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Design and Implementation of IoT-Based Smart Aquarium using ESP32 for Water Quality Monitoring and Automatic Feeding

Kuncoro Banu[1], Yan Sofyan Andhana Saputra[2]
[1,2] Information Technology Study Program, Faculty of Engineering, Darma Persada University
[1,2] Jl. Taman Malaka Selatan No.22, Pondok Kelapa, Duren Sawit, DKI Jakarta, Indonesia 13450
*yansofyan@gmail.com

Abstract — Advances in Internet of Things (IoT) technology have enabled the development of smart monitoring and automation systems across various application domains, including aquarium management. Conventional aquarium monitoring often relies on manual observation, which can be time-consuming and less effective for continuous environmental monitoring. This study aims to design, implement, and evaluate an IoT-based Smart Aquarium system utilizing the ESP32 microcontroller as the central controller. The proposed system integrates multiple environmental sensors, including temperature, pH, turbidity, and water level sensors, to acquire real-time aquarium data. Sensor measurements are processed by the ESP32 and transmitted to a cloud-based database, enabling real-time access through a mobile application. The developed platform also incorporates an automatic feeding mechanism using a servo motor, a monitoring camera for visual observation, and a solar panel subsystem as a supplementary energy source. Experimental results demonstrate that all sensor modules successfully acquired and transmitted environmental data to the monitoring platform. The mobile application was able to display real-time sensor readings and monitoring information through a centralized dashboard. Furthermore, the automatic feeding subsystem operated according to predefined schedules, while the camera monitoring and solar power subsystems functioned as intended. The results indicate that the proposed Smart Aquarium platform successfully integrates sensing, communication, monitoring, and automation technologies within a unified IoT ecosystem. The developed system provides an effective solution for real-time monitoring and remote aquarium management through the integration of embedded systems, cloud services, and mobile computing technologies.

Keywords – Internet of Things, Smart Aquarium, ESP32, Mobile Application, Environmental Monitoring, Automation

I. INTRODUCTION

Goldfish (Carassius auratus) are among the most popular ornamental fish due to their distinctive appearance and attractive coloration. Maintaining a healthy aquarium environment is essential for supporting fish welfare and ensuring stable aquatic conditions. Several water quality parameters, including temperature, pH, turbidity, and water level, must be continuously monitored because significant fluctuations may adversely affect aquarium conditions and increase maintenance challenges [1], [2].

Despite the importance of environmental monitoring, many aquarium owners still rely on conventional methods involving direct observation and manual measurements. This approach requires regular inspection and sufficient user availability, making it less practical for daily use. As a result, changes in water conditions may not be detected immediately, while feeding activities also depend heavily on user presence and consistency [3], [4].

The rapid development of Internet of Things (IoT) technology has enabled the implementation of smart monitoring systems capable of collecting environmental data automatically and providing real-time access through internet-connected devices. By integrating sensors, microcontrollers, cloud services, and mobile applications, IoT-based systems can support continuous monitoring and remote management of aquarium environments. This approach reduces manual intervention while improving accessibility and monitoring efficiency.

Several previous studies have demonstrated the application of IoT technology in water quality monitoring and aquaculture management. Existing systems generally focus on monitoring specific environmental parameters such as temperature, pH, or water quality indicators, while some studies incorporate automatic feeding mechanisms and cloud-based monitoring platforms [5], [6]. These studies demonstrate the potential of IoT technology to improve monitoring effectiveness and operational efficiency.

However, the integration of multiple environmental sensors, mobile-based monitoring, automatic feeding, visual observation through camera systems, and alternative energy support within a single platform remains relatively limited. Most existing implementations focus on individual functionalities rather than providing a comprehensive Smart Aquarium ecosystem that combines monitoring, automation, and remote accessibility.

Therefore, this study proposes an IoT-based Smart Aquarium system utilizing the ESP32 microcontroller as the central controller. The developed platform integrates temperature, pH, turbidity, and water level sensors with an automatic feeding mechanism, cloud-based data communication, mobile application monitoring, camera-based observation, and solar-powered energy support. The objective of this study is to design, implement, and evaluate an integrated Smart Aquarium platform capable of providing real-time monitoring and automated aquarium management through IoT technology.

The proposed system is expected to improve monitoring efficiency, reduce dependence on manual observation, and provide a practical solution for aquarium management through the integration of sensing, communication, automation, and mobile computing technologies.

II. METHODOLOGY

A. Research Method

This study employed the Prototyping development method to design and implement an Internet of Things (IoT)-based Smart Aquarium system. The prototyping approach was selected because it supports iterative development and continuous refinement of system functionality, enabling developers to evaluate and improve the prototype throughout the development cycle [7].

The development process consisted of five stages: requirements analysis, prototype design, system implementation, testing, and evaluation. During the requirements analysis stage, functional requirements related to environmental monitoring, automatic feeding, remote accessibility, and energy support were identified. Based on these requirements, a prototype was designed and implemented by integrating sensors, actuators, cloud services, and a mobile application into a unified Smart Aquarium platform. The completed prototype was subsequently evaluated through a series of functional and integration tests.

B. Prototype Design

The Smart Aquarium prototype was developed by integrating sensing, monitoring, communication, and automation components into a single embedded system. Figure 1 illustrates the physical design of the developed prototype.

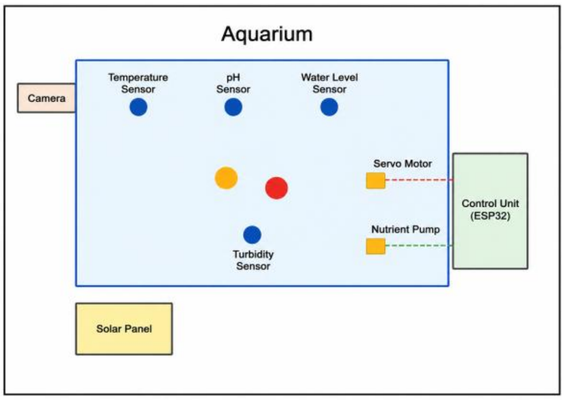

Fig. 1. Smart Aquarium Prototype Sketch

The prototype consists of an ESP32 microcontroller, DS18B20 temperature sensor, pH sensor, turbidity sensor, ultrasonic water level sensor, servo motor, monitoring camera, solar panel subsystem, cloud database, and a mobile application. Environmental data collected by the sensors are processed by the ESP32 and transmitted through a wireless network to the cloud platform.

The servo motor functions as an automatic feeding actuator, while the monitoring camera provides visual observation of aquarium conditions. Solar panels are integrated as a supplementary power source to support continuous system operation and improve energy efficiency. The prototype was designed to provide real-time monitoring, remote accessibility, and automated aquarium management through IoT technology.

C. System Architecture

The proposed Smart Aquarium adopts a multi-layer IoT architecture consisting of sensing, processing, communication, monitoring, and actuation subsystems [8]. The overall system architecture is illustrated in Figure 2.

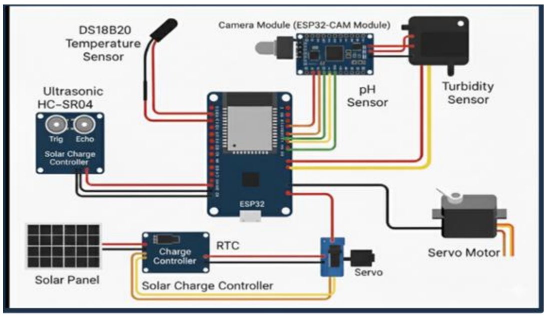

Fig. 2. Smart Aquarium System Architecture

The sensing subsystem comprises a DS18B20 temperature sensor, pH sensor, turbidity sensor, and ultrasonic water level sensor. These sensors continuously collect environmental data and transmit the measurements to the ESP32 microcontroller.

The ESP32 serves as the central processing unit responsible for sensor data acquisition, local data processing, actuator control, and communication with cloud services via wireless connectivity. Sensor readings are transmitted to a cloud database, enabling real-time synchronization between the physical aquarium and the monitoring platform.

The monitoring subsystem is implemented through a mobile application that provides real-time access to sensor data and system status information via cloud-based communication [9]. The application provides real-time environmental information, historical monitoring records, sensor visualizations, actuator status, and camera monitoring features. Through this interface, users can remotely access aquarium information from any location with internet connectivity. Similar approaches have been applied in ESP32-based IoT monitoring systems, where mobile applications are utilized to provide remote access and real-time system monitoring capabilities [10].

The actuation subsystem consists of a servo motor responsible for automatic feed dispensing according to predefined schedules configured within the ESP32 controller. This subsystem enables the platform to perform automated operations without requiring direct user intervention.

The integration of these subsystems forms a complete IoT ecosystem that supports real-time monitoring, cloud-based communication, remote accessibility, and automated aquarium management.

D. Data Communication and Mobile Integration

The Smart Aquarium system employs a cloud-based communication architecture to enable real-time monitoring through a mobile application.

The data acquisition process begins when environmental sensors, including the temperature sensor, pH sensor, turbidity sensor, and water level sensor, collect measurement data from the aquarium environment. These sensor readings are processed by the ESP32 microcontroller and converted into digital values.

The ESP32 connects to a Wi-Fi network and periodically transmits sensor data to a cloud database using Internet Protocol (IP)-based communication. In this study, Firebase Realtime Database was utilized as the cloud platform due to its capability to provide real-time data synchronization between embedded devices and mobile applications.

The transmitted data are stored in structured database nodes consisting of temperature, pH, turbidity, water level, actuator status, and timestamp information. Whenever new measurements are received, Firebase automatically updates the corresponding database records.

The mobile application continuously retrieves data from Firebase through its Application Programming Interface (API). As a result, newly uploaded sensor values are immediately synchronized and displayed on the monitoring dashboard without requiring manual refresh operations.

In addition to monitoring functions, the mobile application also receives actuator status information generated by the ESP32 controller. This mechanism enables users to observe feeding activities, environmental conditions, and overall system status remotely through a smartphone connected to the internet.

E. System Testing

System testing was conducted to evaluate the functionality and integration of all components within the Smart Aquarium platform. The testing process included pH sensor testing, temperature sensor testing, water level sensor testing, turbidity sensor testing, automatic feeding mechanism testing, camera monitoring testing, and integrated system testing.

Each sensor was evaluated based on its ability to acquire environmental data and successfully transmit the information to the cloud-based monitoring platform. The automatic feeding subsystem was tested to verify the operation of the servo motor according to predefined schedules. The camera monitoring feature was evaluated based on its capability to provide real-time visual observation through the mobile application.

Finally, integrated testing was performed to ensure that all sensors, actuators, communication modules, cloud services, and the mobile application operated cohesively as a unified IoT-based monitoring and automation system. The testing results were used to evaluate the overall functionality, reliability, and effectiveness of the developed Smart Aquarium platform.

III. RESULTS AND DISCUSSION

This study successfully designed and implemented an Internet of Things (IoT)-based Smart Aquarium system utilizing the ESP32 microcontroller as the central controller. The developed system integrates multiple environmental sensors, an automatic feeding mechanism, a monitoring camera, cloud-based data storage, and a mobile application into a unified monitoring platform. In addition, solar panels are employed as a supplementary power source to support system operation.

The implementation results demonstrate that all hardware and software components were successfully integrated and operated according to the system design. Sensor data acquired from the aquarium environment were processed by the ESP32 and transmitted to the monitoring application, enabling users to observe aquarium conditions remotely and in real time.

Figure 3 presents the main dashboard of the Smart Aquarium mobile application. The dashboard serves as the primary interface between users and the IoT system, displaying real-time information including water level, pH value, turbidity, temperature, servo status, and nutrient pump status. Through this interface, users can monitor aquarium conditions and control several system functions remotely using a smartphone connected to the internet.

Fig. 3. Smart Aquarium Mobile Application Dashboard

The successful implementation of the mobile dashboard demonstrates the capability of the proposed system to provide real-time monitoring and remote accessibility. Data received from sensors are automatically synchronized with the cloud database and displayed through the application, allowing users to observe environmental conditions without direct interaction with the aquarium hardware.

To evaluate the performance of the monitoring subsystem, pH sensor testing was conducted to assess the sensor's ability to measure water acidity and deliver measurement data to the IoT platform. The testing procedure involved immersing the pH sensor probe into stabilized aquarium water and observing the values displayed through the monitoring application.

The experimental results showed that the pH sensor produced stable readings ranging from 6.9 to 7.1. The consistency of these values indicates that the sensor was able to acquire measurement data reliably during the testing period. Furthermore, all measurement data were successfully transmitted and displayed through the IoT-based monitoring application without communication failure.

Additional testing was performed by gently stirring the water to simulate environmental changes and observe the sensor response. The pH readings initially fluctuated slightly before returning to stable values after a short period. This behavior indicates that the sensor responds appropriately to environmental disturbances and is capable of providing continuous monitoring data.

The successful integration of the pH sensor with the ESP32 microcontroller and the mobile monitoring application demonstrates the effectiveness of the proposed IoT architecture in acquiring, processing, and presenting environmental data in real time. These results confirm that the pH monitoring subsystem can support continuous remote observation within the Smart Aquarium platform.

Temperature sensor testing was conducted to evaluate the ability of the DS18B20 sensor to acquire water temperature data and transmit the measured values to the IoT monitoring platform. The testing procedure involved immersing the temperature sensor in the aquarium water and observing the temperature values displayed through the mobile application. The measurement results obtained during the testing process are presented in Table 1.

Table 1. Temperature Sensor Testing

No	Repetition	Measurement Time	Temperature (°C)	Remarks
1	Testing 1	05:58 PM local time	25.3	Normal
2	Testing 2	06:03 PM local time	25.0	Normal
3	Testing 3	06:09 PM local time	24.8	Normal

The experimental results show that the DS18B20 sensor successfully measured water temperature within the range of 24.8°C to 25.3°C during the observation period. The relatively consistent values indicate stable sensor performance throughout the testing session.

Furthermore, all temperature readings were successfully transmitted from the ESP32 microcontroller to the cloud database and subsequently displayed on the mobile application in real time. The synchronization between the sensor subsystem and the mobile application demonstrates that the communication architecture operated correctly during the experiment.

The sensor was also observed under minor environmental changes to evaluate its responsiveness. The measured values changed gradually according to the surrounding conditions and were automatically updated on the monitoring dashboard. This behavior indicates that the temperature monitoring subsystem is capable of providing continuous and real-time environmental information.

The successful integration of the DS18B20 sensor with the ESP32 microcontroller, cloud database, and mobile application confirms the effectiveness of the proposed IoT architecture. Through the developed mobile application, users can remotely monitor temperature conditions without requiring direct interaction with the physical system, thereby improving monitoring accessibility and operational convenience.

Water level sensor testing was conducted to evaluate the capability of the ultrasonic sensor in detecting changes in aquarium water volume and transmitting the measurement data to the IoT monitoring platform. The testing procedure was performed by gradually reducing the water level and subsequently adding water back to its initial condition. The measurement results obtained during the testing process are presented in Table 2.

Table 2. Water Level Sensor Testing

No	Test Conditions	Measurement Time	Water Height (cm)	Remarks
1	Normal water	05:58 PM local time	25.5	Normal
2	Water reduced	06:03 PM local time	22.8	Downward
3	Water is added back	06:09 PM local time	25.7	Normal

The experimental results show that the ultrasonic sensor successfully detected variations in water level under different testing conditions. When the water volume was reduced, the measured water height decreased from 25.5 cm to 22.8 cm. Conversely, when water was added back into the aquarium, the measured value increased to 25.7 cm, which was close to the initial condition.

The observed changes indicate that the sensor was able to accurately respond to physical variations in water volume. Furthermore, all measurement data were successfully transmitted from the ESP32 microcontroller to the cloud database and subsequently displayed on the mobile application in real time.

The water level values shown on the monitoring dashboard were automatically updated according to the sensor readings, enabling users to remotely observe changes in aquarium water conditions. This functionality is particularly useful for monitoring potential water loss caused by evaporation, leakage, or maintenance activities without requiring direct inspection.

The successful integration of the ultrasonic sensor with the ESP32 microcontroller, cloud database, and mobile application demonstrates the effectiveness of the proposed IoT architecture in providing continuous water level monitoring. These results confirm that the water level monitoring subsystem can support real-time remote observation as part of the Smart Aquarium platform.

Turbidity sensor testing was conducted to evaluate the ability of the sensor to detect changes in water clarity and transmit the measurement data to the IoT monitoring platform. The testing procedure involved observing the sensor readings under three different conditions: clear water, water containing fine suspended particles, and water after sedimentation. The measurement results obtained during the testing process are presented in Table 3.

Table 3. Turbidity Sensor Testing

No	Test Conditions	Measurement Time	Turbidity Value (NTU)	Remarks
1	Clear water (early)	05:58 PM local time	12.4	Clear
2	Water added fine particles	06:03 PM local time	18.6	Cloudy
3	After deposition (stable)	06:09 PM local time	13.1	Clear

The experimental results indicate that the turbidity sensor successfully detected variations in water clarity under different testing conditions. In the initial condition, the sensor recorded a turbidity value of 12.4 NTU when the water was clear. After fine particles were introduced into the water, the measured turbidity increased to 18.6 NTU, indicating a decrease in water clarity. Following the sedimentation process, the turbidity value decreased to 13.1 NTU, approaching the initial measurement condition.

These results demonstrate that the sensor was able to respond appropriately to changes in water turbidity and provide measurable differences between clear and cloudy water conditions. The observed variations confirm the capability of the sensor to continuously monitor water quality parameters related to suspended particles.

Furthermore, all turbidity measurements were successfully transmitted from the ESP32 microcontroller to the cloud database and displayed on the mobile application in real time. The monitoring dashboard automatically updated the turbidity values according to the latest sensor readings, enabling users to remotely observe changes in water conditions through a smartphone.

The successful integration of the turbidity sensor with the ESP32 microcontroller, cloud database, and mobile application demonstrates the effectiveness of the proposed IoT architecture in supporting continuous water quality monitoring. These results confirm that the turbidity monitoring subsystem can provide reliable real-time information as part of the Smart Aquarium platform.

Automatic feeding system testing was conducted to evaluate the performance of the servo motor as the actuator responsible for dispensing feed according to the predefined schedule. The feeding mechanism was controlled by the ESP32 microcontroller using a software-based scheduling algorithm without requiring an external Real-Time Clock (RTC) module.

The testing results demonstrated that the servo motor operated successfully according to the scheduled feeding times configured in the system. During each feeding cycle, the servo motor rotated to the designated position, released the feed, and returned to its initial position without operational failure.

Furthermore, the feeding process was synchronized with the Smart Aquarium monitoring platform, allowing actuator status information to be displayed through the mobile application. This functionality enables users to monitor feeding activities remotely and verify that the automatic feeding mechanism is operating as intended.

The successful operation of the servo motor confirms that the proposed system is capable of performing automated control functions in addition to environmental monitoring. By integrating the feeding mechanism with the IoT infrastructure, the system can execute scheduled operations without requiring direct user intervention.

The implementation results demonstrate the effectiveness of the ESP32 microcontroller in managing both sensing and actuation tasks within a single Smart Aquarium platform. This capability enhances system automation and supports remote aquarium management through the developed mobile application.

To evaluate the overall performance of the Smart Aquarium platform, integrated monitoring tests were conducted by simultaneously collecting data from all installed sensors, including temperature, pH, turbidity, and water level sensors. The purpose of this test was to verify the ability of the ESP32-based system to acquire, process, and transmit multiple environmental parameters concurrently. The integrated monitoring results are presented in Table 4.

Table 4. Integrated Sensor Monitoring Results

No	Time	Temp.	pH	NTU	Level (cm)	Status
1	17:58	25.1	7.0	12.5	25.5	Normal
2	18:03	25.0	7.5	12.4	25.3	Normal
3	18:09	24.8	6.9	13.2	25.8	Normal

The results show that all sensor modules successfully operated simultaneously and provided measurement data to the monitoring platform. Temperature values ranged from 24.8°C to 25.1°C, while pH measurements varied between 6.9 and 7.5. The turbidity sensor recorded values between 12.4 NTU and 13.2 NTU, and the water level sensor reported measurements ranging from 25.3 cm to 25.8 cm.

During the testing period, all sensor readings were successfully processed by the ESP32 microcontroller and transmitted to the cloud database without data loss. The collected information was then displayed on the mobile application dashboard in real time, allowing users to monitor multiple environmental parameters through a single interface.

The integrated monitoring results demonstrate the capability of the proposed IoT architecture to handle multiple sensor inputs concurrently. The synchronization between sensor acquisition, cloud communication, and mobile visualization operated reliably throughout the testing process.

Furthermore, the successful integration of all monitoring subsystems enhances the usability of the Smart Aquarium platform by providing centralized access to environmental information. Users can simultaneously observe temperature, pH, turbidity, and water level conditions through the mobile application without requiring separate monitoring devices.

These findings confirm that the developed Smart Aquarium system is capable of providing continuous, real-time, and integrated environmental monitoring as part of a unified IoT-based aquarium management platform.

As a supporting feature, the proposed Smart Aquarium system is equipped with a monitoring camera that enables users to observe aquarium conditions remotely through the mobile application. Unlike the environmental sensors and actuator modules, the camera is not directly involved in the automatic control process. Instead, it serves as a visual monitoring component that complements the numerical data provided by the sensors.

The camera allows users to verify aquarium conditions in real time, including water appearance, feeding activities, and general system status. By combining visual information with sensor measurements, the monitoring platform provides a more comprehensive representation of aquarium conditions. This feature enhances user confidence in the monitoring system and supports remote observation when direct inspection is not possible.

In addition to the monitoring subsystem, the Smart Aquarium platform incorporates solar panels as a supplementary energy source. The solar panels are utilized to charge backup power storage and provide additional electrical energy for system operation. Experimental observations indicate that the solar panels were capable of supplying sufficient auxiliary power under favorable sunlight conditions.

The integration of renewable energy technology contributes to improving system energy efficiency and supports the development of environmentally friendly IoT-based monitoring solutions. Furthermore, the availability of an alternative power source increases system reliability, particularly during interruptions in the primary power supply.

Table 4 summarizes the integrated monitoring results obtained from the Smart Aquarium platform. The collected data demonstrate that all environmental parameters, including temperature, pH, turbidity, and water level, were successfully acquired, processed, and displayed through the IoT monitoring application.

The experimental results confirm that all major subsystems of the proposed platform operated according to the system design. Sensor measurements were successfully transmitted from the ESP32 microcontroller to the cloud database and subsequently displayed on the mobile application in real time. The actuator subsystem also performed scheduled feeding operations reliably through the servo motor mechanism.

In addition, the integration of the monitoring camera and solar power subsystem further enhanced the functionality of the platform by providing visual observation capabilities and supplementary energy support. These features demonstrate that the developed system extends beyond basic environmental monitoring and provides a more comprehensive Smart Aquarium management solution.

Overall, the Smart Aquarium prototype successfully achieved the objectives of this study. The system was able to perform real-time monitoring of temperature, pH, turbidity, and water level, execute automated feeding operations, provide remote visual monitoring, and support energy-efficient operation through solar panel integration. The results indicate that the proposed IoT architecture effectively integrates sensing, communication, monitoring, and automation technologies into a unified platform for remote aquarium management.

IV. CONCLUSION

This study successfully designed, implemented, and evaluated an Internet of Things (IoT)-based Smart Aquarium system utilizing the ESP32 microcontroller as the central controller. The developed platform successfully integrates multiple environmental sensors, including temperature, pH, turbidity, and water level sensors, into a unified monitoring system capable of acquiring and transmitting environmental data in real time.

The implementation results demonstrate that sensor data can be processed by the ESP32 microcontroller, transmitted to a cloud database, and displayed through a mobile application without communication failure. The developed mobile application successfully provides real-time monitoring capabilities, enabling users to access environmental information remotely through a smartphone. In addition, the platform supports historical data monitoring and centralized visualization of environmental parameters.

The automatic feeding subsystem was also successfully implemented using a servo motor controlled by a software-based scheduling mechanism. Furthermore, the integration of camera monitoring and solar-powered energy support extends the functionality of the platform by providing visual observation capabilities and supplementary power for system operation.

Overall, the experimental results confirm that the proposed Smart Aquarium platform successfully integrates sensing, communication, monitoring, and automation technologies within a single IoT ecosystem. The developed system provides a practical solution for real-time monitoring and remote aquarium management through the integration of embedded systems, cloud services, and mobile computing technologies.

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