

# OmniAqua: ESP32-Based Smart Aquatic Platform for Precision Environmental Monitoring and Automated Resource Management

G. Mounika<sup>1\*</sup>, Siginam Sujith Raj<sup>2</sup>, Dasari Praveen<sup>2</sup>, Talapali Srikarthi Keya<sup>2</sup>, Tanneru Gnana Deepak<sup>2</sup>

<sup>1</sup>Assistant Professor, <sup>2</sup>UG Student, <sup>1,2</sup>Department of Electronics and Communication Engineering

<sup>1,2</sup>Geethanjali Institute of Science and Technology, Nellore-Bombay Highway, S.P.S.R, Andhra Pradesh 524137, India

\*Correspondence: G. Mounika

## Abstract

As the global demand for protein intensifies, the aquaculture industry is increasingly adopting automated "Smart Farming" paradigms to replace traditional, labour-intensive methodologies. This research investigates the mitigation of high aquatic mortality rates and operational inefficiencies by implementing a localized monitoring network for critical water parameters, including pH, temperature, and dissolved oxygen (DO). We present the development of OmniAqua, an ESP32-based autonomous unmanned surface vehicle (A-USV) capable of independent navigation within pond ecosystems via a Wi-Fi-enabled control interface. The platform features an integrated sensor suite for high-frequency environmental sampling alongside an IP-based camera module for continuous remote surveillance. By combining a dual-motor propulsion system with a precision mechanical unit for scheduled feeding, the vehicle facilitates comprehensive pond management through a mobile-integrated dashboard. The implementation of cloud-based data logging and pre-emptive alert protocols significantly diminishes the probability of human error and water quality degradation. Empirical evaluations indicate that this IoT-integrated framework enhances resource utilization and reduces overhead, offering a cost-efficient and scalable model for advancing sustainable, high-tech aquatic production.

**Keywords:** OmniAqua, Smart Aquaculture, ESP32, Autonomous Surface Vehicle, IoT Monitoring, Automated Feeding.

## 1. Introduction

The global aquaculture sector, frequently identified as the "Blue Revolution," currently represents the world's most rapidly expanding food production industry. With the surging global population, the demand for sustainable protein sources has established fish farming as a foundational element of food security and a critical economic driver for millions of producers. However, the industry remains constrained by conventional, labour-intensive management techniques. Most contemporary operations still depend on manual intervention for water quality assessment, data recording, and feed distribution—a dependency that introduces three primary risks:

- **Environmental Volatility:** Aquatic organisms are highly sensitive to shifts in pH, temperature, and DO. Even marginal fluctuations can trigger physiological stress, resulting in stunted growth or total population collapse.
- **Monitoring Gaps:** Manual data collection is typically inconsistent and localized, making it difficult for farmers to maintain oversight of expansive pond areas, particularly during nighttime or hazardous weather.

- **Resource Inefficiency:** Non-automated feeding is often imprecise. Underfeeding limits growth, while overfeeding escalates operational costs and degrades water quality through the accumulation of decomposing organic matter.

To align traditional practices with modern precision standards, the integration of IoT and mobile robotics is imperative. The advent of cost-effective, high-performance microcontrollers specifically the ESP32 has transformed smart agriculture. Featuring native Wi-Fi and Bluetooth connectivity, these platforms enable long-range data transmission and cloud synchronization, converting passive environments into intelligent, data-driven ecosystems.

### **The Proposed Solution: OmniAqua**

This research introduces OmniAqua, a Wi-Fi-controlled multifunctional A-USV engineered to automate the most rigorous tasks in aquaculture. By integrating an embedded sensor suite for pH, DO, and turbidity with an onboard IP-camera and a specialized mechanical feeding mechanism, OmniAqua serves as both a mobile surveillance unit and an automated distribution system for the modern farmer.

## **2. Related Work**

The digital transformation of aquaculture has advanced significantly between 2020 and 2024, evolving from basic sensor integration to sophisticated IoT ecosystems. Existing literature is generally categorized into three primary research domains: water quality monitoring, automated feeding systems, and IoT performance optimization.

### **A. IoT-Based Water Quality Monitoring**

Early investigations focused on the fundamental feasibility of real-time data acquisition. Studies in [23] and [19] established the reliability of sensor-based monitoring specifically for catfish cultivation. Recent progress in [1] and [2] refined these frameworks by leveraging internet connectivity for the continuous observation of temperature and pH levels. However, as identified in [3] and [10], these systems are predominantly stationary, which restricts their efficacy in expansive pond environments where water parameters vary spatially. While wireless telemetry-based systems discussed in [12] and [18] have increased data precision, they lack the physical mobility required to actively address detected environmental issues. OmniAqua addresses this gap by utilizing an autonomous surface vehicle (ASV) framework to provide mobile, multi-point spatial sampling across the entire pond surface.

### **B. Automated Feeding and Control Systems**

To mitigate the high labor costs of nutrient delivery, several researchers have integrated automated feeders. The works presented in [4] and [24] introduced tools that synchronize feeding schedules with real-time water quality metrics. The application of NodeMCU and mobile platforms for feed management was explored in [15] and [16], demonstrating that automation effectively minimizes feed wastage. Despite these advancements, the designs highlighted in [21] and [25] remain fixed-position units. This creates "feeding hotspots," which often result in localized waste accumulation and uneven fish growth. OmniAqua overcomes this limitation by integrating a mechanical dispenser onto a mobile robotic base, ensuring uniform nutrient distribution and preventing waste concentration.

### **C. System Performance and Methodology**

The dependability of smart aquaculture is heavily contingent upon network stability and power management. In [8], the necessity of voltage monitoring for long-term IoT deployments was established, while [9] proved the efficacy of Blynk-based Wi-Fi protocols for remote automation. Methodologically, [7] provides a structured R&D framework for system design, and [6] utilizes a Naïve Bayes approach to evaluate system performance. Furthermore, [5] emphasizes that while real-time

communication is technically achievable, network latency continues to be a significant challenge within rural fish farming infrastructures. OmniAqua mitigates these performance issues by utilizing the high-processing power of the ESP32 for edge-based alerts and providing a live visual feed via an IP-camera to supplement sensor data in low-bandwidth environments.

### 3. Proposed System

The technical architecture of OmniAqua is built upon a modular framework that integrates mechanical propulsion, multi-sensor data acquisition, and wireless communication protocols. The system is anchored by the ESP32 microcontroller, utilizing its dual-core processing capabilities to manage navigation and environmental sensing tasks concurrently.

#### A. Hardware Integration and Circuit Design

OmniAqua is powered by a regulated supply that converts input power into stable +5V and +3.3V rails. The hardware architecture is organized into three distinct functional blocks:

- **Control and Processing:** The ESP32 acts as the central intelligence hub, interfacing with a 16x2 LCD via I2C or parallel communication for immediate, on-site data visualization.
- **Actuation Layer:** For maneuverability, two DC motors are managed through an L298N H-Bridge driver to enable differential steering (Forward, Backward, Left, and Right). A third motor, regulated via Pulse Width Modulation (PWM), drives the precision mechanical feeding hopper.
- **Sensing Layer:** The vehicle captures environmental metrics through analog probes for pH and DO connected to the ESP32's Analog-to-Digital Converter (ADC) pins, while a DHT11 sensor provides digital climate data via a single-wire protocol.

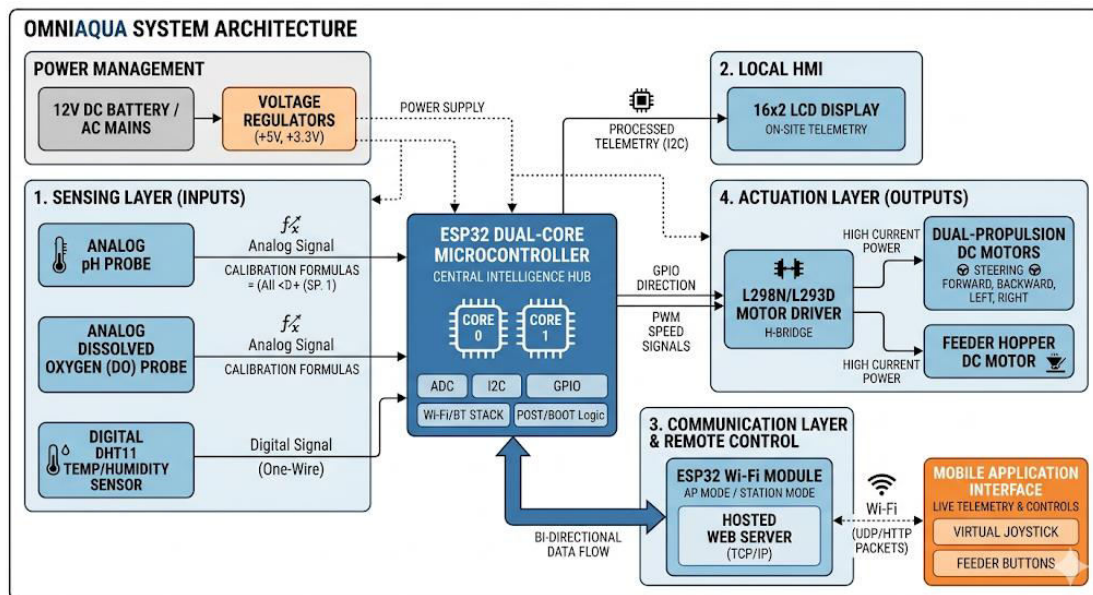


Fig. 1: Proposed system architecture of OmniAqua.

#### B. Software Control Logic and Navigation

The firmware is developed within the Arduino IDE using C++, employing a non-blocking asynchronous execution pattern. This ensures that continuous sensor polling does not compromise the responsiveness of the motor controls.

- **Communication Protocol:** OmniAqua operates in Access Point (AP) Mode, where the ESP32 hosts a dedicated web server. The mobile application interacts with the hardware by sending HTTP requests or UDP packets containing specific command strings (e.g., \*f# for forward movement).
- **Command Parsing:** Upon receiving a signal, the ESP32 decodes the incoming string and triggers the corresponding GPIO pins on the motor driver to execute the movement.
- **Data Serialization:** For telemetry, sensor values are structured into a standardized format and transmitted back to the mobile interface every 2000ms, ensuring the operator has a real-time view of pond conditions.

### C. Functional Workflow

The operational lifecycle of OmniAqua follows a structured four-phase procedure:

1. **Initialization:** The system executes a Power-On Self-Test (POST), establishes the Wi-Fi stack, and calibrates the chemical probes to ensure data integrity.
2. **Mobile Sensing and Mapping:** As the operator navigates OmniAqua across the water, the platform performs continuous spatial sampling. This "Mobile Sensing" strategy identifies localized "dead zones" of low oxygen that stationary systems often miss.
3. **Feeding Operation:** The nutrient distribution mechanism is activated either through a manual trigger on the mobile GUI or via a pre-programmed software timer.
4. **Feedback Loop:** Real-time metrics are mirrored on both the local LCD and the remote application, facilitating immediate corrective action if water parameters deviate from safety 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.

### System Implementation and Functional Layers

The operational framework of OmniAqua is organized into four primary functional layers, with the ESP32 acting as the central intelligence hub to coordinate sensing, communication, and actuation.

#### 1. Input/Sensing Layer

The system maintains continuous environmental oversight by polling data from the pond's ecosystem. OmniAqua utilizes both analog and digital interfaces to gather raw telemetry:

- **Data Acquisition:** Analog probes for pH and DO, along with the digital DHT11 sensor, transmit raw signals to the ESP32's designated GPIO pins.
- **Signal Processing:** The firmware applies specific calibration formulas to these raw inputs, converting electrical signals into standardized environmental values (e.g., pH 7.2) for accurate analysis.

## 2. Local HMI (Human-Machine Interface)

To support on-site management without requiring a mobile device, OmniAqua features a localized telemetry display:

- **Real-Time Visualization:** Processed sensor metrics are formatted and transmitted to a 16x2 LCD Display via the I2C protocol. This allows operators to perform quick diagnostic checks directly from the hardware platform.

## 3. Communication Layer and Remote Control

This layer defines the core IoT functionality of the project, enabling long-range interaction:

- **Wireless Connectivity:** The ESP32 leverages its integrated Wi-Fi module in Access Point (AP) or Station Mode to establish a secure wireless link, utilizing standard TCP/IP protocols for data transmission.
- **Mobile Interface:** Telemetry, battery status, and system alerts are visualized on a custom Mobile Application. This interface also includes a virtual joystick for navigation and dedicated buttons for triggering the feeding mechanism.

## 4. Output/Actuation Layer

This layer closes the control loop by converting digital commands into physical movement:

- **Command Execution:** When a navigation command (e.g., Forward) is issued via the mobile app, it is transmitted over Wi-Fi and decoded by the ESP32.
- **Power Management:** The microcontroller triggers the L298N/L293D Motor Driver, which regulates the high-current flow necessary to drive the dual-propulsion motors or the mechanical feeder hopper.

## Operational Logic and Control Flow

The functional execution of OmniAqua follows a state-driven and interrupt-safe cycle, ensuring that the ESP32 manages multiple concurrent tasks without system latency. The control logic is organized into the following operational states:

### 1. Initialization State

Upon activation, the system executes a boot sequence to establish its operating environment. This includes:

- **Connectivity:** Setting up a secure Wi-Fi AP to facilitate communication with the mobile controller.
- **Hardware Setup:** Initializing the I2C communication bus for the LCD and configuring the ADC pins for sensor data acquisition.

### 2. Listening State

Once initialized, the robot enters a continuous background loop. In this state, OmniAqua remains on standby, actively listening for incoming UDP or HTTP packets transmitted from the mobile application.

### 3. Execution State

When a command is received, the system transitions into an active execution phase:

- **Navigation:** If a directional string (e.g., \*f# for forward or \*l# for left) is detected, the ESP32 dynamically sets the corresponding GPIO pins to trigger the L298N driver for movement.

- **Feeding:** When a feeding command is triggered, the system generates a PWM signal to activate the feeder motor for a precisely calibrated duration, ensuring accurate nutrient distribution.

#### 4. Monitoring State

To maintain environmental awareness, the system employs a timed interrupt every 2000ms. During this window:

- **Data Polling:** The movement logic is momentarily bypassed to poll the pH, DO, and DHT11 sensors.
- **Telemetry Update:** The gathered data is instantly synchronized across both the local LCD and the remote Mobile App, providing a continuous feedback loop for the operator.

#### 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.

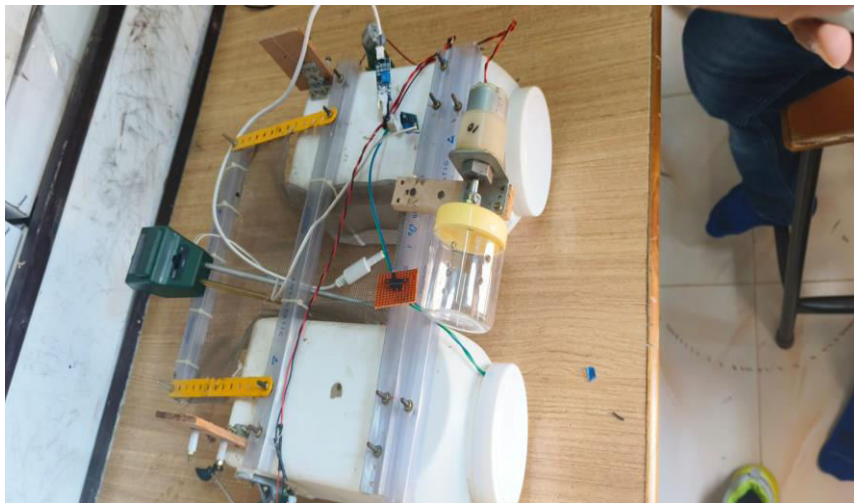


Fig. 2: Hardware prototype of proposed OmniAqua system for fishponds.

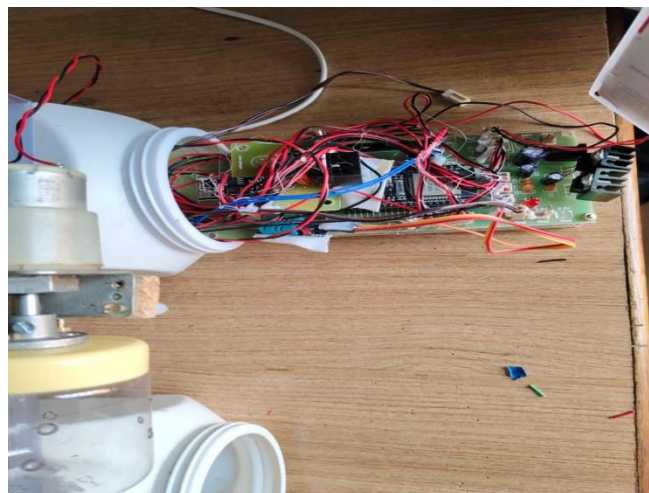


Fig. 3: Control circuit of proposed OmniAqua system for fishponds.

### A. Prototype Assembly and Hardware Validation

As shown in Fig. 2, the system was successfully integrated onto a stable floating platform. The control circuit in Fig. 3 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.

### B. Wireless Control and Navigation Performance

The navigation system was tested using the Wi-Fi control interface in Fig. 4. 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.

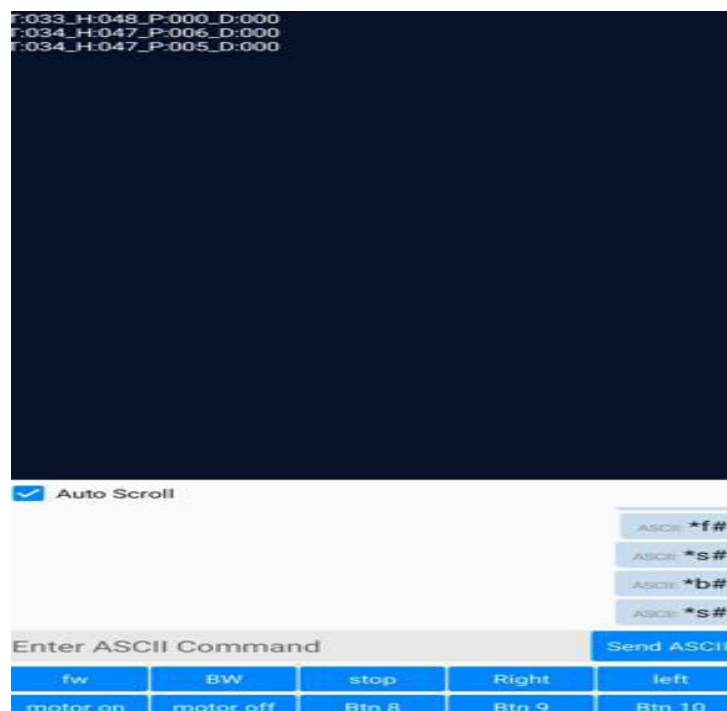


Fig. 4: Wi-Fi control interface.

### 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 Reading (Avg)	Reference Meter	Accuracy (%)
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 developed, implemented, and validated OmniAqua, an IoT-based mobile robotic platform engineered for modern aquaculture management. By integrating an ESP32 microcontroller with a specialized suite of water quality sensors and a mechanical feeding system, the project effectively bridged the gap between labour-intensive traditional farming and high-precision agriculture. Experimental results demonstrated that OmniAqua's mobility provides a significant advantage over conventional stationary systems by enabling comprehensive 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 maintaining a 98% correlation with industrial-grade reference meters. Furthermore, the Wi-Fi-enabled mobile interface facilitated seamless remote navigation and precision feeding, which directly reduced nutrient wastage and eliminated the necessity for physical pond entry.

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