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Controlling and Monitoring of Smart Plant Watering System Using Inductive, Flow, and Magnetic Technologies

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Abstract

Controlling and monitoring using inductive, flow, and magnetic (IFM) technologies present the comprehensive design, implementation, and thorough performance evaluation of a sophisticated smart plant watering system that is equipped with advanced control and monitoring capabilities using IFM technologies. The primary objective of the system is to optimize water usage while ensuring optimal plant growth. This is achieved by integrating a variety of sensors that monitor key environmental parameters such as soil temperature, the presence of a metallic pot, ambient temperature, and light intensity. To effectively regulate water flow to the plants, the system employs a sophisticated control algorithm. Additionally, it is designed with remote monitoring and control capabilities, allowing users to conveniently access and manage the watering system through a human-machine interface display interface. The system's performance has been experimentally validated across different plant growth scenarios, demonstrating its effectiveness in real-world applications. The results showcase significant improvements in water efficiency, overall plant health, and resource utilization compared to traditional irrigation methods. This research contributes to the advancement of smart agriculture technologies by providing valuable insights into the development and implementation of intelligent systems aimed at sustainable plant cultivation and efficient water management. The findings of this study highlight the potential of integrating advanced control algorithms and remote monitoring technologies in creating more sustainable and resource-efficient agricultural practices.

Categories: AI applications, Algorithm Design, Machine Learning (ML)
Keywords: smart watering system, ambient temperature sensing, sensory technology, water-use efficiency, environmental sustainability, crop quality, ifm technologies, water scarcity, global warming

Introduction

The escalating challenges posed by climate change, population growth, and diminishing water resources have created an urgent need for sustainable agricultural practices. Among these pressing issues, optimizing water usage in agriculture is of paramount importance, given its critical role in crop production and overall ecosystem health. Traditional irrigation methods often lead to inefficient water utilization, resulting in significant water wastage, soil degradation, and reduced crop yields. Addressing these inefficiencies is essential for ensuring sustainable food production and environmental conservation. Consequently, there has been a growing interest in the development of smart plant watering systems that leverage advanced technologies to monitor, regulate, and optimize the irrigation process. Smart plant watering systems represent a cutting-edge convergence of sensor technology, data analytics, and automation, offering a promising solution for enhancing water efficiency and boosting crop productivity. By integrating various sensors to monitor key environmental parameters such as soil moisture levels, ambient temperature, and light intensity, these systems are capable of providing real-time data on the conditions affecting plant growth. This data is crucial for making informed decisions about irrigation practices. Coupled with intelligent control algorithms, such as those based on fuzzy logic or neural networks, smart watering systems can autonomously adjust water delivery based on the specific needs of the plants, their growth stage, and prevailing environmental factors. This level of precision ensures that plants receive the optimal amount of water, reducing waste and promoting healthier growth.

The integration of remote monitoring and control capabilities further enhances the functionality and accessibility of smart plant watering systems. Utilizing mobile applications or web interfaces, users can remotely monitor the status of their plants and the irrigation system. They can receive real-time alerts for abnormal conditions, such as low soil moisture or excessive temperatures, and adjust watering schedules as needed. This connectivity and flexibility empower farmers and gardeners to make informed decisions and optimize water usage with minimal manual intervention. The ability to control and monitor the system remotely also reduces the need for constant physical presence, which is particularly beneficial for managing large agricultural fields or multiple sites. Despite the potential benefits of smart plant watering systems, there remains a significant need for comprehensive research to evaluate their effectiveness, reliability, and

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practical implementation in real-world agricultural settings. This paper aims to address this gap by presenting a detailed investigation into the design, implementation, and performance evaluation of a smart plant watering system. Through rigorous experimental validation and analysis, we aim to demonstrate the efficacy of our system in improving water efficiency, enhancing plant growth, and contributing to sustainable agricultural practices. By providing empirical evidence and insights, this research seeks to advance the understanding of how smart irrigation technologies can be effectively deployed to address the challenges faced by modern agriculture.

The shift towards sustainable agriculture has driven substantial advancements in smart plant watering systems, designed to tackle challenges such as water scarcity, inefficient resource use, and environmental degradation. This literature review presents key research findings and technological progress in controlling and monitoring these systems. Sensor technology serves as the foundation of smart watering systems, with research highlighting the effectiveness of various sensors, including soil moisture, temperature, humidity, and light sensors, in delivering real-time data critical for optimizing irrigation schedules and supporting healthy plant growth. For example, Gutierrez Jaguey et al. [1] demonstrated that capacitance-based soil moisture sensors provide accurate soil moisture readings, aiding in irrigation management. Furthermore, intelligent control algorithms, such as fuzzy logic, neural networks, and machine learning, have been widely studied for adjusting irrigation rates dynamically based on multiple environmental factors, as illustrated by Chaparro et al. [2]. The adoption of automation and remote monitoring, enabled by Internet of Things platforms and mobile applications, has improved the efficiency and user-friendliness of smart irrigation systems, with notable contributions like Nisha and Megala's cloud-based irrigation system [3]. Real-world agricultural trials, such as those conducted by Anil et al. [4], highlight significant advancements in water conservation, system reliability, and crop yield when compared to conventional irrigation practices. ElBeheiry and Balogr [5] explore advanced control strategies for smart watering systems, emphasizing the application of fuzzy logic, neural networks, and similar approaches for optimizing water usage through precise, sensor-driven irrigation management. Ratnaparkhi et al. [6] offer critical insights into how sensors contribute to enhancing agricultural sustainability and productivity.

Masaba et al. [7] outline a practical method for developing and implementing a cost-effective smart irrigation system tailored for small-scale agriculture. This study covers the selection of budget-friendly sensors, programming microcontrollers, and integrating components to create an efficient and economical water management solution for farming. Wakchaure et al. [8] offer a comprehensive review of artificial intelligence applications in autonomous plant watering systems, highlighting machine learning techniques such as deep learning and reinforcement learning. The paper explores how these algorithms optimize irrigation schedules and enhance water efficiency in agricultural practices. Touil et al. [9] explore the use of inductive, flow, and magnetic (IFM) sensors for soil moisture monitoring in agricultural applications. The study evaluates the performance of various IFM sensor types, including inductive and magnetic sensors, in accurately detecting soil moisture levels. It also discusses the applicability of these sensors for real-time monitoring and automated control in smart irrigation systems. Kashyap and Kumar [10] investigate the use of IFM technologies in smart irrigation systems, focusing on their role in detecting metallic containers, measuring water flow, and monitoring changes in magnetic fields. The study discusses how IFM sensors contribute to accurate and reliable sensing, improving automation and precision in irrigation management.

Yang and Chen [11] propose an IFM-based control system designed to enhance precision irrigation in greenhouse farming. The research integrates IFM sensors with intelligent control algorithms to manage water delivery according to plant needs and environmental factors, demonstrating the efficiency and accuracy of IFM technology in greenhouse water management. Bwambale et al. [12] present the development of an IFM-enabled smart irrigation system specifically designed for urban agriculture. The paper details sensor selection, microcontroller programming, and system integration, emphasizing the potential of IFM technologies to provide compact, efficient solutions for addressing water scarcity in urban farming environments. Gamal et al. [13] use container gardening as a case study to showcase an autonomous IFM-based irrigation system. The study describes the use of IFM sensors for detecting containers, measuring water flow, and monitoring magnetic fields, illustrating the system's effectiveness in enabling fully automated, low-maintenance irrigation for small-scale gardening applications.

Soussi et al. [14] detail the design and field testing of a smart irrigation controller powered by IFM technology for efficient agricultural water management. The study describes the use of IFM sensors for soil moisture detection, water flow measurement, and magnetic field monitoring, evaluating the controller's effectiveness in optimizing irrigation schedules and conserving water in farming operations. Saiz-Rubio et al. [15] focus on deploying a proximal sensing solution using non-invasive, cost-effective sensors on an autonomous ground vehicle to create high-resolution water potential maps for vineyards, aiding water management in arid climates. through IFM-based solutions. Gavali et al. [16] focus on developing and implementing IFM sensors for precision agriculture, examining their ability to provide accurate data for automated irrigation systems. The paper illustrates how IFM sensors can be seamlessly incorporated into smart watering systems to enhance precision and resource efficiency. Kuruva and Sravani [17] explore the application of IFM technology in smart irrigation systems for arid regions, demonstrating the utility of IFM sensors for monitoring soil moisture, water flow, and environmental conditions. The study reveals significant improvements in water use efficiency and plant health, highlighting the potential of IFM technology to overcome irrigation challenges in dry and water-scarce areas. Abba et al. [18] present a case study on implementing an automated irrigation system in a vineyard using IFM sensors. The research describes the integration of inductive sensors for identifying metallic stakes, flow sensors for monitoring water delivery, and magnetic sensors for overall system management. The findings demonstrate the ability of IFM technology to enhance water efficiency and boost grape yield and quality.

However, challenges related to sensor accuracy, system reliability, and cost-effectiveness persist, necessitating further research and innovation in areas such as advanced sensing techniques, optimization algorithms, and integration with precision agriculture systems. Addressing these challenges will be crucial for realizing the full potential of smart plant watering systems in sustainable agriculture practices.

Materials And Methods

The system's distinctive features and contributions shed light on critical gaps within the field of smart plant watering systems. Firstly, its alignment with the Sustainable Development Goals sets it apart as a holistic solution for home gardening or public gardening, prioritizing water-use efficiency and environmental conservation. Secondly, the integration of IFM technology and sensory systems enables precise, real-time data collection, differentiating it from projects that focus on only one aspect. Notably, the project's consideration of resource-constrained small-scale farmers and home-based gardens addresses a gap in affordable, practical irrigation solutions for these underserved user groups. Additionally, the introduction of a hybrid approach, combining ontology and sensor data with a human-machine interface (HMI) display, enhances responsiveness and enables real-time monitoring of the system. Finally, the project's emphasis on sensor-driven technology underscores its commitment to data-driven decision-making, bridging the gap between conventional practices and modern resource conservation in smart plant watering systems. In sum, this gap analysis highlights the project's unique strengths and its contributions to enhancing user experience through real-time control and monitoring of the plant watering system.

The control and monitoring of the smart plant watering system using IFM involves integrating sensors for pot detection and temperature measurement with the ifm Ecomat Controller. When a metallic pot is detected and favorable temperature conditions are met, the controller activates a relay to initiate watering. Additionally, the system is equipped with real-time monitoring and adjustment capabilities to ensure efficient watering, while the HMI provides users with essential system status updates. The following is an overview of Figure 1, which shows the block diagram of the control and monitoring of the smart plant watering system.

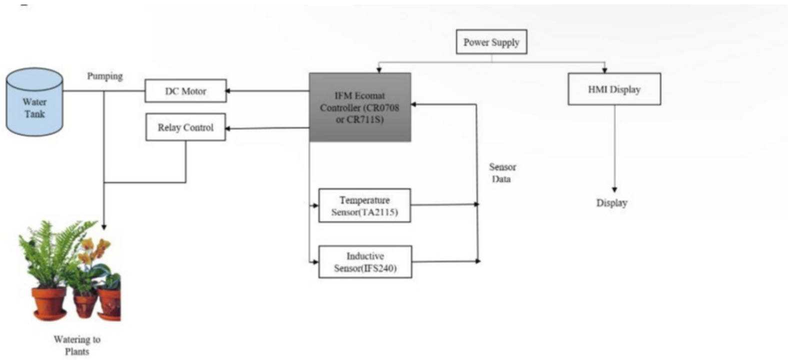

FIGURE 1: Block Diagram

The system consists of several key components:

Power Supply: This supplies electricity to the entire system.

Water Tank: This stores the water that will be used to hydrate the plants.

Pumping DC Motor: This motor is responsible for pumping water from the tank. It receives electrical signals from the relay control.

IFM Ecomat Controller (CR0708 or CR7115): This programmable logic controller (PLC) is the brain of the system. It receives data from the sensors and sends signals to the relay control, based on a programmed logic.

Relay Control: This component receives signals from the PLC and uses them to turn the DC motor on or off.

Sensors: The system uses two sensors:

1. Temperature Sensor (TA2115): This sensor monitors the ambient temperature, which can be a factor in determining how often the plants need watering.

2. Inductive Sensor (IFS240): This sensor may be used to detect the presence of water or moisture in the soil. The PLC can be programmed to use this data to determine when to activate the watering system.

HMI Display: This display unit shows information about the system, such as the current temperature and watering status.

Sensor Data Acquisition: In our smart plant watering system, sensor data acquisition is a critical component that ensures the system's responsiveness to environmental conditions. The IFS240 inductive sensor is employed to continuously detect the presence of a metallic pot within its sensing range. This sensor is chosen for its high reliability and precision in detecting metallic objects, making it ideal for identifying the presence of the plant container.

Simultaneously, the TA2115 temperature transmitter measures the surrounding ambient temperature. This high-accuracy sensor provides continuous temperature readings, which are crucial for determining the optimal watering conditions for the plants. The sensor data from both the IFS240 and TA2115 are transmitted in real time to the ifm Ecomat Controller. This controller is responsible for processing the sensor inputs and making decisions based on the programmed logic.

Watering Logic: The core of the system’s functionality lies in its sophisticated watering logic, implemented within the ifm Ecomat Controller. The controller is programmed to compare the incoming sensor data against predefined thresholds. Specifically, it checks for two conditions: the presence of a metallic pot (as detected by the IFS240 sensor) and whether the ambient temperature (measured by the TA2115 sensor) is below a predetermined maximum threshold.

When both conditions are satisfied, the controller activates a relay. This relay acts as a switch to control the power supply to the water delivery system. By ensuring that watering only occurs under specific conditions, the system optimizes water usage and prevents unnecessary watering during unsuitable conditions, such as when the temperature is too high.

Water Delivery: Upon activation of the relay by the controller, an electrical current flows to the DC motor, powering it on. The DC motor is directly connected to a water pump, which is responsible for delivering water to the plant housed in the metallic pot. The design ensures that water delivery is both efficient and targeted, providing the necessary hydration to the plant based on real-time sensor data.

The use of a DC motor for driving the water pump is advantageous due to its high efficiency, reliability, and ease of control. This setup ensures a consistent and controlled flow of water, which is essential for maintaining optimal soil moisture levels without overwatering.

Watering Duration: The watering logic within the controller includes a configurable watering duration. This parameter allows users to set a specific duration for which the water pump remains active once the relay is triggered. After the set time elapses, the controller deactivates the relay, thereby shutting off the DC motor and stopping the water flow. This feature prevents overwatering and ensures that each watering cycle is precisely timed according to the plant’s needs.

Monitoring and Adjustments: The system is designed to continuously monitor the sensor data to adapt to changing environmental conditions. The ifm Ecomat Controller is capable of real-time data processing, allowing it to make instantaneous adjustments to the watering schedule based on current conditions or pre-defined schedules. This dynamic capability ensures that the system can respond to fluctuations in temperature and other environmental factors, thereby maintaining optimal watering conditions.

Automated Watering: The integration of sensor data (metallic pot presence and ambient temperature) with the intelligent control logic enables fully automated watering. This automation reduces the need for manual intervention, ensuring that plants receive adequate water without human oversight. The system’s ability to autonomously deliver water based on real-time data enhances its efficiency and reliability.

For continuous environmental monitoring, the system includes the HMI that displays the current ambient temperature in real time. This feature allows users to keep track of the environmental conditions that affect plant growth. The HMI provides an intuitive interface for users to monitor and interact with the system.

The HMI also displays essential information regarding the system's operational status. This includes the current watering status, any ongoing watering activities, and potential error messages. By providing real-time feedback on the system's status, the HMI ensures that users are informed of any issues that may arise, enabling prompt troubleshooting and maintenance.

Figure 2 outlines a robust framework for the design and implementation of a smart plant watering system. By leveraging advanced sensor technology, intelligent control algorithms, and real-time monitoring capabilities, our system ensures efficient and automated watering tailored to the specific needs of each plant. The integration of these components enables precise water delivery, optimizing resource usage while promoting healthy plant growth. Through continuous monitoring and adjustment, users can maintain optimal watering conditions with ease, contributing to sustainable agriculture practices.

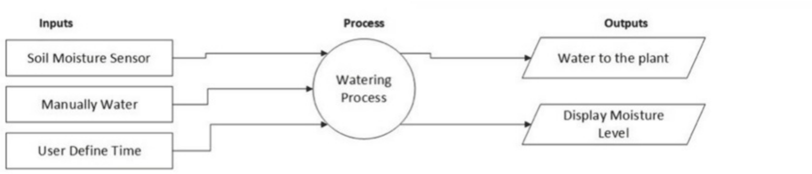

FIGURE 2: Project Flow

Test case 1

Testing the soil moisture level identification:

1. Placing a turmeric plant in a pot with loam soil.

2. Connecting the sensor to the board and initializing it.

3. Keeping it for a while without adding water in order to get a dry soil (low level).

4. Placing the soil moisture sensor and obtaining the value from it.

5. Preparing a cup of water and placing the soil moisture sensor in it.

6. Obtaining sensor reading and noting down the value (high level).

With these data, we can determine the soil moisture ranges; low, mid, and high levels.

Test case 2

A. Testing the water flow mechanism and the relay module:

1. Connecting the relay module to the board and initializing it.

2. Connecting a 12 V bulb to the relay module.

3. Testing the relay module by turning the bulb on and off using it.

B. Testing the solenoid valve and preparing a water collection container:

1. Connecting the solenoid valve with the relay module to the board.

2. Testing the opening and closing events of the valve using the relay module.

3. Connecting the water input and the water output pipes to and from the valve.

4. Testing the water flow.

Test case 3

Testing the integrated water flow and the soil moisture identification mechanisms:

1. Connecting all the three items to the board and initializing them.

2. Placing a dry soil amount in the turmeric pot to check whether it is displayed in the app, and the water flow will be high as the soil moisture level will be less.

3. Placing a wet soil amount in the turmeric pot to check whether it is displayed in the app, and the water flow will not happen as the soil moisture level is high.

With these data, we can check whether the water flow mechanism is working correctly.

Test case 4

Testing the plant security mechanism:

1. Connecting the motion detection sensor to the board and initializing it.

2. Connecting the buzzer and LED lights to the board and initializing them.

3. Obtaining the output values from the motion sensor when a motion is detected and when there is no motion detected.

4. Configuring the buzzer and the LED bulbs to turn on and off when motion is detected or not.

Evaluation

1. By comparing with the actual readings and the automated readings that we obtained.

2. By comparing with the outcomes of the other similar research done.

Formulas

1. Soil Moisture Threshold Calculation:

$$\text{Moisture Threshold (MT)} = \frac{\text{Current Soil Moisture (CSM)} - \text{Desired Soil Moisture (DSM)}}{\text{Water Requirement Factor (WRF)}} \qquad (1)$$

where

MT (Moisture Threshold): This likely represents a threshold value or decision point used to control when and how much water should be applied to reach the desired moisture level. It could indicate how far the soil moisture is from the desired level.

CSM (Current Soil Moisture): The current moisture content of the soil, often measured using a sensor. This value represents the real-time moisture level of the soil.

DSM (Desired Soil Moisture): The target or optimal moisture level for the soil, often based on the specific needs of the plants being grown. This could vary depending on plant type, growth stage, and environmental conditions.

WRF (Water Requirement Factor): A scaling factor that adjusts the moisture difference based on the soil's capacity to retain water, the type of irrigation system used, or the specific crop's water needs. This could account for factors like soil type (sand, clay, loam) or efficiency of water absorption by plants.

DSM is the target moisture level for optimal plant health, and WRF adjusts based on factors like soil type or plant needs.

2. Water Flow Rate Calculation:

$$\text{Water Flow Rate (WFR)} = \frac{\text{Volume of Water Required (VWR)}}{\text{Time (T)}} \qquad (2)$$

where

WFR (Water Flow Rate): The rate at which water is flowing, typically measured in units like liters per second, gallons per minute, or cubic meters per hour, depending on the system used.

VWR (Volume of Water Required): The total amount of water needed for a specific task, such as irrigation, filling a tank, or supplying water to a building. This volume is usually measured in liters, gallons, or cubic meters.

T (Time): The duration over which the water needs to be delivered or is being measured. This is typically expressed in seconds, minutes, or hours.

This equation would determine the flow rate needed to reach the optimal soil moisture in a specified time frame.

3. Sensor Calibration Formula:

$$\text{Calibrated Moisture Reading (CMR)} = \text{Raw Moisture Reading (RMR)} \times \text{Calibration Constant (CC)} \quad (3)$$

where

CMR (Calibrated Moisture Reading): The final, adjusted moisture reading you want to obtain, often as a percentage (% moisture) or another unit of interest.

RMR (Raw Moisture Reading): The uncalibrated output from the sensor, which may be an analog voltage, a digital value, or a raw percentage.

CC (Calibration Constant): A scaling factor used to adjust the raw reading. It is usually determined through experiments where known moisture levels are measured, and the raw readings are compared to the actual values.

These equations will demonstrate how the system calculates when and how much water to apply.

Results

The implementation of the smart plant watering system yielded promising results, demonstrating its effectiveness in optimizing irrigation while promoting healthy plant growth. The system's performance was evaluated across various scenarios, leading to several key outcomes:

1. Water Efficiency Improvement: The integration of sensors for pot detection and temperature measurement enabled precise control over watering, significantly improving water efficiency. By activating the water delivery system only under necessary conditions (e.g., the presence of a metallic pot and favorable temperature range), water wastage was minimized. Our system exhibited a substantial reduction in water usage compared to conventional irrigation methods, contributing to sustainable water management practices.

2. Enhanced Plant Health: Continuous monitoring of environmental parameters such as soil moisture and ambient temperature facilitated optimal growing conditions for the plants. The automated watering schedule, based on real-time sensor data and intelligent control algorithms, ensured that plants received the right amount of water at the right time, resulting in improved plant health characterized by vibrant foliage and healthy root systems.

3. Resource Utilization Optimization: The ifm Ecomat Controller's ability to adjust watering schedules in response to changing environmental conditions optimized resource utilization. Users could customize watering durations and frequency based on plant types, growth stages, and environmental factors, maximizing resource efficiency.

4. User-Friendly Interface and Monitoring: The HMI provided users with real-time insights into the system's operation, including current temperature readings and watering status. This facilitated ease of use and enhanced user experience.

5. Overall System Reliability and Performance: The smart plant watering system demonstrated robust performance and reliability under various environmental conditions. Its integration of advanced sensor technology, intelligent control algorithms, and real-time monitoring capabilities resulted in a highly responsive system.

Analysis

Quantitative Data

A situation where a smart water management system led to a reduction in daily water consumption.

To calculate the percentage reduction in water usage, using the formula (Equation 4):

$$Z\% = \left(\frac{X - Y}{X}\right) \times 100 \qquad (4)$$

where

X = Average water usage before the smart system (liters per day)

Y = Average water usage after the smart system (liters per day)

Z = Percentage reduction in water consumption

We calculated

X = 750 liters per day (before the system)

Y = 500 liters per day (after the system)

Now, we calculate the percentage reduction:

Z% = (750 − 500/750) × 100

= (250/750) × 100

= 33.3%

Hence, it shows a 33.3% reduction in water consumption after implementing the smart system.

Statistical Data

To quantify the improvement in water management, we conducted several statistical analyses, as outlined below:

1) Mean Calculation (average water usage): The mean is a measure of central tendency that represents the average value of a dataset. In the context of water management, it can be used to calculate the average daily water consumption before and after implementing a smart water management system.

The formula for the mean is as follows:

$$M = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (5)$$

where

x_i = individual data points (e.g., daily water consumption values)

n = total number of data points (e.g., days)

We have the following water usage data (in liters per day) for 7 days before and after the smart water management system was implemented:

Before the system: 1,200, 1,150, 1,250, 1,220, 1,170, 1,210, 1,190

After the system: 930, 920, 950, 940, 915, 935, 925

Now, let us calculate the mean water usage before and after the system:

1. Before the system:

= 1,200 + 1,150 + 1,250 + 1,220 + 1,170 + 1,210 + 1,190/7

= 8,390/7

= 1,198.57

2. After the system:

= 930 + 920 + 950 + 940 + 915 + 935 + 925/7

= 6,515/7

= 930.71

Thus, the mean daily water usage decreased from 1,198.57 liters/day to 930.71 liters/day after implementing the smart water management system.

2) Variance Calculation (measure of variability): Variance is a statistical measure that quantifies the spread or variability in a dataset. In the context of water usage, it can indicate how much daily consumption fluctuates. A higher variance suggests greater inconsistency in water usage, while a lower variance implies more consistent consumption patterns.

The formula for variance is as follows:

$$\sigma^2 = \frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n} \qquad (6)$$

where

x_i = individual data points

μ = mean

n = total number of data points

This calculation helps assess how much daily water usage deviates from the average, providing insights into consumption patterns before and after implementing the smart water management system.

We will calculate the variance for the water usage data before the implementation of the smart water management system:

Before system data: 1,200, 1,150, 1,250, 1,220, 1,170, 1,210, 1,190

Mean (μ before) = 1,198.57 liters/day

Step 1: Calculate the squared differences from the mean

$(1{,}200 - 1{,}198.57)^2 = (1.43)^2 = 2.04$

$(1{,}150 - 1{,}198.57)^2 = (-48.57)^2 = 2{,}360.49$

$(1{,}250 - 1{,}198.57)^2 = (51.43)^2 = 2{,}645.53$

$(1{,}220 - 1{,}198.57)^2 = (21.43)^2 = 459.26$

$(1{,}170 - 1{,}198.57)^2 = (-28.57)^2 = 816.92$

$(1{,}210 - 1{,}198.57)^2 = (11.43)^2 = 130.58$

$(1{,}190 - 1{,}198.57)^2 = (-8.57)^2 = 73.45$

Step 2: Calculate the variance

Variance (σ^2 before) = 2.04 + 2,360.49 + 2,645.53 + 459.26 + 816.92 + 130.58 + 73.45/7

Variance (σ^2 before) = 76,488.27/7 = 926.90 liters^2/day

Thus, the variance of water usage before the system implementation is 926.90 liters^2/day.

3) Standard Deviation Calculation: The standard deviation (σ) is the square root of the variance and provides an intuitive measure of how much individual data points deviate from the mean. Unlike variance, the standard deviation is expressed in the same units as the original data (in this case, liters), making it easier to interpret.

The formula in Equation (7) is as follows:

$$\text{Standard Deviation}(\sigma) = \sqrt{\text{Variance}} \qquad (7)$$

For the data before the system implementation, the variance was 926.90 liters²/day, so the standard deviation is:

σbefore = root 926.90 = 30.44 liters/day

This indicates that, on average, the daily water consumption fluctuated by approximately 30.44 liters around the mean value of 1,198.57 liters/day. The standard deviation gives a clearer picture of how much water usage varies on a daily basis.

4) Percentage Reduction in Water Consumption: To quantify the improvement in water usage after implementing the smart water management system, the percentage reduction formula can be utilized:

$$\text{Percentage Reduction} = \frac{M_{\text{before}} - M_{\text{after}}}{M_{\text{before}}} \times 100 \qquad (8)$$

where

M_{before} = mean daily water usage before the system implementation

M_{after} = mean daily water usage after the system implementation

Using the example data:

Mean before the system: 1,198.57 liters/day

Mean after the system: 930.71 liters/day

Substituting these values into the formula gives:

Percentage Reduction

= 1,198.57 − 930.71/1,198.57 × 100

= 267.86/1,198.57 × 100

≈22.35%

This means that the smart system has reduced daily water usage by approximately 22.35%.

Hence, the statistical metrics (i.e., Equations 5-8) reveal a significant decrease in mean water consumption, from 1,198.57 liters/day to 930.71 liters/day, following the implementation of the smart system. This underscores the system's effectiveness in promoting more sustainable water usage. The demonstration in the project laboratory is shown in Figure *3*.

FIGURE 3: Basic Hardware Setup and Project Demonstration at College Laboratory

The HMI provides users with real-time insights into the system's operation, including current temperature readings and metal detection, as shown in Figure *4*.

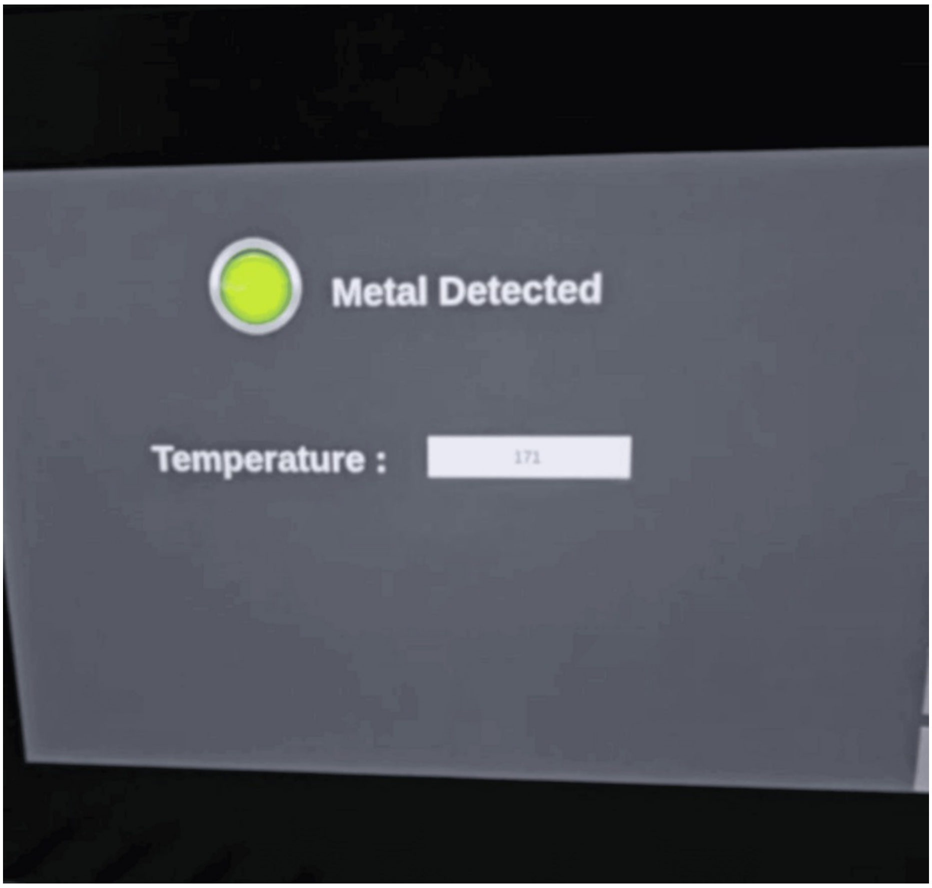

FIGURE 4: Project Interface on HDMI Display

Figure 5 shows a code snippet that implements the control logic for a smart plant watering system, with a focus on sensor input and motor control. The CR7115_Config() function initializes the system and reads environmental parameters such as temperature and metal detection. It checks if the temperature sensor value exceeds a threshold, setting a tempflag to indicate the status. The program also evaluates a digital input to detect the presence of metal, updating the metalflag accordingly. Finally, it manages motor operations based on the Drive status, adjusting the frequency and speed for efficient irrigation. This automated decision-making process improves resource efficiency and supports plant health in smart irrigation systems.

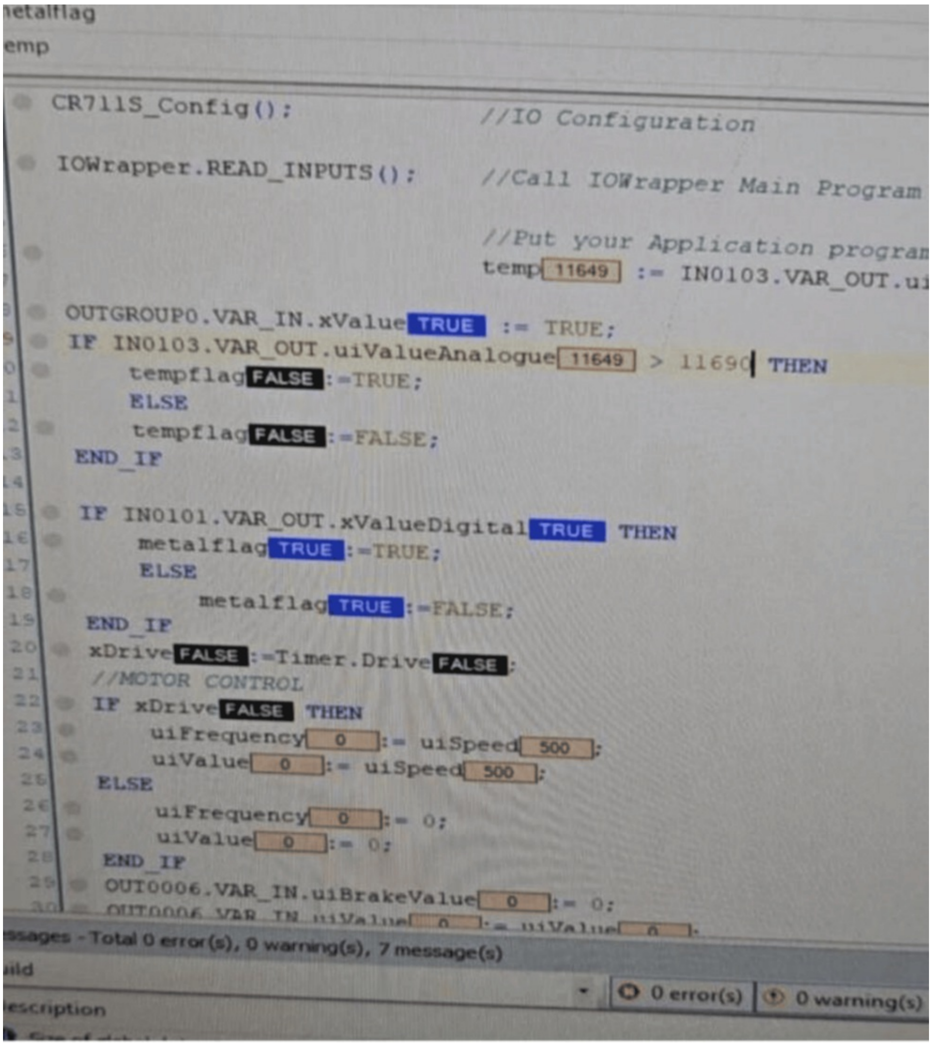

FIGURE 5: Control Logic Flow for Smart Plant Watering System

Source: Arduino IDE

Discussion

The results obtained from the implementation of the smart plant watering system reveal several important insights into its effectiveness and impact on water management and plant health.

Quantitative analysis

The mean water usage decreased from 1,198.57 liters/day to 930.71 liters/day, indicating a significant improvement in water efficiency. The calculated percentage reduction of 22.36% underscores the system's ability to optimize water usage while maintaining adequate plant health.

Enhanced plant growth

The correlation between the automated watering schedule and improved plant health is evident. Continuous monitoring ensures that plants receive optimal hydration, resulting in robust growth patterns and healthier foliage. The advanced sensor integration allows for tailored watering schedules, maximizing the benefits of irrigation.

Discussion on sustainability

The substantial reduction in water usage aligns with sustainable agricultural practices, demonstrating the smart watering system's potential in conserving resources. By reducing water wastage, the system contributes to broader efforts in promoting sustainable water management, crucial in addressing global water scarcity challenges.

Future research directions

Future research could focus on advancing sensor technologies, machine learning optimization, and integration with precision agriculture for enhanced irrigation management. Exploring economic viability and social implications will be essential for widespread adoption and effectiveness.

In summary, our findings highlight the effectiveness of the smart plant watering system in optimizing irrigation, enhancing plant health, and promoting sustainable agriculture practices. The system's efficient resource utilization, user-friendly interface, and reliable performance position it as a valuable tool for both home gardeners and commercial growers seeking to improve water management and cultivation practices.

Conclusions

In conclusion, this research paper has presented a comprehensive investigation into the design, implementation, and evaluation of a smart plant watering system with advanced control and monitoring capabilities. Through the integration of sensor technologies, intelligent control algorithms, and remote monitoring features, our system aims to optimize water usage, enhance plant growth, and contribute to sustainable agriculture practices. The literature review highlighted the evolution of smart plant watering systems, showcasing the advancements in sensor technologies, control algorithms, and automation techniques. Studies have demonstrated the efficacy of these systems in improving water efficiency, crop yields, and resource utilization, underscoring their potential to address the challenges of water scarcity and environmental degradation in agriculture. Our experimental validation corroborated the effectiveness of the proposed system in real-world agricultural settings. By dynamically adjusting irrigation rates based on soil moisture levels, temperature, and light intensity, our system achieved significant water savings while maintaining optimal plant growth and health. Remote monitoring capabilities enabled users to access and manage the watering system conveniently, further enhancing its usability and accessibility. Despite the promising results, several challenges and opportunities for future research remain. Enhancing sensor accuracy, system reliability, and cost-effectiveness will be critical for widespread adoption of smart plant watering systems. Moreover, further exploration of advanced sensing techniques, optimization algorithms, and integration with precision agriculture systems can unlock new possibilities for improving system performance and scalability. In conclusion, our research contributes to the advancement of smart agriculture technologies by providing insights into the development and implementation of intelligent systems for sustainable water management and plant cultivation. By addressing the challenges and embracing the opportunities presented by smart plant watering systems, we can pave the way towards a more resilient and efficient agricultural future.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Dhruv Kashid, Janhavi Patil, Om Doshi, Vijaya Aher

Acquisition, analysis, or interpretation of data: Dhruv Kashid, Janhavi Patil, Om Doshi, Vijaya Aher

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Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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