Linker: (The Journal of Emerging Research in Agriculture, Fisheries, and Forestry)
Volume 4, Issue 1
ISSN (Print): 3082-3625 ISSN (Online): 2815-2018
DOI: https://doi.org/10.65141/jeraff.v4i1.n1

Development of Integrated Solar-Powered Wireless Smart IoT-based Water Level Monitoring Embedded System

Israel M. Eraña[1], Jeoffrey Lloyd Bareng[2], Orlando F. Balderama[3], Rey C. Naval[4], Allan C. Taracatac[5], Freddie Rick E. Labuanan[6], Wilfredo H. Bose Jr.[7], Marijoy C. Awisen[8], Sarah Marie L. Dingoasen[9]
Department of Agricultural and Biosystems Engineering, Quirino State University, Diffun, Quirino, Philippines[1]
College of Engineering, Isabela State University, Echague, Isabela, Philippines[2,3]
Research Development Extension and Training Center, Quirino State University, Diffun, Quirino, Philippines[4]
SWIM R&D Center, Isabela State University, Echague, Isabela, Philippines[5]
Department of Agricultural Engineering, Quirino State University, Diffun, Quirino, Philippines[6,7,8,9]
reyn.qsu@gmail.com; israelsen_09@yahoo.com; jayarbose214@gmail.com

RESEARCH ARTICLE INFORMATION

Received: March 14, 2023
Reviewed: May 30, 2024
Accepted: June 10, 2024
Published: June 30, 2024

ABSTRACT

Agriculture has undergone a significant transformation in recent years, driven by technologies such as the Internet of Things (IoT) and mobile internet. These advancements have greatly improved farm efficiency and profitability by simplifying operations, reducing costs, and enhancing production management. This progress is especially evident in irrigation, where traditional methods often lead to water waste and inefficiency. Smart farming solutions using IoT are crucial for addressing these challenges. In this study, the researchers developed a prototype for a solar-powered, wireless IoT-based water level monitoring system designed to optimize irrigation in paddy fields. This system included an ultrasonic sensor for precise water level measurement, a microcontroller for data processing, wireless modules for data transmission, and a solar power unit to ensure continuous operation, even without sunlight. They integrated these components and tested the system under controlled conditions to assess its performance. The testing demonstrated that the system could measure water levels with 99.50% accuracy and could operate for up to 15 hours on stored solar energy, even without sunlight. These findings suggest that the system can provide precise, real-time control over water distribution, minimizing waste and improving irrigation efficiency. The broader implications of this research indicate that IoT-based technologies can significantly enhance sustainable farming practices. Efficient water management can help address critical issues such as water scarcity and food security. Future work should focus on detailed cost analysis and real-world field evaluations to ensure the system's practicality and effectiveness before conducting broader pilot tests in diverse agricultural environments.

Keywords: *control system, information system, smart farming, water control infrastructures and irrigation management*

Introduction

Water insufficiency is a critical challenge in agriculture, particularly in irrigation for crop production. Agriculture is the largest freshwater-consuming human activity, accounting for nearly 70% of total withdrawal and around 90% of total water consumption, causing remarkable environmental impacts (Soligno, 2019). Poor water management leads to substantial losses, exacerbating water scarcity issues that threaten global food security, especially for the rapidly growing population. Traditional irrigation methods, which are heavily dependent on manual labor, often result in water wastage and inefficiency. Addressing these issues is vital for sustainable agricultural practices and food production.

The rise of the Internet of Things (IoT) offers a promising solution for enhancing water management in agriculture. IoT technologies can automate and optimize irrigation, ensuring that water is used precisely where and when needed, reducing waste, and lowering costs. According to recent studies, IoT-enabled systems provide real-time monitoring and control, significantly improving resource utilization in agriculture. These systems integrate cost-effective devices, low-power wireless technologies, and advanced data analytics to manage water usage efficiently (Shahanas & Sivakumar, 2016; Sinha & Dhanalakshmi, 2022).

Recent advancements in precision agriculture underscore the potential of IoT in revolutionizing irrigation practices. Innovations like GIS-based mapping, remote sensing, and automated nutrient and water management systems have become integral to modern farming (Sishodia et al., 2020). These technologies facilitate precise water application, reduce human intervention, and enhance overall irrigation efficiency. Furthermore, IoT systems can detect leaks, monitor water quality, and provide insights that traditional methods cannot achieve (Pernapati, 2018).

However, despite these advancements, there is still a gap in the adoption of smart irrigation systems among farmers. Many are unfamiliar with these technologies or find them challenging to implement due to cost or complexity. This study aimed to bridge this gap by developing an integrated solar-powered wireless IoT-based water level monitoring system tailored for paddy fields. The system included an ultrasonic sensor for accurate water level measurement, a microcontroller for data processing, wireless communication modules, and a solar power unit to ensure continuous operation.

By evaluating the system's performance, the researchers aimed to demonstrate its potential to improve irrigation efficiency and promote sustainable water management practices. This research not only highlights the benefits of IoT in agriculture but also provides practical insights into its implementation in real-world settings. Future work will focus on cost analysis and field evaluations to validate the system's practicality and effectiveness, paving the way for broader adoption and pilot testing in diverse agricultural environments.

Methods

Materials

Distinct design materials and software applications were accustomed to fabricating the solar-powered IoT-based water level monitoring-embedded system to envision and explicate for improved output to lessen the time depleted during the development and testing stages and better resource usage. SketchUp Pro 2021, AutoCAD 2022, and Google Earth Pro are among the software programs available.

In line with the evolutionary prototyping strategy, the researchers identified and categorized the necessary materials into hardware components and software tools. This approach ensured a clear understanding of the diverse elements involved in developing the prototype.

Hardware Components

Sensing and Processing:

a) Ultrasonic sensor
b) RTC (Real-Time Clock) module
c) GPS Breakout module
d) ESP32 microcontroller
e) Zero PCB board

Power Supply and Management:

a) 30 Watts monocrystalline solar panel
b) 12V lead-acid battery (9AH)
c) PWM solar charge controller
d) 5V regulated power module
e) 20A and 30A D.C. mini circuit breakers (for the battery and solar panel)

Structural and Connectivity:

a) 8-inch diameter PVC pipe
b) 2-inch diameter steel pipe
c) 2-inch threaded coupling
d) 1-inch diameter PVC pipe
e) Angle bar
f) Bolts and nuts
g) Woven wire mesh
h) Weatherproof steel box (computer box)
i) 2 mm thick Galvanized Iron (G.I.) Sheet
j) Micro USB cables
k) Photovoltaic cables
l) 14 AWG stranded wire
m) EC3 wire connectors

n) MC4 connectors
o) Female pin headers

Software Tools

Programming and Development:

a) Arduino IDE for coding and uploading to the ESP32
b) Arduino/ESP32 compatible libraries for sensor integration and data processing

Data Management:

a) MySQL/XAMPP for data storage and retrieval

Prototyping Strategy

The evolutionary prototyping strategy was chosen due to its iterative nature, which allows for ongoing refinement based on stakeholder feedback. This method is ideal for projects requiring incremental improvements to meet user requirements effectively. As outlined in Figure 1, the process begins with constructing an initial prototype, gathering feedback, and then making enhancements in subsequent iterations until the desired functionality is achieved (Panganiban et al., 2019).

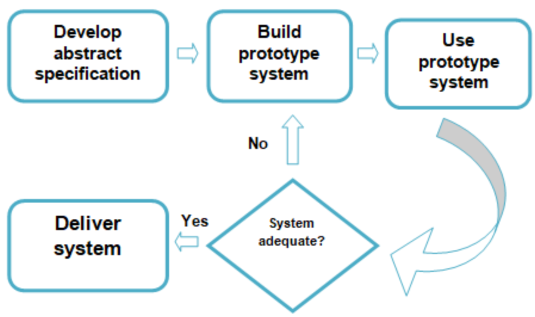

Figure 1. *The Evolutionary Prototyping Method*

Development Method

For the system development and use, the evolutionary prototyping approach guided the development of the IoT-based water level monitoring system. This method involves several iterations where each prototype version incorporates user feedback and system improvements. The process continues until the system meets all operational requirements and stakeholder expectations.

Verification of Application

To verify the accuracy of the integrated solar-powered IoT-based water level monitoring system, the researchers conducted practical measurements comparing the ultrasonic sensor's readings against a reference standard.

Method of Measurement

Measurement Process:

- Setup:
    1) The sensor was mounted horizontally on a stand, positioned 4 inches above the ground to simulate the conditions within an 8-inch diameter PVC pipe.

2) A tape measure was laid out on the floor, with distances marked from 30 cm to 100 cm at 10 cm intervals.

- Procedure:
  1) An 8x8-inch cardboard box was moved along the marked distances to measure the sensor's accuracy.
  2) At each marked distance, the sensor's readings were recorded and compared to the actual distance measured by the tape measure. The accuracy of the tape measure was confirmed to be in class II as per EG (notice MPO no. 339/2000 Sb) (Koval et al., 2016).

Calibration and Accuracy Determination

The accuracy was calculated using the formula;

$$\Delta = (0.3 + 0.2L) \text{ mm}$$

Where: Δ measurement error
L gauge length

The maximum deviation of the ultrasonic sensor's readings relative to the 100 cm range was used to compute the total error:

$$\Delta SSCLK = \pm \frac{\max(|\Delta S| + |\Delta M|)}{100}$$

System Operation and Implementation

This automated system for monitoring paddy field water levels supports the Alternate Wetting and Drying (AWD) rice-growing strategy. It helps farmers optimize water usage in lowland irrigated and rain-fed lowland rice farming systems. Figure 2 illustrates the operational flowchart of the water level sensor, detailing the process from water level detection to decision-making for irrigation control.

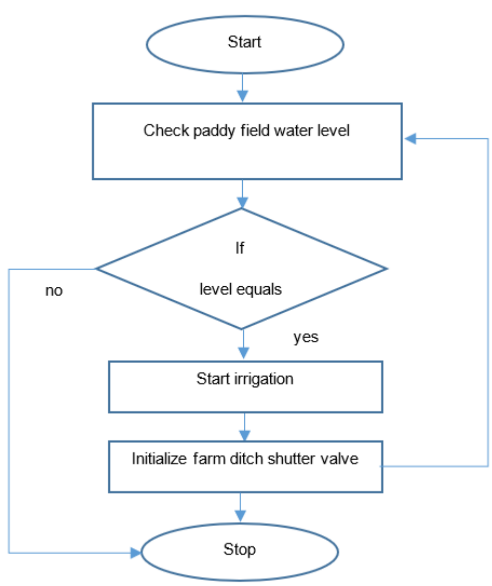

Figure 2. *Flowchart for the Operation of the Paddy Field Water Level Sensor*

Ethical Considerations

Informed consent was obtained from human participants where applicable, and measures were taken to protect the privacy and confidentiality of any data collected. The potential environmental impact of the work was considered and minimized where possible. No conflicts of interest or biases were present in the research or reporting of the findings. Additionally, the researchers had considered making their research openly available to the public, in order to promote transparency and increase access to scientific knowledge.

Results and Discussion

This section presents the outcomes of the prototype development and testing phases of the solar-powered IoT-based water level monitoring system. The researchers detailed the design and functionality of each component, their integration into the overall system, and the performance evaluation, particularly focusing on the accuracy of the ultrasonic sensor. The results were structured into two main sections: prototype development and prototype testing.

Prototype Development

The development of the water level monitoring system involved designing and assembling various components to create a functional prototype. Each component's purpose, functionality, and role within the system are detailed below.

Component Descriptions and Assembly

a. PVC Pipe and Ultrasonic Sensor Assembly

i. PVC Pipe (8 inches): The PVC pipe serves as the primary housing for the ultrasonic sensor. The chosen diameter (8 inches) was found to provide optimal conditions for accurate water level measurements by minimizing interference from pipe wall reflections. The sensor is mounted at a minimum height of 29 cm above the maximum expected water level to ensure reliable readings (Figure 3).

ii. Ultrasonic Sensor: This sensor measures the water level by emitting ultrasonic pulses and detecting their echoes from the water surface. The sensor has a measurement range from 28 cm to 750 cm with a resolution of 1 mm, making it suitable for high-precision water level monitoring. It is connected to the system's CPU via a UART interface, which facilitates data transmission (Figure 4).

iii. Woven Wire Mesh: Installed at the top of the PVC pipe, this mesh prevents insects and debris from entering and obstructing the sensor, ensuring consistent performance.

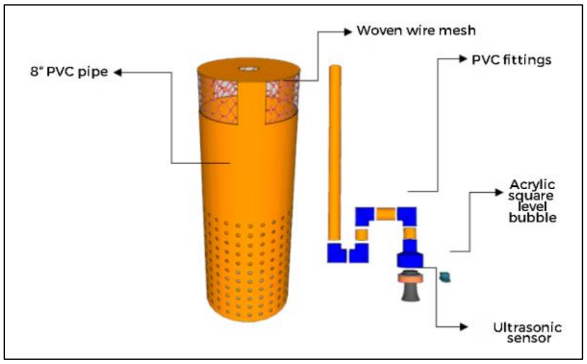

Figure 3. *The PVC Pipe and Ultrasonic Sensor Assembly*

b. Housing and Solar Panel Assembly

i. Metal Box: This enclosure houses critical components including the battery, solar charge controller, mini circuit breaker, and the CPU. It provides protection against environmental elements and physical impacts, ensuring the durability and reliability of the system (Figure 5).

ii. Solar Panel: Positioned on top of the system, the solar panel harnesses sunlight to generate power. The panel's specifications align with the system's energy requirements, ensuring sufficient power generation even under suboptimal conditions.

iii. Steel Pipe and Threaded Coupling: These components serve as the mounting structure for the sensor andsolar panel. The steel pipe provides a stable foundation, while the threaded coupling ensures secure attachment and easy assembly/disassembly.

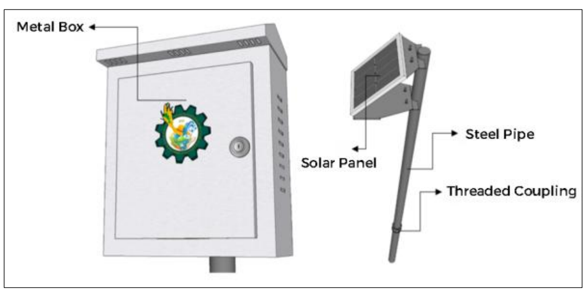

Figure 4. *Housing, Canopy, and the Solar Panel Assembly*

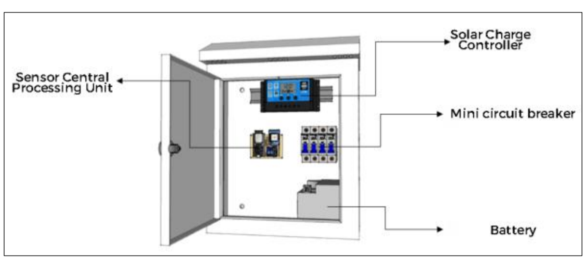

Figure 5. *The Solar Charge Controller, DC Breaker, Battery, and CPU Assembly*

c. Power Management and Control System
   i. Solar Charge Controller: This device regulates the voltage and current from the solar panel to the battery, preventing overcharging and ensuring efficient energy storage. The pulse width modulation (PWM) controller used is suitable for the system's 12V lead-acid battery (Figure 6).
   ii. 12V Lead-Acid Battery (9AH): The battery stores the energy generated by the solar panel, providing a reliable power supply during periods without sunlight. Its capacity allows the system to operate for at least 15 hours on a full charge, ensuring continuous monitoring.
   iii. Mini Circuit Breaker: Installed to protect the system from electrical faults, these breakers can isolate the battery and other components during maintenance or in case of a short circuit, enhancing safety and maintainability.

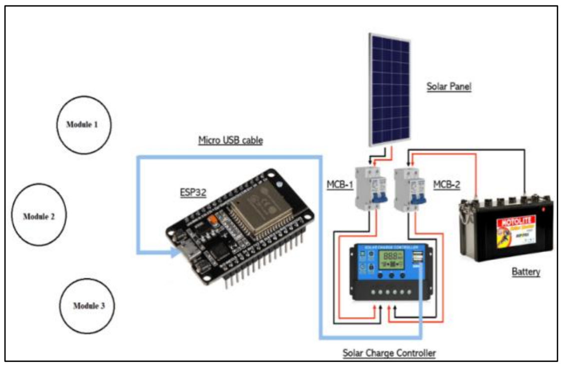

Figure 6. *The Solar Power Generator Assembly*

d. Central Processing Unit (CPU)
   i. ESP32 Microcontroller: This microcontroller is the core processing unit of the system. It manages data collection from the ultrasonic sensor, obtains GPS coordinates, and records timestamps via the Real-Time Clock (RTC) module. The ESP32 also facilitates wireless communication, transmitting data to a MySQL server over Wi-Fi (Figure 8).
   ii. Real-Time Clock (RTC): It provides precise timestamps for the recorded water level data, essential for accurate monitoring and analysis.
   iii. GPS Module: It collects location data, enabling tracking and spatial analysis of the monitoring sites. This feature is particularly useful for managing large paddy fields.

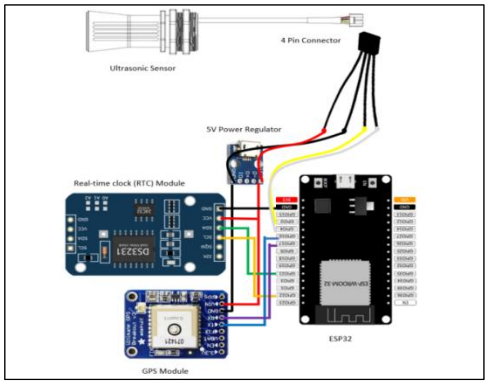

Figure 7. *The Water Level Monitoring Central Processing Unit Diagram*

Complete System Overview

The integrated system, combining all the components described above, formed a compact and modular water level monitoring solution. The prototype assembly, as shown in Figure 8, demonstrates how these components were configured to deliver accurate and reliable performance. Each part was labeled to illustrate its role and connections within the system.

Figure 8. *The Prototype Assembly of the Developed Integrated Solar-Powered Wireless IoT-Based Water Level Monitoring Embedded System (Front, Side Views)*

Prototype Testing

The testing phase focused on evaluating the performance and accuracy of the system, particularly the ultrasonic sensor's ability to measure water levels precisely.

Ultrasonic Sensor Accuracy Analysis

The accuracy of the ultrasonic sensor was assessed through a series of tests comparing its readings to known water levels measured with a tape meter. The following methods were used:

a. The sensor was calibrated and positioned to measure water levels within the PVC pipe.
b. A tape meter was used to measure the actual water levels as reference points.
c. Multiple trials were conducted to ensure the reliability of the sensor readings under consistent conditions.

Table 1 presents the comparison between the sensor readings and the reference measurements for distances up to 100 cm. The sensor consistently demonstrated high accuracy, with errors typically within ±1% of the actual measurements.

Table 1. Accuracy of Ultrasonic Sensor Measurements up to 100 cm

Trial	Tape Meter Distance (cm)	Sensor Distance (cm)	Difference (cm)	Sensor Error (cm)	Total Error (cm)	Accuracy Class (%)
1	30	29.5	-0.5	±0.5	±0.55	0.5
2	40	39.1	-0.9	±0.5	±0.95	0.48
3	50	49.0	-1.0	±0.5	±1.05	0.48
4	60	59.5	-0.5	±0.5	±0.55	0.5
5	70	69.5	-0.5	±0.5	±0.55	0.5
6	80	79.1	-0.9	±0.5	±0.95	0.48
7	90	89.0	-1.0	±0.5	±1.05	0.48
8	100	99.2	-0.8	±0.5	±0.85	0.48

The data indicate that the ultrasonic sensor provides reliable and accurate water level measurements. The error margins are minimal, making the sensor suitable for precise monitoring in paddy fields. These results align with the sensor's specifications and demonstrate its effectiveness in real-world applications.

Conclusion and Future Works

This study aimed to develop a cost-effective, solar-powered, and IoT-based water level monitoring system for managing water in paddy fields using the Alternate Wetting and Drying (AWD) technique. The researchers identified and successfully integrated the necessary hardware and software components to create a robust water level monitoring system. The main components include the ESP32 microcontroller, an ultrasonic sensor, a solar panel, and software tools like SketchUp Pro and AutoCAD for design and simulation. This combination ensured the system was cost-effective, compact, and modular, facilitating easy assembly and maintenance. Furthermore, the project culminated in the fabrication and testing of the system’s CPU and the complete prototype assembly. The design focused on affordability and modularity, ensuring that the system can be easily replicated for larger-scale applications. Initial tests in controlled environments demonstrated the system's high accuracy and reliability in measuring water levels, which is critical for effective irrigation management.

Although the system was primarily tested in controlled settings, it had significant potential for real-world applications. Thus, the researchers recommend it to irrigation managers and farmers for several reasons. First, the system provides precise water level data, enabling better irrigation planning and minimizing water wastage. Second, automation reduces the need for frequent manual monitoring, saving on labor and operational costs. Third, optimized and consistent irrigation can lead to healthier crops and potentially higher yields, enhancing agricultural productivity. Compared to other water level monitoring systems currently available, the developed system stands out due to its combination of cost-effectiveness, ease of assembly, and integration with solar power. Its modular design allows for scalability and customization, making it adaptable to various field conditions and agricultural needs. Lastly, given its advantages, the researchers also recommend this system for adoption in irrigation management practices to promote sustainable agriculture. Government support for the mass production of this technology could drive further innovation in irrigation automation and contribute to significant water conservation.

With regard to future works, the next step involves comprehensive field testing to validate the system's performance over an entire cropping season. Future researchers need to conduct a detailed cost analysis to evaluate the economic feasibility of large-scale adoption. Likewise, future enhancements may focus on integrating automated irrigation control mechanisms. This addition will allow the system to manage water levels autonomously, further reducing the need for manual intervention and optimizing water use.

In addition, to safeguard this innovation, the researchers should pursue intellectual property protection. This will be crucial as we move towards commercialization, ensuring our technology remains proprietary. Exploring partnerships with agricultural technology firms could facilitate the transition from a prototype to a market-ready product. Moreover, conducting comparative studies will help benchmark this system against existing technologies. Hence, ongoing research could aim to enhance the system's features and adaptability for various agricultural applications. By addressing these areas, the community can advance from the current prototype to a fully functional and widely adopted solution for sustainable water management in agriculture.

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Acknowledgment

We would like to express our sincere gratitude and appreciation to DOST-PCIEERD for approving our project and providing us with funding support and valuable assistance. We also extend our thanks to Quirino State University for their provision of technical resources and assistance to our project team. Furthermore, we would like to acknowledge and thank the Ligaya Irrigator's Association, NIA-MARIIS, and the Local Government Unit of Santiago, Isabela, for their unwavering support in enabling the successful execution of our project.