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IoT-enabled system for monitoring and controlling vertical farming operations

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ABSTRACT

In this paper, we present an internet of things (IoT) powered solution that facilitates effortless monitoring and management of vertical farming operations. Our proposed approach employs cost-effective embedded microcontrollers and sensors to keep a tab on crucial parameters like soil moisture, air humidity, and temperature. The data acquired from these sensors can be accessed through a web page that is compatible with all web browsers and smart gadgets such as mobile phones and tablets. Furthermore, the IoT platform offers users the ability to regulate soil moisture and administer ultraviolet light to plants. The system can bring many benefits such as enabling real-time monitoring and control of environmental conditions, reducing energy consumption, improving scalability and flexibility, and contributing to the sustainable and efficient production of food.

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1. INTRODUCTION

Agriculture is one of the most important sectors in the world, providing essential resources such as food and fiber for human consumption. With the world's population continuing to grow and urbanization expanding, the demand for food production is increasing, while the availability of farmland is decreasing [1]. In response to this challenge, vertical farming has emerged as a promising solution that can provide a high yield of crops in a limited space. Other advantages over traditional farming methods include reduced water usage, less dependence on pesticides and herbicides, and reduced transportation costs as the produce can be grown close to urban centers. However, the implementation of vertical farming requires precise control and monitoring of various environmental factors, such as temperature, humidity, lighting, and nutrient supply.

Wong *et al*. [2] discusses four key considerations for starting and maintaining an indoor vertical farm: location, cultivation type, crop type, and technology. The cultivation type can be classified into four types: soil-based, hydroponics, aquaponics, and aeroponics [3]. The paper highlights the benefits of soil-based vertical farms since soil can provide primary nutrients and micronutrients to plants, retain moisture, and support organic farming. The work also discussed the impact of light spectrum on plant growth and phytonutrient content. They explained that although plants can absorb a wide range of light, only the visible light range of 400-700 nm can be used for photosynthesis, while other lights such as ultraviolet (UV) have effects on plant metabolism [4]. Supplemental UV-A light can increase the anthocyanins concentration and induce the accumulation of phenolic compounds and antioxidants in plants. The ideal soil moisture level for plants is also crucial for healthy growth, as per Natsheh *et al.* [5]. Proper irrigation is essential to maintain healthy and productive planting in crops like strawberries. Moore *et al.* [6] stated that the increase in ambient temperature has a direct impact on photosynthetic enzymes, leading to decreased chlorophyll content, which affects crop growth and yield. Fanourakis *et al.* [7] noted that air humidity is another essential parameter that needs to be monitored in vertical farming to ensure that crops can grow optimally. High relative humidity limits nutrient uptake in plants, while low humidity causes stomatal closure, leading to reduced mineral uptake.

The internet of things (IoT) technology has the potential to transform the agricultural industry by enabling real-time control and data monitoring [8]-[12]. By integrating sensors, microcontrollers, and wireless communication, an IoT-enabled system can provide farmers with continuous monitoring of environmental conditions, allowing for data-driven decision-making and precise control of farming operations [13]-[15]. Additionally, by utilizing IoT technology, it is feasible to seamlessly connect both sensors and actuators like robotic platforms, which is essential for creating a fully automated vertical farming system [16]-[20].

While IoT has the potential to revolutionize vertical farming, there are several challenges that need to be addressed for successful implementation. For instance, the IoT technology can be expensive, particularly for small-scale farmers. The cost of IoT sensors, devices, and systems can be a significant barrier to entry for some farmers. Furthermore, IoT devices generate a vast amount of data, which can be challenging to manage and analyze. Farmers need to have the right tools and expertise to process and interpret the data to make informed decisions [21], [22]. In this work, we introduce an IoT-based system that can monitor and control vertical farming operations in a simple and user-friendly manner. Our proposed system employs low-cost embedded microcontrollers and sensors to track soil moisture, air humidity, and temperature. The collected data from these sensors is accessible via a web page that can be viewed using any web browser or smart devices such as mobile phones and tablets in real-time. Moreover, the IoT platform also enables users to regulate soil moisture and administer UV light to plants.

2. METHOD

2.1. Hardware and software

The proposed IoT-based vertical farming system utilizes several software and hardware platforms to function effectively. The main software platforms include the Arduino IDE, SystemLink IoT cloud, and NI LabVIEW. NI LabVIEW is used extensively throughout the project to create a user interface via the SystemLink IoT cloud and G web development software. This interface can be accessed from any web browser on any device, enabling users to control and monitor the farm from anywhere.

In this work, an NI myRIO board is used to act as the server for data communication and control. The measurement system comprises two primary microcontrollers, the Arduino Nano and the NodeMCU ESP8266 Wi-Fi module. The ESP8266 Wi-Fi module interfaces with the DHT22 temperature and humidity sensor and the capacitive soil moisture sensor to collect data on temperature, humidity, and soil moisture. The Arduino Nano works with the ESP8266 Wi-Fi module to establish wireless communication, transmitting the measuring data to the web application. Additionally, the Arduino Nano interfaces with a 12 V 4-channel relay module, which controls the water pumps and UV lighting.

Figure 1 shows the detailed connections of the prototype. It is worth noting that the operating voltages for the Arduino Nano and NodeMCU ESP8266 board are different, with the former requiring 5 V and the latter requiring 3.3 V. As a result, a level shifter composed of 2N2222 transistors and resistors is employed to address the voltage difference in the signal. Additionally, since the water pumps and UV light-emitting diode (LED) light operate at different voltages, a relay module is incorporated to enable the control of the water pump, which has a higher operating voltage of 12 V. An HC4067 multiplexer module is employed to enable sharing of a single analog input pin between the two soil moisture sensors. The DHT22 sensor module is connected to one of the digital I/O pins, and the sensed value can be acquired via the Wi-Fi module. The connection between the sensor and the ESP8266 board is established via the D7 pin, as shown in the figure. The Arduino Nano serves as the 5 V controller for the relay, and six digital I/O pins are utilized, with three serving as input pins and the other three as output pins. The NI myRIO board is connected to the server station via a universal serial bus (USB) cable, completing the monitoring and control system.

2.2. Program flowcharts

Figure 2 shows the program flowchart that has been uploaded to the Arduino Nano. After the setup() function is executed, the loop() function will be initiated, and it will continue to run repeatedly to allow the microcontroller to perform continuous operations. Within this function, the input pins' sensed signal values are continuously displayed on the serial monitor. The signal values received are either 0 or 1 and are displayed accordingly. Furthermore, each signal line contributes to one digital output signal line.

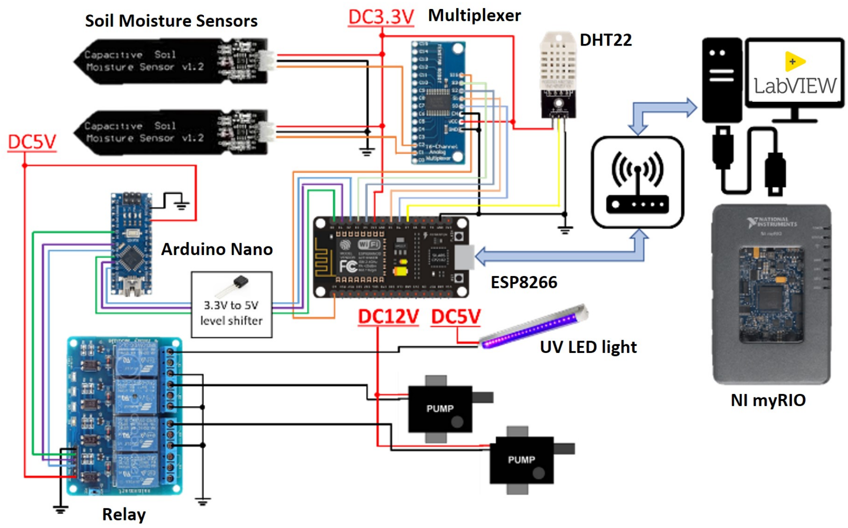


Figure 1. Detailed circuit connections of proposed system

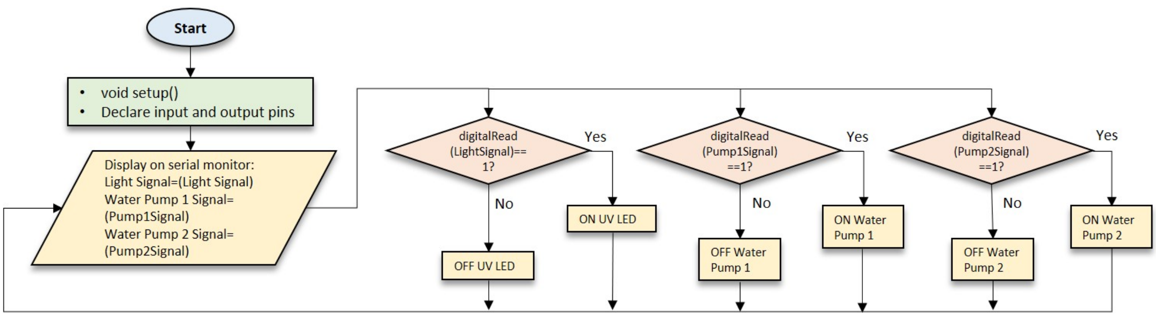
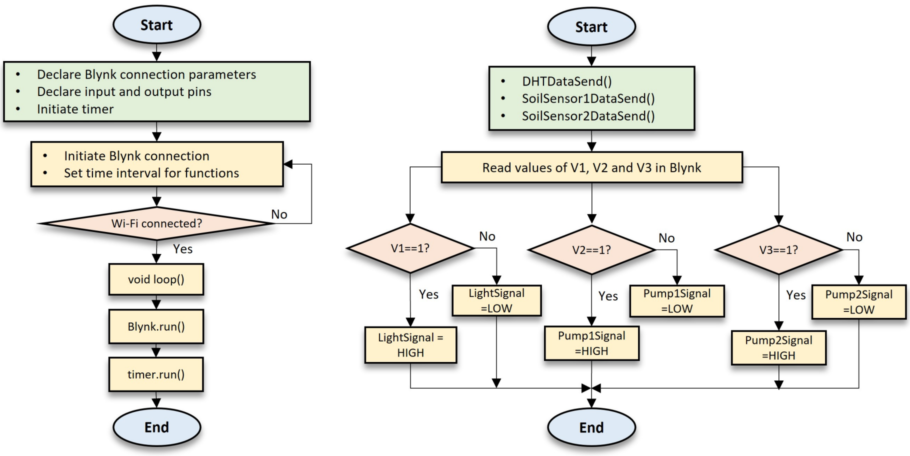


Figure 2. Program flowchart for Arduino Nano

Figure 3 explains how the ESP8266 Wi-Fi module operates and the function in Blynk. The ESP8266 needs to stay connected to the Blynk cloud as shown in Figure 3(a), interface with sensors, and provide digital output signals to the Arduino Nano board. To do this, necessary libraries are included at the beginning of the program. The program is followed by some Blynk connection parameters such as the Wi-Fi connection credentials and the specified authentication token. The declaration of input and output pins as similar to that in Arduino Nano board is done followed by the initiation of timer from Blynk library.

Inside the setup() function, a command having the declared SSID, password and authentication token is executed so that the Wi-Fi module can start to connect to the network. If the Wi-Fi connection is established successfully, the program continue to execute three command lines that declaring the execution time interval for three functions namely the DHTDataSend(), SoilSensor1DataSend() and SoilSensor2DataSend as illustrated in Figure 3(b). Once the Wi-Fi connection is completed, the Blynk server will be accessed and connection status will still be displayed via the serial monitor. The Blynk library will occupy the serial monitor for communication between the board and the Blynk cloud. Thus, after the access to Blynk cloud, the loop() function should be clean enough by having just a few lines of command.



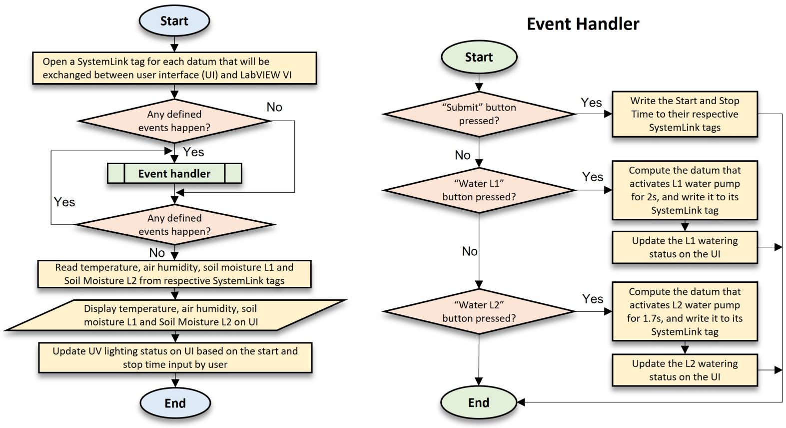
(a) (b)

Figure 3. Program flowcharts of (a) ESP8266 and (b) Blynk.run() function

This work also involves designing and developing a web virtual instrument (VI) using G web development software. The web VI is hosted on the SystemLink cloud server and can be accessed by users through any web browser with an internet connection. The flowchart in Figure 4 shows the program loaded on the web VI. The web VI will open a SystemLink tag for each item exchanged between the user interface and the LabVIEW VI, and check for defined events. When an event occurs, the Event Handler function as described in Figure 4(a) will be called to perform subsequent actions. The web VI will read sensor values such as temperature, air humidity, and soil moisture from the SystemLink tags, and display them on the user interface as both numerical values and graphical charts. The last updated time for each datum will also be displayed. Data is set to update every 10 seconds, but can be adjusted as needed.

The web VI will also update the status of the UV lighting based on user-submitted start and stop times, which can be computed by comparing the input times with the current timestamp. In addition to its other functions, the web VI is capable of writing data to SystemLink tags. This is achieved through the Event Handler as shown in Figure 4(b). The Event Handler checks for registered events on the web VI. When the ”Submit” button is pressed, the web VI writes the start and stop times input by the user to their respective SystemLink tags. Similarly, when the ”Water L1” button is pressed, the web VI computes the datum that activates water pump 1 for 2 seconds and writes it to its SystemLink tag. The L1 watering status is then updated on the user interface. The same thing happens when the ”Water L2” button is pressed, but the computed datum only activates water pump 2 for a shorter duration of 1.7 seconds. This is because the Level 2 of the vertical farm refers to the lower level, and the water takes less time to reach the plants in this case.

A LabVIEW VI is developed in this work for the purpose of retrieving data from and sending data to both the SystemLink cloud server and the Blynk cloud server, as well as performing data processing as needed. The LabVIEW VI is run on the myRIO board which requires a WI-Fi connection. The program begins by establishing an hypertext transfer protocol (HTTP) connection for SystemLink data services to communicate with the SystemLink cloud, which is configured through application programming interface (API) key authentication. Then, the VI opens SystemLink tags for all the items/data that need to be exchanged between the user interface and the LabVIEW VI. The LabVIEW VI is involved in both the monitoring system and the environmental parameters control system. For the monitoring system, a sub-VI is developed to read data from the Blynk cloud server via HTTP client, which simplifies the main LabVIEW VI’s block diagram. Once the sensor data is retrieved, the LabVIEW VI writes the data to the respective SystemLink tags. Regarding controlling the environmental parameters of the vertical farm remotely, the LabVIEW VI reads the start time, stop time, water 1, and water 2 variables from the respective SystemLink tags, and then computes the UV lighting control signal based on the obtained start time and stop time. This involves comparing the start time and stop time with the current timestamp to determine whether the UV light should be turned on. The data responsible for controlling the outputs such as UV lighting, water pump 1, and water pump 2 is written to the Blynk cloud server through HTTP client, with a sub-VI developed specifically for this purpose.



(a) (b)

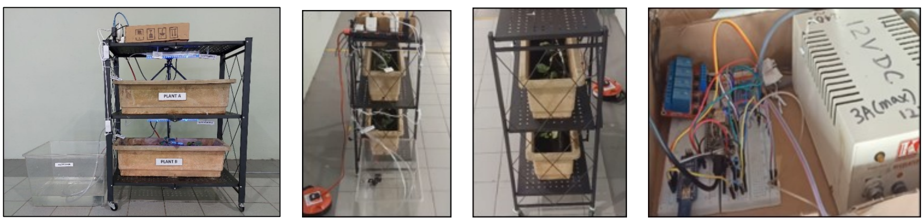
Figure 4. The program flowchart loaded on (a) the web VI and (b) the corresponding event handler's flowchart

3. RESULTS AND DISCUSSIONS

A two-level rack is utilized to hold the flower pots, and each level has a UV light for exposing the plants to UV light, as shown in Figure 5. The prototype's front view, left view, and right view are shown in Figure 5(a), Figure 5(b), and Figure 5(c) respectively. The circuit is depicted in Figure 5(d) which is positioned on top of the rack and covered to prevent water damage. The watering system comprises a water tank and two water pumps connected by two hoses. The water pumps are placed in the water tank, which is located to the left of the physical prototype. The dimensions of the prototype are 85 cm (height) × 72 cm (length) × 31 cm (width), while the water tank's dimensions are 33 cm (height) × 45 cm (length) × 30 cm (width).

The user interface (UI) has been successfully developed by using G web development software as shown in Figure 6. The UI is developed as a web VI, and it is deployed on the SystemLink cloud and can be accessed through the URL: https://hosting.systemlinkcloud.io/webapps/1bbc353d-804d-451a-aec0-958e6ca2fc9-c/content/. The VI has effectively retrieved the sensor values from the Blynk cloud via HTTPs representational state transfer (REST) API, and then transmitted them to the SystemLink cloud. The UI displays these values in both numerical and chart forms. Additionally, the interface also displays the time stamp indicating when the data was last updated.

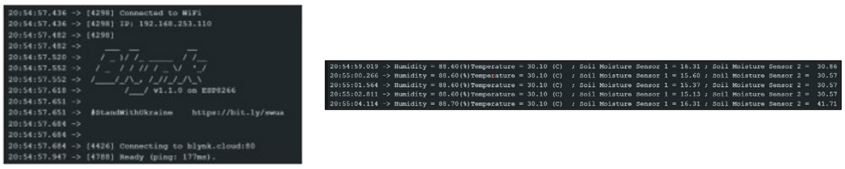
Figure 7 shows the connection to Blynk cloud where Figure 7(a) illustrates the output on the serial monitor when the connection is successful, and Figure 7(b) illustrates the sensed data on the serial monitor. Before the data is displayed on the serial monitor, it undergoes calibration to convert the raw data into readable and understandable values. The DHT22 library processes the sensed data from the DHT22 sensor, while an algorithm is used to process the soil moisture sensor data. This algorithm divides the values with the range of data values, which provides the percentage of soil moisture value. This information has been successfully uploaded onto the Blynk cloud via the Blynk.run() command as depicted in Figure 8, which illustrates the developed Blynk cloud dashboard in mobile application (Figure 8(a)) and Blynk cloud dashboard in web page (Figure 8(b)).



(a) (b) (c) (d)

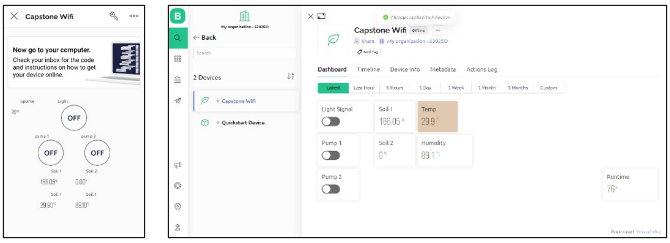
Figure 5. The prototype's (a) front view, (b) left view, (c) right view, and (d) electronic circuit connection

Figure 6. The UI developed using G web development software



(a) (b)

Figure 7. Successful connection to (a) Blynk cloud on serial monitor and (b) an illustration on the sensed input data on serial monitor

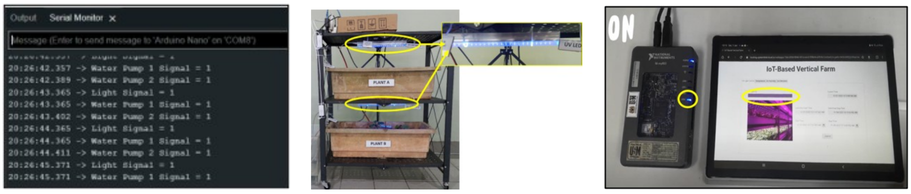


(a) (b)

Figure 8. Blynk cloud dashboard in (a) mobile application and (b) web page

The success of the UV lighting system from the user input to indicators shown on the NI myRIO board's LED and UI is illustrated in Figure 9. When the UV lighting is set to be turned ON, the input data will show '1', and '0' otherwise. Figure 9(a) visualizes the output in the serial monitor while Figure 9(b) and Figure 9(c) depict the corresponding outputs in the prototype and on the NI myRIO board as well as UI respectively. Similar to the UV lighting system, the watering system will also be reflected on the NI myRIO board's LED and UI when it is activated as depicted in Figure 10. Figure 10(a) illustrates the event when the watering system is activated while Figure 10(b) shows the LED indicators for activation of pump 1 and pump 2 on the NI myRIO board and UI.

Overall, the watering system is accurate and reliable, with the correct signals being transmitted from the user interface to the ESP8266 board, controlling the activation of the water pumps. The user interface also displays the watering status for each level correctly whenever the water pumps are activated, despite the small delay caused by the data communication through cloud platforms. To enable the system to be applied on a large scale, new sensors and actuators can be easily added to the system, and the microcontroller can process and send data to the central monitoring system in real-time. This will also allow integration of artificial intelligence (AI) into the system to predict the growth and development of crops based on historical data, environmental conditions, and other factors [23]-[25]. This can help farmers to anticipate potential issues and take preventive measures to avoid crop failure. Autonomous farming can also be implemented by combining AI with robotics to reduce labor costs and increase efficiency [26]-[30].



(a) (b) (c)

Figure 9. User input data in (a) serial monitor, (b) UV lighting system in prototype, and (c) LED indicators for UV Lighting on the NI myRIO board and user interface

(a) (b)

Figure 10. Illustration on (a) the event when the watering system is activated, and (b) LED indicators for activation of pump 1 and pump 2 on the NI myRIO board and user interface

4. CONCLUSIONS AND FUTURE WORK

In this article, we introduce a solution for monitoring and managing vertical farming operations using the IoT. Our proposed approach involves using affordable embedded microcontrollers and sensors to track important parameters such as soil moisture, air humidity, and temperature. The data collected by these sensors can be accessed through a web page that is compatible with various web browsers and smart devices, including mobile phones and tablets. In addition, our IoT platform allows users to adjust soil moisture levels and administer UV light to plants. This system provides several benefits, such as enabling real-time monitoring and control of environmental conditions, reducing energy consumption, and promoting sustainable and efficient food production.

The use of embedded microcontrollers can improve the scalability and flexibility of the vertical farm. In addition, incorporating embedded microcontrollers can enhance the vertical farm's flexibility and scalability. Future works involve merging AI with the system to forecast crop growth and development, taking into account historical data, environmental conditions, and other factors.

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