PlantPulse: A Plant Health Monitoring System

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***Abstract* — PlantPulse is an innovative system designed to simplify plant health monitoring for home gardeners, combining IoT sensors with NDVI imaging to provide a comprehensive understanding of plant wellness. This project integrates multiple environmental sensors with a mobile app interface, enabling users to monitor soil moisture, temperature, UV index, and humidity, with actionable care suggestions based on real-time plant conditions. This paper details the system's design, hardware and software integration, testing methodology, results, and user feedback.**

***Index Terms* — NDVI, IoT, plant health monitoring, sensor networks, remote sensing.**

I. INTRODUCTION

As home gardening continues to gain popularity, gardeners encounter challenges in monitoring and understanding their plants' health, which often leads to inconsistent results. PlantPulse provides an accessible, all-in-one solution that consolidates plant health monitoring through temperature, humidity, soil moisture, and UV sensors, combined with NDVI-based plant health evaluation. Unlike traditional methods, PlantPulse offers real-time insights and actionable care recommendations, reducing guesswork for gardeners.

PlantPulse operates autonomously after setup. Once positioned near plants, the device continuously monitors essential plant health metrics and transmits data to a mobile or web app. The user-friendly app interface displays these metrics and provides actionable recommendations, like "Increase watering" or "Relocate to a sunnier area," helping users make informed care decisions.

II. SYSTEM DESIGN AND METHODOLOGY

A. Hardware Components

The PlantPulse system includes various sensors for temperature, humidity, soil moisture, and ultraviolet light, each selected for reliability, accuracy, and affordability. The SHT45 temperature and humidity sensor offers high accuracy (±0.1 °C for temperature, ±1.0 %RH for humidity), essential for monitoring sensitive environmental conditions. The PIM520 capacitive moisture sensor provides consistent readings at a low cost, while the AS7331 UV sensor covers broad-spectrum UV detection (UV-A, UV-B, UV-C), essential for accurate NDVI readings. A comparison of these sensors' specifications, accuracy, and cost is shown in Table 1.

Table 1.a

Specifications	SHT45
Accuracy-Spec	Avg: ΔRH = ±1.0 %RH, ΔT = ±0.1 °C Worst: ΔRH = ±2.0 %RH, ΔT = ±0.1 °C
Voltage Range	1.08V – 3.6V
Avg current	0.4μA
Interfaces	I2C
Operating Range	0 – 100 %RH, -40 ~ 125ºC
Dimensions	1.5mm x 1.5mm x 0.5mm
Weight	N/A
Price	$3.47 - $7.81 per chip

Table 1.b

Specifications	PIM520
Input voltage	3.3V
Communication	Pulse Width Frequency
Dimensions	99 mm x 10 mm x 5 mm
Price	$4

Table 1.c

Specifications	AS7331
Bandwidth Accuracy	N/A
Bandwidth Range	260 nm – 360 nm
Sensitivity	421 counts/(μW/cm²)
Voltage range	2.7V – 3.6V Typical: 3.3V

Average Current	970µA – 2mA Typical: 1.5mA
Interfaces	I2C
Operating Temperature	-40ºC ~ 105ºC
Dimensions	3.6 mm x 2.6 mm x 1.09 mm
Weight	N/A
Price	$10.86

B. NDVI Camera Module

The PlantPulse system includes an infrared-capable camera for NDVI analysis, calculating photosynthetic activity and plant health based on the NDVI algorithm:

$$NDVI = \frac{NIR-VIS}{NIR+VIS} \quad (1)$$

A sample NDVI image comparing healthy and stressed vegetation is shown in Fig 1.

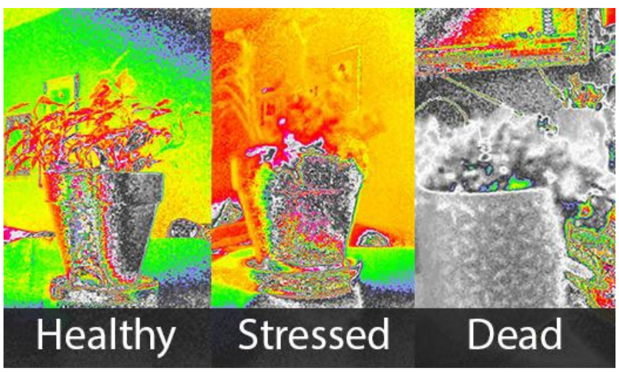


Fig. 1. NDVI data expressed as a heatmap providing insight into the overall health of the plant.

C. Microcontroller System

PlantPulse utilizes two microcontrollers, the ESP32-C3 and the ESP32-S3, both produced by Espressif systems and programmed in C utilizing the ESP-IDF API provided by Espressif. Originally the decision to utilize the ESP32 family of microcontrollers was due to our systems inherit need for wireless communication, and the ESP32 family of microcontrollers provides a very affordable system with built-in Wi-Fi and Bluetooth compatibility. The ESP32-S3 specifically was the microcontroller of choice as it provided PSRAM which would be utilized in the SPI communication protocol to process the camera data, as well as higher SRAM options as well as dual core system for efficient task implementation with FreeRTOS built into the ESP32.

Early on in development the decision to separate the camera and sensor system was decided due to restrictions on the camera options we had available at the time of design. This resulted in us continuing to utilize the ESP32-S3 for the reasons mentioned above, but opted for the ESP32-C3 for the sensor subsystem as it provided the same benefits as the ESP32-S3, but was a more trimmed down version, with no PSRAM, less SRAM, and a single core instead, reducing power consumption as well as cost for the much simpler operations required of this device.

Within the microcontroller system we also utilized the raspberry pi zero II to interface with the raspberry pi cam which was required for generating our no-IR plant images. This device was used exclusively for communicating with the camera and then transmitting the data to the ESP32-S3 for processing to minimize the uptime of the raspberry pi zero two, which draws more power than the ESP32.

D. Power Supplies

The power supply is broken into the camera package power supply and the sensor package power supply. The camera package power supply consists of a solar panel and rechargeable battery pack to focus on sustainability and the sensor package power supply consists of a nine-volt battery to focus on ease of use. Additionally, both power supplies are optimized for lower power operation since the MCUs, and Pi will be idle or asleep for the majority of their operation. The power draw for each component can be seen in table 2 below with net power requirements for each package.

Table 2.

Component	Voltage (V)	Current (mA)
ESP32 S3	3.3	355 (Peak)
ESP32 S3 (light sleep)	3.3	0.24
ESP32 C3	3.3	345 (Peak)
ESP32 C3 (light sleep)	3.3	0.24
SHT45	3.3	0.05
AS7331	3.3	2
Raspberry Pi 02 W	5	220-260
Worst Case 5V	5	500
Worst Case 3.3V	3.3	355

Table 2. Estimated power draw breakdown by component, voltage, and current.

As shown above the worst-case scenario for power draw at the 5V level should be 500mA and at the 3.3V level should be 355 mA. This amounts to a peak power draw of approximately 2.5W. It should also be noted that the active current consumption characteristics for the two ESP32 MCUs are peak values and that the MCUs typically consume less current. Also, the soil moisture sensor has been left off as the manufacturer does not publish current consumption characteristics and the actual current consumption is a low enough level that like the AS7331 and the SHT45 it is not a major contributing factor in terms of power consumption.

With the knowledge of our load requirements, we were able to then move onto designing our two power supplies.

For the ESP32 C3 based sensor package we decided to simply use a 9V battery. This package should have a lower current draw as the C3 only uses BLE to transmit data. A 9V battery will allow the end user to easily replace the battery when it eventually dies. For our system we will be using a lithium 9V battery due to the longer lifetime of lithium batteries, but alkaline batteries are equally acceptable for this application.

For the ESP32 S3 based camera package we decided upon a solar system with a rechargeable battery backup. This package should have a higher overall level of power draw since the S3 transmits over WiFi and the Pi draws considerable power. Because of this higher power draw a battery would need to be replaced considerably more often than the 9V battery on the sensor package. This motivated a solar solution since it should make the power on the camera package mostly autonomous. While any lithium-ion battery would likely be acceptable for powering this package we chose to use 18650 batteries as they are a standardized and readily available package size making their replacement easy if the end user desires to do so. Finally, we selected a 15W monocrystalline solar panel. This solar panel is oversized for our load (an estimated 2.5W peak). However, our selection is to ensure that the backup battery remains off for as long as possible therefore extending its life even further.

To deliver this power we have a 3.3V regulator on the sensor package and a charge controller, 5V regulator, and 3.3V regulator on the camera package. Of all the components in the power supply the most essential one is the solar charge controller. Below we have included a table which compares the various options we considered for the charge controller.

Table 3. Part comparison of various charge controller PMICs

	BQ25756E	BQ24210	BQ25798
NVDC	No	No	Yes
Number of Cells	1-7	1	1-4
Power Topology	Non Power-Path	Non Power-Path	Power-Path

Our selection of the BQ25798 charge controller was motivated by its use of NVDC which would increase the power supply's efficiency as well as its use of power path topology which would further extend the battery life of the lithium-ion battery pack. Finally, we need a charge controller which can handle up to two cells in series since the nominal voltage of 18650 cells is 3.7 volts, the Raspberry Pi zero 2w requires a five-volt input, and a buck-boost regulator would hurt the efficiency of our system.

As for our regulators, our parts selection was motivated primarily by efficiency. The comparison can be seen in the below table.

Table 4.

	TPS62932	LM64460-Q1	TPS566231	MCP16502
Output V Range	.08-22	3-36	0.6-7	1.2-3.7 & .6-1.85
Max Output Current	2	6	6	1-.3
Estimated Efficiency	95%	93%	95%	85-96%

As for the specific solar panel and battery components, the options we chose were primarily motivated by cost and availability. The specific battery and solar panel do not matter in the same way that a regulator or charge controller IC do since their primary function is to be a power reserve. As long as the solar panel is able to output a high enough level of power and as long as the battery is able to provide enough current the power supply will work. Once the 18650 package size was chosen the technologies of lithium ion batteries we could select from was essentially narrowed down to non-polymer based lithium ion batteries. Within the space of 18650 batteries the primary relevant specifications are the total rated power and the number of cycles the battery is rated for. Neither of those specifications, however, actually affect the battery's ability to power the power supply and as such the part selection for this part has been left off. Additionally, the actual manufacturer or technology of the battery used in the nine-volt battery is not important to the function of the power supply.

III. DATA TRANSMISSION AND SOFTWARE ARCHITECTURE

A. Data Transmission

Data from each sensor is transmitted wirelessly between the ESP32-C3 and the ESP32-S3, and then transmitted from the ESP32-S3 to transmit data to the mobile app interface. When deciding on transmission methods three transmission schemes were in discussion, Bluetooth Low Energy (BLE), WiFi, and Espressif ESP-NOW. When considering the needs of this system, which were quick and efficient low power data transmission, Bluetooth Low Energy became the transmission method of choice for the communication between the two microcontrollers, and WiFi became the transmission method between the ESP32-S3 and the mobile app. Espressif's ESP-NOW protocol would have greatly simplified the development of the communication between the two systems, but due to the large amount of power consumed when using this protocol, it was ultimately removed from consideration despite the increased complexity in implementing the Bluetooth stack. Table 3 compares Bluetooth Low Energy, Wi-Fi, and Espressif ESP-NOW on transmission speeds and energy efficiency.

Table 5. Wireless Communications Protocol Comparison

Protocol	Data Rate	Transmission speed	Power consumption (Transmission)
ESP-NOW	588Kbps	0.63Mbps	511-1042mW
Wi-Fi	2048Kbps	0.98Mbps	477-538mW
Bluetooth	938Kbps	24.86Mbps	338-441mW

Table 3

Table 3 shows the parameters which we cared the most about when making our decision on the wireless data transmission method. Not listed is the latency metric, which is where Espressif's ESP-NOW excels at. Unfortunately, considering latency wasn't a big factor for our system, ESP-NOW was outdone by both Bluetooth and Wi-Fi in the other metrics which were important factors. Particularly the high data rate and transmission speed for ESP32-S3 to our mobile app, and Bluetooth for the low power consumption for our ESP32-C3 to ESP32-S3 (D. Eridani).

B. Software Design

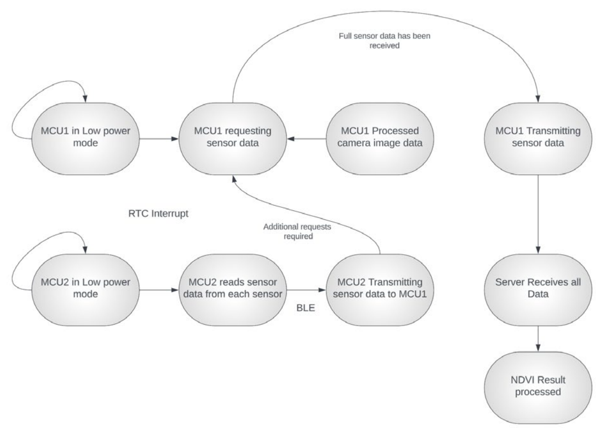
Figure 2 presents the software architecture, showing data flow from sensor data collection to NDVI processing and mobile/web user interface. The software includes:

Sensor Device: Generates data readings from the temperature sensor, the humidity sensor, and the soil moisture sensor. Following the data generation, all data is compiled into a complete package and transmitted to the main device for processing.

Camera Device: Communicates with a raspberry pi zero II hosting a raspberry pi camera to generate and process a no-IR photo of the target plant for NDVI imaging. This system also generates an ultraviolet light reading consisting of ultraviolet light channels a, b, and c and transmits the data to the mobile application for further processing.

NDVI Processing Module: Processes image data to calculate NDVI values, which are then uploaded to the cloud.

Figure 2.



Mobile App Interface: Displays metrics, alerts, and plant care suggestions based on sensor data analysis.

User Interface

The mobile and web apps display real-time plant health metrics in a format that is intuitive and accessible. Users can access historical data, receive notifications, and view detailed visualizations of their plant's health. The interface design is focused on usability for gardeners of all experience levels.

IV. SYSTEM TESTING AND EVALUATION

A. Sensor Testing

During the final phase of our development, we began testing the various sensors associated with the system. Each sensor was tested individually for accuracy and response time. For the purposes of our system, the response time of each sensor reading when initiated was near instant resulting in the response time of the sensors themselves being negligible for the scope of this project.

For testing the temperature sensor, we ran several trials against a known temperature in a fixed location comparing the results and analyzing them. The conclusion of this testing resulted in a real-world accuracy of 98% when compared to the known fixed temperature and can be seen in the table below.

Table 6. Prototyping and testing temperature sensor.

Trial Number	Temperature Reading (In Fahrenheit)
Trial #1	Known Temp: 71ºF Measured Temp: 69ºF
Trial #2	Known Temp: 71ºF Measured Temp: 69ºF
Trial #3	Known Temp: 71ºF Measured Temp: 70ºF
Trial #4	Known Temp: 71ºF Measured Temp: 70º
Trial #5	Known Temp: 71ºF Measured Temp: 70ºF
Trial #6	Known Temp: 71ºF Measured Temp: 70ºF
Trial #7	Known Temp: 71ºF Measured Temp: 70ºF
Trial #8	Known Temp: 71ºF Measured Temp:70ºF
Trial #9	Known Temp: 71ºF Measured Temp: 70ºF
Trial #10	Known Temp: 71ºF Measured Temp: 70ºF
Average Reading	69.8ºF

For the soil moisture sensor, it was difficult for us to measure the accuracy against a particular fixed value as the sensor generated a number value with no real meaning for the given water content. To accommodate this we had to manually test the values achieved under different conditions. We first tested the reading with the sensor in open air (driest condition in our location, which due to air humidity resulted in fluctuation in the value) which resulted in a value of approximately 350. The next test was fully submerged in water, which resulted in a value above 1000, and finally in moist soil which sat around 600. From this we were able to determine a suitable scale for the system which can be seen in the table below.

Table 7. Soil Moisture sensor calibration and testing.

Sensor Value	Soil moisture
350 and below	Completely dry soil
400 through 600	Damp soil
600 through 800	Wet soil
900 and above	Overwatered or submerged soil

For the ultraviolet light sensor, we faced a similar issue with no frame of reference without another suitable source. This meant that we instead tested this sensor for precision instead of accuracy, as the purpose of the sensor was to determine if the light conditions were suitable for the camera image. Considering this, the sensor was able to consistently provide a range of 100 to 160 in the ultraviolet light - A band when outside in the sunlight at a suitable level for the camera, and this was the reference we used, with being in more cloudy areas or shade resulting in lower values.

V. RESULTS

PlantPulse successfully met all project objectives. Sensor accuracy, NDVI reliability, and user satisfaction were high, with consistent data transmission and an intuitive interface. Table 5 summarizes key performance metrics, including sensor accuracy, power efficiency, and communication reliability. User testing indicated that the system was easy to set up, with informative data presentation and care suggestions that improved plant health outcomes.

VI. DISCUSSION

The PlantPulse system proved effective in providing real-time, data-driven insights into plant health, giving users the ability to make informed plant care decisions. The device's consistent data accuracy and easy-to-use interface offer a significant improvement over traditional methods. Limitations observed during testing included NDVI's sensitivity to extreme weather, which could affect data reliability. Future improvements include automated calibration for environmental changes and added diagnostic features for plant health issues like disease and pest detection.

VII. CONCLUSION

PlantPulse integrates IoT sensors, NDVI imaging, and remote monitoring into a powerful tool for plant health management. By delivering real-time insights and actionable recommendations. PlantPulse supports gardeners in cultivating healthier plants. Future development will focus on enhancing NDVI stability, expanding diagnostic capabilities, and improving battery efficiency to extend the system's operational lifespan.

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