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Next Generation Hydroponics: Real Time IoT Monitoring and Live Streaming

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Abstract: *Modern agriculture faces unprecedented challenges due to rapid urbanization, soil degradation, and water scarcity. Hydroponics offers a highly sustainable, soil-less cultivation alternative, though it requires precise environmental control to ensure optimal crop yields. This paper presents the development of a "Next Generation Hydroponic" system that integrates the Internet of Things (IoT) for real-time monitoring, automated actuation, and live video streaming. The core architecture is driven by an ESP32 microcontroller, which seamlessly processes data from a localized sensor network comprising a DHT11 (temperature/humidity), an analog pH sensor, a Light Dependent Resistor (LDR), and an HC-SR04 ultrasonic sensor for water level management. The system executes automated decision-making logic to actuate cooling fans, water pumps, and LED grow lights via a multi-channel relay. Telemetry is transmitted over Wi-Fi to a cloud-based dashboard (ThingSpeak/Blynk) for remote user monitoring. To complement the sensor data, an auxiliary ESP32-CAM module operates as an independent web server, providing a live visual stream of the crop environment. This dual-layered approach—combining quantitative sensor analytics with qualitative visual inspection—minimizes human intervention, conserves resources, and establishes a highly scalable framework for smart urban agriculture*

Keywords: Hydroponics, Smart Agriculture, ESP32, ESP32-CAM, IoT Dashboard, Real-Time Monitoring, Sensor Fusion

I. INTRODUCTION

The global agricultural sector is undergoing a necessary technological revolution to meet the food demands of an expanding population while mitigating the environmental impacts of traditional farming. Hydroponics—a method of growing plants in nutrient-rich water solutions without soil—has emerged as a leading solution. By eliminating soil, hydroponic systems bypass soil-borne diseases, reduce pesticide reliance, and significantly decrease overall water consumption through closed-loop recirculation.

Despite its advantages, hydroponic farming demands rigorous and continuous monitoring. Parameters such as nutrient pH, ambient temperature, humidity, and light intensity must remain within strict physiological thresholds; deviations can rapidly stunt plant growth or lead to crop failure. Traditional manual monitoring is labor-intensive, error-prone, and inefficient for large-scale or remote operations.

To resolve these limitations, this project introduces an automated, IoT-enabled hydroponic monitoring and control system. By leveraging an ESP32 microcontroller, the system continuously senses the microclimate and nutrient reservoir conditions, automatically adjusting actuators (pumps, fans, and lighting) to maintain biological equilibrium. Furthermore, while quantitative sensor data is invaluable, visual inspection remains a critical component of plant care. Thus, this framework introduces a live video streaming node utilizing the ESP32-CAM module, allowing farmers to

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visually inspect leaf health, verify water flow, and confirm system integrity remotely. This synthesis of automated environmental regulation and real-time visual telemetry represents the next generation of precision farming.

II. SYSTEM ARCHITECTURE

The hardware infrastructure is carefully segmented into a sensing layer, a processing and communication core, and an actuation layer, designed around reliable power distribution and modularity.

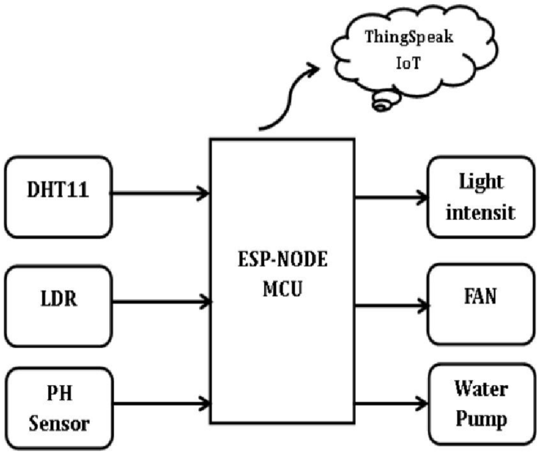


Fig. 1. Block Diagram of the proposed system illustrating the data flow from environmental sensors through the ESP-NODE MCU to the actuators and the ThingSpeak IoT Cloud.

As illustrated in **Fig. 1**, the central hub of the system is the ESP32 NodeMCU. It aggregates data from the DHT11, LDR, and pH sensors, and translates this logic into physical outputs, driving the Light intensity modules, Fans, and Water Pumps. The data is simultaneously pushed to the cloud for telemetry tracking.

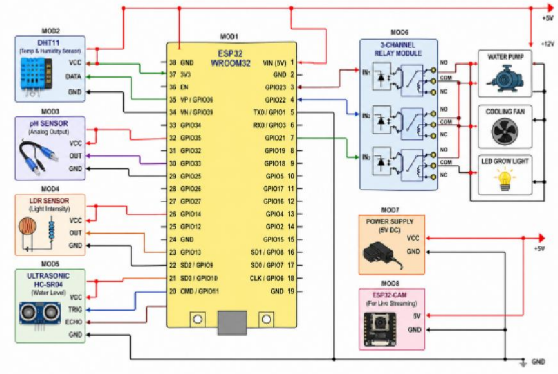


Fig. 2. Circuit Schematic detailing the pin-level connections of the ESP32 WROOM32, the 3-channel relay module, and the isolated ESP32-CAM network.

Fig. 2 details the comprehensive electrical architecture. The system utilizes a dual-voltage power strategy. A 5V DC power supply drives the ESP32 (MOD1), the ESP32-CAM (MOD8), and the logic side of the 3-channel Relay Module (MOD6). The sensors are mapped to specific GPIOs: the DHT11 (Digital), pH Sensor (Analog ADC), LDR (Analog ADC), and HC-SR04 Ultrasonic Sensor (Trigger/Echo Digital). A separate 12V power line is routed exclusively through the Normally Open (NO) terminals of the relay module to safely drive the high-current actuators: the Submersible Water Pump, the DC Cooling Fan, and the LED Grow Light, preventing inductive spikes from resetting the microcontroller.

III. METHODOLOGY

The system's operational logic relies on a continuous, closed-loop state machine that reads, evaluates, and acts upon environmental data in real-time.

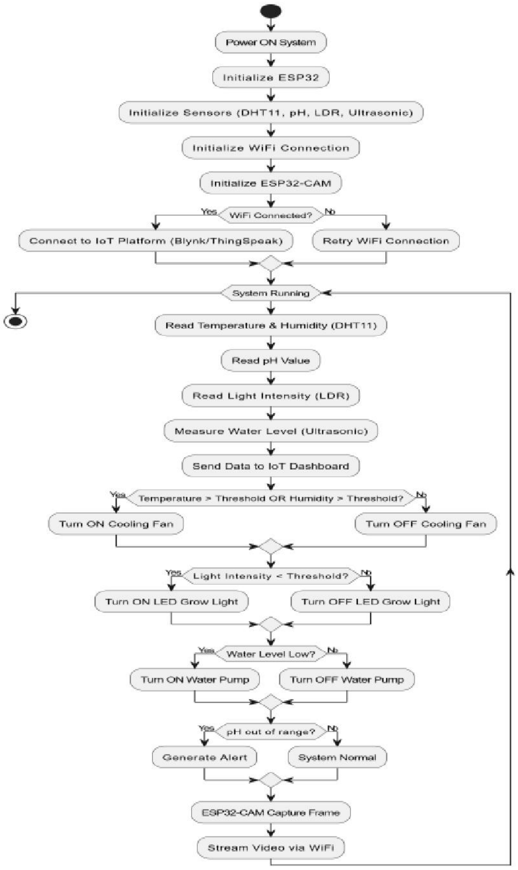


Fig. 3. System Flowchart mapping the initialization sequence, threshold-based decision algorithms, cloud synchronization, and concurrent video streaming processes.

As mapped in the flowchart (Fig. 3), the firmware execution follows these sequential stages:

System Initialization: Upon boot, the ESP32 configures its GPIO pins, initializes the sensor suite, establishes a local Wi-Fi connection, and connects to the designated IoT Platform (Blynk/ThingSpeak). Concurrently, the ESP32-CAM initializes its OV2640 camera sensor and starts the local web server.

Data Acquisition & Telemetry: The main loop reads temperature/humidity from the DHT11, ambient light from the LDR, acidity from the pH probe, and calculates reservoir distance via the Ultrasonic sensor. This payload is immediately published to the IoT dashboard.

Automated Actuation Logic:

Climate Control: If Temperature > Threshold OR Humidity > Threshold, the ESP32 switches the relay to turn ON the Cooling Fan.

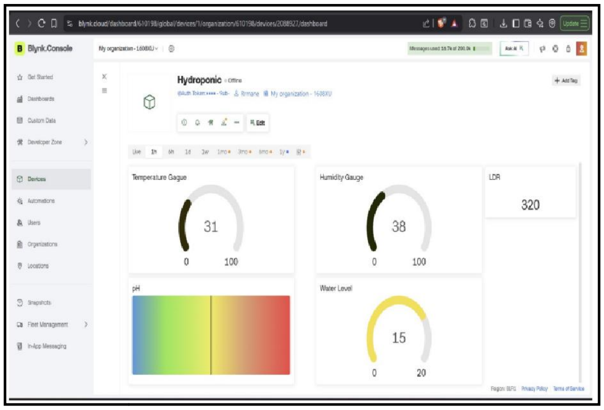
Photosynthesis Support: If Light Intensity < Threshold, the relay activates the LED Grow Light.

Reservoir Management: If the Water Level is detected as 'Low' (Ultrasonic distance > Threshold), the Water Pump turns ON to recirculate the nutrient solution.

Nutrient Alert: If the pH value drifts outside the ideal range (5.5 - 6.5), the system logs a high-priority alert to the dashboard.

Live Visual Feedback: Throughout this process, the ESP32-CAM independently captures frames and streams them over the local network, accessible via a standard web browser IP address, creating a seamless dual-monitoring environment.

IV. RESULTS AND DISCUSSION



The integrated hardware prototype was successfully deployed and evaluated. The ESP32 efficiently managed the multitasking requirements of reading multiple analog/digital sensors and managing cloud communications without experiencing blocking delays.

The integration with the Blynk/ThingSpeak platforms provided highly responsive IoT dashboards. The web and mobile interfaces accurately displayed live gauge readings for Temperature (e.g., 31°C), Humidity (38%), Water Level, and a color-mapped pH indicator. The automated relay logic proved highly reliable; artificial LED lights consistently engaged when ambient room light dropped below the LDR threshold, and the cooling fan effectively stabilized the microclimate around the plant canopy.

Crucially, the ESP32-CAM module functioned as intended, hosting a configuration web-page where parameters like resolution (HVGA 480x320), brightness, and contrast could be tuned dynamically. The live video stream operated smoothly over the 2.4GHz Wi-Fi network, allowing users to remotely inspect water flow dynamics and leaf coloration, effectively bridging the gap between raw data and physical crop reality.

V. CONCLUSION AND FUTURE WORK

This project successfully demonstrates a highly capable, edge-computed "Next Generation Hydroponic" framework. By fusing a robust suite of environmental sensors with an ESP32 microcontroller, the system achieves strict, automated control over the delicate hydroponic ecosystem. The dual-layered monitoring approach—combining real-time quantitative telemetry via cloud dashboards with live qualitative video streaming via the ESP32-CAM—provides farmers with unprecedented remote oversight, drastically reducing the need for manual farm labor while optimizing resource usage.

Future enhancements will focus on integrating Machine Learning (ML) algorithms into the cloud backend to enable predictive analytics for crop yield and automated disease detection from the camera feed. Furthermore, the integration of Electrical Conductivity (EC) sensors will be explored to allow for the fully automated, precise dosing of distinct hydroponic nutrient solutions.

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