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AquaSense: An IoT-Based Automated Closed-Loop Control System for Smart Aquaculture

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***Abstract** - Fish farming is the most underrated business that provides a steady supply of protein-rich food independent of natural water bodies also it gives high yield from a small area. The traditional fish farming faces several problems, such as inconsistent water quality management, increased labour dependency, wasting of food, and thereby reduced productivity due to manual monitoring and feeding management, especially in small-scale or medium-scale aquaculture units. This project proposes a smart solution that improves productivity by automating the entire system and ensuring optimal feeding with minimal human intervention. The system integrates various embedded sensors, control algorithms and actuator modules to perform continuous monitoring and automated regulation of optimum aquaculture conditions along with cleaning and feeding operations. Implementation of the proposed system achieved reliable real-time monitoring and reduced food wastage while minimising manual involvement. This approach contributes to efficient utilisation of resources and the developed framework can be extended to large-scale aquaculture systems with advanced predictive analysis.*

Key Words: **Smart aquaculture, Internet of Things (IoT), water quality monitoring, closed-loop control, automated feeding.**

1. INTRODUCTION

Aquaculture has emerged as one of the fastest-growing food production sectors worldwide due to the increasing global demand for protein-rich aquatic products[1]. However, maintaining optimal water quality and feeding conditions remains a major challenge in fish farming. Parameters such as pH, total dissolved solids (TDS), turbidity, temperature, and water level significantly influence fish growth, metabolism, and survival rate. Conventional aquaculture systems rely heavily on manual monitoring and periodic maintenance, which often leads to inconsistent environmental control, feed wastage, and increased fish mortality. These limitations highlight the need for intelligent and automated monitoring systems capable of ensuring stable aquatic conditions. Recent advancements in the Internet of Things (IoT) and embedded systems have enabled the development of smart agricultural and aquaculture solutions[2]. IoT-based systems allow real-time monitoring of environmental parameters through distributed sensors, cloud connectivity, and remote user interfaces[3]. Several research on this topic have focused on the monitoring of water parameters and predicting fish health based on the comparison with threshold values.so most of the existing systems provide monitoring and alerting mechanisms. And have limited implementation of automatic real-time correction strategies.

To address these challenges, this paper presents Aquasense, an IoT based adaptive closed loop control system that integrates multiple water quality sensors with an ESP32 microcontroller to continuously monitor pH, TDS, turbidity, and water level. Based on predefined threshold values, the system automatically activates dosing pumps, water replacement mechanisms, and feeding units through relay-controlled actuators. Along with that the system employs cloud-based IoT connectivity to enable real-time monitoring and remote control through a mobile interface. Unlike conventional open-loop systems, the proposed framework implements a feedback-driven control mechanism, ensuring automatic regulation of water parameters without constant human intervention. By combining sensing, processing, actuation, and IoT communication, this system aims for optimum aquaculture environment which enhance the productivity while reducing manual efforts and errors.

The remaining part of the paper includes related works ,methodology, result and conclusion.

2. RELATED WORKS AND REVIEWS

Abid et al. proposed an IoT-based smart Biofloc monitoring system integrated with machine learning techniques for predicting fish mortality[4]. The system employs multiple water quality sensors, including pH, turbidity, TDS, temperature, and gas sensors, interfaced with Arduino and NodeMCU modules for cloud-based data transmission and the collected dataset was preprocessed using scaling and ADASYN balancing techniques and evaluated using various classifiers such as Decision Tree, Random Forest, SVM, achieving up to 98% accuracy in mortality prediction. Although the study demonstrates high predictive performance, it primarily focuses on analytics rather than real-time adaptive control.

Karim et al. developed an IoT-based smart fish farming monitoring system designed for real-time water quality assessment using low-cost sensors[5]. The system integrates pH, temperature, turbidity, water level, and motion sensors with an Arduino platform, supported by a local server database and GSM-based alert mechanism. Actuators such as pumps and filtration units are activated when parameters exceed predefined thresholds. While the system enables automated responses, its control strategy is strictly threshold-based and reactive in nature.

Nguyen Quang Huy et al. presented an IoT-enabled automatic water quality monitoring system for aquaculture ponds[6]. The architecture incorporates temperature, pH, and dissolved oxygen sensors connected to Arduino and Raspberry Pi modules, with data transmitted to the ThingSpeak cloud platform and GSM-based alert notifications. An aerator is automatically activated when dissolved oxygen falls below a predefined limit. Although the system demonstrates reliable sensing accuracy, it is limited to threshold-based dissolved oxygen control. The consideration of only three parameters further restricts comprehensive environmental assessment and adaptive regulation.

Nandyala et al. introduced Ecoaquatics, an IoT-based feed-efficient fish health monitoring system that integrates water quality sensing with machine learning-based feed prediction[7]. Using Arduino and ESP8266 modules, the system collects pH, turbidity, temperature, and feed weight data, storing them in a MySQL database. A Random Forest regression model predicts optimal feed quantity, achieving approximately 86% accuracy. A web-based GUI provides user interaction for feed recommendations and threshold alerts. While the system effectively optimises feed management, it does not implement comprehensive environmental closed-loop control. The focus remains on feed prediction rather than dynamic water parameter stabilisation.

Tsai et al. proposed an IoT-Based Smart Aquaculture System (ISAS) incorporating automatic aeration and water quality monitoring using fuzzy inference control[8]. The system integrates temperature, pH, dissolved oxygen, and water hardness sensors with Arduino and Raspberry Pi platforms, transmitting data via MQTT to a cloud database. Experimental evaluation over 1.5 months demonstrated a 33.3% improvement in shrimp survival rate compared to conventional methods. However, the system relies on predefined fuzzy rules rather than adaptive learning mechanisms, limiting dynamic optimisation under varying environmental conditions. Furthermore, validation was conducted in controlled aquarium setups, and large-scale aquafarm deployment challenges remain unaddressed.

3. METHODOLOGY

This section describes the proposed system mechanism adopted for the design and implementation of the AquaSense system. The overall system architecture, water quality monitoring framework, adaptive closed-loop control strategy, and experimental setup are presented in detail to illustrate the operational mechanism and implementation structure of the proposed system.

3.1 Overall architecture

The overall system architecture of AquaSense is designed as an adaptive closed-loop control framework integrating sensing, processing, and actuation layers. The block diagram represents the overall hardware architecture of the proposed AquaSense adaptive closed-loop smart aquaculture system. The system is structured into four major layers: power supply unit, sensing layer, processing unit, and actuation layer, integrated with IoT connectivity. The block diagram of the proposed AquaSense system is shown in Fig.1

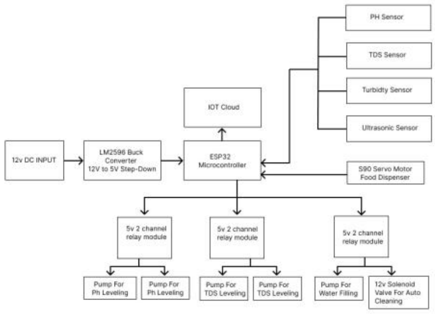

Fig. 1: Block diagram of proposed system

The system operates from a 12 V DC input source, which serves as the primary power supply for high-power devices such as pumps and solenoid valves. The LM2596 buck converter steps down the 12V input to 5V. This converted 5v output powers the components such as the ESP32 microcontroller, sensors(pH, turbidity, TDS and ultrasonic sensor), relay modules and servo motor. This ensures a stable and regulated power supply to all low power components. The ESP32 microcontroller acts as the central control unit of the system. It is suitable for this system due to its salient features includes built-in Wi-Fi capability, sufficient GPIO pins, real-time processing ability and low power consumption. It acquires sensor data and processes environmental parameters. then executes the control logic and driving relay modules accordingly. Also communicating the data with a IoT cloud platform. The sensing part continuously monitors critical water quality parameters. The pH sensor measures the acidity/alkalinity of water, the TDS sensor measures dissolved solid concentration, the turbidity sensor is used for detecting suspended particles and water clarity, and the ultrasonic sensor is used to monitor water level in the tank. All sensors provide real-time input signals to the ESP32 for environmental evaluation.

An SG90 Servo Motor is connected to the ESP32 to operate the automatic food dispenser. The ESP32 controls the servo angle, thus regulating feed quantity. The feeding system supports two operational modes: either manual remote feeding through web based IoT interface or a timer-based automatic feeding mode. The actuation layer of the system uses three 5v dual channel relay modules to control high-power devices. One relay module is used for ph levelling, a second relay module for TDS regulation by water dilution and adding minerals, and the remaining is for water management, such as water plumbing and draining. The relays isolate low-voltage control circuitry from high-voltage actuators, ensuring electrical safety.

The ESP32 transmits real-time sensor data to the IoT cloud platform via Wi-Fi. This system enables remote monitoring, visualization and performance tracking[2]. The proposed architecture integrates sensing, processing, actuation, and cloud connectivity into a unified platform, enabling reliable and automated water quality management in smart aquaculture environments[9].

3.2 Water quality monitoring framework

Continuous monitoring of critical water quality parameters is essential for maintaining aquatic health and environmental stability. In the proposed AquaSense system, pH, total dissolved solids (TDS), turbidity, and water level are selected as primary monitoring parameters due to their direct influence on fish metabolism, waste accumulation, and overall ecosystem balance[10]. The pH sensor measures the acidity or alkalinity of water, while the TDS sensor estimates the concentration of dissolved solids. The turbidity sensor detects suspended particles and organic waste, and the ultrasonic sensor monitors tank water level to prevent overflow or dry-run conditions. All sensor outputs are interfaced with the analog-to-digital converter (ADC) channels of the ESP32 microcontroller. The parameters are sampled periodically and processed in real time for deviation analysis. The hardware interfacing circuit between the ESP32 controller and the sensing modules is illustrated in Fig.2

Predefined operating threshold ranges are configured within the controller to enable continuous evaluation of environmental conditions. The processed sensor data serve as feedback inputs to the adaptive control mechanism, forming the sensing foundation of the closed-loop regulation framework.

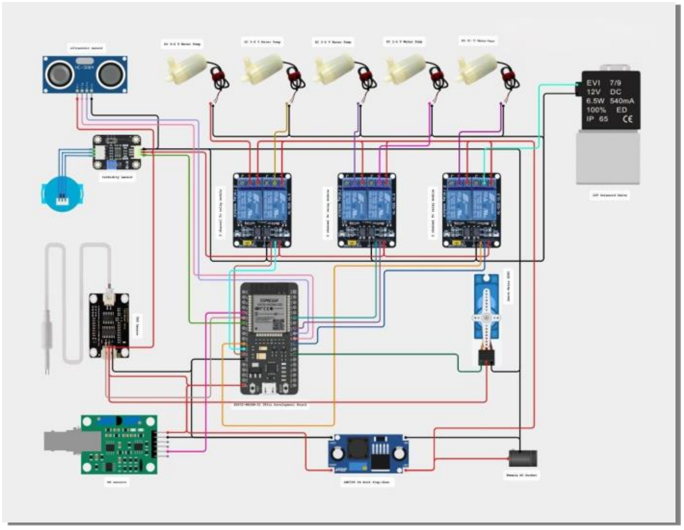

Fig. 2: Circuit diagram

The continuous acquisition and processing of these parameters provide the necessary feedback signals required for adaptive closed-loop regulation.

3.3 Adaptive closed-loop control and actuation mechanisms

The primary objective of the proposed control mechanism is to maintain all water quality parameters within the optimal threshold ranges through continuous feedback-based regulation. The operational flow of the adaptive control mechanism is shown in fig.3. As shown in Fig. 3, the system continuously acquires real-time water quality parameters and compares them with predefined optimal values. If deviations are detected, appropriate actuator responses are triggered.

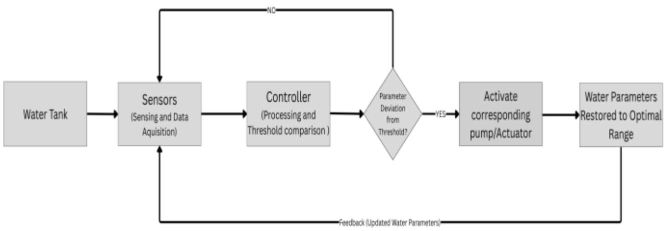

Fig. 3: Operational flow diagram

The system then re-evaluates the updated environmental conditions, thereby forming a continuous feedback regulation loop.. The operational flow of the adaptive regulation process follows a continuous cycle of sensing, deviation analysis, actuation, and re-evaluation, thereby forming a closed feedback loop. This coordinated multi-actuator strategy ensures environmental stability, reduces manual intervention, and enhances the reliability of smart aquaculture management.

3.4 Experimental setup

To validate the performance of the proposed AquaSense system, a laboratory-scale aquaculture setup was developed under controlled conditions. The system was deployed in a water tank equipped with pH, TDS, turbidity, and ultrasonic level sensors, along with actuator units including water pumps, solenoid valve, and servo-based feeding mechanism. All sensors were calibrated prior to experimentation to ensure measurement accuracy. The setup is shown in fig. 4

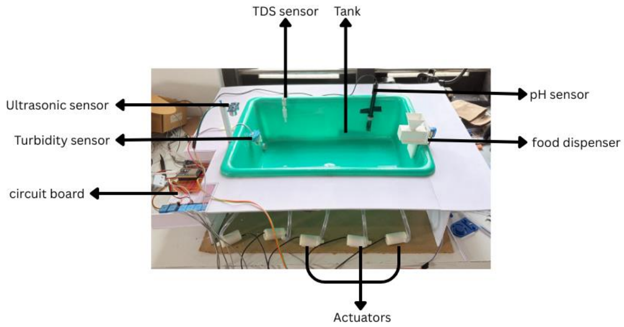

Fig. 4: Experimental set-up

The ESP32 microcontroller was configured to acquire sensor data at predefined sampling intervals and execute the adaptive closed-loop control algorithm in real time. The relays were interfaced with respective pumps and control units to regulate water quality parameters automatically when deviations were detected. The experimental evaluation focused on observing system responsiveness, parameter stabilization behavior, and reliability of actuator coordination under varying environmental conditions. The collected data were transmitted to the IoT cloud platform for remote monitoring and performance analysis. The results of these evaluations are presented in the following section.

4. RESULT AND DISCUSSION

The overall performance of proposed smart fish farming system evaluated successfully by monitored the key water quality parameters such as pH, TDS, turbidity. The system measured these parameters in real-time and automatically activated the corresponding actuators whenever variations from the predefined threshold values were detected. The obtained results demonstrate the ability of the system to detect deviations and correct the parameters to their optimal range.

The graphs presented illustrate the typical variation of water quality parameters during system operation based on the observed behavior of the implemented prototype. Chart – 1 shows the variation in pH over time. Initially, the value remained within the optimum range and at a certain instant of time, the pH value exceeded the upper threshold, that is, the water became more alkaline in nature. The system detected the deviation and activated the corresponding pump, which released the suitable solution into the water, reducing the pH value back to the optimum range. Similarly, at another time instant, the pH value went below the lower threshold(increased acidity), and the system again worked automatically to adjust the value into the normal range by activating the pH down pump.

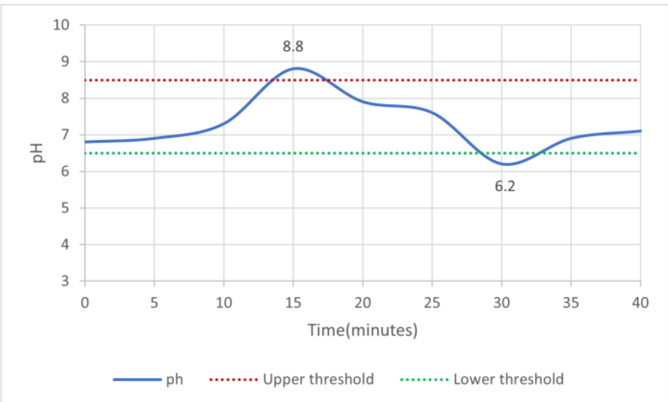

Chart – 1: Variation of pH over time

Chart – 2 illustrates the variations of TDS with respect to time. At first, the value is stable as shown, but a sudden increase in TDS value was observed, which indicates poor water quality. Upon detection, the system activated the control mechanism responsible for restoring the value, which successfully reduced the value back to the stable range.

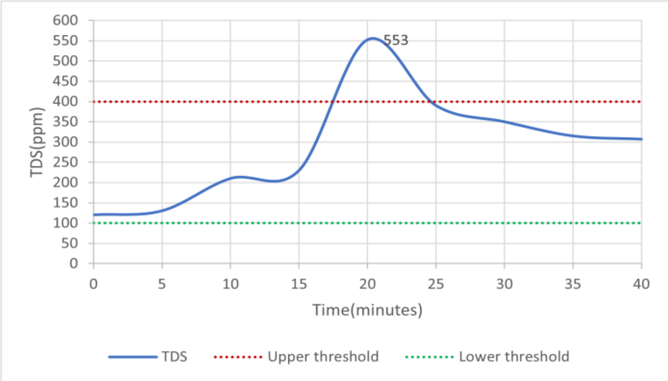

Chart – 2: Variation of TDS over time

Chart – 3 presents the turbidity level monitored by the system. Once the turbidity level exceeded the threshold value, the system detected the deviation and activated the solenoid pump and refill pump for draining the dirty water and refilling the fresh water, respectively. The results show that the turbidity level reduced and returned to an acceptable range in a short period of time.

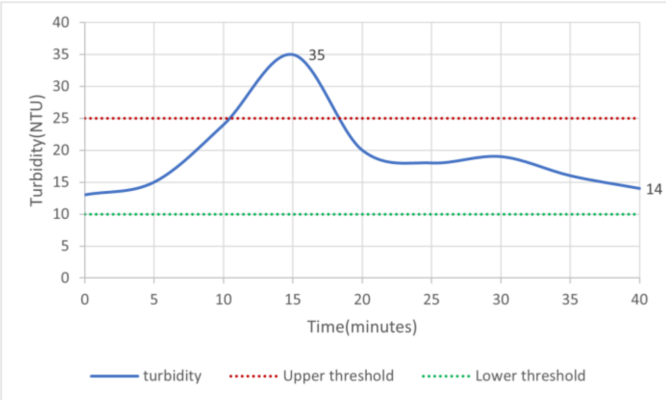

Chart – 3: Variation of turbidity over time

Various corrective agents can be introduced into aquaculture systems to restore water quality parameters to their optimal ranges. Table–1 lists commonly used materials and solutions for regulating pH, TDS, and turbidity in fish tanks. The materials listed in the table are commonly used to regulate water quality parameters in aquaculture. For instance, lime can be added to increase alkalinity when the pH value falls below the optimal range, and if it goes above the threshold limit we can add molasses as it is commonly used material in aquaculture, while partial water replacement helps reduce excessive TDS levels. Similarly, the water replacement is performed to reduce turbidity level.

Table 1: Solutions/materials used for water quality stabilization

Parameter	Optimum range	Action	
		Below the optimal range	Exceeds threshold limit
pH	6.5 – 8.5	Add lime ($CaCO_3$)	Add molasses

TDS	100 – 400 ppm	Add minerals	Water dilution
Turbidity	10 -25 NTU	Add alum	Water replacement

In the proposed system, the controller can activate corresponding pumps to introduce these corrective solutions when deviations from the threshold values are detected. The ultrasonic sensor continuously monitors the water level, and when the water level goes below optimal level the system activated the refilling pump and restored stable tank condition. The feeding mechanism has successfully incorporated with this system which operated through preset time intervals to ensure regular feeding while a manual switching option was also provided for user-controlled feed dispensing.

The real time monitoring values of water parameters and the water level are displayed in the user web interface using IoT cloud platform as shown in fig. 5.

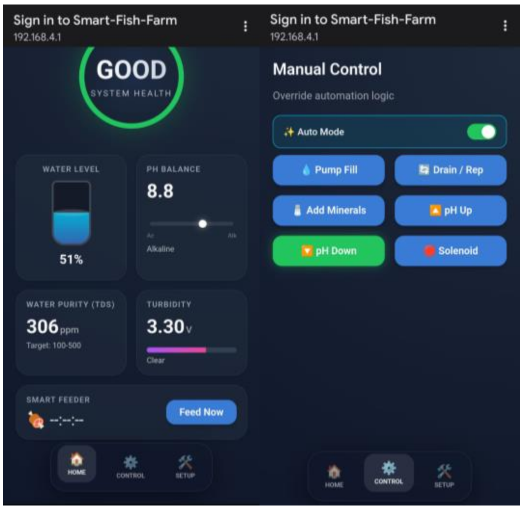

Fig. 5: User friendly web interface

The subsequent interface window displays the real-time actuation status of all pumps in the system. It also includes an Auto Mode control button which is enable for auto mode and disable for manual control of pumps.

5. CONCLUSION AND FUTURE SCOPE

This paper presented AquaSense, an IoT-based adaptive closed-loop system for smart aquaculture monitoring and management. The proposed system integrates multiple water quality sensors, an ESP32 microcontroller, automated actuation mechanisms, and a web-based monitoring interface to ensure continuous supervision of aquaculture environments. The parameters such as pH, turbidity, total dissolved solids, and water level are monitored in real time which enables the system to detect deviations from optimal ranges and initiates appropriate corrective actions through relay-controlled pumps and valves.

The implemented prototype demonstrated here has reliable real-time data acquisition, automatic actuator response, and remote monitoring capability through the IoT platform. Along with that an addition of the dual-mode feeding mechanism allows both timer-based automatic feeding and manual feed dispensing via the web interface, providing flexibility in aquaculture management. The coordinated operation of sensing, processing, and actuation components confirms the effectiveness of the proposed closed-loop control framework for maintaining stable environmental conditions with minimal manual intervention.

Future work will focus on expanding the system with additional sensing parameters like dissolved oxygen and temperature for more comprehensive environmental monitoring. Further improvements may include large-scale deployment, enhanced data analytics, and optimization of control strategies to improve system efficiency and adaptability in commercial aquaculture environments.

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