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Enhancing Aquaponics Efficiency with Microcontroller-Based Control

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Abstract

The aim of this project is to design an aquaponics system that can be automatically monitored and controlled. This system integrates sensors and the Internet of Things (IoT) to help users minimize the time and effort required for system stabilization. The system is built using a Node MCU microcontroller, which interfaces with sensors, software, and applications. Equipped with ESP8266 chips, the Node MCU allows for easy internet connectivity. The system provides real-time monitoring and automated control for the user. It consists of a large blue plastic drum serving as the fish tank at the base, with planters for vegetation positioned on top. A water pump circulates the water, while three sensors—pH, soil moisture, and fluid level sensors— ensure proper system regulation. Additionally, an automatic feeding system is implemented to dispense food at regular intervals. The system is integrated with Thingspeak software and the Virtuino application, providing users with live data monitoring. This automated system, managed through the Node MCU and sensors, enhances food production while reducing the need for constant manual oversight. Users benefit by saving time, conserving energy, and alleviating concerns, thanks to the automated control features.

Keywords: Aquaponics System, Internet of Things (IoT), Smart Farming, Food Production Optimization.

Introduction

Aquaponics, an innovative integration of aquaculture (fish farming) and hydroponics (soil-less plant cultivation), is recognized as a sustainable agricultural approach that addresses the pressing challenges of food security and resource conservation. This closed-loop system recycles fish waste as nutrients for plants while the plants purify water for fish, reducing water usage by up to 90% compared to traditional farming methods (Kumar, Singh, & Mishra, 2020; Taha et al., 2022). The increasing adoption of aquaponics, particularly in urban environments where space is constrained, showcases its potential to enhance local food production (Li et al., 2022).

The integration of Internet of Things (IoT) technologies into aquaponics systems has further revolutionized their management. IoT allows for real-time monitoring of critical environmental factors such as pH, temperature, and nutrient levels, optimizing conditions for both plant and fish growth. This automation reduces the need for manual labor and increases system efficiency, making aquaponics more viable for small- and large-scale operations (Zhang, Li, & Wang, 2021; Yanes et al., 2020). Recent advancements in IoT-enabled aquaponics have shown significant potential in reducing operational costs and improving crop yields, which is crucial for economic viability (Ali, Khan, & Ahmed, 2021).

Moreover, IoT systems facilitate the precise control of environmental conditions, improving resource optimization and sustainability. By automating processes like feeding and water circulation based on sensor data, aquaponics systems can achieve higher productivity with minimal environmental impact (Taha et al., 2022). Studies have demonstrated that integrating IoT can help achieve Sustainable Development Goals (SDGs) by promoting efficient food production practices that are environmentally friendly (Zheng et al., 2022).

As climate change increasingly affects traditional agriculture, aquaponics provides a resilient alternative. These systems can be adapted to various climates and urban settings, making them a practical solution for food production in challenging environments (Mamat, Shaari, & Abdul Wahab, 2016). The scalability of IoT-enabled aquaponics systems offers a promising future for both rural and urban food security, ensuring fresh produce is available locally without relying on extensive supply chains (Yanes et al., 2020; Wang & Liu, 2023).

Research Background and Motivation

Aquaponics, an innovative combination of aquaculture and hydroponics, has gained significant attention in addressing the challenges of global food security, water scarcity, and sustainable agriculture. This system involves growing plants without soil, while fish provide nutrients for the plants through their waste, and the plants in turn purify the water that returns to the fish tanks. This closed-loop system helps optimize resource use by recycling water and nutrients, making it a more sustainable farming option (Mamat, Shaari, & Abdul Wahab, 2016). Aquaponics has emerged as an effective solution, particularly in regions facing the dual pressures of population growth and diminishing arable land (Adler et al., 2000).

However, traditional aquaponic systems face several challenges, such as the need for constant manual monitoring, precise environmental control, and efficient resource management. As a response to these challenges, the integration of Internet of Things (IoT) technologies into aquaponics systems is increasingly being explored. IoT enables real-time data collection, automated decision-making, and remote monitoring, making aquaponics more efficient and scalable (Surnar, Sharma, & Saini, 2015; Hughey, 2005). Recent technological advancements, particularly in sensor technologies, wireless communication, and data analytics, have paved the way for the development of "smart" aquaponics systems. These systems monitor key parameters such as water quality, temperature, and nutrient levels with precision, allowing for enhanced control and optimization (Sace & Fitzsimmons, 2013).

The motivation to integrate IoT into aquaponics stems from several critical factors. First, IoT technology allows for enhanced monitoring and control of key environmental variables. Sensors provide real-time, continuous monitoring, reducing the risks of crop failure or fish mortality by allowing early detection and rapid response to system anomalies (Saaid et al., 2013; Leatherbury, 2014). For instance, Das and Sharma (2021) developed an IoT-based water quality monitoring system that enables aquaponics practitioners to maintain optimal conditions for both fish and plants continuously.

Moreover, IoT facilitates resource optimization in aquaponics. Through automation, systems can adjust feeding schedules, water circulation, and lighting based on real-time data, ensuring efficient use of water, energy, and nutrients (Eze & Onyeke, 2021). This approach not only enhances sustainability but also reduces operational costs, making aquaponics more viable for commercial production (Wang & Liu, 2023). For example, smart aquaponics systems can automatically balance nutrient levels, ensuring both plant growth and fish health while minimizing waste (Goddek & Keesman, 2022).

Scalability is another key benefit of IoT integration in aquaponics. With remote monitoring and control capabilities, large-scale and distributed systems can be managed more effectively, making it possible to oversee multiple aquaponics setups simultaneously (Oyebode & Ighravwe, 2023). This scalability is particularly important in urban farming scenarios where space is limited but food production needs are high. IoT-enabled aquaponics systems can be deployed in urban environments, contributing to food security by producing fresh produce locally (Zhang, Li, & Wang, 2021).

Data-driven decision-making is a crucial aspect of IoT-based aquaponics systems. The vast amount of data collected by sensors can be analyzed using machine learning algorithms to predict crop yields, detect potential issues, and optimize nutrient cycles (Chen & Wang, 2021). For instance, machine learning models have been employed to optimize nutrient balance in aquaponic systems, improving system efficiency and reducing the likelihood of resource wastage (Benyakhlef & Goosen, 2022).

The sustainability aspect of IoT-enabled aquaponics cannot be overlooked. These systems align well with circular economy principles by promoting the efficient use of resources and minimizing waste (Oyebode & Ighravwe, 2023). By enabling precise control of resource inputs and reducing dependency on external inputs, aquaponics contributes to more sustainable food production systems (Quagrainie et al., 2018). Furthermore, the integration of IoT with blockchain technology in aquaponics enhances food traceability and safety, responding to the growing demand for transparency in food supply chains (Fernández-Caramés & Fraga-Lamas, 2022).

IoT integration also offers resilience to climate change, which is increasingly affecting traditional agriculture. Aquaponics systems, especially those equipped with IoT technologies, can be adapted to various environmental conditions and locations, including urban settings and areas with limited water resources (Wang & Liu, 2023). This adaptability makes IoT-enabled aquaponics a promising solution for food production in regions impacted by climate change (Goddek et al., 2015).

Additionally, the development of smart aquaponics systems opens up new economic opportunities in both the agricultural and technology sectors. Innovations in sensor development, data analytics, and automation are driving the growth of this field, with numerous applications in commercial-scale food production (Makhura & Maboko, 2022). Martínez- Rodríguez and Parra-López (2024) conducted a case study on the economic viability of small- scale IoT-integrated aquaponics systems, showcasing the potential for creating sustainable business models.

Educational and research advancements are another critical motivation for the development of IoT-enabled aquaponics systems. These systems provide a unique platform for studying complex ecological interactions and testing new approaches to sustainable food production. As such, they have become important tools in educational settings, offering students hands-on experience in fields ranging from agriculture to data science (Patel & Patel, 2021; Joshi & Kaur, 2022).

In conclusion, the integration of IoT in aquaponics offers numerous advantages, from enhanced resource management and system scalability to the promotion of sustainable agricultural practices. As the world continues to face the dual challenges of food security and environmental sustainability, IoT-enabled aquaponics presents a promising solution that warrants further research and development (Goddek & Keesman, 2022). Future advancements in IoT sensor technologies, AI-driven system optimization, and the commercialization of smart aquaponics systems are expected to play a key role in shaping the future of sustainable agriculture (Martínez-Rodríguez & Parra-López, 2024).

Methodology

Introduction

This project aims to develop a microcontroller-based aquaponics control system integrated with Internet of Things (IoT) for real-time monitoring. The methodology outlines the design, construction, and data collection methods for the aquaponics system.

Project Construction

The project began with the physical construction of the aquaponics system using a blue plastic drum as a fish tank, supported by a steel rack, and vases for the plants as shown in figure 3.1. The water circulation system was designed with a siphon and a water pump that circulates water from the fish tank to the plant containers and back.

- Water Pump: A Kintons 2500 L/h pump (40W) was selected for the system to ensure sufficient water flow. It is placed inside the fish tank to pump water to the top of the vases and maintain circulation.
- Siphon: The siphon ensures water returns from the plant containers to the fish tank, completing the water circulation loop.
- Fish Feeding System: An automated fish feeding system, controlled by a relay, was implemented to feed the fish twice daily. The relay operates on a small current and is programmed to activate at specific intervals.

Figure 3.1 The Aquaponic setup

The figure 3.1 shows a barrel aquaponics system. A blue barrel is used as the base, with a metal rack placed on top to hold several plant containers. The plants are growing in an aquaponics setup. The barrel contains water with tilapia, which is circulated through the system to provide nutrients to the plants.

Microcontroller and Sensors

A Node MCU microcontroller was used to manage the sensors and control systems. The microcontroller was programmed using Arduino software and connected to three types of sensors:

- pH Sensor: Monitors the water pH level in the fish tank, keeping it within an optimal range for both plant and fish health (5-9).
- Soil Moisture Sensor: Measures the moisture content in the plant containers to ensure adequate hydration for plant growth.
- Water Level Sensor: Monitors the water level in the fish tank, ensuring that the water volume remains sufficient for the system's operation.

The data from the sensors is collected and stored for analysis. The microcontroller adjusts the system's components, such as the water pump and feeding system, based on sensor readings.

Software and IoT Integration

The system was integrated with IoT for real-time monitoring. The Node MCU microcontroller was connected to the internet via the ESP8266 chip, allowing the data from the sensors to be uploaded to the Thingspeak platform.

- Thingspeak: A channel was created to visualize the sensor data in real-time, with four fields dedicated to the pH sensor, soil moisture sensor, water level sensor, and fish feeding system.
- Virtuino: An application for live monitoring of the system on a mobile phone, offering visual representations like line graphs and gauges.

The system ensures continuous live monitoring and control of the aquaponics system, with all device interactions visible to the user in real time.

Data Collection Methods

Data collection was carried out in two parts:

- Manual Data Collection: Data on plant and fish growth was recorded manually every three days. The results were analyzed using Excel software.
- Automated Data Collection: Sensor data was collected automatically and visualized using the Thingspeak and Virtuino platforms, providing real-time monitoring through graphs and tables.

This dual approach allowed comprehensive monitoring of both system operation and growth metrics.

Project Outcome

The system successfully maintained a balanced environment for plant and fish growth. Automated monitoring reduced the need for manual intervention, and IoT integration provided remote control and real-time data analysis. The final prototype consisted of a blue plastic drum (fish tank) and vases (plant containers), with all components functioning as expected.

Finding

This section presents the data obtained from the aquaponics system, showcasing its performance in optimizing the growth of fish and plants under controlled conditions. Data are provided from both the fish and plant growth metrics and the performance of the sensors used for monitoring environmental variables. The discussion focuses on the system's efficiency in achieving the intended goals, highlighting both the advantages and limitations observed during the testing phase.

Fish and Plant Growth Data

The aquaponics system was monitored over 12 weeks, and the length of the fish and the height of the plants were recorded. The data are presented in Figure 4.1 and Figure 4.2, respectively, with corresponding tables for precise values.

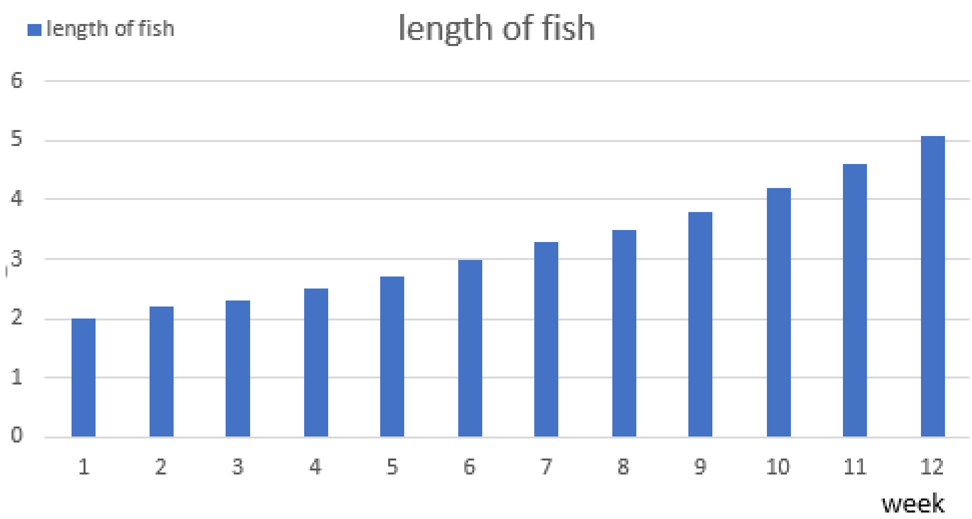

Figure 4.1: Data Length of Fish (cm)

Table 4.1
Length of Fih Over Tie

Week	Length of Fish (cm)
1	2.0
2	2.2
3	2.3
4	2.5
5	2.7
6	3.0
7	3.3
8	3.5
9	3.8
10	4.2
11	4.6
12	5.1

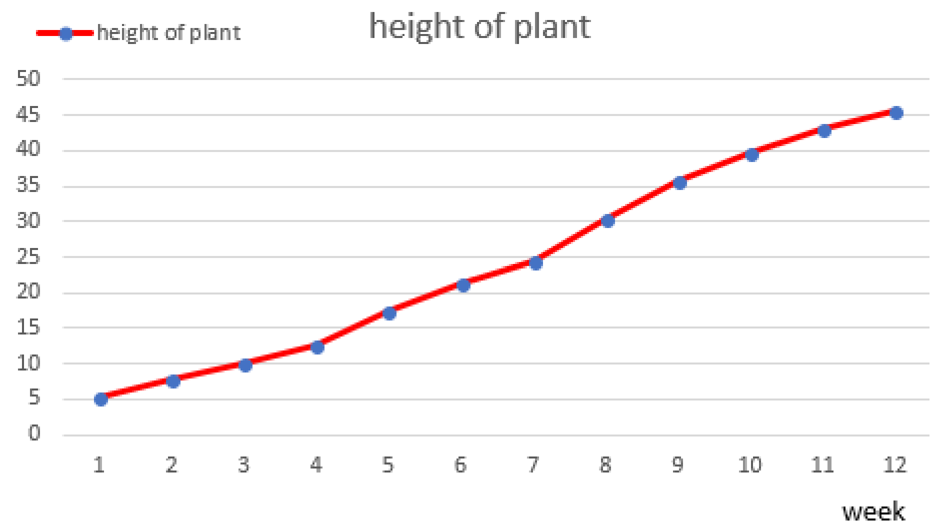

Figure 4.2: Data Height of Plant (cm)

Table 4.2
Height of Plants Over Time

Week	Height of Plants (cm)
1	5.3
2	7.7
3	10.1
4	12.7
5	17.3
6	21.4
7	24.5
8	30.3
9	35.6
10	39.8
11	43.2
12	45.6

The results show steady growth in both fish and plants. Over the 12-week period, the fish grew from an initial average length of 2.0 cm to 5.1 cm, demonstrating a healthy environment for aquaculture. Similarly, the plants increased from an initial height of 5.3 cm to 45.6 cm, further confirming the system's ability to promote robust plant development. Both fish and plant growth trends followed a steady linear increase, indicating the aquaponics system maintained favorable conditions throughout the testing period.

Sensor Data and System Monitoring

The system was monitored using three key sensors: pH, soil moisture, and fluid level. The sensor data are displayed in real time through Virtuino and Thingspeak platforms.

Figure 4.3: Data from Virtuino Application

The data from Virtuino, presented in Figure 4.3, shows how the real-time monitoring system provided consistent updates on the pH levels, soil moisture, and water level. This interface allowed users to track the system's performance remotely.

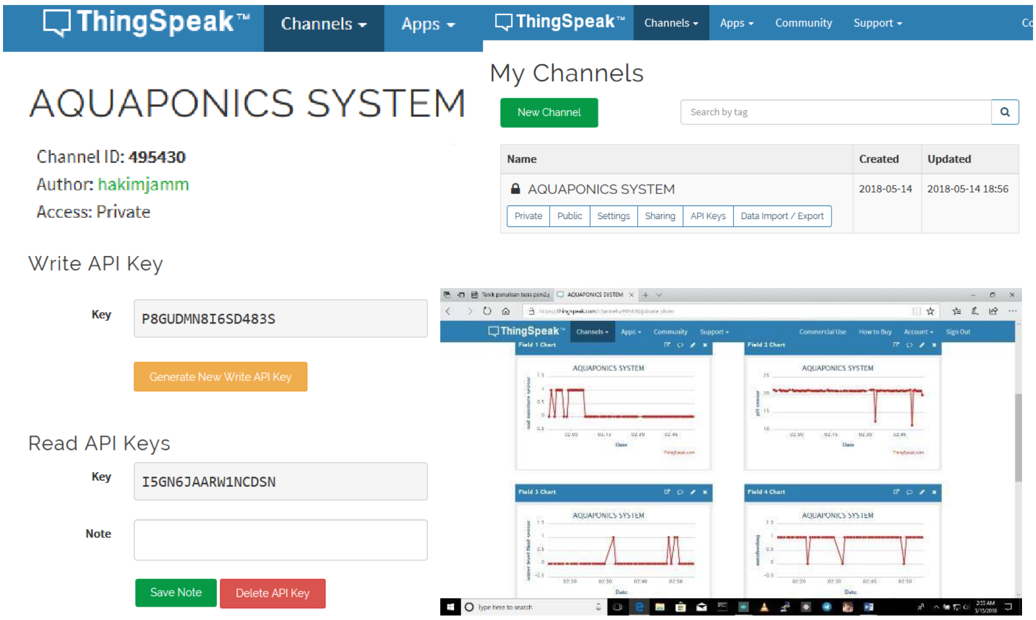

Figure 4.4: Data from Thingspeak Software

Thingspeak data provided more detailed graphical analysis of the sensor readings. As depicted in Figure 4.4, Thingspeak allowed for easy visualization of real-time trends in pH, soil moisture, and water levels.

Soil Moisture Sensor Data

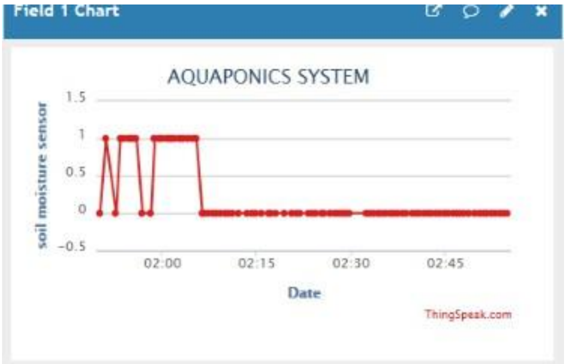

Figure 4.5: Soil Moisture Sensor Output

The soil moisture sensor indicated whether the plants had adequate water. A value of "1" signifies sufficient water, while "0" indicates insufficient moisture. Throughout the testing period, the sensor consistently reported values of "1," indicating that the plants were well-irrigated.

pH Sensor Data

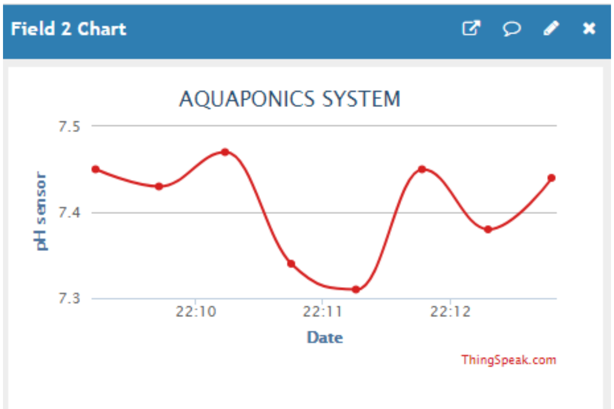

Figure 4.6: pH Sensor Output

The pH sensor maintained values between 7.3 and 7.5, as shown in Figure 4.6, which is within the optimal range for both plant growth and fish health. The steady pH level confirms that the system was able to regulate the water chemistry effectively.

Water Level Sensor Data

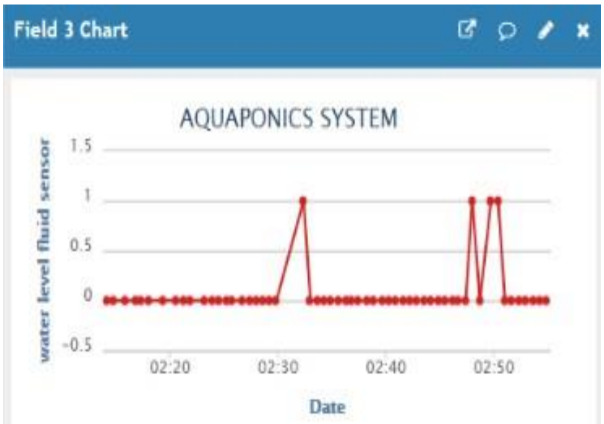

Figure 4.7: Water Level Sensor Output

The water level sensor recorded whether the water level in the fish tank was high or low. As shown in Figure 4.7, the sensor consistently reported values of “1,” indicating a high water level was maintained throughout the experiment.

Auto Feeding System Data

The system included an automatic fish feeder, which was set to feed the fish twice daily at 7:00 AM and 7:00 PM. Data from the relay controlling the feeder are shown in Figure 4.8.

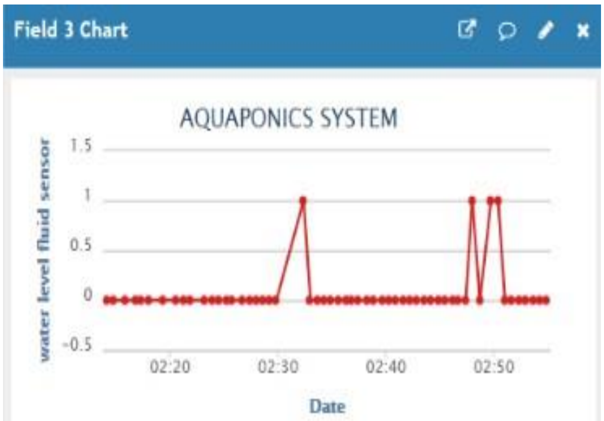

Figure 4.8: Relay Data for Auto Feeding System

The data show that the relay successfully triggered the feeding mechanism at the scheduled times, providing a consistent feeding routine for the fish.
Data Analysis from Auto Feeding System

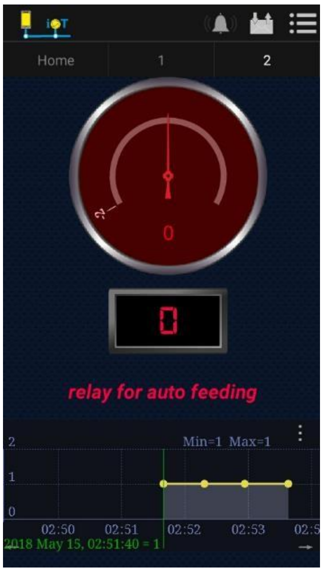

Figure 4.9: Data from Relay Auto Feeding System

The feeding system was designed to operate automatically, and the relay successfully functioned as programmed. This ensured the fish were fed without the need for manual intervention, proving the system's reliability and efficiency.

Discussion

The aquaponics system successfully achieved its goal of automating key processes such as pH regulation, soil moisture monitoring, water level control, and fish feeding. The results demonstrate that the combination of sensors and IoT technology not only maintained optimal conditions for both fish and plant growth but also reduced the need for manual intervention, saving time and energy for users.

The growth rates of both the fish and plants were consistent with expectations for a well-functioning aquaponics system. The sensors provided reliable data, allowing for real-time adjustments to be made as necessary, particularly in monitoring pH levels and ensuring appropriate water circulation.

Key Benefits

1. Automated Control: The integration of sensors and a microcontroller ensured that the system could operate autonomously, reducing the need for constant manual supervision.
2. IoT Integration: The use of Thingspeak and Virtuino provided real-time data access, giving users the ability to monitor the system from anywhere.
3. Efficient Growth: Both fish and plants exhibited healthy growth rates, which confirms that the system maintained optimal conditions for both aquaculture and hydroponic plant cultivation.

Limitations

- The system could benefit from additional sensors to monitor other variables such as temperature, which may further enhance the control over the aquaponics environment.
- Future improvements could include incorporating live video monitoring to provide a visual check on the system in addition to the sensor data.

Overall, the microcontroller-based aquaponics system demonstrated high reliability and efficiency. The use of sensors allowed for real-time monitoring and control of critical environmental factors, and the IoT integration made it convenient for users to manage the system remotely. The project offers a practical solution for automating aquaponics systems, with the potential for further improvements in future iterations.

Conclusion and Future Work

The investigation into the microcontroller-based aquaponics control system has demonstrated the viability and effectiveness of integrating IoT and automated technologies into aquaculture and plant cultivation. The system successfully maintained optimal environmental conditions for both fish and plants, evidenced by the consistent growth patterns observed over the course of the study. Critical environmental parameters such as pH, soil moisture, and water levels were monitored and controlled autonomously, reducing the need for manual intervention and providing a significant time and labor-saving benefit.

The incorporation of IoT platforms, including Thingspeak and Virtuino, allowed for real-time monitoring and data visualization, making it possible to track system performance remotely. This not only enhances user convenience but also ensures that any irregularities in the system can be detected and addressed promptly. Overall, the system achieved its objectives of increasing the efficiency and sustainability of food production through the automation of essential functions.

Future Work

While the system proved to be effective, several improvements could further enhance its functionality and scalability:

1. Temperature Monitoring and Control: Adding sensors to monitor the water and ambient temperature would provide more comprehensive data on environmental conditions, ensuring even greater control over the system's variables. Temperature is a critical factor in the health of both fish and plants, and automating its regulation could improve system resilience in varying climates.
2. Expanded IoT Capabilities: Integrating advanced data storage and visualization tools, such as Grafana, would allow for more sophisticated analysis of long-term trends in system performance. Additionally, incorporating a Telegram Bot for real-time notifications would improve user engagement and allow for faster responses to any system anomalies.
3. Live Video Monitoring: Introducing a CCTV system to provide live video feeds of the aquaponics setup would add an extra layer of oversight. Visual monitoring, in conjunction with sensor data, would enhance the user's ability to assess the system's condition, particularly in detecting issues that sensors might not capture, such as pest intrusion or equipment malfunction.
4. Commercial-Scale Implementation: Scaling the system for larger commercial applications could open new possibilities for widespread, sustainable food production. This would

involve optimizing the system for larger fish populations and plant yields while maintaining automation and minimal manual oversight.

By implementing these enhancements, the system could become a more robust and adaptable solution, offering even greater sustainability, scalability, and convenience in aquaponics management.

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