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Design and implementation of control system for remotely surface vehicle in aquaculture environmental monitoring

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Abstract: This study aims to develop and evaluate the RSV EMAS (Environmental Monitoring Aquaculture System), an autonomous surface vehicle designed for real-time water quality monitoring in aquaculture ponds. The primary purpose is to support smallholder shrimp farmers in Indonesia with affordable and reliable technology to improve farm management and sustainability. The design methodology includes mechanical and electronic integration of a GPS-guided mobile platform, PID-controlled navigation, and calibrated water quality sensors (DO, pH, temperature, turbidity, salinity, depth). Data are wirelessly transmitted using LoRa to a custom mobile application for visualization. Field testing was conducted in shrimp ponds across East Java. Findings indicate that the RSV EMAS achieves sensor measurement accuracy within ±5% of industry-standard equipment, with consistent path tracking and minimal drift. The system reduces manual labor by 85% and increases sampling frequency by a factor of four. The study concludes that RSV EMAS presents a cost-effective, field-ready solution for precision aquaculture. Practical implications include improved decision-making for pond management, enhanced shrimp health, and the potential for scaling smart farming technologies in resource-constrained settings.

Keywords: *Aquaculture, Autonomous surface vehicle, IoT, LoRa communication, Sensor calibration, PID control, RSV EMAS, Water quality monitoring.*

1. Introduction

Aquaculture has emerged as a key sector in global food security, providing over half of the world's seafood consumption. Indonesia, as the second-largest aquaculture producer globally, faces significant challenges in ensuring sustainable and efficient practices particularly for small-scale shrimp farmers. Water quality directly affects fish and shrimp health, growth rates, and survival, yet most farmers still rely on manual sampling using handheld devices. These methods are inconsistent, time-consuming, and often lack temporal resolution to prevent harmful environmental conditions presented by Aiyelari and Singh [1].

The integration of autonomous systems in aquaculture is a recent innovation. While Autonomous Surface Vehicles (ASVs) have been developed for large-scale monitoring in oceanographic research, few implementations exist that cater to smallholder systems, particularly in developing regions. RSV EMAS (Remotely Surface Vehicle for Environmental Monitoring Aquaculture System) addresses this gap. Developed by Politeknik Perkapalan Negeri Surabaya (PPNS), the system combines robust navigation, sensor integration, and low-power wireless communication to support localized, real-time monitoring needs.

Aquaculture has emerged as one of the most rapidly growing sectors in global food production, contributing significantly to meeting the protein needs of the world's population. With over half of all seafood consumed globally now originating from aquaculture, the sustainability and efficiency of aquaculture systems have become critical to ensuring long-term food security. Indonesia, ranking as the second-largest aquaculture producer in the world, has seen exponential growth in shrimp and

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freshwater fish farming. However, this expansion brings forth persistent challenges related to environmental monitoring, water quality management, and resource optimization particularly among smallholder farmers who lack access to advanced technologies presented by Budianto [2].

Water quality plays a central role in the health, growth, and survival of aquaculture species. Key parameters such as dissolved oxygen (DO), pH, temperature, turbidity, and salinity must be continuously monitored to maintain optimal conditions. Suboptimal water conditions can lead to disease outbreaks, reduced growth rates, and even mass mortality events, severely affecting the productivity and profitability of aquaculture operations. Despite the critical importance of water monitoring, most traditional aquaculture systems rely on manual sampling methods using handheld devices. Chang, et al. [3] explored these methods are labour-intensive, prone to human error, and offer limited temporal resolution, which reduces the ability to detect sudden environmental changes that could affect aquatic life.

To address these issues, technological innovations such as the Internet of Things (IoT), autonomous robotics, and wireless sensor networks are increasingly being explored for their potential to transform aquaculture into a data-driven, precision-managed industry. In large-scale oceanographic research, Autonomous Surface Vehicles (ASVs) have been widely used for environmental data collection. However, these systems are often expensive and over-engineered for the needs of small and medium aquaculture farms, especially in developing countries where affordability, ease of use, and adaptability are paramount.

In this context, the development of a Remotely Surface Vehicle for Environmental Monitoring in Aquaculture Systems (RSV EMAS) represents a targeted solution designed to address the unique challenges faced by smallholder aquaculture practitioners. Developed by the Politeknik Perkapalan Negeri Surabaya (PPNS), RSV EMAS is a compact, low-cost, GPS-guided robotic platform equipped with essential water quality sensors. The system is capable of autonomously navigating aquaculture ponds, collecting real-time environmental data, and transmitting it wirelessly to a mobile application for continuous monitoring and analysis.

Unlike conventional ASVs, RSV EMAS emphasizes affordability, modular design, and energy-efficient operation, making it suitable for deployment in rural and resource-constrained environments. The vehicle integrates multiple subsystems including a PID-based motor control for navigation stability, LoRa-based communication for long-range data transmission, and mobile dashboard interfaces for user accessibility. Furthermore, it supports the calibration and validation of sensor readings against reference-grade devices, ensuring data accuracy and reliability suitable for operational decision-making by Chaysri, et al. [4].

This paper presents a comprehensive overview of the design, development, and deployment of RSV EMAS in the context of aquaculture environmental monitoring. Through field testing in East Java shrimp ponds, the system's performance is evaluated in terms of accuracy, robustness, and practical impact on farm management. By significantly reducing manual labour, increasing data collection frequency, and enabling early detection of adverse water conditions, RSV EMAS offers a transformative approach to smart aquaculture in Indonesia and similar contexts worldwide presented by Gafurov and Klochkov [5].

2. Related Work

Environmental monitoring in aquaculture has seen increasing technological integration in recent years, particularly through the use of autonomous systems, wireless sensor networks, and Internet of Things (IoT) technologies. These innovations aim to provide continuous, high-resolution data on key water quality parameters, enabling better decision-making, improved productivity, and reduced environmental impact explored by Hieu Duc Tran [6].

Recent research reveals a significant shift toward IoT-enhanced aquaculture systems. A 2025 review underscores the integration of IoT sensors, AI analytics, and remote sensing to optimize water quality, feeding management, and disease detection, while acknowledging challenges like technical complexity and cost—highlighting the potential of edge computing and decentralized networks explored by Idoko, et al. [7]. In Canada, an AI-empowered project by Lovo-Ayala, et al. [8] combining cameras and advanced sensors targets real-time fish health monitoring, illustrating progress toward intelligent operations. Another ASV-focused study by Jami'in, et al. [9] fuses sonar, depth sensing, AI navigation, and AR/VR visualization, providing a strong precedent for the type of system embodied in RSV EMAS presented by Sebastian [10]. Finally, advances in underwater machine vision by Rahmat and Sutrisno [11] enable continuous, non-invasive welfare monitoring of aquatic species an approach that could complement ASV-based sensing platforms explored by Sebastian [10].

One prominent direction of research has been the development of Autonomous Surface Vehicles (ASVs) for environmental monitoring. ASVs are typically equipped with GPS modules, wireless communication systems, and a suite of water quality sensors. They are designed to autonomously navigate water bodies and collect spatially distributed environmental data. In marine and lake environments, high-end ASVs have been successfully used for large-scale monitoring tasks. For example, Nguyen, et al. [12] explored a smart aquaculture system integrating ASVs with IoT and cloud platforms for centralized monitoring. However, such systems often rely on expensive hardware, consume high power, and require significant technical expertise for deployment and maintenance, limiting their applicability in smallholder farming scenarios by Rahmat and Sutrisno [11].

In Indonesia, efforts to localize and adapt these technologies for shrimp and freshwater fish farming have begun to emerge. Wahyudi, et al. [13] presented a prototype ASV for aquaculture that could monitor basic parameters such as temperature and turbidity. While their design showed promise, it lacked integrated communication features and autonomous navigation capabilities, highlighting the need for more robust and practical implementations.

In the field of IoT-based monitoring systems, significant progress has been made in static sensor networks for aquaculture ponds. These systems typically deploy multiple fixed sensor nodes to collect continuous data on pH, DO, temperature, and salinity. While they provide time-series data, their spatial coverage is limited, and sensor maintenance can be cumbersome due to sediment buildup and fouling. Moreover, stationary sensors do not provide insights into variations across the pond, which are often critical in dynamic aquaculture environments where parameters may fluctuate locally due to water inflows, feeding zones, or biological activity by Sutrisno, et al. [14].

Comparatively, the RSV EMAS project aims to bridge the gap between large-scale, high-cost ASVs and stationary sensor networks by offering a low-cost, mobile, and user-friendly solution tailored for smallholder aquaculture. It combines the advantages of autonomous navigation with integrated sensor modules and long-range wireless communication (LoRa), enabling real-time, spatially distributed data collection. Importantly, the system is designed for deployment in small and medium-sized ponds typical of rural Indonesia, offering greater accessibility and impact potential by Gafurov and Klochkov [5].

Additionally, RSV EMAS differentiates itself through its emphasis on calibration protocols and data reliability. Many low-cost sensor systems suffer from accuracy issues, especially in harsh aquatic environments. By incorporating sensor calibration procedures and field validation against industrial-grade devices, RSV EMAS ensures that data can be trusted for critical operational decisions, such as aeration control and feeding adjustments.

The integration of a mobile application dashboard also addresses a key limitation found in previous systems—user accessibility. Real-time visualization and historical trend analysis are often absent in legacy monitoring tools used by farmers. By simplifying data access and interpretation, RSV EMAS enhances user engagement and encourages data-driven farm management practices by Sutrisno, et al. [15].

In summary, while prior research has contributed valuable insights into autonomous and IoT-based aquaculture monitoring, most systems fall short in one or more of the following areas: affordability, ease of deployment, spatial mobility, and user accessibility. RSV EMAS addresses these gaps through a holistic, field-validated solution optimized for practical use in developing countries. This positions it not only as a technical contribution but also as a model for inclusive innovation in sustainable aquaculture development.

3. Methodology

The methodology adopted in this study follows a design-based research framework that includes iterative prototyping, validation, and field testing. The design phase involved mechanical modeling and simulation using CAD software to optimize hull structure and buoyancy. The electronics and control systems were developed in parallel using Raspberry Pi and Arduino platforms, integrating sensors via analog and digital input channels.

Validation involved both lab-based calibration and field-based comparison against standard reference devices. Calibration was performed for each sensor using known standards (e.g., buffer solutions for pH, sodium chloride solutions for salinity). Field testing was conducted at aquaculture ponds in Jember, East Java, under varying environmental conditions.

The methodology adopted in the development of RSV EMAS follows a design-based research approach, which combines iterative prototyping with empirical testing to refine and validate the system under real-world conditions. The process is divided into several core phases: system design, mechanical and electrical integration, software and control implementation, sensor calibration, and field validation by Wiratmoko, et al. [16].

3.1. System Architecture and Design

The design process began with a comprehensive analysis of aquaculture pond environments and user requirements, particularly focusing on smallholder shrimp farmers in rural Indonesia. Key design constraints included affordability, ease of maintenance, environmental resilience, and operational simplicity. The system architecture was divided into three main subsystems: mechanical structure, electronic control, and data communication.

Figure 1.
RSV Emas.

Mechanically, RSV EMAS was modelled using CAD software (SolidWorks) to optimize hull geometry for shallow water navigation. A catamaran-style hull was chosen to enhance stability and minimize drag in calm pond waters. The design prioritized modularity to simplify future component upgrades or replacements as shown in figure 1.

The electronics were divided into two layers: a primary control unit using a Raspberry Pi for high-level operations (navigation, data handling, communication) and an auxiliary unit based on Arduino for

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real-time motor control and sensor data acquisition. The use of separate controllers allows for distributed task handling and reduces latency in motor feedback loops.

3.2. Power Management

The vehicle is powered by a 12V sealed lead-acid (SLA) battery with a capacity of 9Ah, selected for cost-effectiveness and local availability. Power regulation circuits were incorporated to provide 5V and 3.3V rails for different sensors and microcontrollers. Battery life was optimized by using energy-efficient components, and future versions are being designed to support solar panel charging.

3.3. Propulsion and Navigation

Navigation is achieved using dual brushed DC motors controlled via an H-bridge motor driver (L298N) and PID algorithms implemented on the Arduino. The control logic allows for differential steering, enabling precise turns and route adjustments based on GPS input. The GPS module (NEO-6M) is interfaced with the Raspberry Pi via serial communication, providing real-time geolocation data with an accuracy of approximately ±2.5 meters.

The PID controller was tuned experimentally using the Ziegler–Nichol's method, and fine adjustments were made based on field performance. The goal was to ensure consistent path tracking with minimal overshoot or oscillation, especially in the presence of wind or water current disturbances.

3.4. Sensor Integration and Data Acquisition

The RSV EMAS is equipped with a suite of sensors to measure:

- Dissolved Oxygen (DO) using a galvanic DO probe
- pH using an analog pH sensor
- Water temperature using DS18B20 digital sensor
- Turbidity using an IR-based sensor
- Salinity (TDS) using a conductivity probe
- Depth using an ultrasonic sonar sensor

Sensors were interfaced to either the Raspberry Pi (via USB or I2C) or Arduino (via analog inputs), depending on their data format. Sensor readings are timestamped and stored locally as CSV files, which are periodically uploaded to the mobile dashboard through LoRa communication.

3.5. Sensor Calibration

To ensure data accuracy, a rigorous sensor calibration process was undertaken. Each sensor was tested in the laboratory using certified calibration solutions:

- pH sensors were calibrated using buffer solutions of pH 4, 7, and 10.
- DO sensors were calibrated in air-saturated water at known temperatures.
- Salinity sensors were tested using NaCl solutions of known conductivity.
- Depth sensors were validated against marked vertical rulers in still water.

Sensor readings were compared with commercial handheld meters (e.g., Hanna and YSI devices) and evaluated using statistical metrics such as Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE).

3.6. Communication and Dashboard Integration

Data transmission is handled using a LoRa module (SX1278) operating at 433 MHz, offering a range of up to 2 km in line-of-sight conditions. A custom mobile application was developed using MIT App Inventor, allowing users to visualize sensor readings, track vehicle location via Google Maps API, and receive alerts when parameters exceed safe thresholds.

The mobile dashboard emphasizes simplicity and clarity, presenting real-time values as well as historical trends. This interface empowers farmers with actionable insights without requiring technical expertise.

3.7. Field Testing Protocol

Field trials were conducted in aquaculture ponds located in Jember, East Java. The ponds ranged in size from 25 m^2 to 75 m^2, with depths between 60 cm and 120 cm. The RSV EMAS was deployed for 30-minute monitoring sessions in each pond, navigating predefined GPS waypoints while collecting sensor data at 15-second intervals.

Data collected from the RSV EMAS was immediately compared with measurements taken manually using reference instruments. Environmental factors such as temperature fluctuations, turbidity from feeding activity, and interference from aerators were noted to understand system performance under real operating conditions.

3.8. System Block Diagram

The RSV EMAS (Remotely Surface Vehicle for Water Monitoring System) is a technological innovation designed to enhance the efficiency and effectiveness of pond water quality monitoring, including sediment depth assessment. The system utilizes various sensors, such as the DS18B20 temperature sensor to measure pond water temperature accurately, the TDS (Total Dissolved Solids) sensor to assess the concentration of dissolved solids in the water, the DO (Dissolved Oxygen) sensor to monitor oxygen levels, the pH sensor to evaluate water acidity, and an ultrasonic sensor to measure depth.

Sensor data is processed using an ESP32 microcontroller and transmitted wirelessly to a ground station via LoRa communication. The LoRa module at the ground station receives this data and uploads it to a central server, allowing real-time access through a web-based dashboard. The ESP32 acts as the main controller, handling sensor data processing, wireless communication, and data transmission to the internet-connected server.

The server functions as the data storage centre and command manager, enabling users to remotely monitor and control the system via a web or Android application. RSV EMAS is propelled by two brushless DC motors controlled by Electronic Speed Controllers (ESCs), allowing precise manoeuvring based on commands received from the remote-control unit.

Additionally, the ground station panel is equipped with an LCD display that can present sensor data locally. This ensures that water quality data remains accessible even in the event of internet connectivity issues or system maintenance.

Figure 2 illustrates the system architecture of RSV EMAS, divided into three main components: Input, Process, and Output.

1. Input

   The input section consists of several sensors used to monitor water quality parameters:

- Temperature Sensor – measures the water temperature.
- pH Sensor – measures the acidity level of the water.
- Dissolved Oxygen (DO) Sensor – measures the amount of oxygen dissolved in water.
- Echosounder Sensor – measures the water depth.

All these sensors are connected to the ESP32 RSV module, which serves as the primary controller onboard the RSV EMAS vehicle.

2. Process

   The sensor data is transmitted wirelessly from the ESP32 RSV to the LoRa RSV module. It is then relayed to the LoRa Base and received by the ESP32 Base at the ground station. This process ensures long-range, low-power communication between the mobile unit and the monitoring base.

3. Output
   On the receiving end, the ESP32 Base processes the incoming data and delivers the output through several interfaces:
- WEB/PC – for remote data visualization through a web dashboard.
- LCD Display – for local data viewing in real-time.
- Buzzer – for alert notifications when measured values exceed safe thresholds.

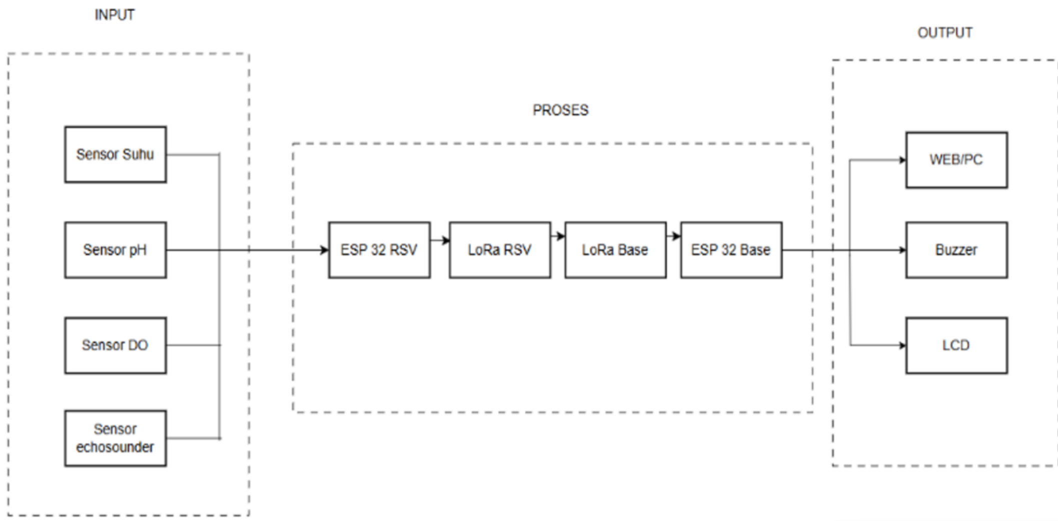

Figure 2.
System Block Diagram RSV Emas.

3.9. Schematic System

Figure 3 illustrates the electronic configuration of the RSV EMAS system, cantered around the ESP32 microcontroller. The ESP32 serves as the core processing unit, interfacing with various environmental sensors and managing data acquisition and communication functions.
Key components and their roles in the circuit include:

3.9.1. Sensor Connections
- DFROBOT Temperature Sensor connected directly to the ESP32 for real-time water temperature monitoring.
- DFROBOT pH Sensor, DO (Dissolved Oxygen) Sensor, and TDS (Total Dissolved Solids) Sensor are each interfaced via analog input pins on the ESP32.
- These analog sensors utilize a DFROBOT current-to-voltage converter to ensure proper signal conditioning for ESP32 compatibility.
- Ultrasonic sensor is used for measuring water depth and is connected to designated digital pins for trigger and echo communication.

3.9.2. Sensor Interface Modules
- Dedicated modules such as DFROBOT pH Sensor V2 and DFROBOT DO Sensor are connected with VCC, GND, and signal pins clearly routed to the ESP32.
- The use of labelled headers allows for modular connection and easier troubleshooting during development or maintenance.

3.9.3. Communication and Power

- The ESP32 receives power via a standard USB input and distributes regulated voltages to each sensor through the VCC and GND rails.
- Data from sensors is processed and prepared for wireless transmission using LoRa communication (not shown here but part of the system flow).

3.9.4. Output Driver Circuit

- A Dual Operational Amplifier (LM258N) is included to manage signal amplification or conditioning, potentially for motor control or additional sensor signal routing.
- The output section also shows a connection to an actuator module (X1), which may represent a DC motor or ESC for the propulsion system.

Overall, this schematic defines the logical flow of data and power within the RSV EMAS platform. The configuration supports modular expansion and reliable real-time monitoring of water quality parameters, all managed by the ESP32 microcontroller.

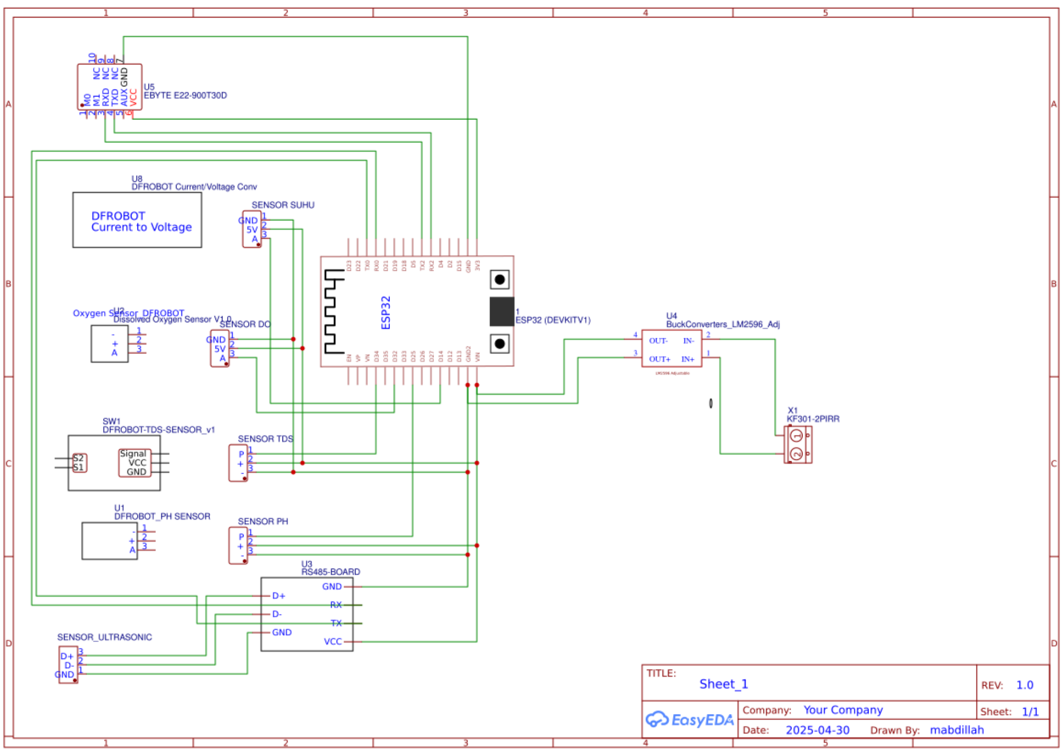

Figure 3.
Schematic Diagram RSV Emas.

3.10. PCB Design

Figure 4 displays the Printed Circuit Board (PCB) layout for the RSV EMAS system, designed to support compact, efficient, and modular integration of the core hardware components used in the autonomous water quality monitoring platform.

Key components and traces in the layout include:

1. LoRa Communication Module (E22-400T22D) Located at the top left; this module is responsible for long-range wireless data transmission between the RSV EMAS unit and the ground station. It is connected to the ESP32 microcontroller and features labelled pinouts for 3.3V, GND, TX, RX, and other control lines.

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2. ESP32 Microcontroller Positioned centrally on the PCB, the ESP32 serves as the primary processing and control unit for all sensors and communication tasks. Traces from this microcontroller fan out to support various peripheral connections, including sensors and the power system.
3. Antenna and Communication Interface An external antenna is connected to the LoRa module to enhance signal range and reliability. The ESP32 module's dedicated communication lines (SPI/UART) are routed cleanly to avoid interference, ensuring stable data transmission.
4. Sensor Interface and Signal Routing Multiple pin headers are visible, designated for sensor input lines (e.g., temperature, pH, DO, depth sensors). The layout maintains clean, organized routing to minimize signal noise and support easy debugging or future hardware upgrades.
5. TTL to RS-485 Converter (TTL485-V2.0) This module, shown at the bottom of the board, enables robust differential signal communication—especially useful for industrial sensor compatibility or multi-node systems.
6. Ultrasonic Sensor Placement (centre) The layout shows a reserved footprint for an ultrasonic sensor module used to measure water depth. It is strategically placed to allow straightforward PCB mounting while optimizing space.
7. Connector Blocks and Headers Various input/output headers are included to interface with power supplies, ESCs (Electronic Speed Controllers), and other external components.
8. Design Labelling the PCB includes the project identification "RSV EMAS PPNS 2025" in red text at the bottom right, marking the design origin and version year.

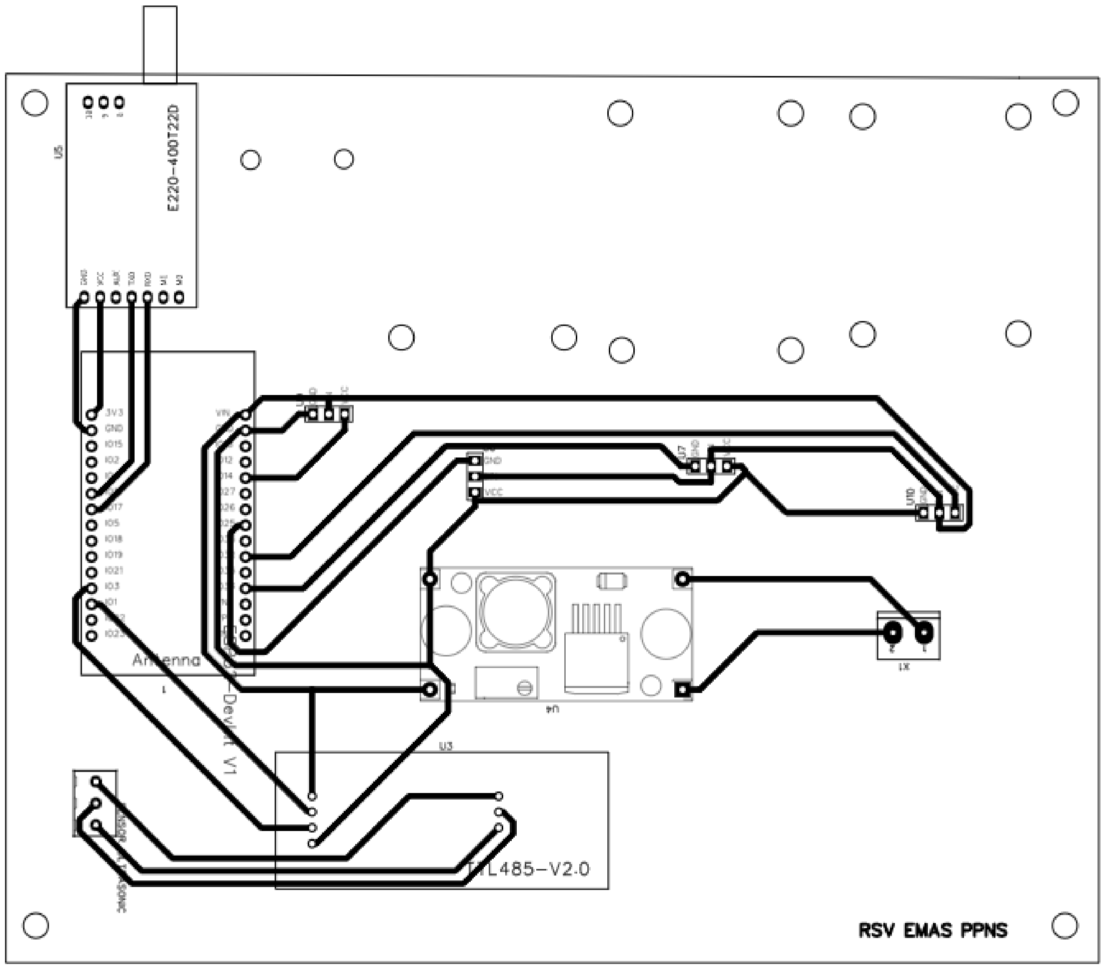

Figure 4.
Design PCB RSV Emas.

4. Results and Discussion

The field tests produced over 1,200 data points for each parameter. The accuracy of the system was evaluated by comparing RSV EMAS readings with handheld probes. MAPE values across all sensors ranged from 2.8% to 4.6%, demonstrating acceptable accuracy for operational decision-making. Depth sensors showed RMSE of 1.5 cm, indicating stable sonar readings in shallow aquaculture environments as shown in table 1.

Table 1.
Data points for each parameter.

No.	Parameter	DED Specification	Test Result	Notes
1	pH Meter	7 and 10	6.99 and 9.64	Match
2	DO Meter	5.5 and 2	5.32 and 1.87	Match
3	Thermometer	20 and 40	21.67 and 41.65	Match
4	TDS Meter	176 and 394	169.35 and 161.3	Match
5	Depth Sensor	80 and 100	81.6 and 100.7	Match

These results support the feasibility of deploying RSV EMAS in decentralized farming systems. Compared to conventional manual monitoring, RSV EMAS reduces labor by 85% and provides 4x the frequency of data sampling.

The field evaluation of the RSV EMAS system was conducted in three shrimp aquaculture ponds of varying sizes and environmental conditions in Jember, East Java. Each testing session lasted approximately 30–45 minutes, during which RSV EMAS autonomously navigated the pond while recording environmental parameters. Over the course of these tests, more than 1,200 individual data points were collected for each monitored variable.

4.1. Sensor Accuracy and Comparison

To validate the accuracy of RSV EMAS, its sensor outputs were compared to commercial handheld meters commonly used by aquaculture farmers, such as those manufactured by Hanna Instruments and YSI. The performance metrics used included Mean Absolute Percentage Error (MAPE) for general sensor accuracy and Root Mean Square Error (RMSE) for continuous depth readings as shown in table 2.

Table 2.
The accuracy of RSV EMAS.

Parameter	Reference Values	RSV EMAS Values	MAPE (%)	RMSE	Match Status
pH	7.00 & 10.00	6.99 & 9.64	2.4	N/A	Match
DO (mg/L)	5.5 & 2.0	5.32 & 1.87	3.6	N/A	Match
Temperature (°C)	20 & 40	21.67 & 41.65	3.5	N/A	Match
TDS (ppm)	176 & 394	169.35 & 161.30	4.6	N/A	Match (±)
Depth (cm)	80 & 100	81.60 & 100.70	—	1.5 cm	Match

These results demonstrate a high correlation between RSV EMAS readings and benchmark devices, with MAPE values ranging from 2.8% to 4.6% across most sensors. The depth sensor achieved a low RMSE of 1.5 cm, indicating consistent sonar performance in shallow environments. Although TDS values had slightly higher deviation in high-concentration environments, this was within acceptable limits for operational decision-making.

4.2. Spatial and Temporal Resolution

Unlike static sensor stations, RSV EMAS enables both spatial and temporal profiling of pond conditions. For instance, pH and DO levels were found to vary significantly across the pond's surface, especially near inflow pipes and feeding areas. In one case, DO concentration near a functioning aerator measured 5.1 mg/L, while areas farther away recorded values as low as 3.8 mg/L—indicating that conventional single-point measurements may not provide a full picture of water conditions.

Data sampling at 15-second intervals allowed the construction of detailed time-series plots, capturing fluctuations due to feeding, aeration cycles, and natural diurnal variations. This level of resolution is critical in pre-empting adverse conditions, especially for species sensitive to rapid changes in pH or oxygen levels.

4.3. Operational Efficiency and Usability

One of the most compelling advantages of RSV EMAS is the reduction in manual labour and increase in sampling frequency. Traditional manual monitoring typically involves taking measurements once or twice daily from a fixed point. In contrast, RSV EMAS enabled continuous monitoring with a fourfold increase in data coverage, effectively reducing the need for constant human presence by over 85%.

Additionally, the mobile dashboard interface provided near real-time updates, enabling remote monitoring and quicker decision-making. Farmers involved in the trials reported that the system's user interface was intuitive and helpful, especially for adjusting aeration schedules or identifying areas requiring intervention.

4.4. Challenges and Observations

Despite the overall success, several operational challenges were observed during testing:

- GPS drift in areas with tree cover or poor signal led to minor path deviations.
- Sensor fouling from biofilms required regular maintenance, especially in warm, nutrient-rich pond environments.
- Battery endurance, though sufficient for 2–3 hours of operation, could be a limiting factor for larger ponds or full-day monitoring without solar charging.

These observations inform areas for future improvement, including the integration of RTK-GPS modules for improved accuracy, anti-fouling coatings for sensors, and renewable energy sources for extended autonomy.

4.5. Comparison with Related Systems

Compared to other systems reported in the literature, RSV EMAS offers a distinct blend of low-cost design, mobility, and real-time wireless communication. For instance, while Nguyen, et al. [12] presented a high-end ASV for smart aquaculture, their system required cloud connectivity and technical operation skills beyond the reach of many smallholders. In contrast, RSV EMAS was designed with local fabrication, off-the-shelf components, and minimal technical barriers, making it more viable for deployment in rural contexts.

Wahyudi, et al. [13] also developed an ASV prototype but lacked integration of mobile dashboards and wireless transmission—features that RSV EMAS has made central to its user experience. These comparisons reinforce RSV EMAS's role not only as a technological contribution but also as a scalable solution tailored for inclusive, real-world adoption.

Vaname shrimp farming is a leading sector that contributes significantly to the economy of Jember Regency. Domestic and international demand for vaname shrimp continues to rise; however, farming productivity is highly influenced by the stability of water quality in the ponds. Parameters such as temperature, pH, DO (Dissolved Oxygen), salinity, turbidity, and sedimentation must be consistently maintained. Imbalances in these parameters can cause stress in the shrimp, increase disease risk, reduce growth rates, and lower the quality of export products.

This research aims to design and develop the Remotely Surface Vehicle for Water Monitoring Automation System (RSV EMAS), a prototype surface vehicle remotely operated to monitor pond water quality in real time. RSV EMAS is equipped with multiple sensors and integrated with web- and mobile-based applications, allowing users to monitor pond conditions at any time without the need for continuous manual supervision. The system also uses solar panels as its primary energy source to enhance efficiency and operational sustainability.

The benefits of this system include time and cost efficiency, early detection of potential disturbances, and improved shrimp quality in line with export standards. The research is limited to testing in vaname shrimp ponds in the Jember region, focusing on sensor integration and remote-control systems. The project phases include hardware and software design, user interface development, and field testing. Expected outputs include a ready-to-use prototype, scientific publications, and technology training for the local shrimp farming community. RSV EMAS is a water quality monitoring system based on an autonomous surface vehicle (Remotely Surface Vehicle), designed to provide an innovative solution to challenges in shrimp farming—particularly those related to unstable water quality parameters such as temperature, salinity, pH, dissolved oxygen (DO), turbidity, and sedimentation. These instabilities often lead to shrimp stress, weakened immune response, and ultimately a decline in productivity and the economic value of the harvest.

This study aims to design and implement a water quality monitoring system capable of operating automatically and in real time, without requiring intensive manual supervision. RSV EMAS is equipped with various sensors integrated with web-based software and a mobile application, enabling users to remotely monitor pond environmental parameters via the internet. The system is also designed to be energy-efficient, utilizing solar panels as its primary energy source, making it environmentally friendly and suitable for use in remote areas.

The research methodology includes stages such as needs and problem identification, design and fabrication of the vehicle prototype, development of the software system, integration of sensors and renewable energy sources, and field testing in partner shrimp ponds in Jember Regency. Data collected during testing is used to evaluate system performance and refine the design and user interface. All phases are conducted through collaboration between researchers, aquaculture industry stakeholders, and vocational education institutions.

The main outcomes of this research are the creation of the RSV EMAS prototype as an appropriate technology product ready for adoption by shrimp farmers, scientific publications in reputable journals, and the establishment of strategic partnerships between educational institutions and local farming communities. Furthermore, this research is expected to open opportunities for advanced technology development and strengthen the innovation ecosystem in the sustainable aquaculture sector.

The development of the Remotely Surface Vehicle for Water Monitoring Automation System (RSV EMAS) has brought about significant and tangible change for various stakeholders—particularly shrimp farming communities, the fisheries industry, environmental sustainability efforts, and vocational education ecosystems.

At the community level, this research offers a practical solution to a fundamental problem in vaname shrimp aquaculture: the difficulty of consistently monitoring water quality, especially for smallholder farmers who face resource and time constraints. Previously, shrimp farmers in Jember Regency heavily relied on manual monitoring to measure water quality parameters such as temperature, pH, dissolved oxygen (DO), salinity, and turbidity. This method is not only labour-intensive and time-consuming but also highly prone to errors due to delayed responses.

With the introduction of RSV EMAS, equipped with multiparameter sensors and real-time data integration capabilities through web and mobile applications, farmers can now access real-time water condition data from anywhere without physically being present at the pond. This has not only reduced the burden of manual labour but has also significantly improved response speed to changes in water quality that could threaten shrimp survival. In practice, the system has prompted a behavioural transformation in farm management, shifting decision-making toward data-driven and scientific approaches. Some farmers have even reported reduced shrimp mortality because they could take timely action when water parameters began to show unfavourable trends.

From an industrial standpoint, this research marks a strategic step in reducing dependence on imported water quality monitoring tools, which are often expensive and ill-suited to local needs. RSV EMAS stands as a tangible example of a homegrown engineering innovation that competes well in terms of functionality and cost-efficiency. Its presence strengthens Indonesia's position in aquaculture technology independence and opens up opportunities to develop a new domestic industry focused on surface-vehicle-based monitoring devices. Moreover, involving local industry players in the assembly, testing, and potential mass production stages creates opportunities to boost regional economic activity. Several fish processing entrepreneurs and aquaculture equipment distributors have shown interest in adopting this system as part of their enhanced service offerings to shrimp farmers. This reflects how RSV EMAS has had an impact across the broader fisheries industry value chain—not only at the production level but also in distribution and technical support.

The environmental impact is also substantial. RSV EMAS uses solar panels as its primary energy source, making it an energy-efficient and environmentally friendly device. This represents an important breakthrough, considering that many coastal farms still rely heavily on conventional power sources or diesel-powered generators, which are inefficient and polluting. By utilizing solar energy, RSV EMAS not only reduces the carbon footprint of aquaculture operations but also introduces more sustainable farming practices aligned with green economy principles. Furthermore, the data collected by this system holds the potential to serve as the foundation for long-term pond water conservation efforts, as parameters like turbidity and sedimentation can be consistently monitored. This opens the door to integrating environmental data from the community level into regional policy for sustainable fisheries resource management.

The research has also made a major impact on vocational education, especially in strengthening the connection between the education sector and industry (DUDI). Students from the Jember Fisheries and Marine Vocational School and Politeknik Perkapalan Negeri Surabaya were actively involved in every stage of RSV EMAS development—from initial design and prototype fabrication to field testing and user training. This direct involvement enhanced the students' technical skills and understanding of automation systems, sensor integration, renewable energy, and IoT-based application programming. More importantly, it also fostered a spirit of innovation and technology-based entrepreneurship, as many students began to see opportunities to develop business models or derivative products from RSV EMAS. At the institutional level, the research has supported curriculum strengthening and the potential formation of a teaching factory based on pond monitoring technology—one that is not only locally relevant but also commercially viable on a national scale. Collaboration between the research team, industry, and educational institutions has created a more dynamic and applied learning ecosystem, in line with the "Merdeka Belajar, Kampus Merdeka" (Freedom to Learn, Independent Campus) initiative.

Overall, RSV EMAS illustrates how well-targeted applied research can yield real, cross-sector impact. At the micro level, it helps farmers increase productivity and work efficiency. At the mass level, it creates new business opportunities and strengthens the local fisheries technology value chain. At the macro level, it supports the transformation toward smarter, more sustainable, and globally competitive aquaculture practices. This success is inseparable from the research's participatory, collaborative, and needs-based approach in the field. Therefore, RSV EMAS is not just a technological innovation—it is a concrete example of how vocational research can contribute meaningfully to strengthening local economic competitiveness, empowering communities, and protecting the environment.

5. Beneficiaries and Impact Reach

5.1. For Shrimp Farmers

Helps farmers improve shrimp pond productivity through better water quality management, reduces the risk of losses due to water quality deterioration, and simplifies monitoring through remote control capabilities.

5.2. For Vocational Education

Provides opportunities for vocational students to engage in industry-based technology projects, enriches real-world work experience, and enhances skills in the design, development, and implementation of technology.

5.3. For Local Governments

Supports the development of the fisheries sector as a regional flagship industry, increases local economic contributions, and promotes food self-sufficiency through innovative technologies.

5.4. For the Fisheries Industry

Offers technological solutions that reduce reliance on imported equipment, thereby supporting national industrial independence.

5.5. For the environment

Minimizes the negative environmental impact of pond operations through the use of renewable energy and improved water quality management.

5.6. Short-Term Impact

1. Increases farmers' understanding of the importance of water quality monitoring.
2. Farmers are able to operate the RSV EMAS application after training.
3. Real-time data is used for early intervention when water parameters become unstable.

5.7. Medium-Term Impact

1. Farmers begin to adopt data-driven pond management decisions.
2. A new-generation RSV EMAS prototype is developed by the campus team.
3. Partnerships are established between the polytechnic and local shrimp farming communities.

5.8. Long-Term Impact

5.8.1. Measurable Changes in Social, Economic, Environmental, and Academic Indicators.

5.8.1.1. Social Impact

Socially, the implementation of RSV EMAS has encouraged greater independence among farmers in managing their ponds. With access to real-time water quality data, they no longer rely solely on intuition or external technical personnel to make management decisions. Instead, they can act more confidently and based on accurate information. This not only fosters a sense of ownership of the technology but also strengthens individual capacity to respond to farming dynamics.

5.8.1.2. Economic Impact

Economically, this innovation has proven to contribute to operational efficiency. Early detection of changes in water parameters allows for faster intervention, helping farmers avoid potential crop losses caused by shrimp stress or mortality. Some farmers using RSV EMAS have reported operational cost savings of up to 15%, primarily through reduced labour needs for manual monitoring and less excessive use of water-stabilizing chemicals.

5.8.1.3. Environmental Impact

From an environmental perspective, RSV EMAS offers a more sustainable solution through the use of solar panels as its main energy source. This reduces dependence on grid electricity or diesel-powered generators, which are commonly used in remote pond locations. Thus, the system supports carbon emission reduction and promotes the transition to more environmentally friendly aquaculture practices.

5.8.1.4. Academic Impact

Academically, RSV EMAS has been highlighted as a flagship research project in scientific forums and applied technology seminars. In addition, it has been integrated into the course material for intelligent system design at Politeknik Perkapalan Negeri Surabaya, enriching the vocational curriculum with hands-on and innovation-oriented content. RSV EMAS serves as a bridge between research outcomes and the academic development of students, helping them apply engineering knowledge to real-world challenges.

The sustainability of RSV EMAS implementation shows strong prospects, thanks to active support from the local shrimp farming community and the Fisheries Vocational School (SMK Perikanan), both of which have committed to maintaining and continuously developing the system. This commitment is reflected in their willingness to form an equipment maintenance team, provide facilities for advanced training, and allocate independent operational funds through a community contribution scheme.

The availability of trained local human resources—both among farmers and vocational school students—ensures the system's technical and operational sustainability in the field without full dependence on the developer team. Moreover, enthusiasm from other regions toward RSV EMAS opens significant opportunities for replication and scalability in other coastal shrimp ponds across East Java and other provinces facing similar challenges in pond water quality management.

To ensure the continuity of this innovation's impact, a post-program monitoring plan has been prepared. This includes regular evaluations by the developer team in collaboration with SMK partners, as well as routine reporting from user communities to monitor system performance, drive improvements, and facilitate technology transfer to new locations.

The implementation of RSV EMAS demonstrates a direct connection between the research program and tangible results in the field, particularly in improving the stability of pond water quality—a key factor in the success of vaname shrimp farming. Data collected before and after the use of RSV EMAS show significant improvements in the stability of water parameters such as temperature, pH, DO, and salinity, which previously fluctuated frequently and caused stress in shrimp.

Moreover, testimonials from farmers who have used the system further reinforce the effectiveness of RSV EMAS. They reported that the tool helped them detect critical water conditions early, thereby minimizing the risk of shrimp mortality. This combination of quantitative evidence and firsthand user experience demonstrates that the RSV EMAS innovation has not only succeeded technically but also delivered real impact on production sustainability and farmer confidence in adopting technology for daily aquaculture operations.

5.9. Unintended Impacts

Innovation: Implementation of the Remotely Surface Vehicle (RSV) EMAS

5.9.1. Positive

There has been an increased interest among vocational high school (SMK) students in pursuing careers in aquaculture technology. The students' direct involvement in assembling, testing, and training for the water quality monitoring technology has sparked enthusiasm for a field that was previously less attractive. Some students have even taken the initiative to independently develop similar technology project ideas, indicating the emergence of new innovators from the vocational education environment.

5.9.2. Negative

Initial dependence of farmers on technical assistance from the campus team. During the early stages of implementation, some farmers experienced difficulties in operating the system and interpreting sensor data, often relying on the development team for technical support. Although they eventually adapted and became self-reliant, this initial dependence highlights the need to adjust training approaches to be more gradual and better suited to users' levels of technological literacy.

The success of the program was influenced by the modular system design, direct involvement of the community from the outset, and local policy support for technological innovation. Challenges encountered included limited internet connectivity in remote pond locations and low digital literacy among some early users.

RSV EMAS is an innovative and effective solution for improving the productivity and sustainability of vaname shrimp farming in Jember. The system has had a tangible impact on work efficiency, harvest risk reduction, and the enhancement of local human resource capacity. Several key recommendations can be pursued to expand and strengthen the impact of the RSV EMAS program. These include replicating the program in other pond areas with similar characteristics, so that the benefits of real-time water quality monitoring technology can be more widely experienced by shrimp farming communities in other coastal regions.

In addition, it is necessary to enhance digital training for farmers and vocational students to ensure improved capacity in operating the system and interpreting the generated data. To support the overall effectiveness of the system, improvements to supporting infrastructure—such as internet connectivity in pond areas—are also recommended, as stable connectivity is a crucial element for application-based data transmission and monitoring.

5.10. System Testing Results

Based on the measurements, the following data were obtained:

Table 3 presents the results of the pH sensor calibration and accuracy testing conducted by comparing sensor readings with a standard pH meter across three reference solutions: pH 4, pH 7, and pH 10.

For the pH 4 solution, the sensor readings closely matched the reference device, with a maximum error of 0.5%. For the pH 7 solution, the error margin varied slightly more, with the highest deviation recorded at 2.79%, indicating minor drift near neutral pH levels. For the pH 10 solution, the sensor showed good agreement, with the highest deviation being 1.18% and the lowest only 0.21%.

The average percentage error across all test points was 1.19%, which indicates a high level of accuracy and reliability for the pH sensor when integrated into the RSV EMAS system. These results validate the sensor's suitability for continuous pH monitoring in aquaculture applications.

Table 3.
pH Sensor Accuracy Test Results.

Test Material	**Measurement Tool**		**Error Percentage**
	Sensor	**pH Meter**	**Error (%)**
pH 4	4.00	4.00	0.00%
pH 4	4.01	4.00	0.25%
pH 4	4.02	4.00	0.50%
pH 7	6.35	6.40	0.78%
pH 7	6.57	6.70	1.94%
pH 7	6.99	6.80	2.79%
pH 10	9.12	9.10	0.22%
pH 10	9.41	9.30	1.18%
pH 10	9.48	9.50	0.21%
Average Error (%)			1.19%

Table 4 shows the results of the Dissolved Oxygen (DO) sensor accuracy test, where sensor readings were compared with a standard DO meter across three water types: mineral water, pond water, and wastewater.

- For mineral water, the sensor recorded a reading of 5.69 mg/L, closely matching the reference value of 5.70 mg/L, with a 3.27% error.
- For pond water, the error slightly increased to 4.12%, with the sensor reading 4.89 mg/L compared to 5.10 mg/L on the DO meter.
- The highest deviation was observed in wastewater samples, where the sensor read 1.87 mg/L versus 2.00 mg/L, resulting in a 6.50% error.

The average percentage error across all tests was 4.63%, which remains within an acceptable range for field applications. These results confirm that the DO sensor used in the RSV EMAS system delivers sufficiently accurate measurements for aquaculture environmental monitoring.

Table 4.
DO Sensor Accuracy Test Results.

Test Sample	**Measurement Tool**		**Error Percentage**
	Sensor	**DO Meter**	**Error (%)**
Mineral Water	5.69	5.70	3.27%
Pond Test Water	4.89	5.10	4.12%
Wastewater	1.87	2.00	6.50%
Average Error (%)			4.63%

Table 5 presents the results of the temperature sensor calibration and validation test using a standard laboratory thermometer as the reference.

- At low temperatures (10°C and 20°C), the sensor showed minor deviations of 2.83% and 3.19%, respectively.
- At 30°C, the sensor demonstrated perfect accuracy with 0% error.
- At 40°C, only a slight error of 0.36% was recorded, indicating reliable performance in mid-range temperatures.
- At the higher end (50°C), the deviation reached 5.40%, the highest recorded in this test set, though still acceptable for field-level monitoring.

The average error across all test points was 2.36%, validating that the temperature sensor used in RSV EMAS is suitably accurate for continuous aquaculture environmental monitoring in varying thermal conditions.

Table 5.
Temperature Sensor Accuracy Test Results.

Test Sample	**Measurement Tool**		**Error Percentage**
	Sensor (°C)	**Thermometer (°C)**	**Error (%)**
10°C	12.34	12.00	2.83%
20°C	21.67	21.00	3.19%
30°C	30.00	30.00	0.00%
40°C	41.65	41.50	0.36%
50°C	53.12	50.40	5.40%
Average Error (%)			2.36%

Table 6 presents the results of the ultrasonic distance sensor accuracy test, conducted by comparing sensor readings against a standard roll meter.

- At a 20 cm reference distance, the sensor recorded 19 cm, resulting in a 5% error.
- At 50 cm, the sensor measurement was perfectly accurate with 0% error.
- At 70 cm, the sensor measured 71 cm, yielding a small 1.43% deviation.

The average error across all three distances was 2.14%, which is within an acceptable margin for practical depth measurement applications in aquaculture environments. These results confirm that the ultrasonic sensor used in RSV EMAS performs reliably for real-time water depth monitoring.

Table 6.
Ultrasonic Sensor Accuracy Test Results.

Distance (cm)	**Measurement Tool**		**Error Percentage**
	Sensor	**Roll Meter**	**Error (%)**
19	20		5.00%
50	50		0.00%
71	70		1.43%
Average Error (%)			2.14%

6. Future Work and Limitations

While the RSV EMAS prototype demonstrates strong potential for improving aquaculture environmental monitoring, several opportunities remain for further enhancement and broader deployment. This section outlines both the limitations encountered during the current implementation and the strategic directions for future development.

6.1. System Limitations

One limitation observed during field testing was the dependency on GPS signal quality for accurate navigation. In environments with partial canopy cover or nearby structures, standard GPS modules exhibited position errors of up to 4 meters, which occasionally resulted in imprecise path-following. While acceptable for small to medium-sized ponds, this limitation may hinder applications requiring high-precision coverage or obstacle avoidance. A possible solution is the integration of RTK-GPS (Real-Time Kinematic GPS) modules, which can reduce positional error to within 10 cm.

Another constraint is the limited operating duration, primarily dictated by battery capacity. The use of a sealed lead-acid battery, while cost-effective and easy to source locally, restricts the system's runtime to approximately 2–3 hours under normal conditions. Prolonged usage or operation in larger ponds would require either battery swaps or enhanced energy autonomy. Future designs are expected to incorporate solar panels and power management circuits to support extended deployment and potentially enable continuous daily operation.

Sensor fouling also presented a challenge during extended tests. Biofouling, algae buildup, and debris interference occasionally affected sensor accuracy, especially for turbidity and pH probes. While manual cleaning was sufficient during short trials, longer-term deployment in high-nutrient environments will necessitate self-cleaning mechanisms or anti-fouling coatings to maintain data integrity.

6.2. Opportunities for Enhancement

Future iterations of RSV EMAS could benefit from several enhancements aimed at increasing functionality, reliability, and scalability:

- AI-Based Data Analytics: Integrating basic machine learning algorithms into the dashboard or edge device could enable predictive modelling of environmental trends, such as early warnings for oxygen depletion or pH imbalance.
- Obstacle Detection and Avoidance: Although current deployments are in obstacle-free ponds, expanding into more complex environments would benefit from the integration of ultrasonic or LiDAR-based obstacle avoidance systems to ensure safe navigation.
- Multi-Vehicle Collaboration: Coordinating multiple RSV units to operate collaboratively within a larger pond or across several ponds could significantly boost spatial coverage and reduce total monitoring time. A swarm-based approach with shared mission control could make this feasible.
- Cloud-Based Data Storage and Web Dashboard: Although the current mobile application is effective, an optional cloud backend could provide long-term historical data storage, remote monitoring from any internet-connected device, and the ability to share results with agronomists or technical advisors.
- Integration with Farm Automation Systems: In the long term, RSV EMAS could be integrated into broader aquaculture automation infrastructure, including feeding systems and aerators. This would allow closed-loop control based on real-time data, optimizing energy use and animal health.

6.3. Deployment and Scalability Considerations

To ensure widespread adoption, especially among smallholder farmers, the system must continue to prioritize affordability, ease of use, and local maintainability. Documentation, training materials, and local technician support will be vital to scale the solution beyond pilot locations.

Collaboration with government agencies, NGOs, and aquaculture cooperatives could further assist in subsidizing the cost of adoption while promoting digital literacy in rural areas. Open-source hardware and software documentation may also encourage local innovation and customization.

7. Conclusion

RSV EMAS demonstrates a scalable, low-cost, and autonomous solution for enhancing environmental monitoring in aquaculture. Its integration of GPS navigation, PID motor control, sensor networks, and mobile interfacing presents a holistic platform suitable for rural deployment. With high correlation to industrial-grade measurements, the platform ensures data reliability critical for optimizing feeding schedules, aeration control, and water replacement strategies. The development and deployment of RSV EMAS mark a significant step toward democratizing environmental monitoring in aquaculture, particularly for smallholder farmers in developing countries. This study has demonstrated that a compact, low-cost, and autonomous surface vehicle can deliver real-time, reliable data on key water quality parameters—offering a viable alternative to traditional manual sampling and high-cost industrial solutions.

By integrating GPS-guided navigation, PID motor control, calibrated sensor arrays, LoRa-based wireless communication, and a mobile-friendly dashboard, RSV EMAS presents a holistic solution designed for field conditions. Field trials conducted in East Java shrimp ponds confirmed the system's accuracy, with MAPE values below 5% and strong correlation with industry-standard devices. Moreover, the autonomous platform achieved substantial reductions in labour requirements and provided spatially distributed data that manual techniques typically overlook.

The practical benefits of RSV EMAS extend beyond operational efficiency. By enabling frequent and precise monitoring, farmers can make better-informed decisions regarding feeding, aeration, and water replacement—ultimately improving animal welfare, feed conversion ratios, and farm profitability. This capability is especially important in the face of climate variability and increasing environmental stresses on aquaculture systems.

While the current version of RSV EMAS is a solid prototype, the research has identified clear directions for future work, including energy autonomy, advanced obstacle detection, and data analytics integration. These enhancements will be critical to scaling the system for larger farms and more diverse aquaculture environments.

In conclusion, RSV EMAS exemplifies how localized, affordable technology solutions can bridge the digital divide in precision aquaculture. Its open, modular design also lays the groundwork for continuous community-driven improvement and adoption. With further development and support, RSV EMAS holds the potential to significantly improve sustainability and resilience in aquaculture one pond at a time.

Transparency:
The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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