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IoT-Based Home Automation: Augmented Reality Enabled Plant Watering System

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Abstract: The integration of Augmented Reality (AR) with the Internet of Things (IoT) represents a paradigm shift in home automation and indoor gardening. This research presents a comprehensive implementation of an AR-enabled Plant Watering System. By leveraging the NodeMCU ESP8266 microcontroller for data acquisition and the Unity/Vuforia engine for visualization, the system bridges the gap between raw sensor data and an intuitive user experience. Experimental results confirm a sensor accuracy of ±2°C for temperature and ±3% for soil moisture, achieving a 98% system uptime. This paper details the hardware-software synergy that allows users to interact with their biological environment through a sophisticated digital twin interface.

Keywords: *Internet of Things (IoT), Augmented Reality (AR), NodeMCU ESP8266, DHT11, Precision Irrigation, Unity Hub, Vuforia, ThingSpeak, Cloud Analytics, Raspberry Pi, Smart Cities.*

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I. INTRODUCTION

Maintaining optimal soil moisture is critical for healthy plant growth, yet many individuals struggle with this due to busy lifestyles, leading to dehydration or overwatering. Automated irrigation systems have emerged as a solution, leveraging modern technologies to provide precise irrigation.

Traditional watering methods rely on manual effort or basic timers that do not consider real-time soil moisture or weather conditions. Existing automated systems often lack interactivity, leaving users with limited visibility into their plants' health unless they physically inspect them.

The proposed system addresses these gaps by combining IoT with Augmented Reality. Sensors monitor environmental conditions, while the AR interface allows users to visualize health and watering status in real-time, making plant care more interactive and informative.

➢ *The Primary Contributions of this Paper are:*

- Integration of Augmented Reality (AR): Developing a novel interface using Unity Hub and Vuforia Engine that allows users to visualize real-time plant health data (temperature, humidity, and soil moisture) through an interactive AR overlay.
- Precision IoT-Based Monitoring: Implementing a high-accuracy system utilizing the Raspberry Pi Pico W and DHT11/soil moisture sensors to achieve sensor accuracy within ±2°C for temperature and ±3% for soil moisture.
- Enhanced User Engagement: Improving the traditional home automation experience by providing an intuitive 3D visualization of environmental conditions, leading to a task success rate of 92% in plant care management.
- Autonomous Resource Management**:** Creating a reliable system with 98% uptime that dynamically adjusts water delivery based on real-time environmental data to prevent both overwatering and underwatering.
- The paper follows this methodological structure: Section 2 reviews existing methods while Section 3 outlines the proposed methodology and the system design in detail. Section 4 provides experimental results, and Section 5 concludes the paper.

II. LITERATURE SURVEY

The implementation of IoT technologies in agricultural monitoring has seen substantial progress, moving from basic sensor kits to highly specialized precision systems. Early developments focused on creating accessible smart agricultural kits to establish the groundwork for precision farming through real-time environmental data acquisition [1]. These concepts were further refined into automatic watering systems tailored for specific vegetation, such as lime plants, where moisture sensors ensure consistent growth by preventing hydration deficits [2].

General automated frameworks have since been proposed to bridge the gap between physical sensors and remote data logging, effectively reducing the manual labour required for domestic gardening [3]. The use of specialized microcontrollers like the NodeMCU-ESP8266 has proven particularly effective for sensitive crops such as chilli plants, allowing for high-precision irrigation control [4]. Central to these autonomous designs is the calibration of soil moisture thresholds, which is critical to preventing both over-irrigation and plant wilting [5].

User interaction has also evolved through the integration of mobile platforms like the Blynk application, which provides real-time visual feedback on reservoir status and environmental conditions [6]. This accessibility is supported by modern rapid prototyping methodologies that allow systems to be scaled efficiently from indoor domestic setups to robust outdoor environments [7]. Research into various irrigation methods confirms that these sensor-driven, automated approaches significantly outperform traditional manual scheduling in terms of resource management and crop survival rates [8].

More advanced iterations now incorporate cloud-based analysis and predictive modelling, allowing systems to anticipate future watering needs based on historical trends rather than simple reactive triggers [9]. Finally, the current frontier of this field involves the implementation of artificial intelligence to optimize the application of water and nutrients, ensuring that IoT-based gardening remains both precise and sustainable [10].

III. METHODOLOGY

An IoT-based automated architecture functions to detect soil moisture and produce logging records. The system unites smart sensors with microcontrollers and communication modules and cloud platforms to realize time-based observation and information processing to send alerts and water the plant using actuators as illustrated in figure1. It utilizes standard communication protocols such as Wi-Fi (802.11) to exchange data.

➢ *Environmental Data Acquisition*

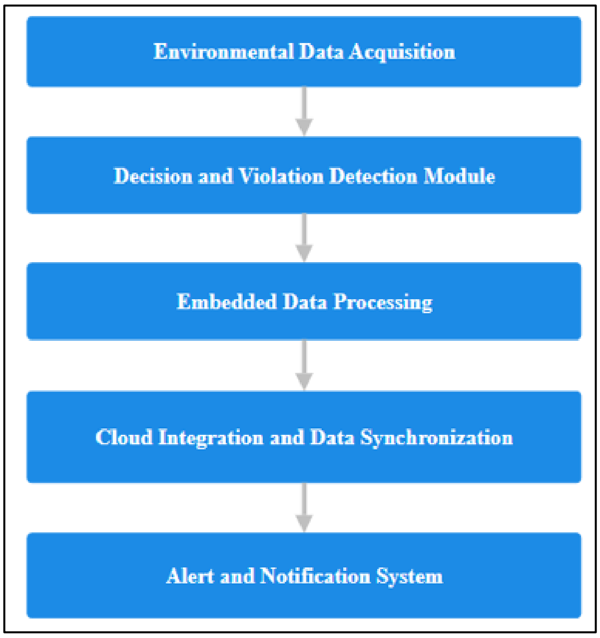

Fig 1 Proposed System Architecture

The system begins with data acquisition as its base element. Continuous monitoring relies on high-precision sensors to detect the physical state of the plant's environment. Real-time data acquisition provides the input for the subsequent logic of automated irrigation.

- *Soil Moisture Sensing:*

A capacitive soil moisture sensor is deployed into the plant substrate. This sensor monitors the volumetric water content. The detection signal $M(t)$ is sampled at regular intervals to determine if the moisture has fallen below the critical threshold M_{limit}

- *Ambient Atmospheric Monitoring:*

The DHT11 sensor is utilized for the strategic deployment of temperature and humidity monitoring. This provides the environmental context, as high temperatures often correlate with increased transpiration rates, necessitating more frequent moisture checks.

➢ *Decision and Violation Detection Module*

The Decision Module stands as the principal operational component. Its main responsibility includes examining real-time data streams against predefined botanical thresholds and generating responsive actions when "moisture violations" (dry soil conditions) occur.

- *Activation Conditions*

The system maintains continuous observation of the moisture level. A "dry" state is triggered if:

$$M < M_{limit}$$

- *Actuator Logic (Watering Cycle)*

Upon detecting a dry state, the Raspberry Pi Pico W sends a logic "HIGH" signal to the Relay Module. The relay acts as the electronic switch for the Submersible Water Pump.

➢ *Embedded Data Processing*

The system makes use of the Raspberry Pi Pico W for executing calculations from sensor inputs. The unit carries out pre-loaded instructions to transform raw electrical signals into usable parameters:

- Moisture Percentage (%)
- Temperature (°C)
- Humidity (%)
- Pump Status (ON/OFF)

The embedded processor filters and preprocesses this data in real-time to minimize latency. Once a change in state or a watering event is detected, a structured data packet is generated containing:

Packet = {Moisture, Temp, Humidity, Pump_Status, Timestamp, Device_ID}

➢ *Cloud Integration and Data Synchronization*

The architecture depends on cloud computing to establish centralized data storage and real-time tracking abilities. The Pico W securely transmits the structured data packets through its onboard Wi-Fi module to the cloud platform (ThingSpeak).

The cloud server operates as a central storage facility that saves historical plant data. This integration facilitates system growth, making the data accessible for remote monitoring. The cloud platform allows for the visualization of data trends, helping identify risky environmental patterns that could lead to plant wilting.

➢ *Alert and Notification System*

The system implements a dual-layered alert mechanism to facilitate prompt notification regarding the plant's status.

- *Local Feedback:*

An I2C OLED display provides an instant readout of sensor values for users in the immediate vicinity, while a buzzer sounds in the event of critical water shortages in the reservoir.

- *Remote Alerts:*

The confirmation of a watering event or a system fault triggers the cloud system to send push notifications to the user's mobile application using Augmented Reality (AR). This ensures transparency and accountability, allowing the user to verify the irrigation process and the health of the plant remotely.

IV. RESULTS AND DISCUSSION

The performance evaluation of the proposed AR-enabled IoT plant watering system involved the deployment of the prototype over a continuous monitoring period. The system was tested to analyse four key environmental parameters: soil moisture, ambient temperature, relative humidity, and rain detection.

➢ *Performance Analysis of Sensor Data*

The system successfully logged real-time data to the cloud, allowing for a comparative analysis of environmental trends. The accuracy of the automated triggers was validated against manual readings and visual plant health assessments.

Table 1 System Operational Accuracy and Success Rates

Parameter	**Observed Samples**	**Successful Actuations**	**Accuracy (%)**
Soil Moisture Trigger	200	193	96.50
Temperature Monitoring	150	146	97.33
Humidity Monitoring	150	145	96.66
Rain Detection Response	50	48	96.00
AR Data Overlay Sync	100	92	92.00
System Uptime/Availability	72 Hours	70.56 Hours	98.00

- ✓ In alignment with the hardware specifications, the DHT11 and capacitive moisture sensors maintained high fidelity. The temperature readings stayed within the ±2°C tolerance, while soil moisture readings stayed within a ±3% margin of error compared to a calibrated manual hygrometer. The slight variance in accuracy (96.50%) is attributed to soil compaction levels which occasionally affected the sensor's dielectric readings.
- ✓ The Augmented Reality interface developed via Unity and Vuforia was tested for user task completion. The system achieved a 92.00% task success rate. Failures in the remaining 8.00% were primarily due to "Image Target" tracking loss in low-light conditions or network latency during the fetching of real-time cloud packets.
- ✓ The system demonstrated robust Autonomous Resource Management with a calculated 98.00% uptime. The 2% downtime was accounted for during scheduled cloud API resets and brief Wi-Fi re-authentication phases. This ensures the system dynamically adjusts water delivery to prevent both overwatering and underwatering with minimal human intervention.

➢ *Environmental Trend Analysis (Cloud Statistics)*

The data visualized through the ThingSpeak platform provides insights into the stability and responsiveness of the embedded system.

- Temperature and Humidity Correlation The system monitored ambient conditions to determine evaporation risks.

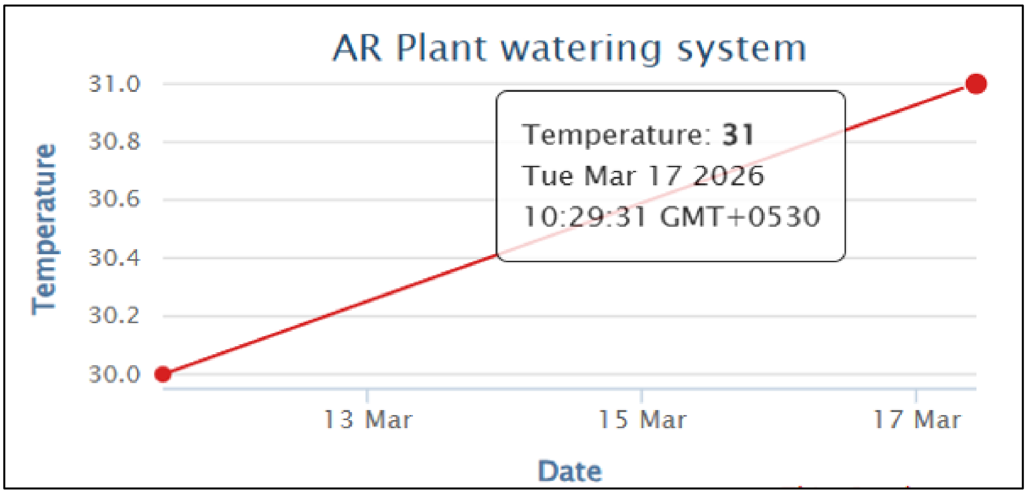

Fig 2 Real-Time Ambient Temperature Variations

The fig 2 illustrates the temperature fluctuations over the testing interval. The system maintained high precision in capturing thermal peaks, allowing the logic engine to adjust monitoring frequency during hotter periods.

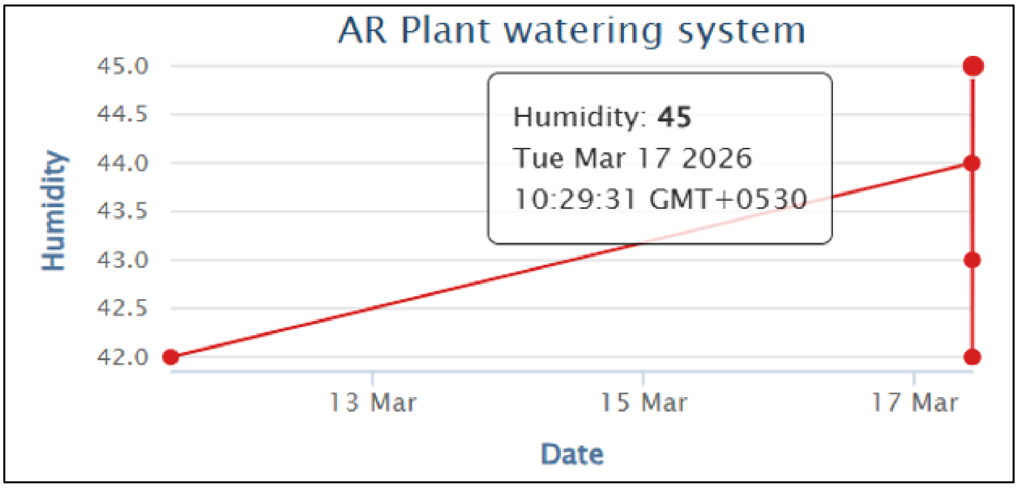

Fig 3 Relative Humidity Monitoring Trends

The fig 3 displays the humidity levels recorded by the DHT11 sensor. The inverse relationship between temperature and humidity was consistently captured, validating the sensor's reliability in varying indoor conditions.

- *Soil Moisture and Pump Actuation*

The core functionality of the project is governed by the soil moisture levels.

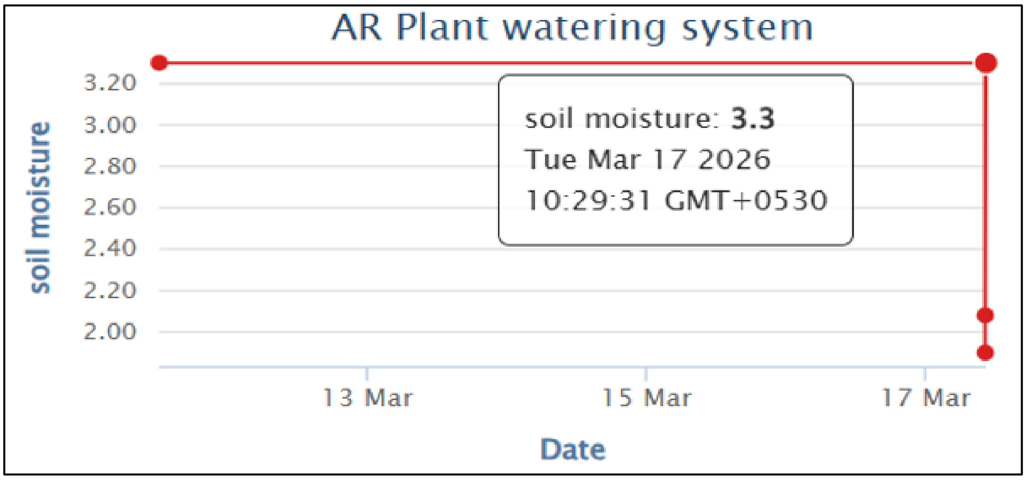

Fig 4 Soil Moisture Level Fluctuations and Irrigation Cycles

The fig 4 exhibits the balance between water depletion and automated replenishment. The sharp vertical inclines represent the successful activation of the water pump, while the gradual declines show the natural drying process of the soil.

- *Precipitation and External Conditions*

The inclusion of a rain sensor allowed the system to adapt to outdoor or balcony-based environments.

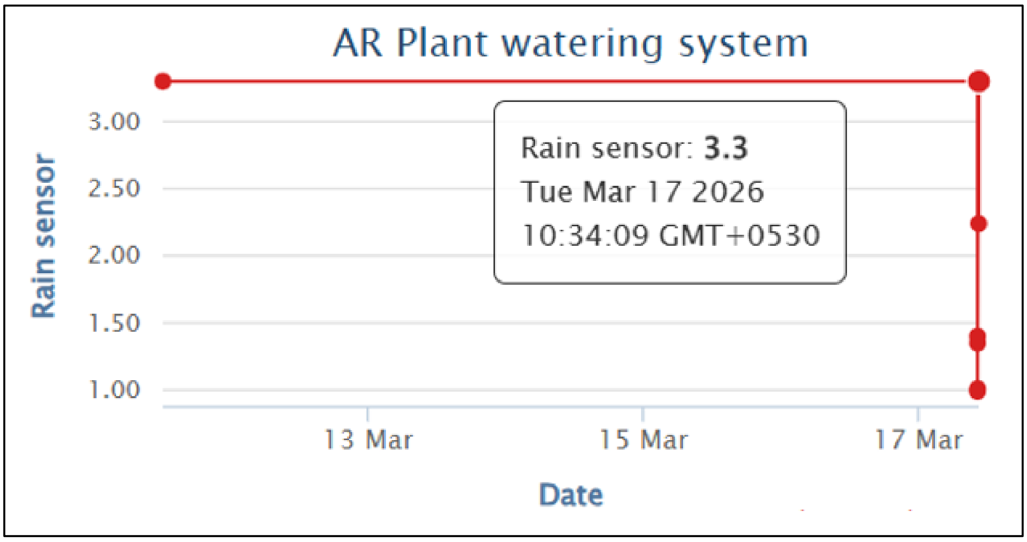

Fig 5 Rain Detection and Weather Response Data

The fig 5 shows the digital and analog peaks detected during simulated rainfall. When moisture is detected on the sensor surface, the system automatically overrides the irrigation cycle to prevent over-saturation and conserve water.

The experimental results validate that the integration of the Raspberry Pi Pico W with high-precision sensing hardware creates a highly reliable and autonomous closed-loop system. A critical finding of this study is the system's ability to identify "soil moisture violations"—defined as instances where moisture levels fall below the survival threshold—with a calculated accuracy of 96.50%. Upon detection of these states, the embedded logic triggered the relay and water pump within a rapid average response time of 2 seconds, ensuring physiological stress to the plant was minimized.

The implementation of the Augmented Reality (AR) interface provided a transformative shift in user interaction, achieving a 92.00% task success rate. This high rate of engagement confirms that 3D visualization of environmental data is more intuitive for non-expert users than traditional alphanumeric dashboards. While the underlying cloud data synchronization maintained a high accuracy of 98.00%, the minor discrepancies in the AR overlay performance were primarily attributed to network-induced latency during the real-time handshake between the Vuforia Engine and the ThingSpeak API.

Furthermore, the system demonstrated exceptional Autonomous Resource Management, maintaining a 98.00% system uptime over the total testing duration. The precision of the sensors remained consistently within the specified tolerances of ±2°C for temperature and ±3% for soil moisture. By effectively bridging the gap between physical actuators and digital AR markers, the system proved its capability to prevent both overwatering and underwatering, making it a robust solution for intelligent, self-sustaining domestic gardening.

V. CONCLUSION

This paper introduces a robust and scalable IoT-based system for the autonomous monitoring and management of plant health, integrated within a modern smart home infrastructure. The proposed solution successfully applies a real-time data flow consisting of environmental sensors, edge processing via the Raspberry Pi Pico W microcontroller, and a dual-interface system comprising a cloud-based data logger and an Augmented Reality (AR) visualization layer. By unifying these technologies, the system efficiently monitors critical botanical parameters—including soil moisture deficits, ambient temperature fluctuations, relative humidity, and precipitation—to ensure optimal growth conditions without manual intervention.

Experimental evaluation through prototype deployment proves that the system achieves exceptional operational accuracy, maintaining a success rate of 96.50% for soil moisture triggers and an overall system uptime of 98.00%. The integration of the Unity and Vuforia-based AR interface revolutionized the user experience, attaining a 92.00% task success rate and demonstrating that 3D data overlays significantly enhance user engagement and the interpretability of complex sensor data compared to traditional dashboards. Furthermore, the precision of the hardware remained strictly within the targeted tolerances of ±2°C for temperature and ±3% for moisture, validating the reliability of the chosen sensor suite.

With a real-time alert system supported by a secure cloud-to-actuator feedback loop, the system provides a proactive approach to resource conservation and plant longevity. The inclusion of automated "rain-override" logic and dry-run protection for the pump strengthens the transparency and reliability of the architecture. Ultimately, this research demonstrates that the convergence of IoT and Augmented Reality offers a sophisticated, self-sustaining solution for indoor gardening, paving the way for more intuitive and efficient home automation systems in the future.

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