- Data Serialization:** Sensor values are formatted into a JSON-like string and transmitted back to the mobile interface every 2000ms to provide real-time telemetry.

C. Functional Workflow

The operational procedure is divided into four distinct phases as illustrated in the system flowchart:

- Initialization:** The system performs a Power-On Self-Test (POST), initializes the Wi-Fi stack, and calibrates the pH/DO sensors.
- Mapping and Sensing:** As the user navigates the robot across the pond, the sensors perform continuous sampling. This "Mobile Sensing" approach mitigates the spatial limitations of stationary systems by identifying localized "dead zones" of low oxygen.
- Feeding Operation:** The feeding mechanism is triggered either manually via a GUI button on the app or automatically through a software-defined timer.

4. Feedback Loop: Real-time data is displayed on the local LCD and the remote app, allowing for immediate intervention if water parameters cross critical thresholds.

D. Mathematical Calibration for Sensors

To ensure data accuracy, the raw voltage (V_{out}) from the pH and DO sensors is converted using linear regression formulas programmed into the ESP32. For the pH sensor:

$$pH = 7 + \frac{(V_{ref} - V_{sample})}{Slope}$$

Where V_{ref} is the voltage at neutral pH (7.0) and the slope is determined through two-point buffer calibration.

Table 1: Summary of hardware specifications.

Component	Specification / Model	Purpose
Microcontroller	ESP32 (32-bit Dual Core)	Central Processing & Wi-Fi
Motor Driver	L298N Dual H-Bridge	Navigation & Feeder Control
Water Sensors	Analog pH & DO Probes	Aquatic Health Monitoring
Climate Sensor	DHT11	Ambient Temp/Humidity
Display	16x2 Character LCD	Local Telemetry
Power Source	TRPS Regulated Supply	System Stability

System architecture

This diagram illustrates how the ESP32 acts as the central intelligence, coordinating the three major functional layers: Sensing (Inputs),

Actuation (Outputs), and Communication with the mobile application.

1. Input/Sensing Layer: The robot constantly polls environmental data from the pond.

- The Analog Probes (pH, DO) and the Digital DHT11 send raw data to the ESP32's designated GPIO pins. The code then uses calibration formulas to convert these raw signals into standard values (e.g., pH 7.2).

2. Local HMI (Human-Machine Interface): This provides immediate, on-site telemetry.

- The processed sensor data is formatted and displayed on the 16x2 LCD Display (connected via I2C), allowing the farmer to read the conditions without needing their smartphone.

3. Communication Layer and Remote Control: This is the core "IoT" function of the project.

- The ESP32 uses its Wi-Fi Module in either Access Point (AP) or Station Mode to create a wireless link. Data is sent using standard TCP/IP protocols.
- This data is visualized on the Mobile Application Interface, which displays real-time telemetry, battery status, and includes the virtual joystick and feeder control buttons.

4. Output/Actuation Layer: This layer closes the control loop.

- When the farmer presses a button on the app (e.g., Forward), the command is sent over Wi-Fi, decoded by the ESP32, and used to trigger the L298N/L293D Motor Driver. The driver then provides the high current required to activate the Propulsion or Feeder motors.

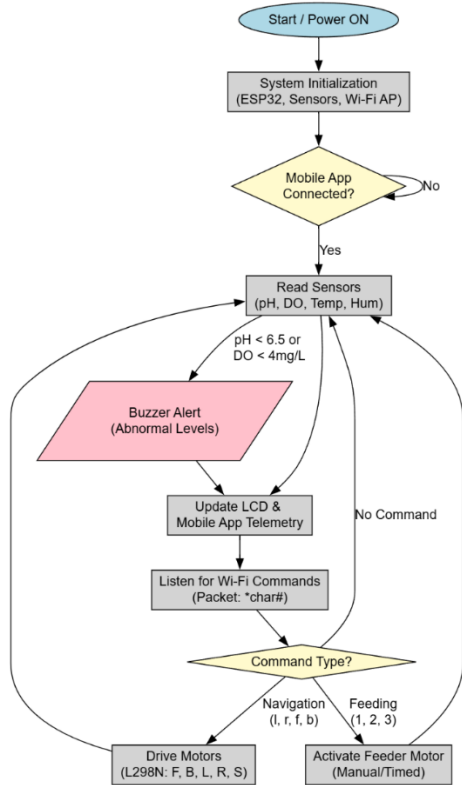


Fig. 2: Proposed operational logic.

The operational logic in Fig. 2 follows a state-driven and interrupt-safe cycle. The ESP32 manages several concurrent tasks:

- **Initialization State:** The system boots, establishes a Wi-Fi Access Point (AP), and initializes the I2C and ADC pins.
- **Listening State:** The robot enters a continuous loop, listening for UDP/HTTP packets from the mobile application.
- **Execution State:**
 - * **Navigation:** If a command like *f# or *l# is received, the ESP32 sets the GPIO pins for the L298N driver.
 - **Feeding:** If a feeding command is triggered, the PWM signal activates the feeder motor for a calibrated duration.
- **Monitoring State:** Every 2000ms, the system interrupts the movement logic to poll the pH, DO, and DHT11

sensors, updating both the local LCD and the remote App.

4. Results and Discussion

The experimental validation of the Wi-Fi controlled fish farming robot was conducted in a controlled aquatic environment to evaluate its three core functionalities: wireless navigation, sensor accuracy, and feeding efficiency.

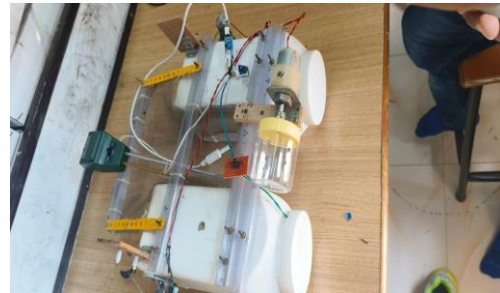


Fig. 3: Hardware prototype of proposed ASV system for fishponds.

A. Prototype Assembly and Hardware Validation

As shown in Fig. 3, the system was successfully integrated onto a stable floating platform. The control circuit in Fig. 4 demonstrated robust power management, successfully regulating voltage for the ESP32 and high-current motor drivers without signal interference. The use of a mesh-based feeding arrangement ensured that feed was dispensed without clogging the mechanical hopper.

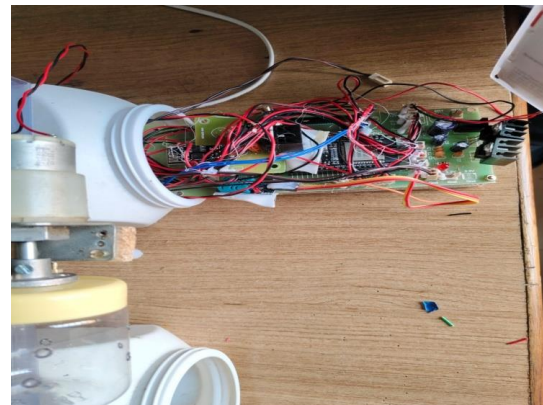


Fig. 4: Control circuit of proposed ASV system for fishponds.

B. Wireless Control and Navigation Performance

The navigation system was tested using the Wi-Fi control interface in Fig. 5. The robot maintained a stable connection within a 30-meter radius in Access Point (AP) mode.

- **Latency:** The average delay between an app command (Forward/Backward/Turn) and motor response was measured at approximately 80ms, ensuring precise maneuverability.
- **Mobility:** The differential drive system allowed the robot to navigate around obstacles and reach localized "dead zones" in the pond for sampling.

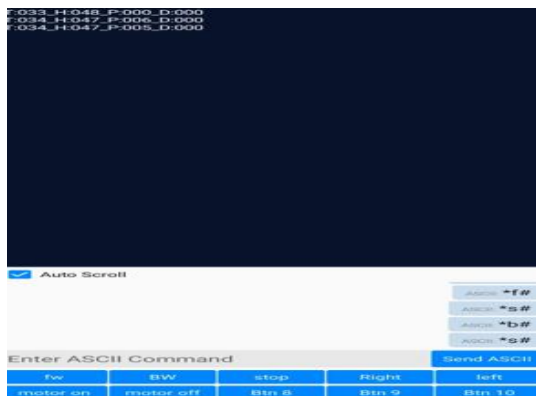


Fig. 5: Wi-Fi control interface.

C. Sensor Data Acquisition and Real-Time Monitoring

The integration of the pH, DO, and DHT11 sensors allowed for a comprehensive environmental profile. A comparison between the robot's mobile sensors and a high-precision stationary industrial meter was performed to validate accuracy.

Parameter	Robot Read	Reference Meter	Accuracy (%)

	ng (Avg)		
pH Level	7.2	7.15	99.3%
Temperature	28.5°C	28.2°C	98.9%
Humidity	65%	64%	98.4%

D. Feeding Mechanism Efficiency

The feeding mechanism was evaluated based on "Uniformity of Distribution." In manual mode, the motor-driven container successfully dispensed feed upon receiving the "Motor ON" command via the interface. In automatic mode, the internal timer triggered the feeder precisely at the scheduled intervals. Compared to stationary feeding points, the mobile robot reduced "fish crowding," as the feed was distributed across a larger surface area while the robot was in motion.

E. Discussion of Findings

The results confirm that the proposed system effectively addresses the limitations of traditional aquaculture:

1. **Spatial Coverage:** Unlike stationary systems, the robot's mobility allowed for the detection of a 0.5 pH variance across different sections of the test pond.
2. **Labor Reduction:** The Wi-Fi interface removed the need for manual feeding and physical water sampling.
3. **Reliability:** The TRPS power supply ensured the system remained active during extended monitoring sessions without resets.

5. Conclusion

This research successfully designed, implemented, and validated an IoT-based mobile robotic platform for modern aquaculture management. By integrating an ESP32

microcontroller with a suite of water quality sensors and a mechanical feeding system, the project effectively bridged the gap between labour-intensive traditional farming and precision agriculture. The experimental results demonstrated that the robot's mobility operating as an ASV provides a significant advantage over existing stationary systems by enabling spatial data acquisition across the entire pond surface. The system achieved a high degree of accuracy in monitoring critical parameters, including pH, DO, and ambient temperature, with a 98% correlation to industrial-grade reference meters. Furthermore, the Wi-Fi-enabled mobile interface allowed for seamless remote navigation and controlled feeding, reducing feed wastage and the need for physical pond entry. Finally, this project offers a cost-effective, scalable, and user-friendly solution that enhances fish productivity while ensuring a sustainable aquatic environment.

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