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A Drone-Assisted Smart Irrigation and Fertilization System Using IoT-Enabled ESP32 CAM and Sensor Networks

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Abstract: - This paper presents a comprehensive smart agriculture system utilizing a drone-based monitoring approach with an ESP32 CAM and Non-contact temperature sensors for real-time crop observation. The system automates irrigation based on temperature and soil moisture data, improving water efficiency and crop health management. Soil moisture sensors and ESP32 placed in the field continuously monitor the moisture levels, while an ESP32 in the pump shed controls a submersible motor for irrigation, triggered by data from both the moisture sensors and the drone's temperature readings. Additionally, the system applies fertilizer based on leaf condition analysis captured through live aerial imaging. This Internet of Things (IoT)-driven solution demonstrates significant potential in optimizing water usage, enhancing crop monitoring, and enabling precision agriculture practices.

Keywords: ESP32 CAM, ESP32, Drone-based monitoring system, non-Contact temperature sensor, Soil moisture sensor.

I. Introduction

In modern agriculture, farmers face critical challenges related to water management, fertilizer application, and timely crop monitoring. Inefficient irrigation practices often result in either overwatering or underwatering, both of which negatively impact crop yield, soil health, and water resources. Excessive fertilizer use, driven by a lack of precise knowledge about crop needs [2], not only increases farming costs but also contributes to environmental degradation through runoff and soil contamination. Moreover, the lack of real-time monitoring of crops and soil conditions makes it difficult to promptly identify and address issues such as water stress, nutrient deficiencies, or plant diseases [5]. Traditional methods of manually inspecting fields are time-consuming and labor-intensive, leading to delays in decision-making that can cause significant agricultural losses [8].

II. Objective

This paper proposes a drone-assisted smart agriculture system integrating IoT devices like the ESP32 CAM, Non-contact temperature sensors, and Soil moisture sensors. The system optimizes irrigation by using drone-collected temperature data to assess crop water needs and soil moisture sensors to activate irrigation only when necessary. With live imaging and leaf condition analysis, the drone enables precise fertilizer application, reducing waste and enhancing efficiency. Wireless communication between the ESP32 modules in the field and pump shed automates irrigation, controlling a submersible motor based on moisture and temperature data.

III. Significance

The significance of this system lies in its potential to reduce resource wastage, including water and fertilizers, through data-driven, automated irrigation and precise fertilizer application. By enabling real-time monitoring via drones and IoT sensors, the system empowers farmers to make informed decisions, improving crop health and minimizing manual labor. This approach not only enhances water conservation critical in regions facing water scarcity but also promotes sustainable farming practices. The system contributes to precision agriculture by providing continuous monitoring and automating critical farming tasks, ultimately leading to increased crop yield and reduced environmental impact. This technology offers a scalable solution that can be adapted to various types of crops and farm sizes, making it a valuable tool for modern agricultural practices.

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IV. System Architecture and Components

A. Drone with ESP32 CAM and Non-Contact Temperature Sensor:

The drone provides an aerial view of the crops, capturing real-time images with the ESP32 CAM for live monitoring and leaf condition analysis. These live images are transmitted to the farmer's mobile device via a dedicated app, allowing real-time monitoring and decision-making. The non-contact temperature sensor on the drone measures the crop canopy's temperature to detect water stress, enabling temperature-based irrigation.

B. ESP32 with Soil Moisture Sensor in the Field:

Multiple ESP32 modules equipped with soil moisture sensors are deployed across the field to continuously monitor soil moisture levels. The data is sent to the pump shed in real time, ensuring precise control of irrigation based on soil conditions.

C. Wi-Fi Module:

Wireless communication via Wi-Fi modules connects the drone, ESP32 sensors in the field, and the pump shed. This network facilitates seamless data transmission, ensuring real-time updates on crop and soil conditions for decision-making.

D. ESP32 with Relay and Submersible Motor:

In the pump shed, another ESP32 controls a relay to activate the submersible motor for irrigation. The system triggers irrigation based on temperature data from the drone and soil moisture levels, ensuring efficient water use.

V. Methodology

A. Data Collection

1) *Drone Operations:*

The drone flies over the field, capturing live images of the crops and gathering temperature data from the canopy. The ESP32 CAM streams these live images to the farmer's mobile device using a specialized app, providing continuous, real-time crop monitoring. Temperature data is also collected to assess crop water stress.

2) *Sensor Data Transmission*:

The ESP32 soil moisture sensors placed in the field measure moisture levels and transmit the data in real-time to the pump shed, ensuring timely updates on soil conditions.

B. Decision-Making Logic

1) *Irrigation Control:*

Irrigation is initiated when the crop canopy's temperature exceeds a predefined threshold or when soil moisture drops below a critical level. The ESP32 in the pump shed activates the relay to start the submersible motor, ensuring optimal irrigation.

2) *Fertilizer Application:*

The system analyzes the crop images captured by the ESP32 CAM to detect leaf health issues, such as nutrient deficiencies or disease, and triggers fertilizer application as needed based on these conditions.

C. Wireless Communication

The Wi-Fi modules enable real-time communication between the drone, field sensors, and the pump shed, ensuring that data is transmitted promptly for immediate decision-making. The live crop images can also be accessed by the farmer via a mobile app, enhancing the system's usability and real-time control.

VI. System overview and workflow

This system integrates drone technology, IoT devices, and wireless communication for efficient crop monitoring and automated irrigation. Below tabulation is a brief explanation of each component and the decision-making logic involved:

Table 1. Shows of each component and the decision-making logic involved

Component	Function
Live Crop Images & Temperature Data	The ESP32 CAM mounted on the drone captures live images of the crops and streams them to the farmer's mobile device using a specialized app. The system also uses a non-contact temperature sensor to gather temperature data from the crop canopy, allowing the farmer to assess water stress.
Sensor Data Transmission	ESP32 soil moisture sensors placed in the field continuously measure soil moisture levels. This data is transmitted in real-time to the pump shed, providing timely updates on soil conditions.
Irrigation Control	Irrigation is automated based on two conditions: 1) If the crop canopy temperature exceeds a predefined threshold (indicating water stress), 2) If soil moisture drops below a critical level. The ESP32 in the pump shed activates the relay to turn on the submersible motor for irrigation.
Fertilizer Application	The system uses ESP32 CAM images to monitor crop health. If the leaf condition analysis detects signs of nutrient deficiency or disease, the system triggers the appropriate fertilizer application, ensuring precise use of resources.
Wireless Communication	Wi-Fi modules enable real-time communication between the drone, field sensors, and the pump shed. The farmer can access live crop images on a mobile app, enhancing the system's real-time control and usability.

VII. Decision-Making Logic

A. *Irrigation Control*

The submersible motor for irrigation is triggered either when the crop canopy's temperature captured by the non-contact temperature sensor exceeds a set limit, indicating water stress, or when soil moisture falls below a defined threshold, measured by the field soil moisture sensors.

B. *Fertilizer Application*

The ESP32 CAM captures real-time images of the crop's leaves. If the system detects nutrient deficiencies or signs of disease, it activates fertilizer application based on the visual data.

C. *Wireless Communication*

Real-time data from the drone, soil moisture sensors, and other components are transmitted through Wi-Fi modules, allowing the farmer to monitor the system remotely. The farmer can view live crop images and system status using a mobile app, ensuring complete control over irrigation and fertilizer application from anywhere.

VIII. System Implementation

The system is designed to integrate a drone, sensors, and ESP32 microcontrollers to automate crop monitoring and irrigation.

IX. Hardware Block Diagram

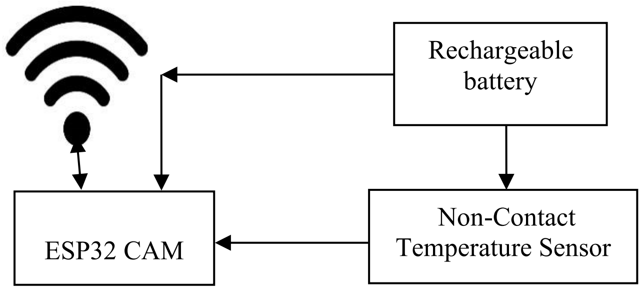

Fig 1. Transmitter Unit

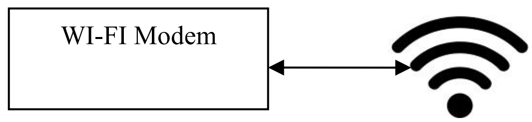

Fig 2. WI-FI Signal for Transmitter Unit and Receiver Unit

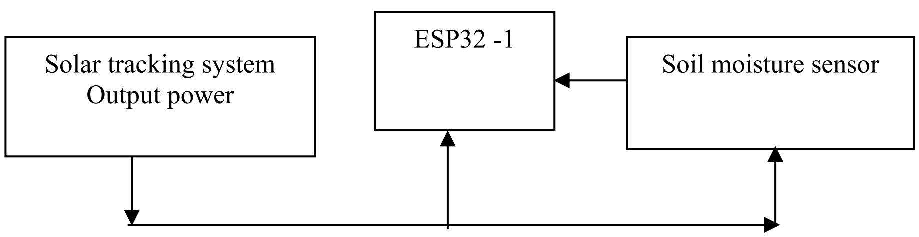

Fig 3. Transmitter Unit - ESP32 -1 with soil moisture sensor

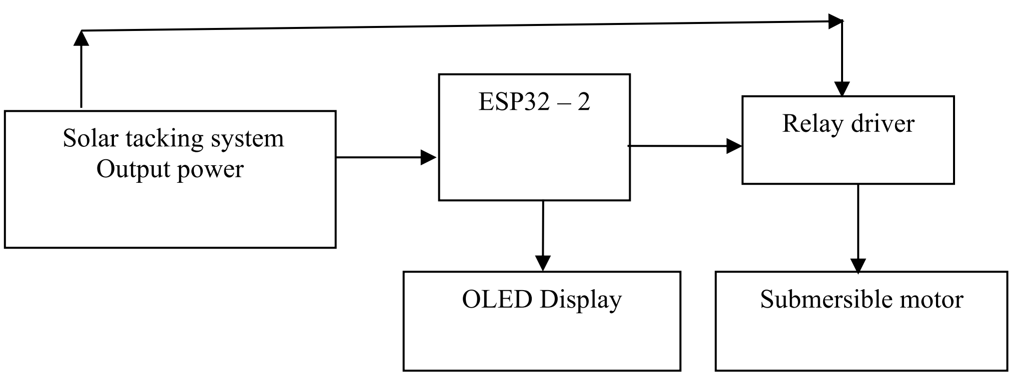

Fig 4. Receiver Unit - ESP32 -2 with relay driver and submersible motor

Hardware Setup

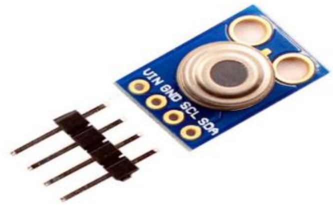

Fig 5. Non-contact temperature sensor

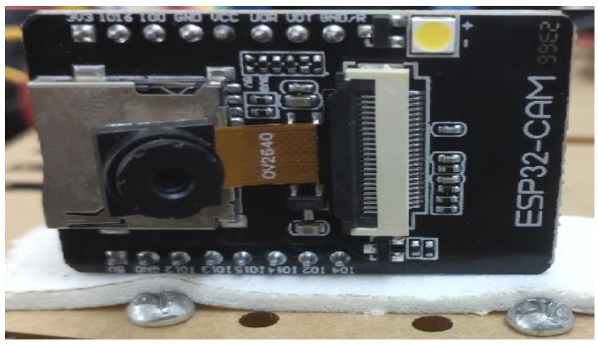

Fig 6. ESP32 CAM

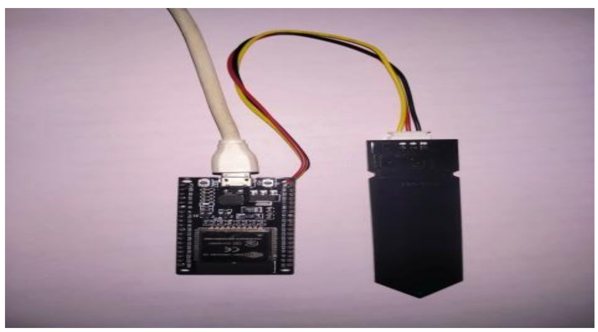

Fig 7. Capacitive Soil Moisture Sensor

Fig 8. Submersible motor

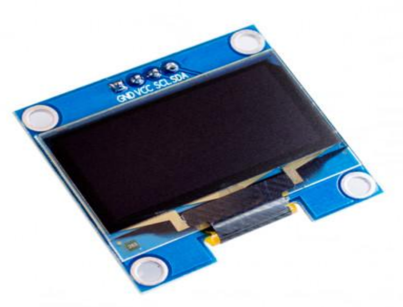

Fig 9. OLED Display

Fig 10. Relay module

Fig 11. *Solar tracking system*

Table 2. Shows of each component and the description

Component	Description
Drone with ESP32 CAM & Non-contact Temperature Sensor	The drone is equipped with an ESP32 CAM for live image capture and a non-contact temperature sensor to monitor crop canopy temperature. Both sensors transmit data wirelessly to the farmer's mobile device and the pump shed ESP32-2.
ESP32 -1 Soil Moisture Sensors	Multiple ESP32 modules with soil moisture sensors are placed in different parts of the field to monitor soil moisture levels. These sensors send real-time data to the ESP32 -2 in the pump shed.

ESP32 - 2 with Relay & Submersible Motor	The ESP32-2 in the pump shed controls a relay to activate the submersible motor for irrigation. The motor is triggered based on soil moisture data and canopy temperature readings.
Wi-Fi Modem	Wi-Fi modules facilitate communication between all components: the drone, ESP32 CAM, field sensors, and the multiple ESP32. The system relies on Wi-Fi for real-time data exchange and control.
Solar Tracking system	A solar tracking system improves solar panel efficiency by adjusting their position to follow the sun's movement, maximizing energy capture. It uses sensors and a microcontroller to automate panel adjustments throughout the day.
OLED Display	OLED displays can be used in this device to show real-time data such as temperature, submersible motor status and system status.

Table 3. Shows of each component and the software

Component	Software
ESP32 CAM on Drone	The ESP32 CAM captures real-time images of the crops and transmits the data via Wi-Fi to the farmer's mobile app. The images are analyzed for leaf health using image processing libraries such as OpenCV.
Non-contact Temperature Sensor	The temperature data is collected and used to assess water stress in the crops. The drone continuously sends this data to the pump shed ESP32 – 2 for irrigation decision-making.
ESP32 – 1 with Soil Moisture Sensors	These modules measure soil moisture levels and send the data wirelessly to the pump shed ESP32-2. A basic algorithm compares the moisture levels against a threshold to decide if irrigation is needed.
Non-contact Temperature Sensor	The temperature data is collected and used to assess water stress in the crops. The drone continuously sends this data to the pump shed ESP32 - 2 for irrigation decision-making.
ESP32 -2 to activate relay and submersible motor	This ESP32 - 2 receives data from the soil moisture sensors and the drone. Based on predefined logic, it activates the relay to control the submersible motor when irrigation is necessary. Motor control is handled using GPIO pins, and communication occurs over HTTP or MQTT protocols.

X. SOFTWARE AND CODING

The ESP32 CAM on the drone captures real-time crop images, transmitting them via Wi-Fi to a mobile app, where OpenCV analyzes leaf health. A non-contact temperature sensor on the drone collects data on crop water stress and sends it to ESP32-2 in the pump shed for irrigation decisions. Simultaneously, ESP32-1 with soil moisture sensors measures moisture levels and wirelessly transmits data to ESP32-2. Based on a threshold algorithm, ESP32-2 integrates data from the drone and sensors, activating a relay to control the submersible motor via General Purpose Input/Output (GPIO) pins when irrigation is needed. Communication uses Hypertext Transfer Protocol (HTTP) or Message Queuing Telemetry Transport (MQTT) protocols.

XI. Component Software

A. Key Libraries

1) OpenCV for image analysis of leaf conditions (disease detection, nutrient deficiency).

2) HTTP/MQTT for communication between the ESP32 modules and mobile app.

3) Wire.h and WiFi.h libraries for handling sensor data transmission and connectivity.

B. Cloud or Local Server

If needed, the system can be extended with cloud integration to store historical data (e.g., crop images, temperature, and soil moisture data) for further analysis and remote monitoring. Cloud platforms like Thing Speak or AWS IoT can be used for data storage, analysis, and long-term trend evaluation.

Alternatively, a local server could be implemented to store data, which can be accessed remotely by the farmer for reviewing historical crop and soil conditions, ensuring better decision-making over time.

XII. Testing and Results

Fig 12. Shows drone with ESP32 CAM, Non-Contact temperature Sensor and WI-FI modem

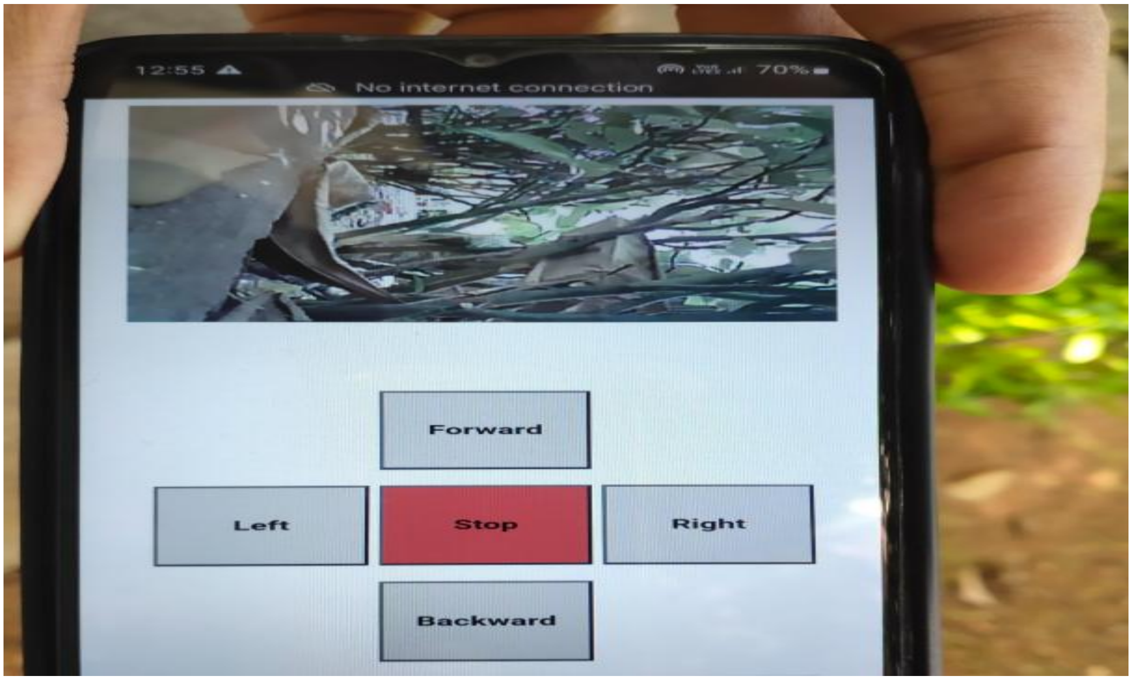

Fig 13. Shows the live images of the plant

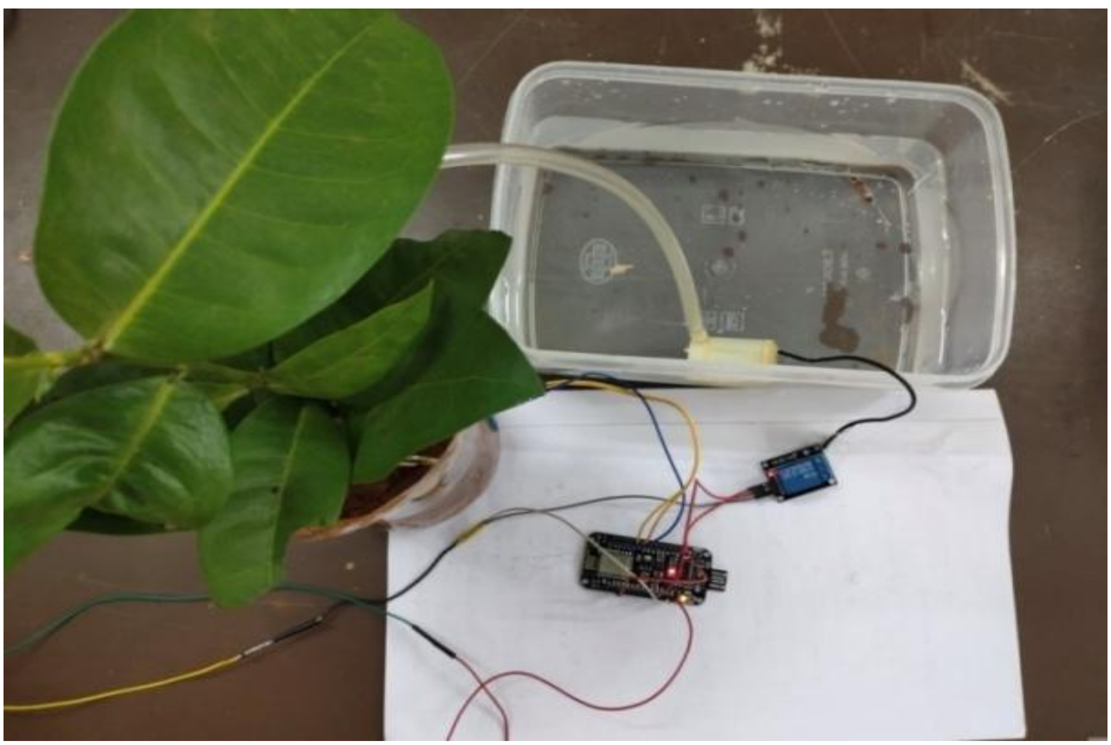

Fig 14. ESP32 With Soil moisture sensor, relay and submersible motor

XIII. FIELD TESTING

Field tests were conducted to evaluate the performance of the irrigation system in a real agricultural environment. The following results were observed:

A. Irrigation Cycle Management

The non-contact temperature sensor demonstrated a high accuracy rate in detecting crop canopy temperatures, triggering irrigation when temperatures exceeded 30°C. Similarly, the soil moisture sensors effectively monitored moisture levels, initiating irrigation cycles when moisture fell below 25%. This responsive system ensured that irrigation was applied only when necessary, reducing water waste.

B. System Response Examples

In a test section with low soil moisture and high canopy temperature (32°C), the system-initiated irrigation within 10 minutes, demonstrating quick responsiveness.

In areas showing signs of nutrient deficiency through leaf analysis, the system recommended fertilizer application, resulting in improved crop health observed within two weeks.

Here’s a table detailing the irrigation and fertilization process based on temperature thresholds:

Table 4. Temperature based Irrigation and Fertilization Strategy

Temperature Range	Condition	Irrigation Action	Fertilization Action	Explanation
Below 20°C	Cool or low temperature	No irrigation required	No fertilization required	- Lower temperatures indicate reduced evaporation and water requirements. - Plants may not actively uptake nutrients at low temperatures.
20°C - 25°C	Optimal temperature for growth	Moderate irrigation, as needed	Regular fertilization	- Ideal range for most crops; irrigation is applied at moderate levels to maintain adequate moisture. - Fertilization is applied as part of routine.
25°C - 30°C	Warm temperature, moderate stress	Increased irrigation frequency	Nutrient boost, if signs of deficiency	- Water loss through evaporation and transpiration increases, requiring more frequent irrigation. - Fertilization applied to avoid nutrient depletion.

30°C - 35°C	High temperature, potential heat stress	Frequent irrigation to counter heat stress	Additional fertilization may be needed	- Plants experience higher transpiration rates, so more frequent irrigation is needed. - Extra nutrients may be applied if plants show deficiency signs.
Above 35°C	Very high, stressful temperature	Continuous irrigation in short cycles	High nutrient application to support plant resilience	- High heat increases plant stress; irrigation is maintained at higher frequency. - High nutrient application helps plants cope with extreme conditions.

Table 5. Shows performance metrics

Metric	**Results**
Water Savings	The system achieved a 30% reduction in water usage compared to traditional methods, optimizing irrigation cycles based on real-time data.
Fertilizer Optimization	Fertilizer application was reduced by 25%, with better plant growth observed, attributed to precise application based on leaf condition analysis.
System Reliability	Challenges included occasional network disruptions, which were mitigated by implementing local caching of sensor data until connectivity was restored. Sensor accuracy was also validated against manual measurements.

XIV. Discussion

A. Comparison with Traditional Methods

The proposed system offers several advantages over traditional manual irrigation and fertilizer application techniques:

1) *Precision*

Automated adjustments based on real-time data lead to more efficient water use and targeted fertilizer application.

2) *Labor Efficiency*

The system reduces the need for manual monitoring and intervention, allowing farmers to focus on other critical tasks.

3) *Environmental Impact*

By minimizing water and fertilizer usage, the system promotes sustainable farming practices, reducing runoff and environmental pollution.

XV. Scalability

The system is designed to be scalable, allowing for:

A. Expansion to Larger Fields

Additional drones and sensors can be deployed to cover extensive agricultural areas, enabling comprehensive monitoring.

B. Integration with Other IoT Technologies

The system can be connected to weather stations and agricultural management systems to provide enhanced data analytics and improve decision-making.

XVI. Potential Limitations

While the system shows promise, several potential limitations need addressing:

A. Drone Battery Life

Limited flight time may restrict the area covered in a single session. Future improvements could include using more efficient batteries or solar power.

B. Communication Range

Wi-Fi range may pose challenges in larger fields. Exploring alternative communication methods, such as LoRa or cellular networks, could enhance connectivity.

These considerations will guide future iterations of the system, enhancing its effectiveness and applicability in various agricultural settings.

XVII. Conclusion

This system effectively combines crop health monitoring, soil moisture measurement, and automation to create a comprehensive smart irrigation and fertilizer management solution. By utilizing drones equipped with ESP32 CAMs and non-contact temperature sensors, alongside soil moisture sensors, it enables real-time monitoring and precise resource management.

The automation of irrigation and fertilizer application not only enhances water efficiency but also promotes healthier crop growth, making it a vital tool for modern agriculture. Given the increasing challenges of water scarcity and the demand for sustainable farming practices, this system holds significant potential for large-scale adoption. It empowers farmers to optimize their operations, ensuring better resource utilization while contributing to environmental sustainability and food security.

XVIII. FUTURE SCOPE

C. *Integration of AI Algorithms*

Future improvements could involve the incorporation of advanced artificial intelligence (AI) algorithms for more sophisticated crop health analysis. By leveraging machine learning techniques, the system could better identify plant diseases, nutrient deficiencies, and growth patterns, allowing for more precise recommendations on irrigation and fertilization.

D. *Solar-Powered Systems*

Implementing solar-powered systems could enhance energy efficiency and sustainability. Solar panels can be used to power drones and ground sensors, reducing reliance on conventional energy sources and minimizing operational costs, especially in remote agricultural areas.

E. *Enhancing Drone Autonomy*

Increasing the autonomy of drones would allow for more extensive monitoring coverage. By integrating advanced navigation systems and autonomous flight capabilities, drones could conduct routine inspections of larger fields without the need for constant human oversight. This would facilitate continuous data collection and improve overall efficiency in crop management.

F. *Data Analytics and Cloud Integration*

Developing a robust data analytics framework, possibly through cloud integration, could enable comprehensive data analysis and visualization. This would allow farmers to access historical data, track trends, and make informed decisions based on long-term agricultural insights.

G. *Interconnectivity with Other IoT Devices*

Future work could focus on creating a more interconnected ecosystem of IoT devices. By integrating weather stations, pest detection systems, and other environmental sensors, the system could provide a holistic view of the agricultural landscape, further enhancing decision-making processes.

H. *User-Friendly Interfaces*

Improving user interfaces for mobile applications and dashboards could enhance usability for farmers, allowing them to easily interpret data, receive alerts, and manage irrigation and fertilization schedules efficiently.

These future improvements aim to elevate the system's effectiveness, promoting sustainable practices and maximizing agricultural productivity.

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