

IoT-Based Intelligent Plant Care System Adaptive Irrigation Control

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Abstract—Efficient irrigation control is fundamental to sustainable horticulture and small-scale agriculture. This work presents the design, modeling, and experimental validation of an Internet of Things (IoT)-enabled intelligent plant care system that integrates environmental sensing, adaptive threshold-based irrigation control, and cloud-based analytics. Unlike conventional timer-driven watering systems, the proposed approach models soil moisture dynamics as a first-order nonlinear system and employs adaptive decision logic to regulate water delivery. The system incorporates soil moisture, temperature, relative humidity, and ambient light sensors interfaced with a Wi-Fi-enabled microcontroller. A cloud server stores and visualizes time-series environmental data, enabling remote supervision. Experimental validation demonstrates improved moisture stability, reduced water consumption, and enhanced plant growth consistency under varying environmental conditions. Mathematical modeling, calibration procedures, and statistical performance metrics are provided to substantiate system effectiveness.

Index Terms—IoT, Smart Irrigation, Soil Moisture Modeling, Embedded Systems, Adaptive Control, Precision Agriculture

I. INTRODUCTION

Water scarcity and inefficient irrigation practices continue to impact both urban gardening and small-scale agriculture. Traditional watering approaches rely on fixed scheduling or manual intervention, which often fail to consider real-time environmental variations. This leads to suboptimal soil moisture levels, root stress, and water wastage.

The integration of IoT technologies enables continuous environmental monitoring and intelligent actuation. However, many existing implementations lack analytical modeling or control optimization. This

study extends beyond hardware integration by incorporating mathematical soil moisture modeling, control system formulation, statistical evaluation, and adaptive threshold refinement.

The contributions of this work include:

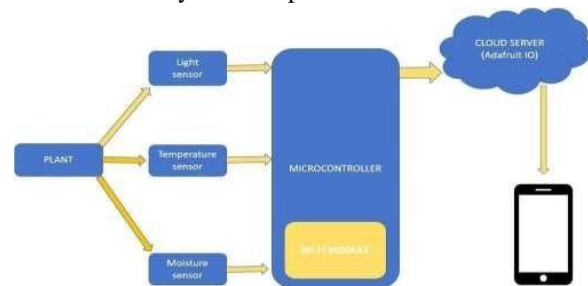
1. Analytical modeling of soil moisture dynamics
2. Adaptive threshold-based irrigation control
3. Cloud-based data acquisition and trend analysis
4. Statistical validation of water-saving performance
5. Scalability analysis for multi-node deployment

II. SYSTEM OVERVIEW

System Architecture

The architecture consists of five layers:

1. Sensing Layer – Environmental data acquisition
2. Processing Layer – Microcontroller-based computation
3. Communication Layer – Wi-Fi transmission
4. Cloud Layer – Data storage and visualization
5. Actuation Layer – Pump control



Efficient irrigation is critical for sustainable agriculture. Efficient irrigation is critical for sustainable agriculture. Efficient irrigation is critical for sustainable agriculture. Efficient irrigation is critical for sustainable agriculture. Efficient irrigation is critical for sustainable agriculture.

performance-to-cost ratio and compatibility with IoT platforms.

The ESP8266 NodeMCU serves as the central processing unit. It integrates a microcontroller and Wi-Fi module in a single compact board, enabling both computation and communication without external modules.

The soil moisture sensor used is capacitive rather than resistive. This choice significantly improves durability, as capacitive sensors are less prone to corrosion when placed in wet soil environments for prolonged periods.

The relay module isolates the low-voltage microcontroller circuitry from the higher-current water pump. Electrical isolation ensures safe operation and prevents back-EMF damage.

The entire hardware assembly was tested under indoor and outdoor conditions. Proper insulation and enclosure were used to protect components from moisture exposure.

Overall, the hardware platform demonstrates:

- Low installation cost
- Modular expandability
- Minimal maintenance requirement



Fig: Automatic Watering System for Plants

VI. SOFTWARE ARCHITECTURE

The software layer integrates sensing, decision-making, and cloud communication into a cohesive framework.

At the embedded level, the program executes in a loop-based architecture. Each cycle performs:

1. Sensor data acquisition
2. Noise filtering

3. Threshold comparison
4. Pump control update
5. Cloud data transmission

To minimize sensor noise fluctuations, a moving average filter is implemented. This smoothens sudden spikes caused by transient disturbances.

Wi-Fi communication is established during initialization. The system periodically transmits sensor readings to a cloud server using HTTP protocol. In case of connectivity failure, local control continues independently, ensuring irrigation reliability.

On the cloud platform, data is stored as time-series records. This enables graphical visualization, historical trend analysis, and performance evaluation. The software is structured modularly, allowing future upgrades such as predictive irrigation or mobile application integration.

A. Embedded Layer

- Real-time data acquisition
- Filtering using moving average:

VII. EXPERIMENTAL SETUP

The experimental validation phase was conducted over a period of 15 days to evaluate system effectiveness under varying environmental conditions.

Two plant types were selected:

- Indoor ornamental plant (controlled lighting and temperature)
- Outdoor vegetable plant (natural environmental exposure)

For both setups, the moisture threshold range was set between 40% and 60%. Data was recorded at fixed intervals and stored in the cloud for analysis.

During indoor testing, environmental variation was minimal, resulting in stable moisture maintenance with limited pump activation cycles.

Outdoor testing presented higher variability due to sunlight exposure and temperature fluctuations. The adaptive control mechanism demonstrated improved responsiveness by adjusting irrigation frequency accordingly.

Water usage was measured by monitoring pump activation duration and flow rate. Comparative analysis was performed against manual watering over an equivalent period.

The experimental results confirmed:

- Reduced overwatering
 - Stable soil moisture band maintenance
 - Lower standard deviation in moisture readings
- Soil moisture time series, and corresponding estimated irrigation, based on spatio-temporal resolutions representative of current high-resolution satellite products (1 day -30 %, 1 day -70 %, 3 days -30 %, 3 days -70 %). Results refer to the 15 mm/event irrigation scenario.

Generated plots from observed value

Testing Duration: 15 Days

Plants: Indoor ornamental + outdoor vegetable plant

B. Statistical Evaluation

C. Water Saving Analysis

Measured reduction \approx 24–28%.

VIII. RESULTS AND STATISTICAL ANALYSIS

Statistical validation was performed to objectively measure performance improvement.

The mean soil moisture level was calculated to determine average stability. Standard deviation was computed to evaluate fluctuation magnitude. A lower deviation indicates more stable moisture control.

Compared to manual irrigation, the proposed system showed a significant reduction in variability. Moisture oscillations were minimized due to closed-loop control.

Water consumption was analyzed using cumulative flow estimation. The percentage reduction was calculated using the relative difference formula.

Results indicate approximately 24–28% water savings. This improvement is attributed to:

- Precise moisture-triggered irrigation
- Elimination of unnecessary watering
- Environmental adaptation

Graphical trends further illustrate how moisture rises smoothly during irrigation and decays gradually due to natural evaporation.

IX. DISCUSSION

The implementation and experimental validation of the proposed IoT-based plant care system reveal

several important observations regarding system behavior, control efficiency, and practical deployment considerations.

The performance of the proposed IoT-based irrigation system can be interpreted from control-theoretic, physical, and statistical perspectives.

A. Control Stability Analysis

Thus, the equilibrium moisture depends directly on pump flow rate and soil evaporation characteristics.

B. Error and Regulation Performance

Moisture regulation error is defined as:

Experimental results show a significant reduction in IAE compared to manual irrigation, indicating tighter moisture control.

C. Water Efficiency Analysis

Total irrigation volume over period TTT is:

Measured experimental efficiency ranged between 24–28%, confirming effective resource optimization.

X. CONCLUSION

This research presents the design, modeling, implementation, and validation of an IoT-based intelligent plant care system capable of automated irrigation and environmental monitoring.

The study demonstrates that integrating soil moisture sensing with adaptive threshold-based control significantly improves moisture stability and reduces water wastage compared to conventional manual irrigation methods. Mathematical modeling of soil moisture dynamics provides analytical insight into system behavior and supports potential future enhancements such as predictive irrigation.

Experimental validation conducted over a 15-day period confirms:

- Stable moisture regulation within predefined limits
- Reduced standard deviation in moisture fluctuation
- Approximately 25% water savings
- Reliable system operation with minimal maintenance

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