Wireless Sensor Networks Technology Enabled Realtime Aquaculture Monitoring System

[1]G. S. L. Narasimha,[2]B. Srinivas,[3]B. V. Saran Teja,[4]Y. Bhanu Prakash, [5]P. Pranitha

[1,2,3,4]U. G Student, Dept ELECTRONICS AND COMMUNICATION ENGINEERING, St.Ann's College of Engineering and Technology (Autonomous), Chirala, Bapatla Dist, Andhra Pradesh – 523187, India

[5]Assistant Professor, Dept ELECTRONICS AND COMMUNICATION ENGINEERING, St.Ann's College of Engineering and Technology (Autonomous), Chirala, Bapatla Dist, Andhra Pradesh – 523187, India

ABSTRACT

The WSN-Enabled Real-Time Precision Aquaculture Monitoring System presents a vital and innovative application of low-power Wireless Sensor Network (WSN) technology, designed to enable automated, continuous, and highly reliable environmental surveillance. The primary objective of this system is to proactively prevent catastrophic fish mortality events, mitigate chronic environmental stressors, and significantly enhance overall aquaculture productivity and yield. At the core of the system lies a robust WSN node, implemented using the versatile Raspberry Pi W microcomputer. This platform is specifically selected due to its low power consumption, compact form factor, and integrated Wi-Fi capability, which is essential for seamless communication in dynamic and challenging aquatic environments. The Raspberry Pi W performs dual critical functions: it operates as a Data

Keywords: ***Wireless Sensor Network (WSN), Aquaculture Monitoring System, Raspberry Pi W, Real-Time Monitoring, Automated Environmental Surveillance, Dissolved Oxygen (DO), Temperature (LM35), Remote Monitoring, Cloud Platform, Precision Aquacult***

INTRODUCTION

The global aquaculture sector, while playing a crucial role in ensuring future food security, faces significant challenges due to traditional, reactive farming practices. These methods rely heavily on infrequent and manual monitoring, often resulting in severe and irreversible losses caused by sudden environmental fluctuations—particularly declines in dissolved oxygen (DO) levels and increases in toxic compounds such as ammonia. This dependence on periodic inspection introduces a critical delay between the onset of adverse conditions and the implementation of corrective measures, leading to substantial economic losses, deterioration of stock health, and limitations in optimizing key parameters such as feeding strategies and stocking densities. To address this fundamental challenge, the WSN-Enabled Real-Time Precision Aquaculture Monitoring System presents a transformative and proactive solution based on advanced low-power Wireless Sensor Network (WSN) technology. The system is specifically designed to enable continuous, automated environmental monitoring in dynamic and demanding aquatic environments. At the core of the system is the WSN node, implemented using the versatile **Raspberry Pi W microcomputer**, which functions as both the Data Acquisition Unit (DAU) and the Local Control Unit (LCU). This platform is selected for its high efficiency, compact form factor, and integrated wireless communication capabilities, ensuring reliable and scalable deployment. The node interfaces with a comprehensive multi-parameter sensor suite, enabling a holistic assessment of water quality. This includes a high-accuracy dissolved oxygen (DO) probe for monitoring oxygen availability, a temperature sensor (such as LM35 or equivalent) for precise thermal regulation, a turbidity sensor to evaluate suspended particles and water clarity, and a specialized gas sensor (MQ-135) for early detection of harmful gases such as ammonia (NH_3) and carbon dioxide (CO_2) accumulation.

The system's operational intelligence resides within the LCU, where an embedded control algorithm continuously processes raw sensor data by validating and converting it into standardized engineering units (e.g., ppm, °C, NTU). These values are then instantly compared against predefined, species-specific threshold limits, which are remotely configurable and locally stored to ensure minimal response latency. This architecture enables the system's most critical capability: **autonomous actuation**, allowing immediate and intelligent responses to adverse environmental conditions, thereby minimizing risks and enhancing aquaculture efficiency.

LITERATURE SURVEY

The evolution of aquaculture monitoring systems has been significantly influenced by advancements in Wireless Sensor Network (WSN) technology. WSNs consist of distributed sensor nodes that enable continuous monitoring of environmental parameters across large and remote aquaculture farms. Early studies highlight their effectiveness in replacing labor-intensive manual methods and improving data availability. However, initial WSN implementations relied on centralized processing, where data is transmitted to remote servers for analysis, introducing significant latency. This delay limits the system's ability to respond to rapid environmental changes such as sudden drops in dissolved oxygen (DO). To overcome this limitation, edge computing has emerged as a modern paradigm, enabling local data processing and real-time decision-making at the sensor node level. Devices such as the Raspberry Pi W are widely adopted due to their low power consumption, cost-effectiveness, and sufficient computational capability. Literature also emphasizes the importance of autonomous actuation, allowing immediate corrective actions without network dependency. Furthermore, the use of species-specific operational thresholds enhances system accuracy and supports optimized aquaculture practices. Integration of multiple sensors, including DO, temperature, turbidity, and gas sensors, provides comprehensive environmental monitoring. Lightweight communication protocols such as MQTT ensure efficient and reliable data transmission in IoT-based systems. Continuous real-time data streaming supports visualization, historical analysis, and predictive decision-making. Despite these advancements, challenges such as system complexity, maintenance, and energy management persist. Overall, WSN-based solutions represent a significant step toward precision aquaculture by enabling intelligent, data-driven farm management.

EXISTING SYSTEM

The existing aquaculture monitoring systems are primarily based on traditional manual methods and early electronic centralized architectures. In manual systems, water quality parameters such as temperature and pH are measured using handheld devices at fixed intervals, resulting in low temporal resolution. This approach fails to detect sudden environmental changes like rapid dissolved oxygen (DO) depletion, leading to delayed responses and potential fish mortality. Additionally, manual monitoring is labor-intensive, prone to human error, and lacks comprehensive parameter coverage. To address these limitations, early electronic systems introduced sensors and basic Wireless Sensor Networks (WSNs) for continuous data collection. However, these systems rely on centralized processing, where sensor data is transmitted to remote servers for analysis and decision-making. This architecture introduces communication latency, delaying corrective actions and making the system reactive rather than proactive. Furthermore, these systems require high initial investment in hardware and infrastructure. Maintenance challenges such as sensor biofouling and frequent calibration reduce data accuracy over time. The need for skilled personnel to manage embedded systems and network configurations increases operational complexity. Power management and network reliability remain critical concerns, particularly in remote aquaculture environments. Improper threshold settings and lack of localized intelligence further reduce system efficiency.

Mechanical failures of actuators and vulnerability to environmental damage also impact reliability. Additionally, continuous data generation may lead to information overload and reduced effectiveness of alerts. Overall, existing systems lack real-time autonomous control, limiting their ability to ensure optimal aquaculture conditions.

PROPOSED SYSTEM

The proposed system is a WSN-enabled real-time aquaculture monitoring and control system designed to overcome the limitations of existing approaches. It utilizes a network of sensors to continuously monitor critical water quality parameters such as dissolved oxygen (DO), temperature, turbidity, gas concentration, humidity, and TDS. These sensors are interfaced with a Raspberry Pi W, which acts as the edge processing unit for data acquisition, analysis, and decision-making. The collected data is processed locally and compared against predefined species-specific threshold values to determine environmental suitability. In case of any deviation from safe limits, the system autonomously triggers actuators such as DC water pumps or aerators through a relay module. This ensures immediate corrective action with minimal latency, eliminating dependence on centralized processing. The system also incorporates alert mechanisms such as buzzers and LEDs to notify nearby personnel. Additionally, sensor data is transmitted to the ThingSpeak cloud platform using the MQTT protocol for real-time visualization and remote monitoring. A solar-powered energy system with battery backup ensures continuous operation in remote locations. The integration of edge computing, multi-parameter sensing, and autonomous actuation enhances system reliability and efficiency. The proposed system reduces manual intervention and enables proactive aquaculture management. It also supports scalability and adaptability for different aquaculture environments. Overall, the system provides a cost-effective, intelligent, and sustainable solution for precision aquaculture.

ARCHITECTURE

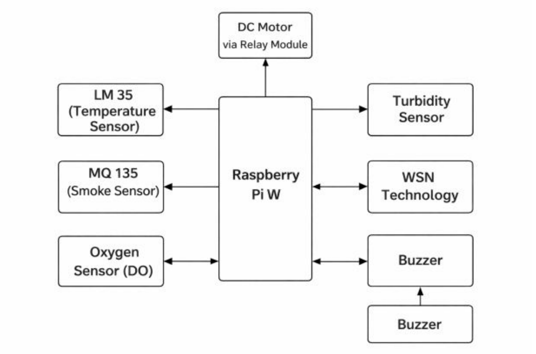

Fig 1: Block Diagram

The operational success of the WSN-enabled Precision Aquaculture Monitoring System relies on the efficient integration of core hardware components categorized into processing, sensing, actuation, and power units. The central unit is the Raspberry Pi W, functioning as both the Data Acquisition Unit (DAU) and Local Control Unit (LCU), enabling real-time data processing and wireless communication via MQTT. It interfaces with sensors and actuators through GPIO pins, ensuring low-latency autonomous control. The sensor array includes a Dissolved Oxygen (DO) sensor, temperature sensor (LM35/DS18B20), turbidity sensor, and gas sensor (MQ-135) to monitor critical water quality parameters. Analog sensors are integrated using an ADC module for digital conversion. Based on threshold analysis, the system triggers actuators such as a DC motor connected to an aerator or pump through a relay module. Additional alert mechanisms include buzzer and LED indicators for immediate local notification. The relay board ensures electrical isolation between low-power control and high-power devices. The system is powered by a solar-based Power Management Unit (PMU) with battery backup, enabling continuous operation. All components are housed in a waterproof enclosure to ensure durability and reliability in harsh aquatic environments.

METHODOLOGY DESCRIPTION

A. Data Collection

The system continuously collects real-time data from multiple sensors deployed in the aquaculture environment, including Dissolved Oxygen (DO), temperature, turbidity, and gas sensors. These sensors monitor critical water quality parameters affecting fish health. Analog outputs from sensors are converted into digital signals using an Analog-to-Digital Converter (ADC and forwarded to the Raspberry Pi W.

B. Data Pre-processing

The acquired sensor data is filtered and calibrated to remove noise and ensure accuracy. This step includes normalization and validation of sensor readings to handle fluctuations and environmental disturbances. Pre-processing ensures reliable input for further analysis and decision-making.

C. Data Processing and Analysis

The processed data is analyzed locally by the Raspberry Pi W, which acts as the edge computing unit. The system compares real-time sensor values with predefined threshold limits (e.g., critical DO levels, maximum temperature). Based on this comparison, the system determines whether the environmental conditions are within safe limits or require corrective action.

D. Output and Actuation

If any parameter exceeds safe thresholds, the system automatically triggers actuators such as aerators or water pumps via a relay module to restore optimal conditions. Simultaneously, alert mechanisms like buzzer and LED indicators notify local personnel. The system also transmits real-time data to a remote monitoring platform using the MQTT protocol for visualization and supervision.

HARDWARE AND SOFTWARE REQUIREMENTS

Raspberry pi W:-

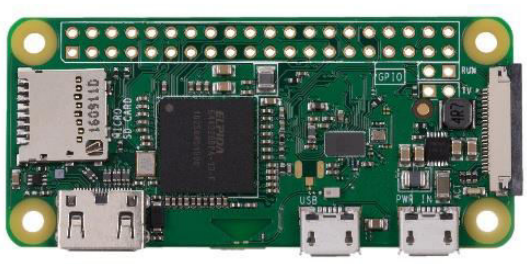

Fig 2.1: Raspberry Pi W

The Raspberry Pi W is a compact, low-power microcomputer that serves as the core processing unit in the proposed system. It integrates built-in Wi-Fi and Bluetooth, enabling seamless wireless communication within the WSN. The device is responsible for data acquisition, local processing, and decision-making based on predefined thresholds. Its GPIO pins allow direct interfacing with sensors.

TurbitySensor:-

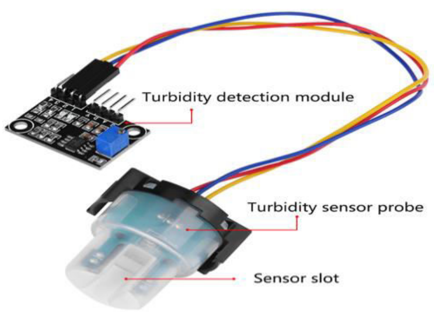

Fig 2.2: Turbity Sensor

The turbidity sensor is used to measure the clarity of water by detecting the scattering of light caused by suspended particles. It provides output in Nephelometric Turbidity Units (NTU), indicating the level of impurities such as silt, algae, and organic matter. High turbidity levels can reduce light penetration and affect aquatic life, often indicating poor water quality. The sensor typically generates an analog signal, which is converted into digital form using an ADC module for processing. In the proposed system, turbidity monitoring helps in identifying early signs of water contamination. Continuous observation enables timely corrective actions to maintain a stable and healthy aquaculture environment.

Gas Sensor

Fig 2.3: Gas sensor

The gas sensor (such as MQ-135) is used to detect harmful gases present in the aquaculture environment, particularly ammonia (NH_3) and carbon dioxide (CO_2). It operates based on changes in resistance when exposed to different gas concentrations, producing an analog output signal. This signal is converted into digital form using an ADC module for processing by the Raspberry Pi W. The sensor is typically placed above the water surface to monitor gaseous emissions resulting from biological waste and decomposition. Elevated gas levels indicate poor water quality and potential stress to aquatic life. Continuous monitoring enables early detection of toxic conditions and supports timely corrective actions.

Disolved Oxygen Sensor

Fig 2.4: DO Sensor

The Dissolved Oxygen (DO) sensor is a critical component used to measure the concentration of oxygen dissolved in water, typically expressed in mg/L or ppm. It plays a vital role in assessing the suitability of water for aquatic life, as oxygen levels directly impact fish survival and metabolism. The sensor operates using electrochemical or optical principles and generally produces an analog output signal. This signal is converted into digital data using an ADC module for processing by the Raspberry Pi W. Low DO levels indicate hypoxic conditions that can lead to fish.

Buzzer

Fig 2.5: Buzzer

The buzzer is a simple audio output device used to provide immediate alerts in the aquaculture monitoring system. It is activated when any critical parameter, such as low dissolved oxygen or high temperature, exceeds predefined threshold limits. The buzzer generates an audible signal to notify on-site personnel about abnormal conditions requiring attention. It is directly controlled by the Raspberry Pi W through GPIO pins, often using a driver circuit if required. This ensures quick human awareness alongside automated system response. The buzzer enhances system reliability by providing a real-time local warning mechanism.

DC Motor

Fig 2.6: DC Motor

The DC water pump is a primary actuation component used to regulate water flow and maintain optimal environmental conditions in the aquaculture system. It is activated when sensor readings indicate unsafe conditions, such as low dissolved oxygen or high turbidity. The pump facilitates water circulation, aeration support, or partial water exchange to restore water quality. It is controlled by the Raspberry Pi W through a relay module, which enables safe switching of higher current loads. The use of a DC pump ensures energy efficiency and compatibility with battery or solar-powered systems. This actuator plays a crucial role in implementing the system's autonomous corrective actions.

A. Arduino IDE

Arduino IDE is used for programming and interfacing sensor modules within the system. It facilitates data acquisition from sensors such as turbidity, gas, and temperature sensors, ensuring reliable communication between hardware components.

C. ThingSpeak Cloud Platform

ThingSpeak is utilized for real-time data visualization, storage, and remote monitoring. It provides graphical dashboards to analyze variations in parameters such as dissolved oxygen, temperature, turbidity, and gas concentration.

D. MQTT Protocol

MQTT is used as a lightweight communication protocol for transmitting sensor data from the edge device to the cloud. It ensures efficient, reliable, and low-latency data transfer in the wireless sensor network.

E. Supporting Libraries

Various software libraries are used for sensor interfacing, ADC communication, and GPIO control. These libraries ensure smooth hardware–software interaction and enhance overall system performance.

RESULT AND DISCUSSION

ThingSpeak Visualization Results

The real-time sensor data acquired from the system is visualized using the ThingSpeakcloud platform. The graphical representation of parameters such as dissolved oxygen (DO), temperature, turbidity, and gas concentration enables continuous remote monitoring and analysis.

ThingSpeak Visualization Results

The real-time sensor data acquired from the system is visualized using the ThingSpeak cloud platform. The graphical representation of parameters such as dissolved oxygen (DO), temperature, turbidity, and gas concentration enables continuous remote monitoring and analysis.

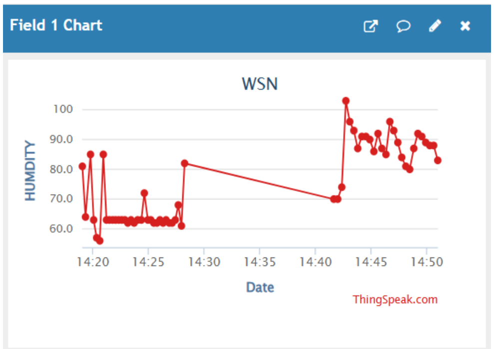

Fig 3.1: Humidity

shows the variation of humidity over time. The graph illustrates changes in atmospheric moisture levels around the aquaculture environment, which can influence water conditions and overall system stability.

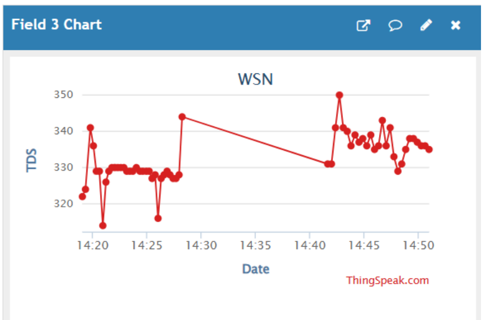

Fig 3.2: TDS

+presents the variation of Total Dissolved Solids (TDS). The graph indicates the concentration of dissolved substances in water, which is a key indicator of water quality. Fluctuations in TDS values reflect changes in impurity levels, and the system effectively monitors these variations in real time.

Fig 3.3: Temperature

depicts the variation of temperature over time. The results demonstrate the system's ability to continuously monitor thermal changes, which are critical for maintaining suitable conditions for aquatic life.

CONCLUSION

The proposed WSN-enabled real-time aquaculture monitoring system successfully addresses the limitations of traditional and centralized approaches by integrating edge computing and autonomous control. The system ensures continuous monitoring of critical water quality parameters and enables immediate corrective actions through local decision-making. By utilizing a Raspberry Pi W, multi-parameter sensors, and MQTT-based communication, the system achieves low-latency response and reliable data transmission. The incorporation of cloud platforms like ThingSpeak allows effective remote monitoring and visualization. Additionally, the use of solar-powered energy enhances system sustainability and suitability for remote deployments. Overall, the proposed solution improves operational efficiency, reduces manual intervention, and supports sustainable and precision aquaculture practices.

FUTURE ENHANCEMENT

The proposed system can be further enhanced by integrating advanced machine learning algorithms for predictive analysis and early detection of water quality issues. The inclusion of additional sensors, such as pH and salinity, can improve monitoring accuracy and provide a more comprehensive assessment of aquatic conditions. Future work may also focus on developing a mobile application for real-time alerts and user-friendly control. The use of LoRa or 5G communication technologies can improve network reliability and coverage in large-scale farms. Additionally, implementing automated feeding systems and AI-based optimization can further enhance productivity. These improvements will contribute to a more intelligent, scalable, and fully autonomous aquaculture management system.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[2] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer Networks*, vol. 52, no. 12, pp. 2292–2330, 2008.

[3] L. Ruiz-Garcia, L. Lunadei, P. Barreiro, and J. I. Robla, "A review of wireless sensor technologies and applications in agriculture," *Computers and Electronics in Agriculture*, vol. 69, no. 2, pp. 209–217, 2009.

[4] S. R. Nandurkar, V. R. Thool, and R. C. Thool, "Design and development of precision agriculture system using wireless sensor network," *IEEE International Conference*, 2014.

[5] K. Ashton, "That 'Internet of Things' thing," *RFID Journal*, 2009.

[6] A. Mainwaring et al., "Wireless sensor networks for habitat monitoring," *ACM International Workshop on Wireless Sensor Networks*, 2002.

[7] M. Li and Y. Liu, "Underground coal mine monitoring with wireless sensor networks," *ACM Transactions*, 2007.

[8] P. Rawat, K. D. Singh, H. Chaouchi, and J. M. Bonnin, "Wireless sensor networks: A survey on recent

developments," *Journal of Network and Computer Applications*, vol. 64, pp. 23–45, 2016.

[9] A. Zanella et al., "Internet of Things for smart cities," *IEEE Internet of Things Journal*, vol. 1, no. 1, pp. 22–32, 2014.

[10] O. Vermesan and P. Friess, *Internet of Things: Converging Technologies*, River Publishers, 2013.

[11] R. Buyya and A. V. Dastjerdi, *Internet of Things: Principles and Paradigms*, Elsevier, 2016.

[12] A. Banks and R. Gupta, "MQTT version 3.1.1," *OASIS Standard*, 2014.

[13] ThingSpeak Inc., "ThingSpeak IoT Analytics Platform," MathWorks, 2020.

[14] Raspberry Pi Foundation, "Raspberry Pi W Datasheet," 2021.

[15] Arduino, "Arduino IDE Documentation," 2022.

[16] S. Sarkar, S. Chatterjee, and S. Misra, "Assessment of the suitability of fog computing in IoT," *IEEE Transactions*, 2016.

[17] M. Chiang and T. Zhang, "Fog and IoT: An overview," *IEEE Internet of Things Journal*, 2016.

[18] J. Gubbi et al., "Internet of Things (IoT): A vision, architectural elements," *Future Generation Computer Systems*, 2013.

[19] FAO, "The State of World Fisheries and Aquaculture," *Food and Agriculture Organization*, 2020.

[20] S. Sendra, J. Lloret, J. M. Jimenez, and L. Parra, "Underwater wireless communications in freshwater," *IEEE Communications Magazine*, 2016.