ECE 445
Senior Design Lab
Project Proposal

AquaSense: Affordable ML-Based Water Quality Monitoring for Aquariums

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Content

Abstract

AquaSense is an affordable water quality monitoring system aimed at aquarium owners. It continuously measures three key parameters quantifying aquarium health: pH, temperature, and dissolved oxygen via an ESP32 microcontroller. The system wirelessly transmits parsed real-time data into a cloud-powered mobile dashboard feed, empowering users to monitor trends in water quality and receive alerts when conditions fall outside preferred ranges specific to their aquarium. Additionally, Machine Learning algorithms can analyze historical user-specific data to detect anomalies and predict trends in water quality issues. With this emphasis on affordability, accuracy, intelligence, and consumer-facing design, AquaSense provides a unique and accessible solution for maintaining a healthy aquatic environment with minimal hassle for the owner.

1 Introduction

Maintaining optimal water quality in aquariums is crucial for the health and longevity of aquatic organisms. As an aquarium owner, you may have experienced the anxiety of leaving your fish unattended for an extended period — whether for work, travel, or vacation — without knowing if water conditions remain safe. Poor water quality can quickly deteriorate, leading to illness or even fatal consequences for fish and aquatic plants. Yet, many hobbyists and small-scale fishkeepers lack access to affordable, real-time water monitoring solutions that can provide timely alerts in the event of harmful fluctuations.

1.1 Problem

Maintaining optimal water quality in aquariums is crucial for the health of aquatic organisms. Poor water quality is a leading cause of illness in fish, and maintaining proper water parameters is essential for their well-being [1]. However, many hobbyists and small-scale fishkeepers lack access to affordable, real-time water monitoring solutions. Traditional testing methods involve manual kits that require frequent intervention, making it difficult to detect rapid fluctuations in parameters such as pH, temperature, or dissolved oxygen, which can be harmful to fish and aquatic plants [2].

Existing automated water quality monitoring solutions are often expensive and designed for industrial-scale applications, leaving home aquarium owners with few accessible options. For instance, advanced monitoring systems are tailored for large-scale aquaculture operations and may not be cost-effective for individual hobbyists [3]. To bridge this gap, there is a need for a low-cost, plug-and-play solution that continuously monitors water conditions and provides real-time alerts when the water quality becomes unsuitable for fish. Such a system would enable aquarium enthusiasts to maintain healthier environments for their aquatic life.

One example of an affordable monitoring device is the Kactoily Smart 7-in-1 Aquarium Monitor, which offers real-time water quality tracking with built-in Wi-Fi, allowing users to oversee parameters such as pH and temperature continuously [4]. Implementing accessible monitoring solutions can significantly enhance the ability of hobbyists to maintain optimal water conditions, thereby promoting the health and longevity of their aquatic organisms.

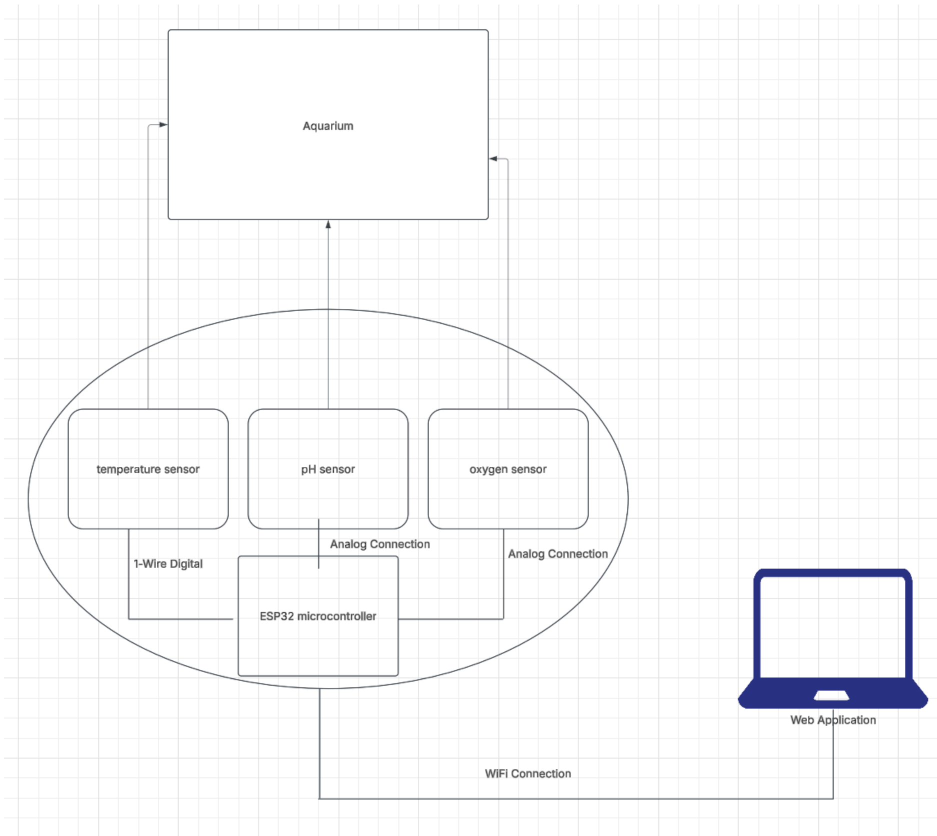
1.2 Solution

We propose AquaSense, a cost-effective, ESP32-based plug-and-play PCB designed to provide real-time water quality monitoring for aquarium owners. This compact system integrates multiple sensors to continuously track key parameters, including pH, temperature, and dissolved oxygen, ensuring a healthier aquatic environment. By leveraging the ESP32 microcontroller, AquaSense offers seamless Wi-Fi and Bluetooth connectivity, allowing users to remotely monitor water conditions via a web dashboard with real-time data logging and trend analysis.

In addition to continuous monitoring, the system provides automated alerts through mobile notifications whenever water parameters deviate from safe ranges, enabling timely intervention to prevent potential harm to aquatic life. With an emphasis on affordability and ease of installation, AquaSense is designed for both beginner and experienced aquarium keepers, offering peace of mind through continuous oversight and proactive alerts.

1.3 High Level Overview (Visual Aid)

The following diagram provides an overview of AquaSense’s key components and their interconnections within the system:



1.4 High-Level Requirements

To consider our project successful, these are the requirements that we aim to satisfy:

HLR-1: Continuous Monitoring of Critical Water Quality Parameters

To maintain an optimal aquatic environment, AquaSense must perform continuous, high resolution monitoring of pH, temperature, and dissolved oxygen — parameters that critically influence fish metabolism, immune response, and overall biotic stability. The system shall capture and log readings at 5 to 10 second intervals to detect transient perturbations that could otherwise be missed by manual or infrequent testing methods. Each sensor must operate within stringent accuracy tolerances — ±0.2 pH units, ±0.5°C, and ±0.5 mg/L for dissolved oxygen — to ensure not only data fidelity but also to facilitate precise adjustment to aquarium conditions when required.

Furthermore, the sensors and associated electronics must be engineered for lasting at least 60 days of continuous operation before recalibration is necessary. This goal is set with the mindset of minimizing downtime and user intervention. Data pertaining to these parameters/sensors will be stored in a rolling 30 day database, capturing a minimum of 1,000 data points per parameter to enable robust retrospective analyses for the user and for the ML algorithm described in HLR-3. By integrating these rigorous data collection and accuracy standards, AquaSense will provide scientifically sound insights into the aquarium's water chemistry dynamics and empower aquarium owners to make evidence based interventions when they see fit.

HLR-2: Wireless Data Transmission and Real-Time Alerts

To facilitate real-time situational awareness and immediate response to critical water quality fluctuations, AquaSense shall incorporate Wi-Fi and Bluetooth communication protocols capable of reliably transmitting sensor readings to a secure, cloud based dashboard within 2 seconds of data acquisition. The system's network architecture must support live updates at intervals of 10-15 seconds, ensuring that rapid changes in water chemistry — such as sudden temperature drops or possible pH spikes — are detected and displayed almost instantaneously to the user. Upon identifying parameter excursions beyond user configured thresholds, AquaSense will trigger alert notifications, employing at least two delivery methods (push notifications and email) to mitigate the risk of delayed or overlooked alarms on the user's part. These alerts will be paired with intelligent suggestions for the user to take action: *"-- pH levels low… consider performing a partial (25%) water change --"*, for example.

This multi-pronged alert strategy is designed to address the diverse connectivity preferences and constraints of aquarium owners. Furthermore, user customizable threshold values will allow for adaptation to different aquatic species (fish and even plants) and according system configurations as well. By integrating robust wireless communication and expedited notification mechanisms, AquaSense ensures that fishkeepers can respond proactively to mitigate stressors and avert destabilization to their aquatic ecosystem.

HLR-3: Automated Water Quality Trend Analysis and Machine Learning–Based Anomaly Detection

Beyond real time monitoring, AquaSense must also employ advanced machine learning (ML) techniques to detect emerging patterns and proactively alert aquarium owners to potential water quality risks. The system will be recording and processing at least 1,000 data points per parameter (pH, temperature, and dissolved oxygen) over a rolling 30-day period, providing a rich dataset for training and updating predictive models. ML algorithms (specifically time series forecasting models or anomaly detection networks) will be used to analyze historical and real time sensor readings to learn baseline behaviors and identify deviations that may signal equipment malfunctions, biological imbalances, and even sudden chemical shifts. These models must update at least once every 24 hours to adapt and 'learn' from evolving aquarium conditions, maintaining current knowledge of normal fluctuations.

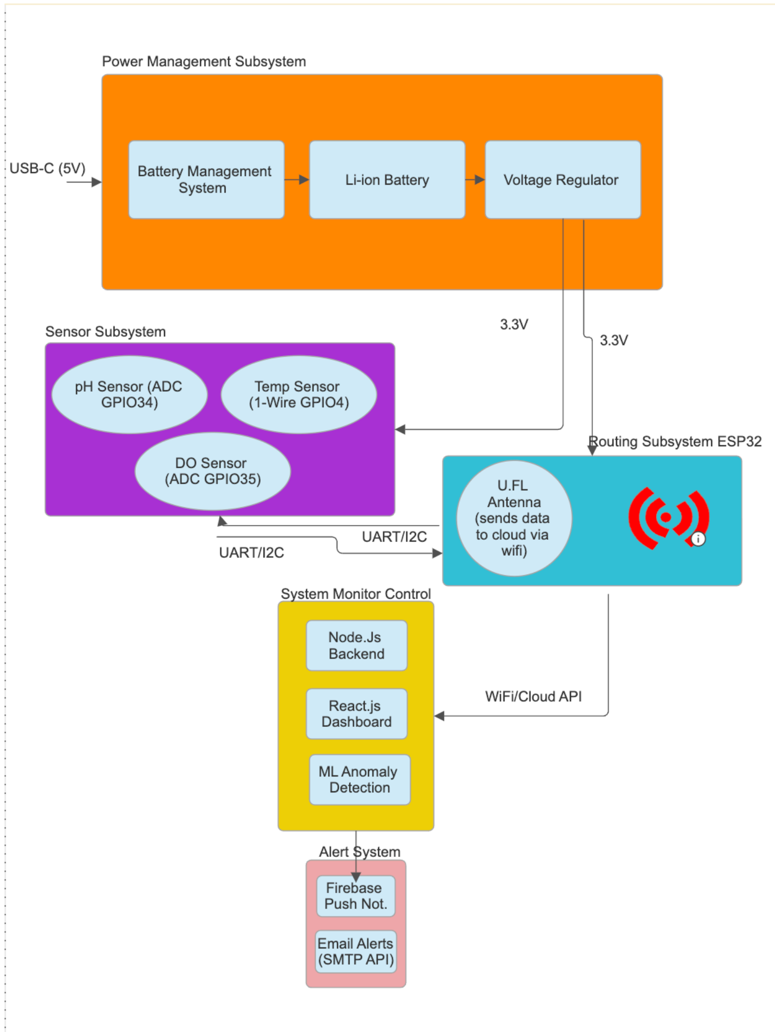
A web based dashboard will present time graphs, moving averages, and confidence intervals, updated every day, allowing users to track both recent and historical long term trends. The ML based anomaly detection mechanism shall generate an alert when a parameter deviates from its learned baseline by more than 3 standard deviations. We would also like to achieve at least 90% accuracy in predicting issues such as heater failures, water aeration malfunctions, and critical pH swings. This data driven, adaptive approach ensures that AquaSense will proactively notify aquarium owners before detrimental changes become critical, further enhancing the overall stability and health of the aquatic environment.

HLR-4: Energy Efficiency and Hardware Longevity

Given that AquaSense will operate continuously in home and commercial settings, the system's power profile and component durability are extremely crucial for sustained deployment. The core electronics — anchored by the ESP32 microcontroller — shall be optimized to maintain active power consumption under 1.5W, with a low power standby mode drawing below 0.5W, thus enabling battery based operation for at least 30 days when connected to a 5,000 mAh lithium battery. Hardware selection and board design must prioritize robust sensor materials and corrosion resistant enclosures, ensuring two years of reliable performance under standard aquarium conditions. A built in self diagnostic subroutine will continuously evaluate sensor health as well, alerting users to calibration drift or component failure prior to the expected loss of accuracy. By coupling energy conscious electronics with durable sensor elements and predictive maintenance capabilities, AquaSense effectively reduces user intervention while sustaining a high level of measurement accuracy and reliability over extended operational periods.

2 Design

2.1 Block Diagram



2.2 Subsystem Overview

2.2.1 Power Management Subsystem

The Power Management Subsystem is responsible for supplying stable and efficient power to the entire AquaSense device, ensuring uninterrupted operation whether it is plugged into a 5V USB source or running on battery power. This subsystem incorporates voltage regulators to maintain consistent output levels under varying input conditions, enabling sensitive sensors and the ESP32 microcontroller to perform accurately. When operating on battery, the subsystem should support continuous monitoring for extended periods—up to 30 days on a 5,000 mAh lithium-ion battery—by leveraging a low-power standby mode. This mode conserves energy by allowing the ESP32 to switch into a reduced consumption state when water parameters remain stable, yet it can instantly wake the system if an abnormal reading is detected. Robust power design is thus paramount to satisfy both short-term operational demands and long-term reliability targets outlined in HLR-4 (Energy Efficiency and Hardware Longevity).

2.2.2 Sensor Subsystem

The Sensor Subsystem acquires three primary water quality parameters—pH, temperature, and dissolved oxygen—that are essential for monitoring aquarium health. It uses a SEN0161 pH Sensor to measure acidity or alkalinity with ±0.2 pH unit accuracy, a DS18B20 Digital Temperature Sensor to read water temperature with ±0.5°C precision, and a DFRobot Gravity Dissolved Oxygen Sensor to detect oxygen levels within ±0.5 mg/L. These sensors connect to the ESP32 microcontroller, which gathers data at 5–10-second intervals. The Sensor Subsystem may also include an Analog Turbidity Sensor if extended clarity monitoring is required. Once collected, the readings are validated, logged, and broadcast via Wi-Fi or Bluetooth, ensuring near-instant alerts if parameters exceed user-defined thresholds.

2.2.3 System Monitor

The System Monitor is a full-stack solution comprising a Node.js backend and a React.js frontend. It stores historical readings, enforces configurable alert thresholds, and presents data through a dynamic dashboard. Users can view real-time graphs of pH, temperature, and dissolved oxygen, as well as any optional turbidity readings. For multi-location installations, a map-based interface (using the Google Maps API) displays the status of each AquaSense node. This subsystem supports anomaly detection by applying machine learning or statistical methods to the stored sensor data. When outliers occur, the System Monitor triggers immediate notifications and logs the event for deeper analysis.

2.3 Subsystem Requirements (Criterion for Success)

2.3.1 Power Management Subsystem Reqs

The Power Management Subsystem must maintain a regulated 5V supply, preventing voltage drops that compromise the accuracy of sensors or disrupt the ESP32. Active mode power consumption must remain below 1.5W, transitioning to under 0.5W in standby. When using a 5,000 mAh battery, it should operate continuously for at least 30 days without user intervention. Tests must confirm that the system transitions seamlessly between active and standby modes, while ensuring consistent output voltage under varying load conditions and real-world aquarium environments.

2.3.2 Sensor Subsystem Reqs

The Sensor Subsystem must capture and transmit pH, temperature, and dissolved oxygen readings every 5–10 seconds. It must maintain ±0.2 accuracy for pH, ±0.5°C for temperature, and ±0.5 mg/L for dissolved oxygen for at least 60 days without recalibration. Alerts must be issued within 2 seconds of detecting values outside predefined thresholds, aligning with the system's real-time monitoring objective. If a turbidity sensor is installed, it should integrate without affecting the performance or reliability of the main sensors. All data transfers to the ESP32 must be validated to avoid missed readings or unexplained gaps in the measurement logs.

2.3.3 System Monitor Reqs

The System Monitor must display real-time sensor values at 10-second intervals or less, with an end-to-end latency of under 2 seconds from measurement to dashboard update. Data logging must capture at least 1,000 data points per parameter over a 30-day rolling window, enabling machine learning or statistical algorithms to detect anomalies that exceed three standard deviations from the mean. These algorithms must achieve at least 90% accuracy in identifying critical events such as heater failures or oxygen depletion. The interface must support multiple AquaSense nodes, allowing users to view, configure, and receive alerts for each aquarium independently. Performance tests must confirm rapid data retrieval, reliable alert distribution, and intuitive navigation under typical home or light-commercial networking conditions.

2.4 Tolerance Analysis

Each sensor must operate within reasonable accuracy tolerances in order to maintain adequately healthy environments for fish to thrive. In particular, the sensor readings should reflect and communicate to the user in a “hands-free” way that recommends simple and easy-to-follow steps to improve aquarium vitals upon detecting imperfect conditions.

To start, in regards to the acidity levels, the diversity of fish species leads to a rather specific hierarchy of pH tolerances:

pH Sensitivity [pH]	Fish species
5.5-6.5	Angelfish, Betta, Cardinal Tetra, Discus
6.5-7.0	Corydoras Catfish, Gouramis, Neon Tetra
7.0-7.5	Guppy, Molly, Swordtail, Zebrafish
7.5-8.5	Goldfish, African Cichlid, Live

The system should support accurate readings with a minimum specificity to adhere to the ranges listed above. Whether or not our system is capable of delivering on this front depends on the measurement accuracy of the sensor (how correct the measured value is compared to the true value) and the precision of the analog-to-digital resolution of the microcontroller interfacing the sensor. The SEN0161 Kit should have accuracy of ±0.1 [pH] within a reasonable temperature range (around 25°C). To ensure this accuracy is not being bottlenecked, we can perform a granularity analysis of the STM32 ADC using the Nernst equation:

$$E = E_0 - (\frac{RT}{F}) ln(|H^+|)$$

From here, we can extract the relationship between voltage and pH:

$V/pH = (0.025692) \times (2.303)$ = +0.05916 [V] change in voltage per +1.0 [pH].

ADC_Res_{STM32} = 12-bit = $2^{12} = 4096$ levels

STM32 operating voltage: 3.6 [V]

Voltage per ADC step: $\frac{3.6}{4096} = 0.00087890625$ [V]

Granularity: $\frac{0.00087890625\,[V}{0.05916\,[V]} = 0.0148564275$

Our system should theoretically be able to support a precision of nearly 0.01—10 times the sensor accuracy.

Furthermore, temperature and acidity have a direct interplay due to the nature of the pH sensor. It follows that temperature is yet another variable that must be added to the equation for computing the safety level displayed by the mobile app. To compensate for voltage output of the pH probe changing with temperature, we use 25°C as a pivot to adjust our granularity denominator when normalizing our acidity sensor voltage reading into pH level:

$pH_{final} = \frac{(E_0 - V)}{V/pH}$, where $V/pH = 0.05916 \times \frac{T_{Kelvin}}{298.15}$

For oxygen, as stated earlier—±0.5 mg/L for dissolved oxygen—to ensure not only data fidelity but also to facilitate precise adjustment to aquarium conditions when required.

3 Ethics & Safety

Our team adheres to the IEEE Code of Ethics, as adopted by the IEEE Board of Directors in June 2020 [6], recognizing that the technology we create has a real impact on people's lives. As we develop AquaSense, we are committed to maintaining the highest ethical standards, ensuring that our system is both reliable and safe for users. We take responsibility for designing a product that provides accurate, trustworthy data, allowing aquarium owners to make informed decisions about the health of their aquatic ecosystems.

One of our key ethical considerations is data integrity and transparency. Since AquaSense continuously monitors and logs water conditions, it is crucial that users can rely on the readings it provides. We aim to prevent false or misleading sensor outputs by achieving high tolerance levels through high-quality components, regular calibration reminders, and thorough testing to verify accuracy. Users will also have access to clear documentation on how the system works, including its limitations, so they can understand what to expect. Our goal is to provide honest, practical information rather than overpromising performance.

We are also mindful of user privacy and security, particularly since AquaSense transmits data via Wi-Fi and Bluetooth. To ensure that user data remains protected, we will implement basic encryption for wireless communication and provide secure authentication for remote access.

While AquaSense is not handling personal or financial information, we still believe it's important to take precautions against unauthorized access or tampering.

On the safety side, we are designing AquaSense with electrical and environmental protection in mind. Because this system operates near water, we will take steps to waterproof exposed components and insulate electrical connections to prevent short circuits or accidental damage. The power system will be designed to prevent overheating and will include fuse protection to reduce the risk of malfunctions. Additionally, if a battery-powered version is implemented, we will ensure that it operates efficiently and safely over long periods.

Beyond technical and safety concerns, we also care about making technology accessible. Many existing water monitoring solutions are too expensive for casual aquarium owners, and we want to provide a low-cost, user-friendly alternative. By keeping AquaSense affordable and easy to use, we hope to help more people maintain healthy aquatic environments, whether they are hobbyists, educators, or researchers.

Ultimately, we believe that technology should be practical, safe, and built with responsibility. By following ethical engineering practices, prioritizing accuracy, and ensuring user safety, we aim to create a product that people can trust and benefit from without unnecessary risks.

4 Future Developments

Building on its core architecture, AquaSense holds significant potential to evolve into a robust, scalable IoT platform for both home and commercial aquariums. A key avenue of growth involves AI-based predictive analytics, enabling more sophisticated trend detection and forecasting of water parameters over extended time periods. By leveraging these advanced models, AquaSense could proactively signal emerging threats—such as gradual ammonia buildup or nitrate spikes—well before they reach critical levels, thus facilitating timely interventions. Further enhancements may include automated filtration control, allowing the system to autonomously initiate water changes or adjust filtration settings when specific thresholds are breached. An expanded sensor suite could integrate ammonia and nitrate probes, offering a comprehensive view of water chemistry and supporting more precise ecosystem management. Additionally, a battery-powered variant would extend the platform's usability to outdoor ponds, fish farms, and remote applications, ensuring continuous monitoring under off-grid conditions. Beyond benefiting aquarium owners, such expansions would also serve educators, researchers, and environmental conservationists, fostering a broader community dedicated to maintaining stable, thriving aquatic environments.

References:

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