CropWatch:

Adaptive Greenhouse Irrigation for Sustainable Growth

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Abstract

In Jordan, water conservation is a national priority due to limited water resources and dry climate conditions. This project introduces a novel approach to developing an Intelligent Greenhouse Irrigation System that utilizes sensors, microcontrollers, transistors, and IoT technology to optimize water usage and foster sustainable plant growth. By combining soil moisture, soil and air temperature sensors with an ESP32 microcontroller and an adaptive algorithm informed by research on sustainable agriculture practices, the system makes data-driven decisions, minimizing water wastage and maximizing efficiency in a context where every drop of water is valuable. The project also serves as a valuable educational resource for understanding the integration of sensors, microcontrollers, and IoT platforms in agriculture. Ultimately, our goal for this project is to see technology play a key role in creating sustainable and resilient food production systems for the future.

Acknowledgments

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Chapter I: Introduction

1.1 Project Motivation

Imagine a world where you get the most out of your crops and their cultivation thrives within the constraints of limited resources. Our project is driven by this vision—a vision of integrating intelligent solutions to transform traditional greenhouse cultivation into a model of resource efficiency and sustainability.

Our motivation stems from the urgent necessity to enhance crop yields and improve resource management in the face of global challenges such as water scarcity and climate change. By leveraging physical sensors, microcontrollers, transistors, and Internet of Things (IoT), we aim to create a system that contributes to a future where technology enhances sustainable plant growth, not only optimizing water usage but also the overall health and productivity of crops.

1.2 Project Objectives

The primary goal is to design and develop a working irrigation system that utilizes sensor data and IoT connectivity to automate irrigation, tailored to a mini greenhouse setup. This system makes informed decisions to activate a water pump based on an adaptive algorithm. Another objective extends the functionality beyond irrigation, incorporating control over environmental variables such as temperature, ventilation, and light within the mini greenhouse by autonomously opening and closing greenhouse windows based on sensor data to further influence plant health and growth. This multifaceted approach contributes to an overall efficient and sustainable greenhouse environment.

1.3 Report Structure

The remainder of the paper is organized as follows: Chapter 2 presents an overview of the project requirements, which were informed by extensive research, while Chapter 3 introduces the methodology, including the general architecture of the project, and the background. Chapter 4 explains the data collection. The results and analysis for this study are provided in Chapter 5. Lastly, the conclusion is presented in Chapter 6.

Chapter II: Project Requirements

2.1 Greenhouse Components

The greenhouse is the foundation of our system, designed to maximize productivity while ensuring ease of access for maintenance and monitoring. Each component plays a crucial role in the overall functionality and efficiency of the system. These components include:

- Mini greenhouse framework
- Insulated hub for hardware and materials
- Water pump
- Servo Motor

2.2 Hardware Components

Hardware is the backbone of the intelligent system, enabling the data collection necessary for making informed decisions on watering and environmental control, data processing, and actuation. Other hardware is also necessary to ensure consistent operations and reliable connections, facilitating seamless data transfer and power distribution across the system. Our hardware components include:

- Soil moisture, air temperature, and humidity sensors
- ESP32 Microcontroller
- MOSFET Transistor
- Power supply (for microcontrollers, sensors)
- Communication hardware (wiring, breadboard, jumper cables)

2.3 Software Components

Software integration brings together all the hardware components, enabling data-driven automation, remote monitoring, and efficient resource management. Our main software components are:

- Blynk IoT connectivity module
- PlatformIO for code integration (including Arduino, sensor, and Wifi connectivity libraries, as well as BlynkSimpleESP32.h for IoT integration)

Chapter III: Methodology and Background

3.1 Approach

The project follows a phased approach to develop an intelligent irrigation and environmental control system for a mini greenhouse. Initially, comprehensive research is conducted on sustainable agriculture, relevant sensors, microcontrollers, and IoT interfaces. This research informs the subsequent construction of the mini greenhouse framework, as well as the components to be obtained.

Following the framework setup, we shift to hardware integration for data collection. This involves acquiring the necessary components—such as sensors, an ESP32 microcontroller, and MOSFET transistors—and integrating them into the system. Concurrently, a web dashboard is created using IoT technology, allowing for remote monitoring as well as manual control of the greenhouse environment.

The software development phase involves writing code to collect data at regular intervals from all sensors, which is then sent to the IoT interface for processing and display. Establishing seamless communication between the microcontroller and the IoT interface is crucial for real-time data updates and control. An adaptive algorithm is integrated to analyze soil moisture data, making automated decisions about turning the water pump ON or OFF based on predefined thresholds. Similarly, air temperature and humidity data are analyzed to control the opening and closing of greenhouse windows via servo motors. Manual control of the system is also enabled.

These decisions are sent to the relevant hardware components, ensuring an optimal growing environment. Once the system is operational, Rocket seeds are planted to initiate the growing process, and the system's performance is monitored through the web dashboard. Any abnormalities or system states are tracked and addressed promptly. The system undergoes thorough testing to ensure reliability and accuracy. Sensors are calibrated to maintain precise measurements, and any necessary adjustments are made. Throughout the project, detailed documentation is maintained.

3.2 Use Case Diagram

The use case diagram in Figure 1 illustrates the interactions between different actors and the system, highlighting how our system functions to enhance sustainable agricultural practices.

The administrator of the system is responsible for overseeing CropWatch system operations. The admin has access to the algorithm, and their role includes configuring the system, setting thresholds, and maintaining overall functionality by making decisions based on the sensor data received from the greenhouse. These algorithm-based decisions are then transmitted by the system to the responsible hardware components.

The end-user of the system, the farmer, relies on CropWatch to monitor the greenhouse environment and make informed decisions regarding crop management. The farmer accesses the system through a web dashboard, which provides real-time data and system statuses. While CropWatch is designed to operate autonomously, the farmer can manually intervene through the web dashboard if necessary. This feature ensures that the farmer retains ultimate control over the greenhouse environment.

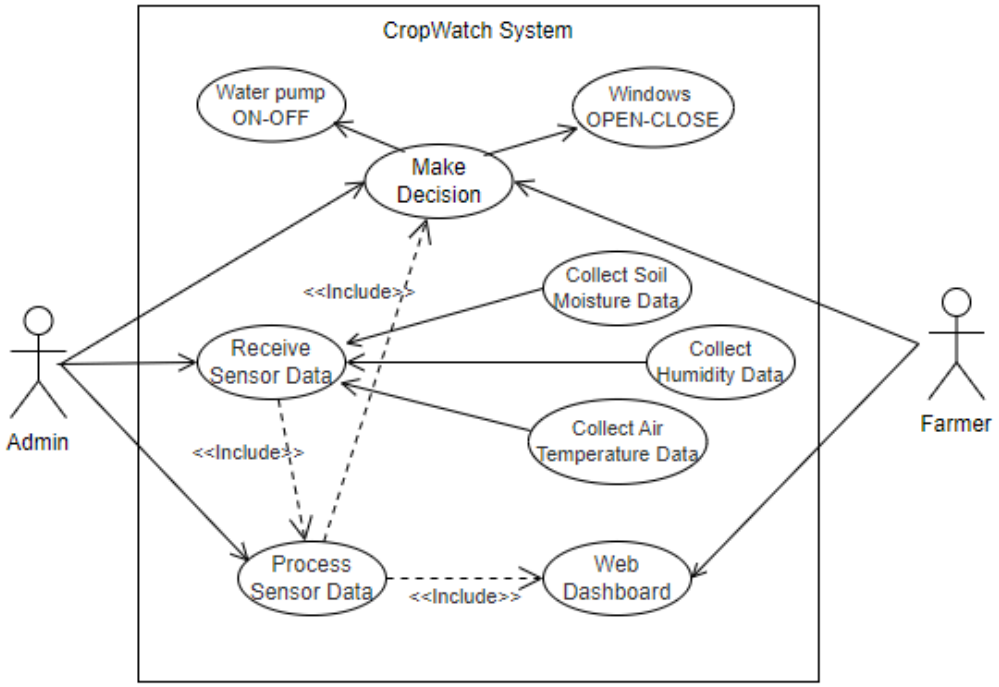


Fig.1 Use Case Diagram

3.3 General Architecture

In Figure 2, the general architecture of the proposed work is presented. The data received via the sensors is collected by the ESP32 microcontroller and sent to the IoT interface via WiFi connectivity. The IoT interface allows remote user monitoring for current and recent historical data and manual control. It also sends sensor data to the adaptive algorithm and code logic for automated decision-making, also through WiFi. The irrigation or ventilation decision is then transmitted to the MOSFET and servo motor through the ESP32. The relevant device can activate the water pump or open and close the greenhouse windows, according to this decision.

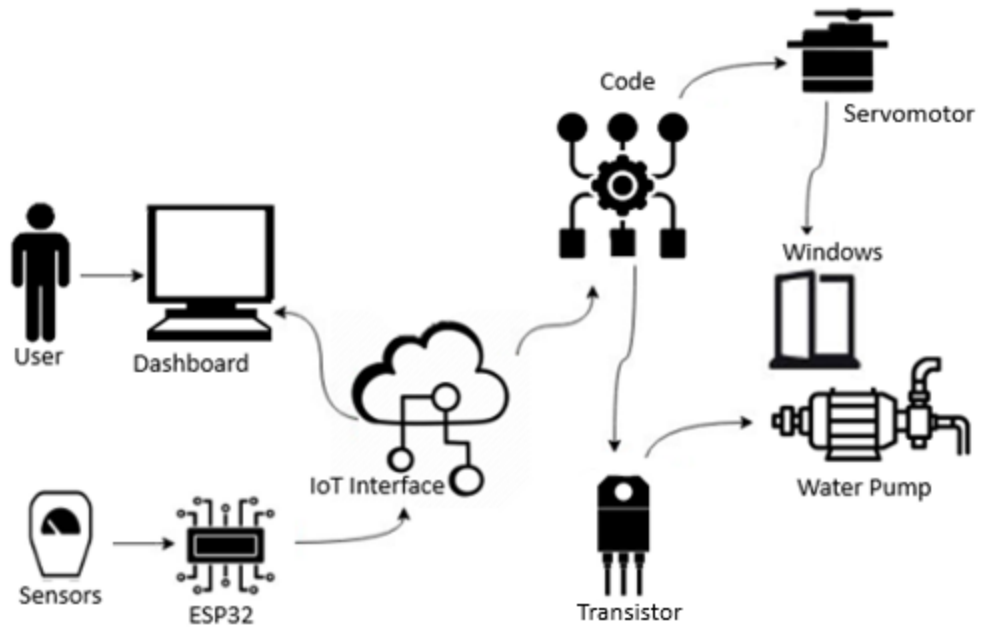


Fig.2 Architecture Diagram

3.4 Background

3.4.1 Sustainable Agriculture and Precise Irrigation

The FAO's report, "The State of Food and Agriculture 2023," addresses the challenge of feeding a growing global population amidst water scarcity in agricultural regions. To meet the rising demand for food by 2050, a 70% increase in production is needed. This requires sustainable

farming practices and innovative solutions to water wastage, where currently 70% of irrigation water is wasted (FAO 2023).

Precision irrigation, a solution that targets precise water application, is therefore crucial. It aims to minimize water wastage by delivering the right amount of water at the right time and place considering several variables. To do this efficiently we need better monitoring and control, facilitated by advancements in the Agricultural Internet of Things (IoT) and Wireless Sensor Networks (WSN), and supported by data analytics for decision-making. Using more precise irrigation can also lessen the potential for soil salinization and groundwater degradation.

3.4.2 Hardware Usage

To ensure a robust, efficient, and sustainable solution for automated greenhouse management, we made use of the following components:

- **ESP32 Microcontroller**

  The ESP32 is ideal for this project due to its versatility and compatibility with a variety of sensors and actuators. Its ability to monitor crucial environmental parameters like soil moisture and temperature, paired with its processing power to run advanced algorithms, ensures precise control over irrigation and climate conditions. Its IoT capabilities enable seamless wireless network integration, ensuring reliable and sustainable operation.

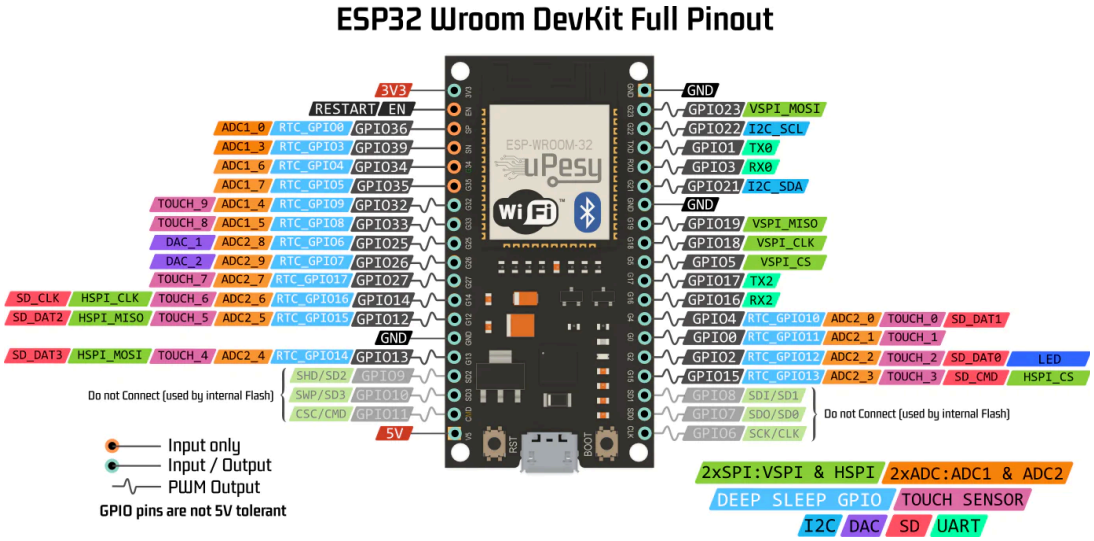


Fig.3 Esp32 Board Pinout Diagram

- **Soil Moisture Sensor (IIVVERR FC-28 Hygrometer Fork Electrode and LM393 Sensor Converter)**

  This soil moisture sensor measures the resistance between its legs and converts it into a voltage that a microcontroller can read to keep track of the moisture content of the soil. This technique helps to keep plants at the proper water levels, avoid over- or underwatering, promote strong root development, and reduce the risk of disease.

Fig.4 Soil Moisture Sensor

- **Air Temperature and Humidity sensor (DHT11)**

  The DHT11 is a commonly used Temperature and humidity sensor that comes with a dedicated Negative Temperature Coefficient (NTC) to measure temperature and an 8-bit microcontroller to output the values of temperature and humidity as serial data. DHT11 sensor assists in achieving optimal growth environments while safeguarding against diseases and pests, efficiently utilizing water resources.

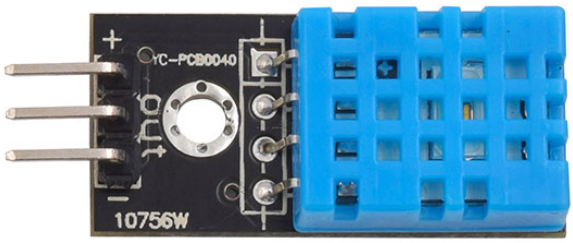


Fig.5 DHT11 Sensor

- **Servo Motor**

  The servo motor is a specific kind of linear or rotary actuator with an assembly of four DC motors, a gearing set, a control circuit, and a position sensor. Upon receiving a command, it can move to a certain target position. The servo motor will be used to control the opening and closing of the greenhouse window.

Fig.6 Servo motor

- **MOSFET Transistor (IRF540)**

  The IRF540 is an N-Channel MOSFET known for its high efficiency and capability to handle a maximum continuous drain current of 33 amperes (A) under ideal conditions. It features a low R_DS(on), which minimizes power losses and enhances performance in high-current applications. Initially, a relay module was considered for transmitting irrigation decisions to the water pump. However, the IRF540 MOSFET proved to be a better choice due to its faster switching times and higher efficiency. Additionally, the MOSFET's lack of mechanical parts enhances reliability and longevity, making it more suitable for the system's load current requirements.

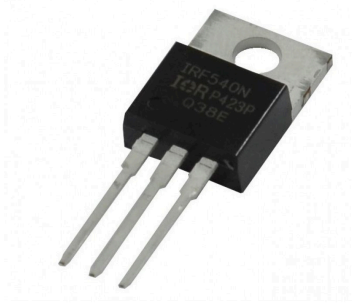


Fig.7 MOSFET Transistor

Figure 8 shows a breadboard circuit diagram that replicates our final physical setup, containing the hardware mentioned as well as other hardware necessary for the consistent operation of CropWatch system.

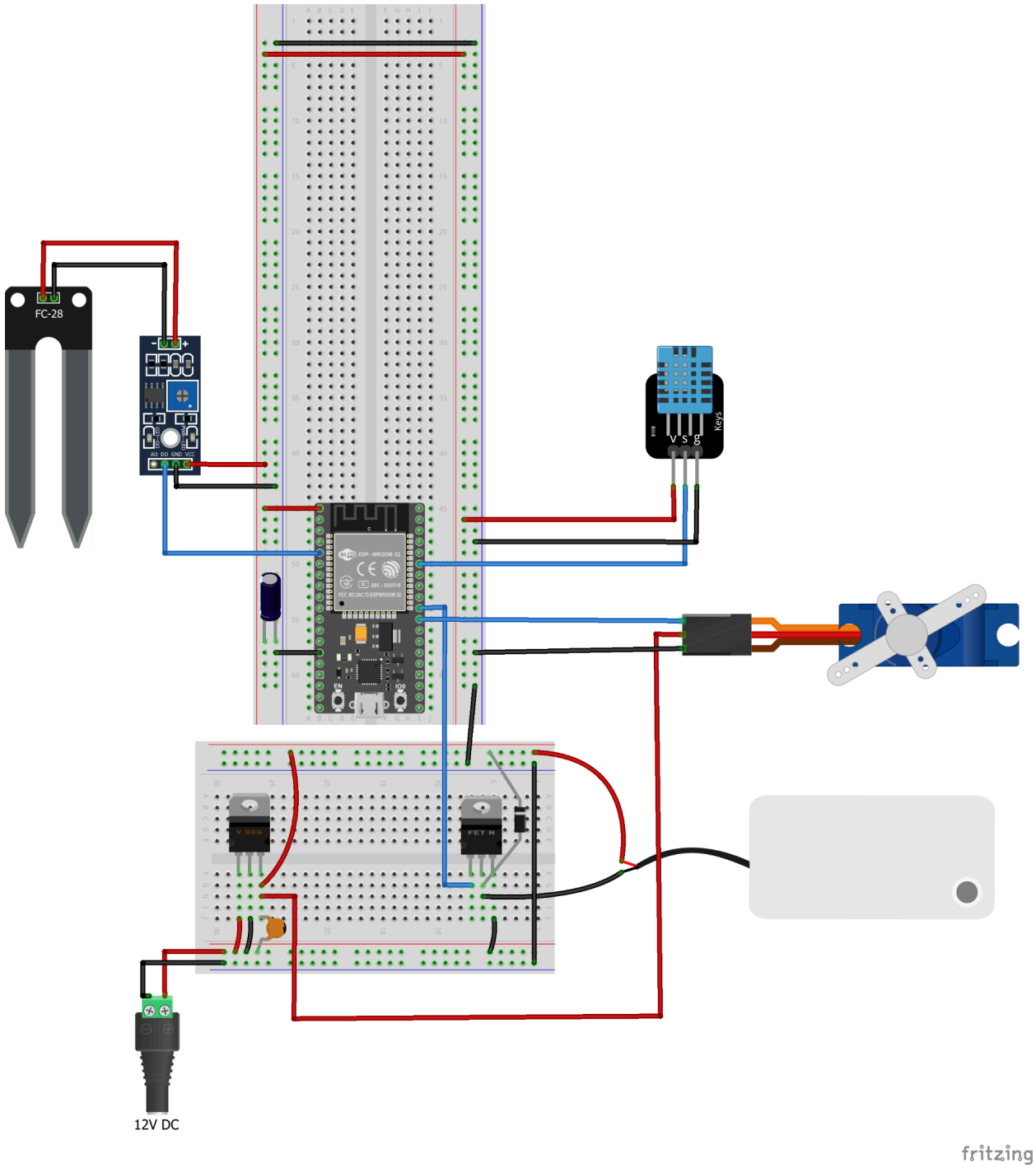


Fig.8 Final Setup Diagram

3.4.3 Software Tools

- **Blynk IoT Connectivity Module**

Utilizing IoT technology in greenhouse farming is crucial in its advancement. It enables comprehensive analysis and storage of collected sensor data, as well as visualization of insights. Stakeholders can access these datasets from any internet-enabled device, helping them optimize crop production and energy usage. The integration of IoT in greenhouse operations is gaining attention, with notable achievements reported in recent studies (Subahi, A.F. 2020, A. Abiodun Emmanuel et al. 2021, Pereira, G.P. 2023).

Blynk's user-friendly interface and seamless integration make it the perfect fit for our project. With Blynk, we can easily monitor and control real-time sensor data remotely through the web dashboard created and accessed through the platform, and receive alerts for critical events or abnormalities. Its scalability also ensures our system can grow with our needs.

3.4.4 The Algorithm

Model Predictive or Receding Horizon Control (RHC) method, derived from industrial control theory, is a class of control algorithms that utilizes predictive modeling, optimization, and real-time feedback to manage complex systems. At each time step, the algorithm optimizes the control actions over a finite prediction horizon to minimize a cost function that captures the system's states and control inputs.

In the context of irrigation management in precise irrigation systems, the RHC algorithm uses feedback from an embedded sensor system to forecast soil moisture levels several management time steps into the future based on recent data. It adjusts control parameters such as irrigation application rates according to the predicted soil moisture over a defined "receding time horizon" to maintain them within desired thresholds. This approach enables adaptive management of irrigation practices, allowing for efficient water use and improved crop growth while minimizing the risk of over- or under-watering (Park et al.).

The RHC algorithm can be summarized as follows:

1. System Model: The system dynamics are described by a set of mathematical equations that relate the control inputs, states, and outputs of the system through some function. The RHC algorithm can accommodate different levels of model complexity depending on the system being controlled. For our case of adaptive irrigation management, the algorithm doesn't explicitly define a mathematical model of the system dynamics, but employs an implicit understanding of the behavior of the greenhouse system through empirical relationships between observed sensor readings and control actions.

2. Objective Function: The goal of the control system is to minimize a cost function that describes the deviation of system states and control inputs from desired values. Our code's control logic has the optimization objective of maintaining certain environmental conditions within predefined thresholds by minimizing deviations (cost) while conserving water resources. This optimization objective is inherent in the design of the control algorithm.

3. Optimization: The optimization problem involves finding the control inputs that minimize the cost function subject to system dynamics and constraints. Although traditional optimization schemes require computation resources beyond the capabilities of our ESP32 or the scope of our project, by incorporating a hysteresis threshold our code optimizes the control of the water pump by reducing oscillations around the desired soil moisture setpoint. This is a rule-based optimization approach that, combined with adaptive control actions based on historical sensor data, helps minimize our water wastage and enhance plant growth.

4. Receding Horizon Strategy: Optimization is performed over a finite time horizon, and at each time step, the control inputs are calculated and applied for the current time step only, with the process repeating with a new horizon advancing one time step every time.

Our code captures new sensor data and updates the historical records used for predictions and control decisions. This continuous update process embodies the receding horizon approach. Our prediction step involves averaging recent readings, a moving average, as the oldest stored reading is discarded at each time step. This model captures the prevailing moisture trend and forecasts future soil moisture levels to predict near-term conditions. It serves as a foundational predictive mechanism that aligns with RHC.

It also takes the stability of soil moisture readings as a performance metric, according to which the length of the horizon is adjusted. By adjusting the horizon length based on the variance of recent readings, the decision-making process is stabilized and the system employs a balance between precision and efficiency. When readings are stable (low variance), a shorter horizon length can also make the system more responsive to new conditions without being overly influenced by past stable conditions.

While our approach is relatively simple, it captures the essence of RHC to effectively make decisions over a short-term horizon while remaining computationally efficient, a critical factor for real-time embedded systems.

Chapter IV: Data Collection

4.1 How is the data collected and processed for insights?

1. **Sensor Readings Acquisition:** The Soil Moisture Sensor measures the moisture content of the soil, while the DHT11 Sensor measures ambient temperature and humidity within the greenhouse.
2. **Data Processing:** Upon acquiring sensor readings, the ESP32 microcontroller processes the data to ensure appropriate formatting and scaling.
3. **Data Transmission to IoT Interface:** Processed sensor data is transmitted to the Blynk IoT interface using Wi-Fi connectivity. Users can monitor real-time data and greenhouse conditions.
4. **Automated Control:** Moving averages over an adaptive horizon length are calculated for the processed data, utilizing arrays of stored sensor readings from recent history. Subsequently, automated control mechanisms utilize the calculated averages to make informed decisions regarding irrigation scheduling and environmental adjustments.
5. **Alert Mechanism:** The system includes an alert mechanism to notify users of critical events detected in soil moisture sensor readings. User intervention is prompted to mitigate potential issues.
6. **Manual Control Integration:** The Blynk app enables manual control over the water pump and greenhouse windows, allowing users to override automated processes if needed. Manual control inputs are synchronized with the ESP32 microcontroller, ensuring seamless interaction between manual and automated modes.
7. **Continuous Monitoring and Analysis:** Data logging and analysis support the ongoing evaluation and optimization of sustainable agriculture practices. The system continuously monitors sensor data and system states, providing users with insights into greenhouse performance and crop health.

4.2 Flowcharts

The following figures show flowchart representations of the different processes incorporated in the CropWatch system, including data collection, data processing, automated control, and manual control.

Figure 9 represents the general flow, i.e. the RHC algorithm-based decision making, while Figure 10 represents the alternate flow involving manual farmer intervention.

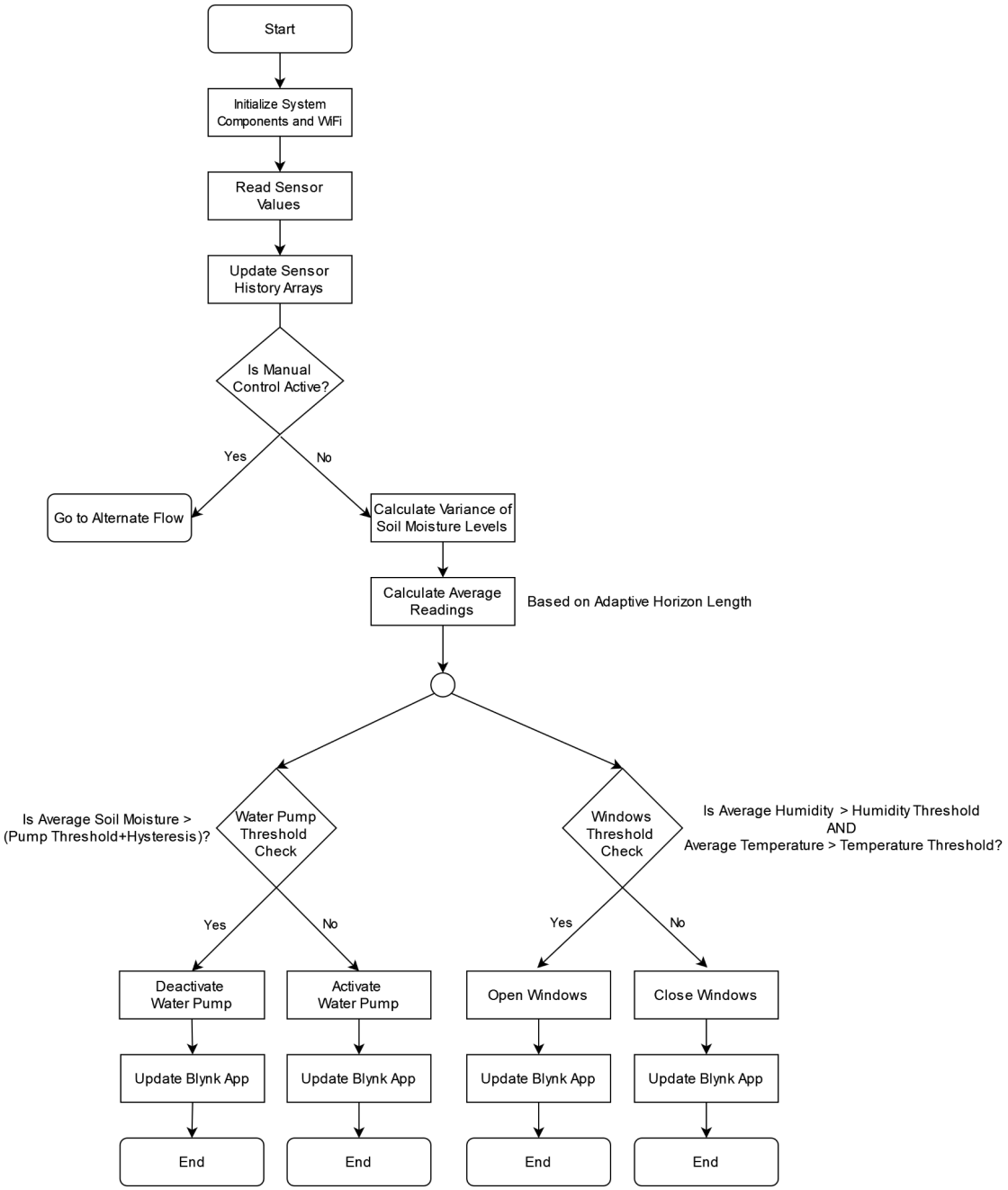


Fig.9 General Flow Diagram

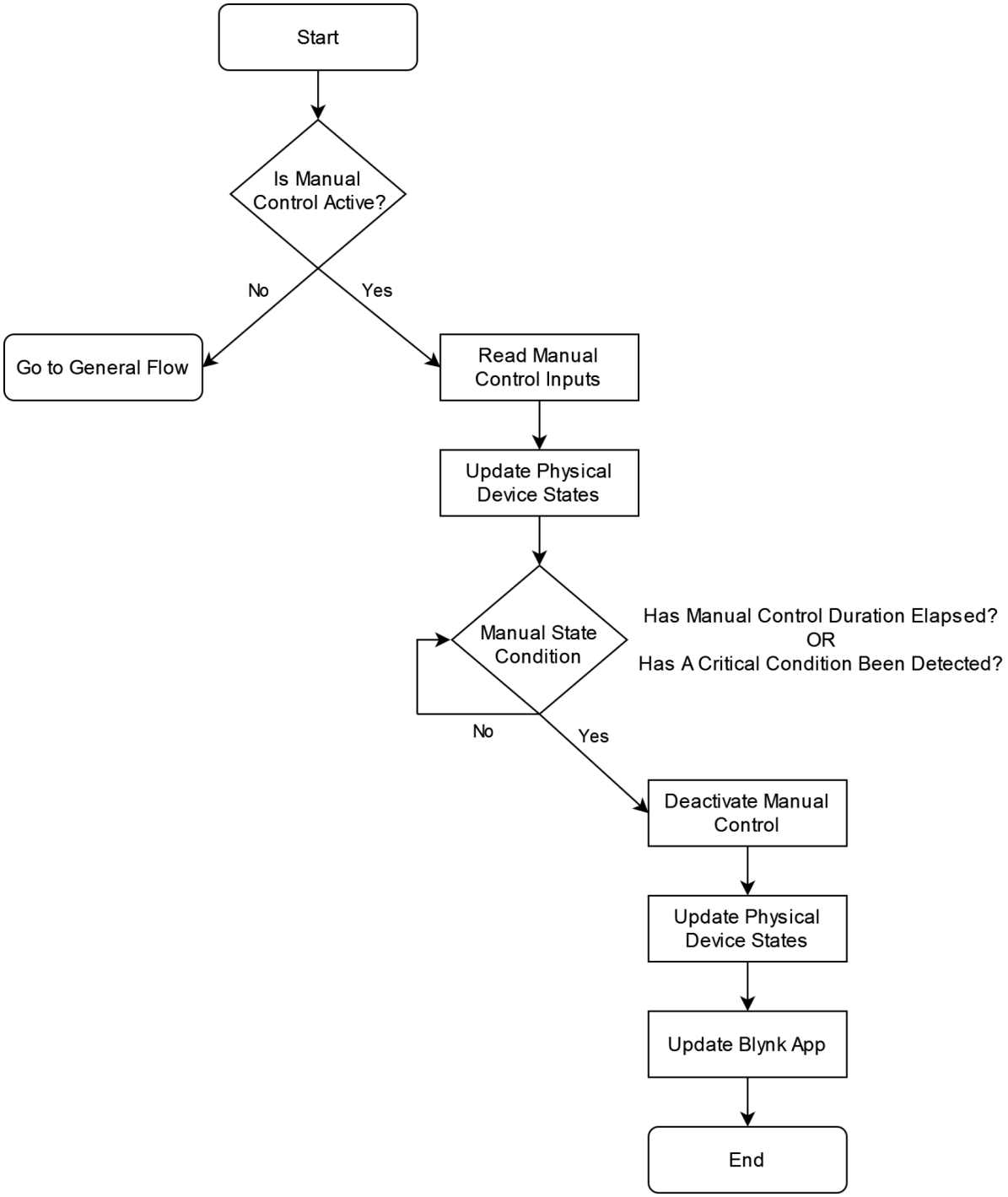


Fig.10 Alternate Flow Diagram

Chapter V: Results and Discussion

5.1 Results

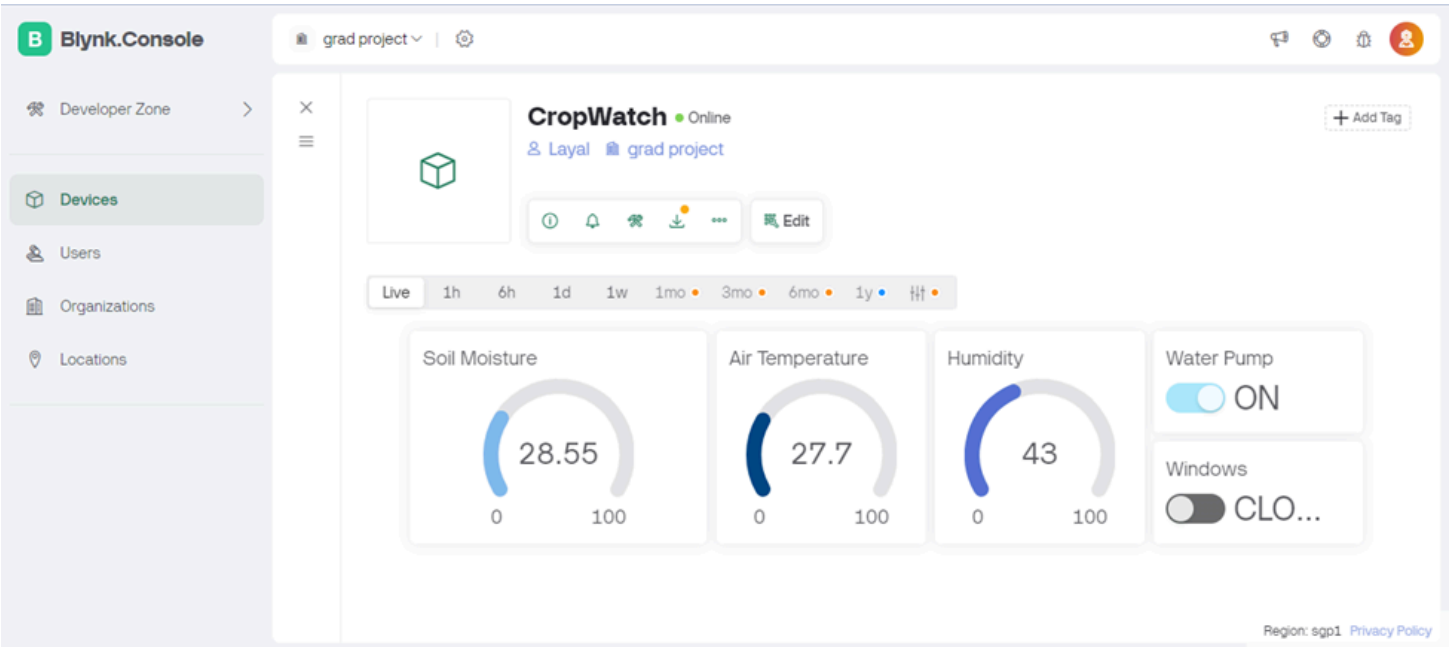
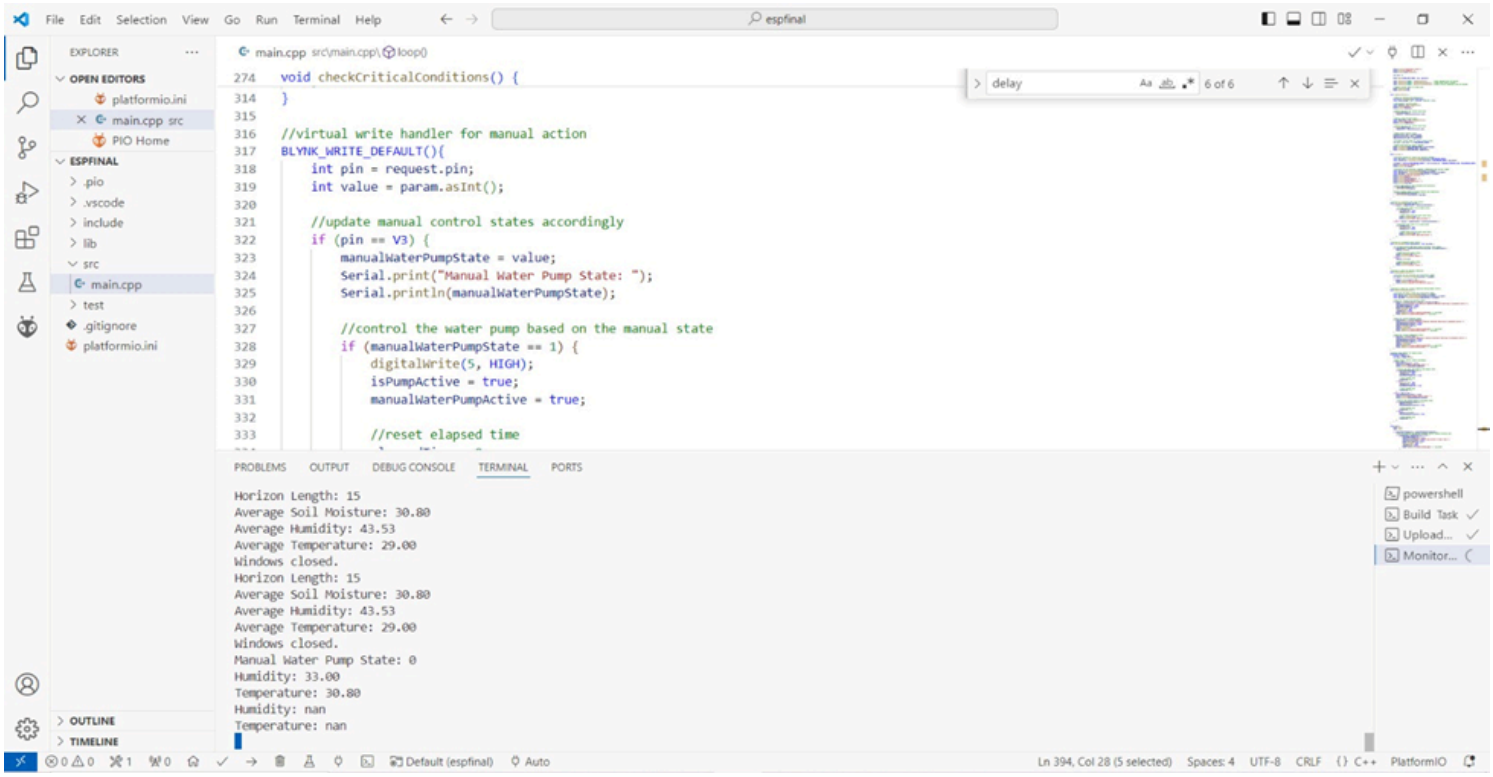


Fig.11 Screenshot from Blynk Dashboard: Pump ON according to RHC

RHC automated control is implemented successfully, controlling both the water pump and window based on calculated moving averages of the environmental conditions within the greenhouse. The adaptive horizon length is continuously updated according to the stability of recent soil moisture readings.

The PlatformIO serial monitor displays messages of the calculated averages of soil moisture, humidity, and temperature with every new sensor reading taken in order to validate the proper function of the RHC algorithm. The horizon length is also printed, as well as the device states for the windows and pump. When a device is in automated mode, its manual state is 0 to indicate that.



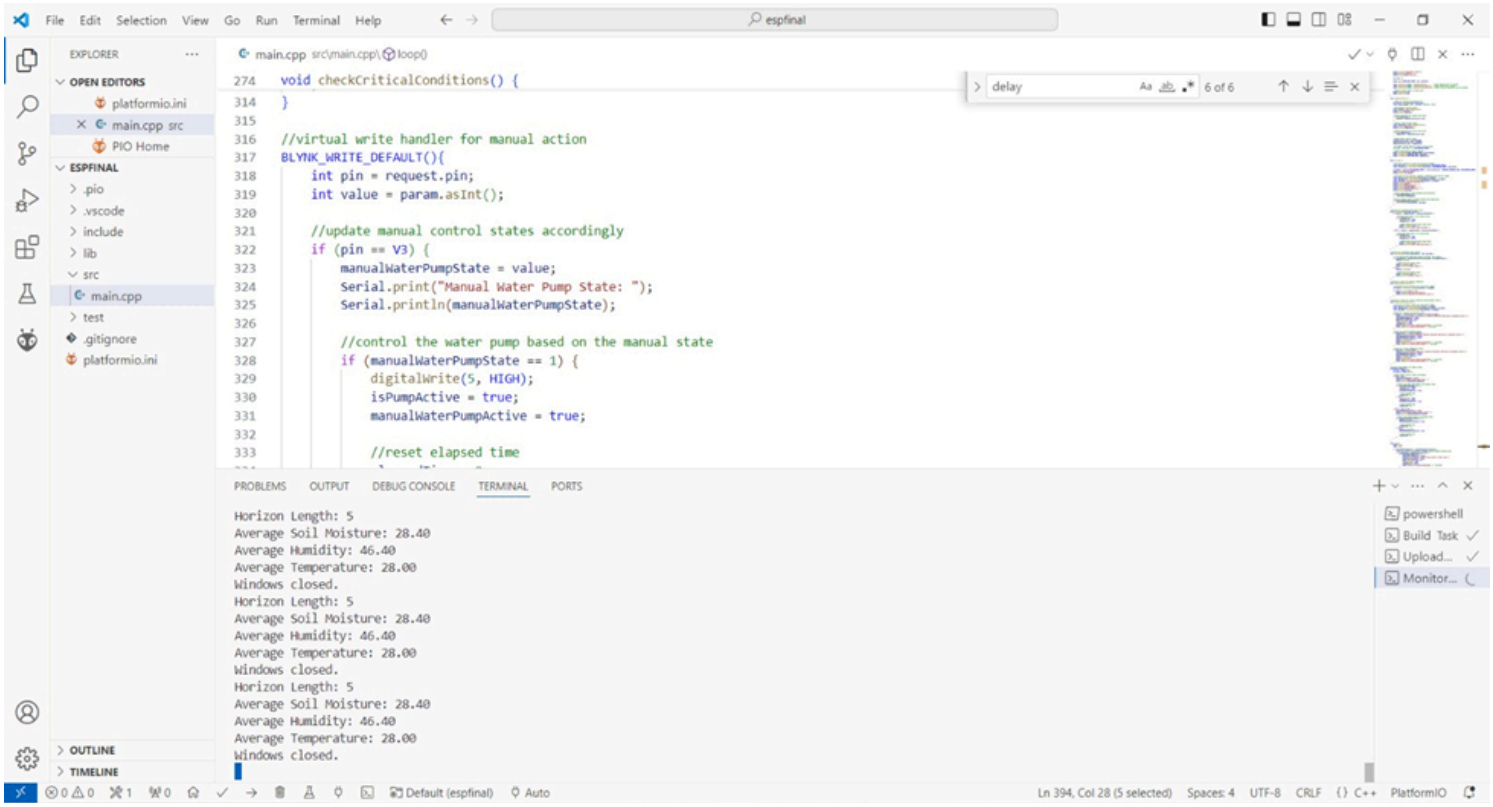


Fig.12 & 13 Example Serial Monitor Output for RHC Algorithm

Manual control is implemented successfully via Blynk virtual write handlers. A granular control mechanism is implemented to allow the farmer to switch either device to manual mode without disrupting automated operations of the other unless manual input is detected to that device as well. A periodic check for critical conditions is successfully implemented during manual control to allow RHC to override it in case of emergencies.

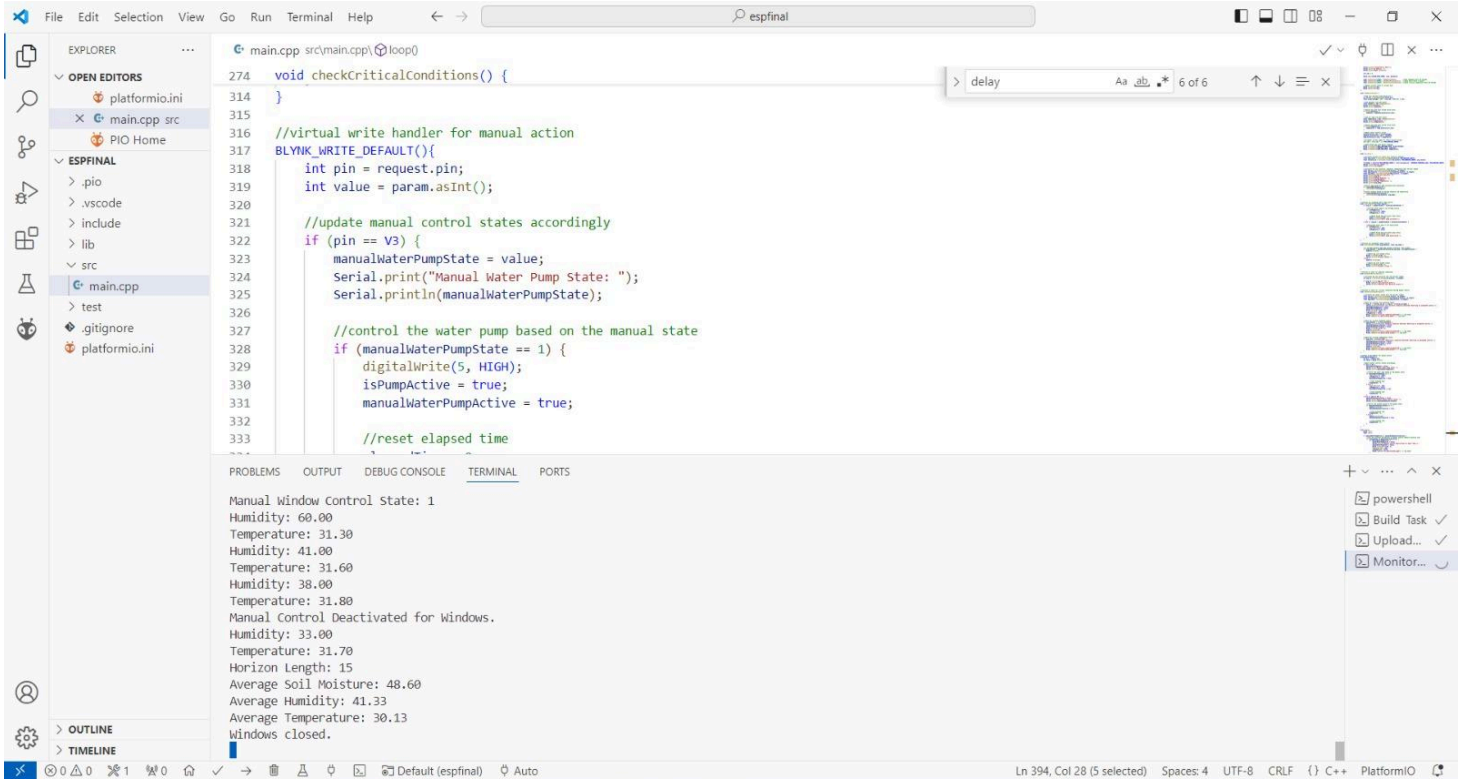


Fig.14 Example Serial Monitor Output for Manual Control Activation & Deactivation for Windows

Mode switching is successful, with manual control overriding and deferring back to the RHC algorithm smoothly upon manual input and the elapsing of the defined default duration, as well as RHC overriding manual control in the case of critical condition detection.

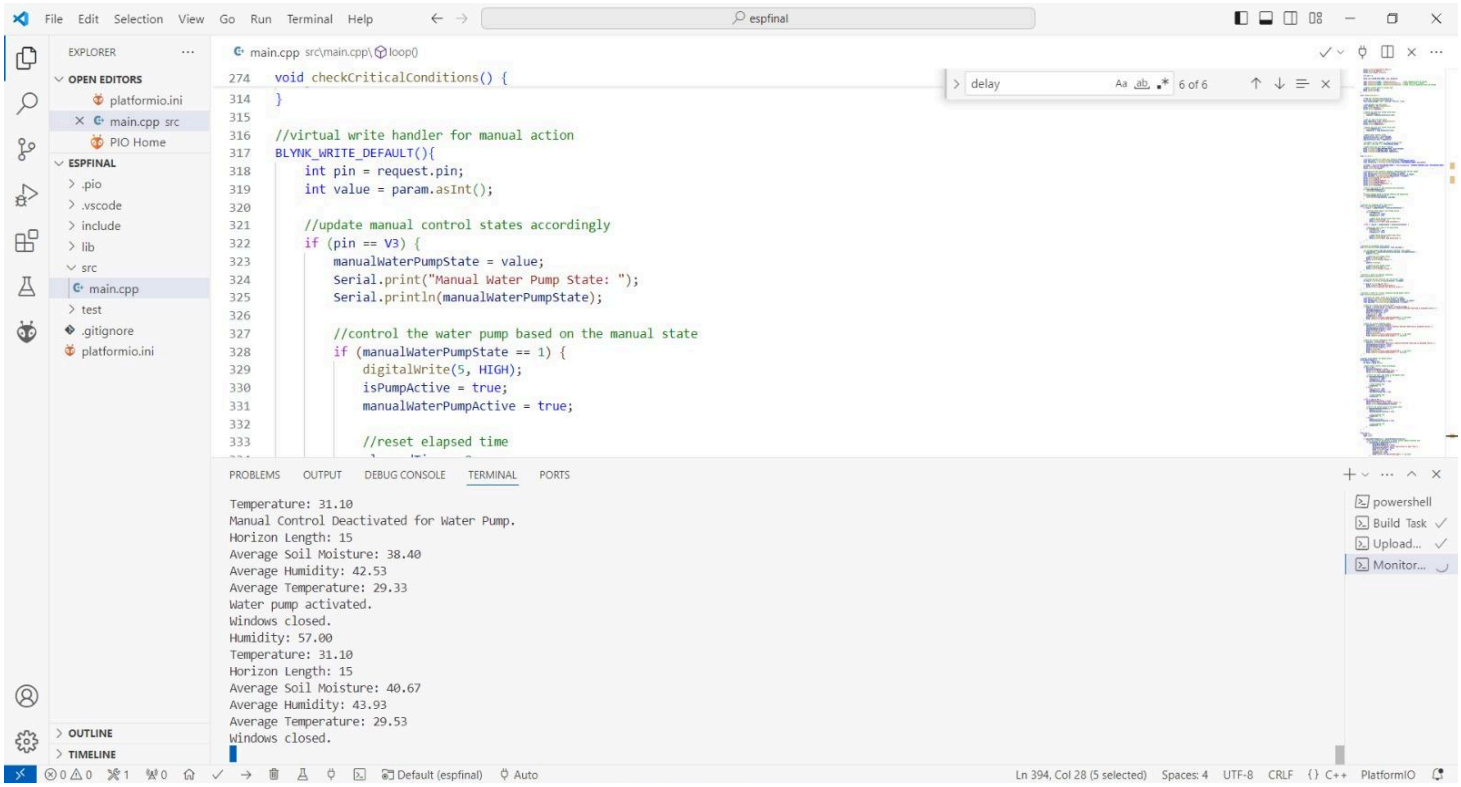
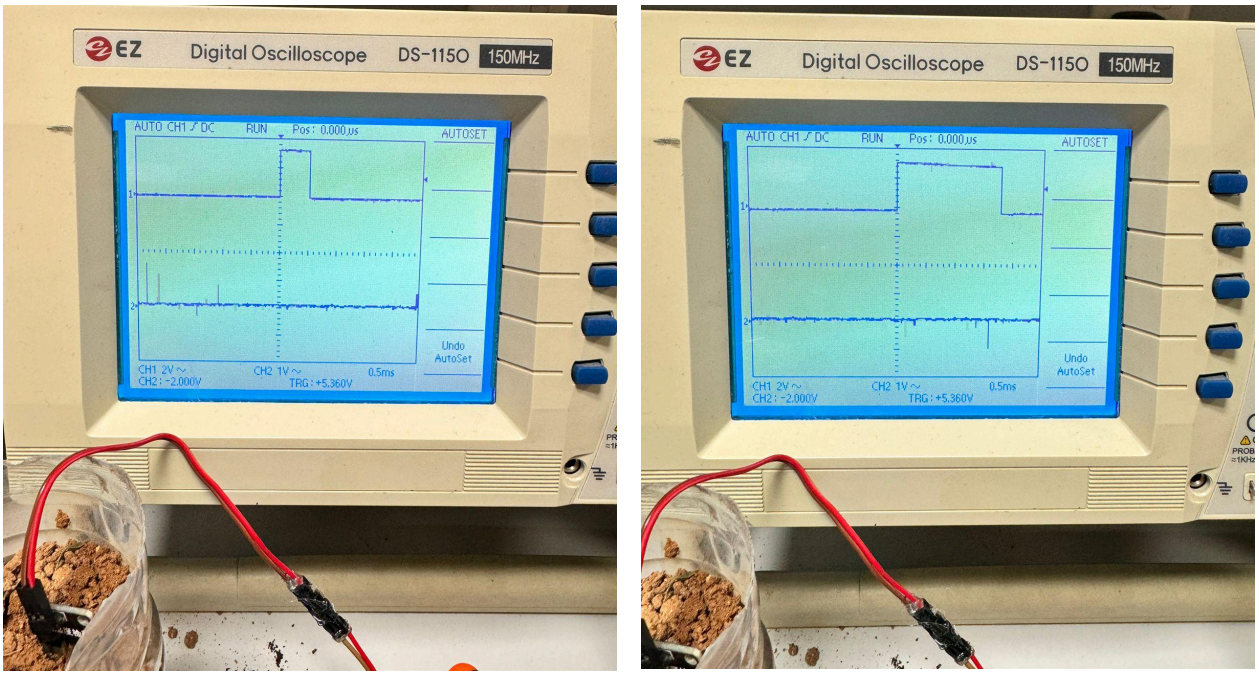


Fig.15 Example Serial Monitor Output for Mode Switching for Water Pump

The serial monitor also prints messages whenever manual mode is deactivated for a certain device. When manual mode for the pump is deactivated, the message “Manual Control Deactivated for Water Pump” is printed, before a different message, “Water Pump Activated” is printed, indicating that the system switched to the RHC algorithm.

A digital oscilloscope was also used during the initial setup and testing phases to ensure that the proper signals are being received by the relevant device with every command from the ESP32. The oscilloscope allows for real-time observation and analysis of electrical signals. This step, alongside software debugging, was crucial in validating the overall functionality of our CropWatch system.

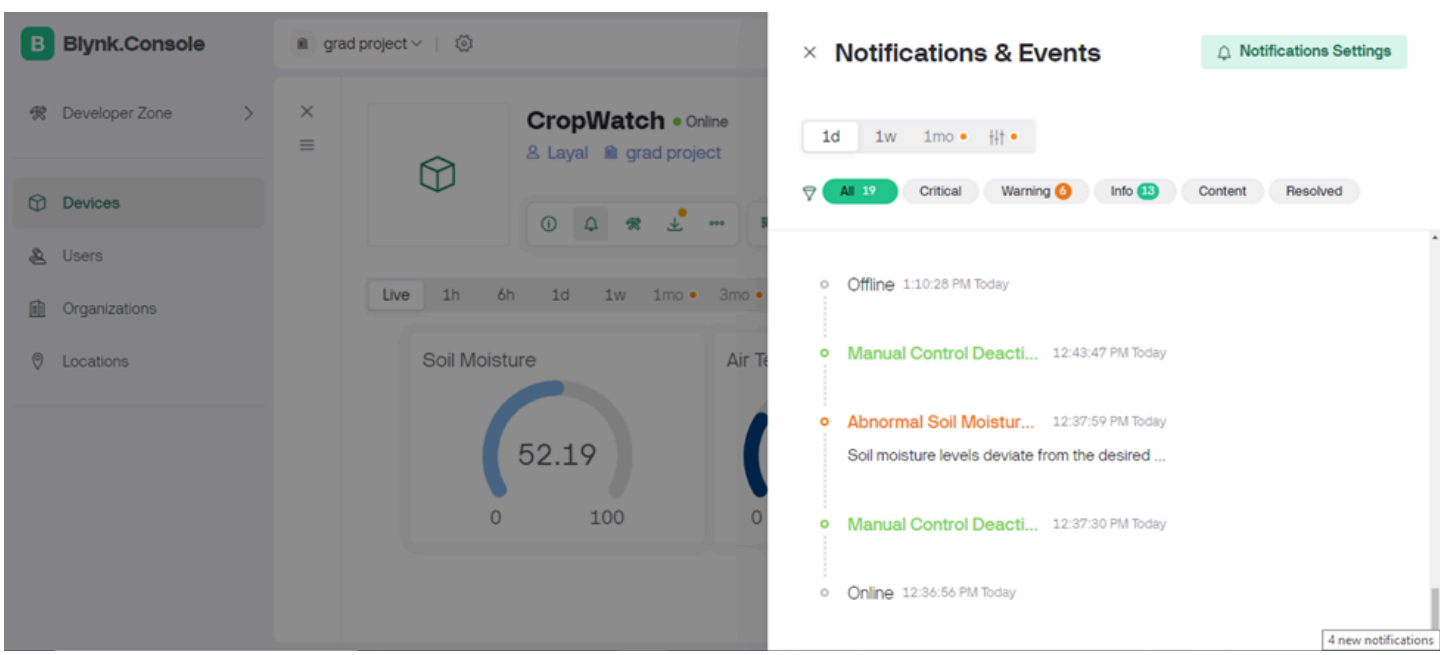
Figure 16 shows how the oscilloscope confirmed that the servo motor receives the correct signals to change state, or position, in response to both manual and automated commands, ensuring reliable opening and closing of the greenhouse windows.



(a) (b)

Fig.16 Oscilloscope signal when windows are a) open and b) closed

The Blynk dashboard continuously reflects real-time sensor readings and device states, as well as receiving and logging events for online times, offline times, abnormal soil moisture levels, critical conditions, and manual control deactivation.



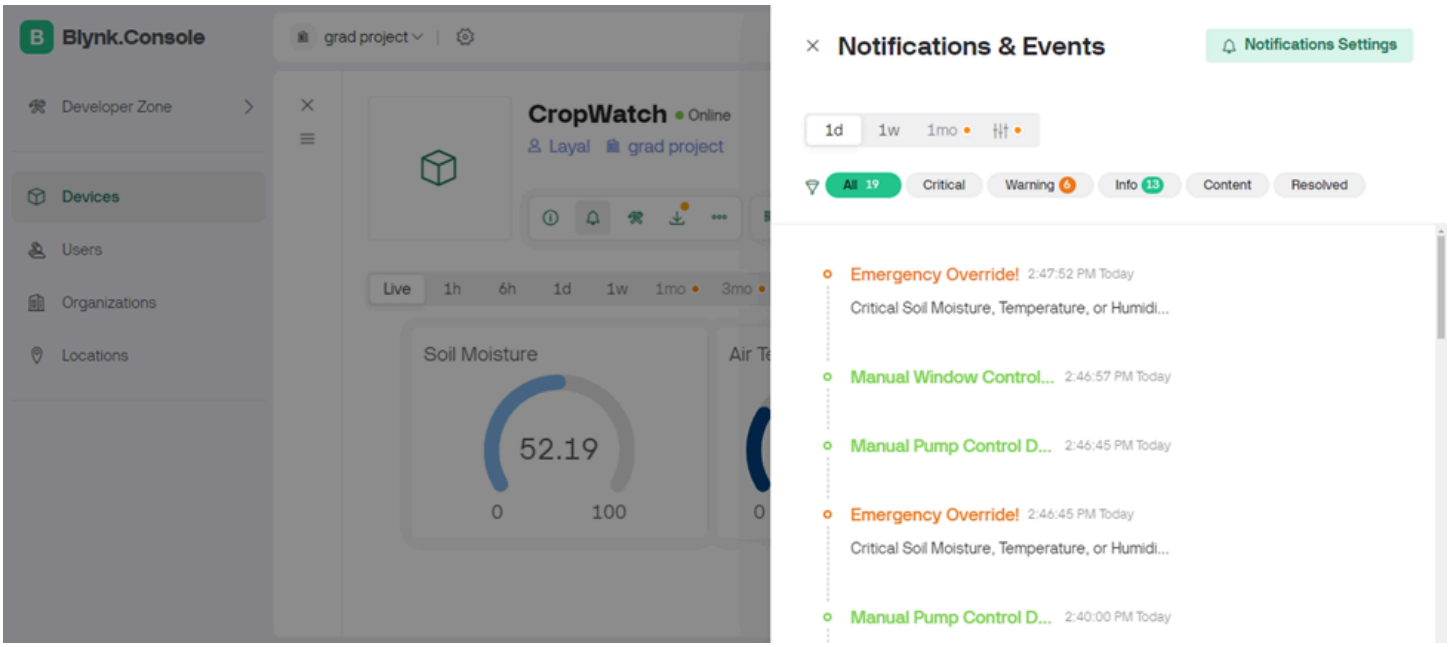


Fig.17 & 18 Screenshots from Blynk Dashboard: Notifications Tab

5.2 Discussion

The CropWatch system presented in this project is supported by the results, demonstrating a significant step into the field of sustainable agriculture, particularly in water conservation. We were able to successfully integrate sensors, microcontrollers, transistors, and IoT technology to optimize water usage and foster sustainable plant growth.

One key strength of the system is its ability to make data-driven decisions based on real-time sensor data, accurately determining when and how much to water the plants without relying on extensive past data or any future data. Moreover, the system's integration of environmental control variables, such as ventilation, adds another layer of efficiency to greenhouse operations. Additionally, the granular control mechanism implemented to transition between manual and automatic modes is another crucial strength. We had previously implemented a mechanism where manual input to one device triggered a shift to manual mode for the entire system, and manual mode could then be deactivated before the defined default duration was over by manually deactivating both devices in order to maximize the efficiency of the RHC algorithm. However, we hadn't considered that this blanket transition could instead be a limitation that

potentially disrupts automated processes, necessitating a more nuanced approach. Currently, manual activation or deactivation of a specific component only affects that particular process, leaving other automated processes unaffected unless explicitly overridden. Manual control then defers to RHC after the default duration elapses. Furthermore, a periodic check for critical conditions ensures that if any are detected, the system also defers to the RHC algorithm. This process helps avoid unintentional drawbacks to manual control, such as excessive energy consumption or reduced system performance leading to suboptimal environmental conditions for plant growth, and maintains the efficiency of the RHC algorithm.

To ensure the sustainability of our CropWatch system, it is imperative to also analyze power consumption, considering the individual energy requirements of each component. From the DHT11 sensor to the ESP32 microcontroller, every element contributes to the overall power consumption, and a total daily energy consumption of 175.2 watt-hours (Wh) was calculated by evaluating both the power requirements and their respective operating durations. Several strategies were employed that aimed to reduce energy usage without compromising the system's efficiency and reliability, such as sensor power management, as sensors are only activated when readings are taken and powered down when not in use by implementing a duty cycle approach. The CropWatch system transmits sensor readings periodically instead of continuous data transmission, optimizing the balance between real-time monitoring and power consumption. Additionally, placing the RHC algorithm at the core of our system ensures that the water pump and window actuators operate only when absolutely necessary unless manual intervention occurs, thereby conserving power. If manual intervention does occur, we have also implemented a timeout and a check for critical conditions so the system reverts to automated control, ensuring that the components are not left in a high-power state. Finally, since the water pump contributes notably to power consumption during its operational periods, utilizing the high-efficiency, low-power loss characteristics of the IRF540 MOSFET instead of using a relay module also optimizes power usage.

While the system shows great promise, there are some limitations and areas for improvement. For example, the current system focuses on a mini greenhouse setup, and its scalability and reliability needs to be further explored. Additionally, the dependence on WiFi connectivity for

data transmission may pose challenges in areas with limited internet access, as rural areas tend to be. Moreover, energy consumption can be further optimized by integrating renewable energy sources such as solar panels, and the manual override can be further refined for better system performance.

5.3 Future Work

Although our smart greenhouse integrating ESP32 and IoT technology displays significant potential, ongoing research and development are crucial to improve its precision for larger scale projects. One idea is to add a pH sensor to the soil to monitor plant health. Machine learning integration can also be a vital aspect to consider in the future advancement of this technology, such as an LSTM model for forecasting water requirements, since the Receding Horizon Control method we implemented remains limited without a more holistic predictive model. Another idea is to add a camera and image processing software to monitor plant health and adjust irrigation rates accordingly, aligning with the multi-objective RHC algorithm and sensor data. Additionally, we can integrate renewable energy sources such as solar panels, as previously mentioned, and upgrade hardware components, such as the microcontroller used, types of sensors, number of sensors, and quality of wires, to optimize energy usage and performance in the realm of precise irrigation.

Chapter VI: Conclusion

In conclusion, our IoT-powered smart greenhouse irrigation system for farmers demonstrates advancements in the realm of sustainable agriculture practices, particularly in water conservation and efficient plant growth management. By integrating sensors, ESP32 technology, adaptive algorithms, and IoT technology, we've developed an intelligent irrigation solution that optimizes water usage based on real-time data. This approach addresses the pressing need for resource-efficient agricultural practices in regions like Jordan, where water scarcity is a significant concern.

Furthermore, the extension of our system's functionality to include control over environmental variables such as temperature and ventilation adds a layer of versatility and adaptability to greenhouse management. By autonomously adjusting greenhouse conditions according to short-term forecasts based on actual sensor data, we enhance overall efficiency and sustainability in agricultural production, while also taking into consideration the daily power consumption of these components. Additionally, integrating manual control so that ultimate control of the CropWatch system still lies with the farmer allows for a harmonious blend of technological automation and human intuition in greenhouse management.

Moreover, the educational aspect of our project cannot be overstated. By documenting our methodology, hardware and software integration, and algorithmic approach, we provide a valuable resource for students and researchers interested in the intersection of agriculture and technology.

Looking ahead, the insights gained from this project lay groundwork for further innovation in sustainable agriculture. As technology continues to evolve, we anticipate broader applications of our CropWatch system, offering increased efficiency, and data-driven decision-making in greenhouse management and beyond.

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