GardenSense

Internet-of-Things

Environmental Monitoring for Soil Sensing

Master of Information Management and Systems Capstone 2023

Chris Ferenci, Marissa Khoury, Kendra Moore

Advisor: Dr. John Chuang

Berkeley SCHOOL OF INFORMATION

1. Introduction and Background of Sensing

1.1. Introduction to Remote Sensing

The Internet of Things (IoT) refers to the interconnected network of physical devices –"things"– that are embedded with sensors, software, and other technologies in order to connect and exchange data. Remote sensing describes the use of sensors and other technologies to gather data about the environment, among many other applications.

Up until the last two decades or so, remote sensing technologies have existed predominantly in applications of geographical information systems in forms related to maps, aerial photographs, and other similar images [1]. In recent years, chip manufacturing improvements have significantly reduced the size and cost of chips and improved their computational capabilities. These changes have led to the mass adoption of various remote sensing technologies in the consumer, commercial, and public sectors alike.

From this chip production efficiency renaissance, new sensing technology classifications, such as Internet-of-Things (IoT) devices, have entered the market to great effect. IoT devices are estimated to increase by an average of two billion devices per year until 2030 [2]. IoT devices are a significantly smaller and lower-cost class of remote sensors compared to their satellite-grade cousins. A standard IoT device comes equipped with a combination of sensors, a computer system to collect and process data, and components that can transmit data wirelessly over technologies like Bluetooth, WiFi, 4G/5G, and Long Range wireless radio frequency (LoRa). Common IoT capabilities are also seen in smart watches, smart thermostats, and even air quality monitors.

Remote sensing technologies like the above-mentioned allow for high temporal and spatial data collection resolution. At any given time an IoT-enabled device can capture, process, and transmit data at a specific location in real time. New data and new relationships are revealed each day, and these small remote sensors enable the collection of data from a wide range of locations.

1.2. Sensing Applications in Agriculture

1.2.1. Traditional Remote Sensing in Satellites

Most notable forms of remote sensing use data captured primarily through satellite technologies leveraging high-resolution imagery data. According to a study by Precedence Research on Remote Sensing Technology Markets [3], some of the core challenges in remote sensing are its high costs, technical complexity, and data availability. As such, many of these services are expensive and make it difficult for small business farmers or gardeners to capture information that may be critical to farming diagnosis. This is where the recent advances in IoT technologies can show their promise and value.

1.2.2. Internet-of-Things to Improve Data Collection

A market report from Markets and Markets estimated that the United States market for IoT devices was $300.3 billion in 2021 [4]. This same market is expected to double to $650.5 billion by 2026. This growth indicates many potential opportunities for businesses and governments through increased adoption and use of effective and usable remote-sensing IoT devices. The technology, however, remains limited in access to many individuals and organizations who are interested in using these devices because of difficulties in building the hardware components and integrating the technologies into a centralized data management system.

What sets IoT devices apart from existing satellite remote sensing is that these devices offer increased access to high temporal and spatial data (i.e., real-time data) [5]. Increasing access to these sensor technologies and wireless data transmission can allow for real-time crop monitoring data to be transferred across hundreds of acres of land to a central system. A farmer could have multiple sensors located throughout various crop fields collecting real-time data for each field. This provides farmers the opportunity to monitor and diagnose their crops and, with proper analysis tools, identify optimal growth conditions that can provide the best yield. It is our goal with this project to enable gardeners and small business farmers to use these and gain valuable information with these technologies

2. Grower and Farmer User Research

2.1. Research Overview

To understand more about the feasibility and current challenges of using IoT devices for garden and crop health, we conducted a large user survey and multiple user interviews over the course of one year. Interviews were conducted over the phone and in person to understand the costs and challenges with current plant and crop health monitoring. Our survey was conducted using Google Forms and received over 27 individual responses on interests, challenges, and costs associated with personal gardening and small business farming.

2.2. Survey Insights

For our survey, we primarily focused on home growers who are interested in exploring improved monitoring of their home gardens and plant health. To recruit participants, we distributed flyers throughout the Berkeley School of Information at the University of California, Berkeley as well as local student housing in the city of Berkeley. We also posted the survey on Slack and on gardening subreddits.

The survey consisted of 38 questions ranging from experience using sensors, specific conditions one is interested in, and how much they would like to pay. Specific to plants, we asked questions on the types of plant health conditions they may be interested in monitoring such as water and nutrient levels, ambient temperature, humidity, and light exposure.

Our survey showed that users primarily wanted information on plant temperature, light levels, and humidity. We discovered that most users were gardening in an indoor, confined space and were fairly new to gardening. Many users were open to using an open-source, low-cost tool to provide gardening insights but 60% of respondents rated their technology skills as average or below average. Despite wanting to improve their gardening knowledge, many users did not want to pay for a platform. For that reason, we focused on more low-cost and low-tech solutions.

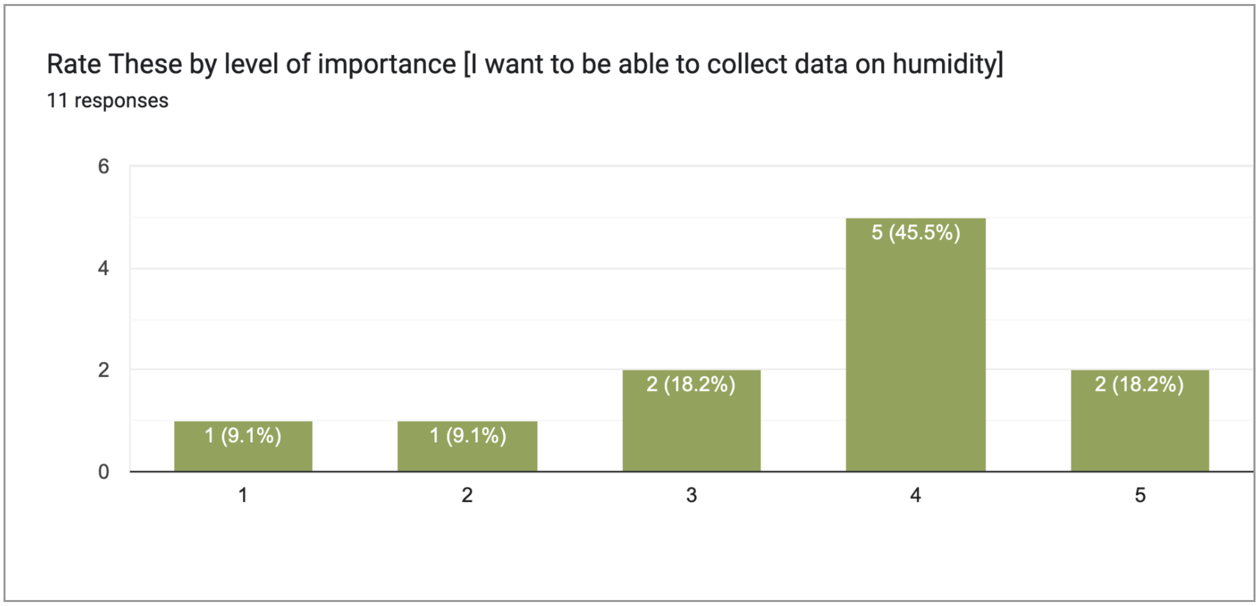


Figure 1 - Humidity Responses

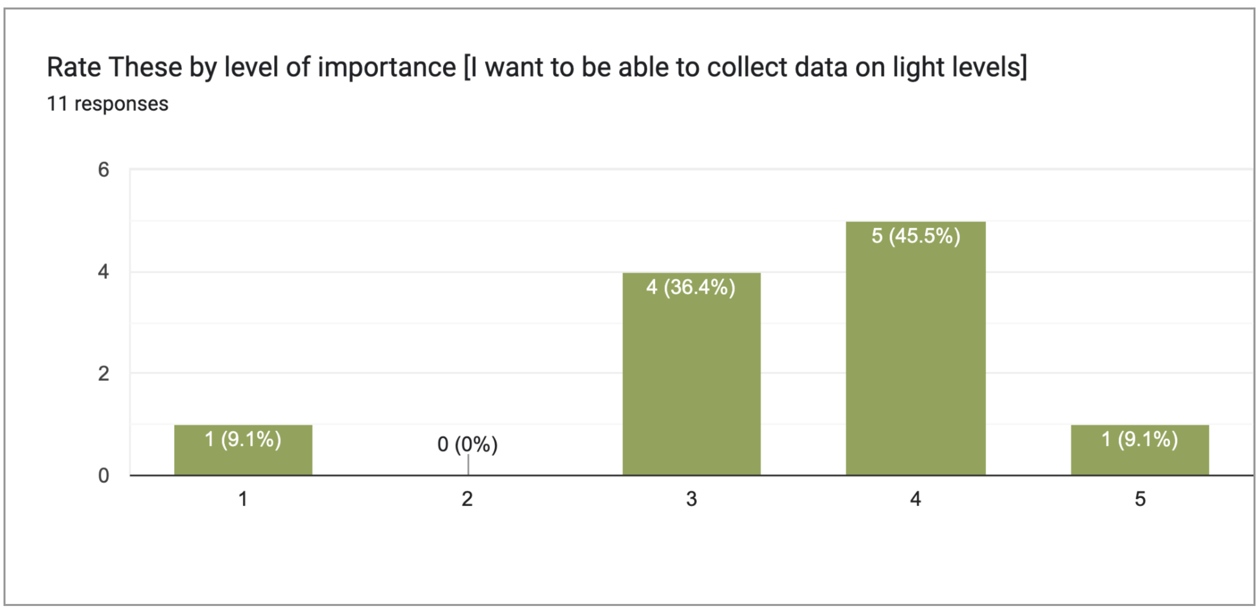


Figure 2 - Light Level Responses

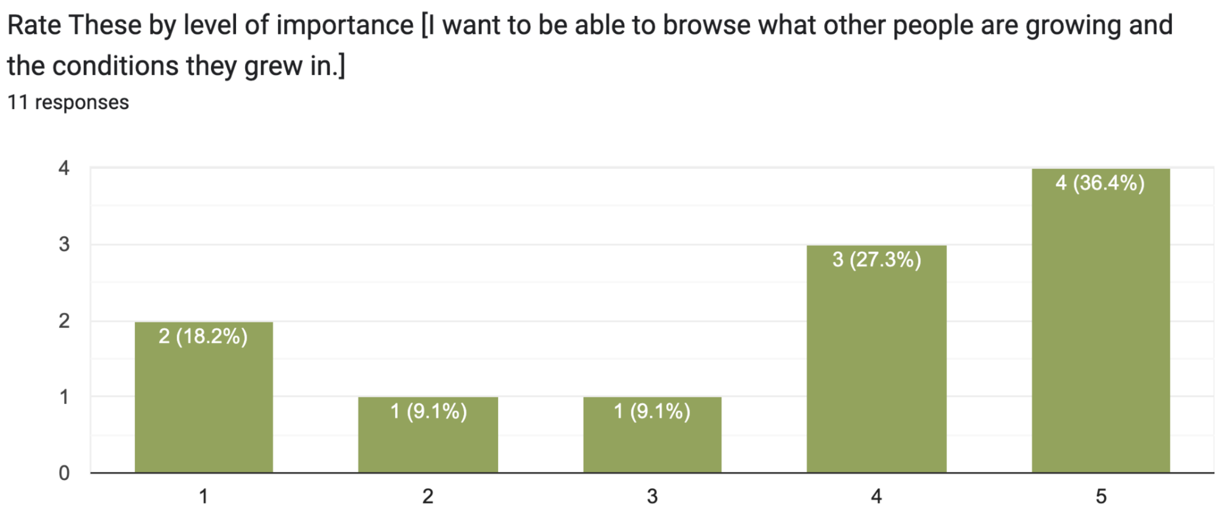


Figure 3 - Desire for Community

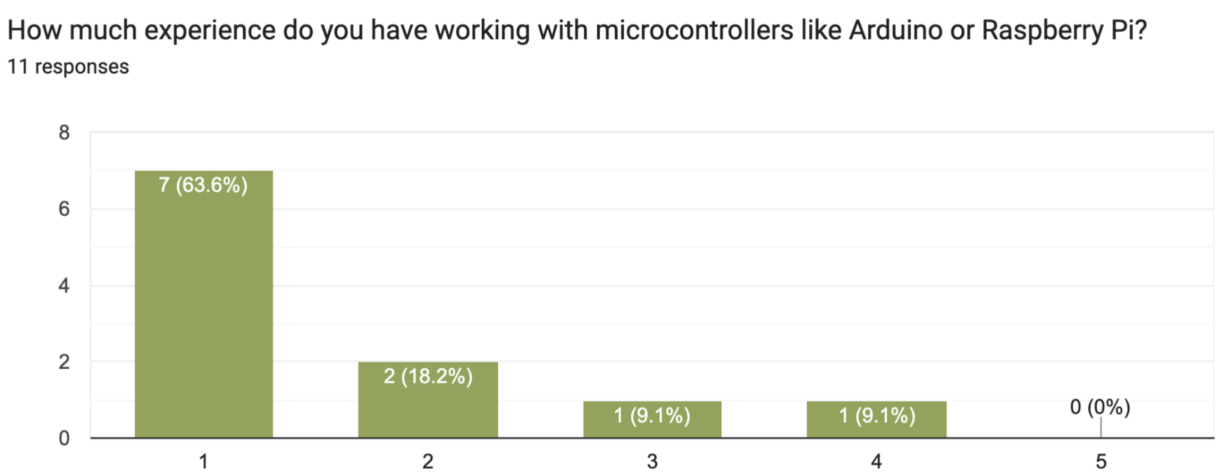


Figure 4 - Familiarity with IoT Devices

2.3. Qualitative Insights

In our survey, we asked a series of qualitative questions such as desired features in a soil monitoring system. Generally speaking, users wanted a system that was easy to use and not too complicated, the ability to track the growth changes and characteristics of a plant, and information on how not to overwater, over-fertilize, and avoid pests.

"Ability to track progress pictures of plants and reminders for when to water them or give them sunlight"

"Most of the time the plant dies because it was either overwatered, over-fertilized or it has pests, I find most plants thrive on negligence"

From 2022-2023, we conducted interviews with individuals who either work on farms, manage technology on farms, or work with adjacent land management processes to collect qualitative data on challenges associated with crop management and farming. One particular interviewer stood out as unique, as he was responsible for the introduction of soil sensors to Bowle's Farm water management process.

Interview Participant - Emery
Emery was the former Chief Technology Officer for Bowles Farms based in Los Banos, California. Emery was responsible for introducing and integrating technology solutions into Bowles Farm's land management and irrigation processes. Emery has years of experience leveraging remote sensing solutions to account for crop health and yield metrics as well as researching and implementing remote device sensors across various crop fields.

One task Emery was given by the owner was to source out a soil-sensing solution to integrate into their water accounting and allocation system. He was given $30,000 to pilot a program to purchase and integrate sensors. In our conversation, Emery identified three key obstacles to the successful implementation and monitoring of plant health: difficulty setting up sensors, technician training, and complicated software user experiences. He also stated that many farmers want a relationship with the organization building the software and that customer service is very important when it relates to introducing new technologies to their business.

2.3. Building Toward A Solution

Based on these insights from our survey and interviews, we concluded there were three core challenges to take on as part of our capstone project. First, sensors can be difficult to set up and fairly technical, so we need to explore a solution where we can build simple sensors and offer a setup guide. Second, reliable data can be a persistent issue with wireless transmission, thus our solution will need to use proper IoT data transmission protocols. Lastly, people want a way to share information with each other, so building social sharing is a great way to increase engagement.

3. Our Interactive Solution - GardenSense

3.0. Solution Overview

The goal of our Capstone project is to build an integrated sensor hardware and software platform that streams real-time plant health data. In order to accomplish this, our team of three built two IoT sensor devices based on the Arduino hardware platform, a dashboard utilizing InfluxDB for time-series data streaming and Grafana for advanced visualization, and an interactive React prototype to add new plants, sensors, and follow other growers and cultivators. This section provides an in-depth analysis of the technical specifics of the project.

3.1. Custom-Built Sensors

Small and Portable Sensor

Throughout the course of the project, we experimented with several different microcontrollers to ensure proper and reliable data transmission. The key requirements we established for our microcontroller were: 1) It needed to be battery-powered, 2) It needed to be compatible with temperature, humidity, and soil sensors, and 3) It needed to be capable of transferring data via Message Queuing Telemetry Transport (MQTT) in order to be reliable under unreliable internet connections (MQTT is a lightweight protocol used by IoT devices for its ability to support devices with an unreliable and limited internet connection).

For the first version, we explored the capabilities of the Arduino Uno, a fairly standard microcontroller board useful for many experimental IoT projects. We quickly found the Uno did not support MQTT, so next experimented with a different microcontroller, the ESP32. The ESP32 is a low-cost, small-size Wifi and Bluetooth-capable microcontroller that packs a lot of power in a small form factor. We created a program to run on the ESP32 that connects to a user's wifi, makes a connection to the MQTT transfer protocol, collects temperature, humidity, and soil moisture data, and then transmits that data wirelessly. The device is also capable of transmitting data via a personal hotspot, and as such is able to transfer data anywhere you take a mobile phone, so long as it is within range of the sensor unit.

Once we established successful data transmission after multiple tests, we set on to explore the latest in live data transmission tools and ways to make our device more portable.

3.2 Suite of Tools

MQTT (Message Queuing Telemetry Transport) is a lightweight publish-subscribe messaging protocol that is widely used in IoT applications to enable communication between devices and applications. We elected to use MQTT, as opposed to HTTP (Hypertext Transfer Protocol) for many reasons such as:

> 1) MQTT is designed to be lightweight, with small message sizes and low network overhead. This makes MQTT ideal for communication in low-bandwidth and high latency environments.
> 2) MQTT has a lower power consumption than HTTP, making it a better choice for battery-powered IoT devices.
> 3) Reliability
> 4) Scalability

MQTT has several benefits over HTTP for IoT applications.

Node-RED is an open-source flow-based development tool. It provides an easy-to-use platform for creating flows that can communicate with MQTT brokers and other MQTT-enabled devices.

InfluxDB is a time-series database system which is optimized for providing time series format with high efficiency and availability. Essentially, the storage and querying of data are optimized for data points with a time component.

Grafana is the leading open source software for time-series analytics. It can connect to many different data sources including InfluxDB. It also supports many visualization options, like graphs, tables, gauges, and heat maps.

3.3. Pipeline

When selecting tools to build this platform, we focused on open-source and free software to keep costs low. Our sensors utilize low-cost microcontrollers and our data pipeline uses open-source data platforms MQTT, InfluxDB, and Grafana **(Figure 5).**

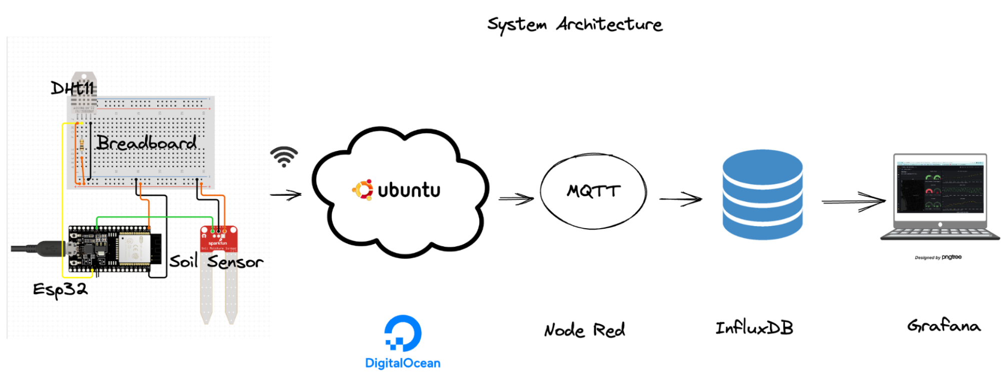
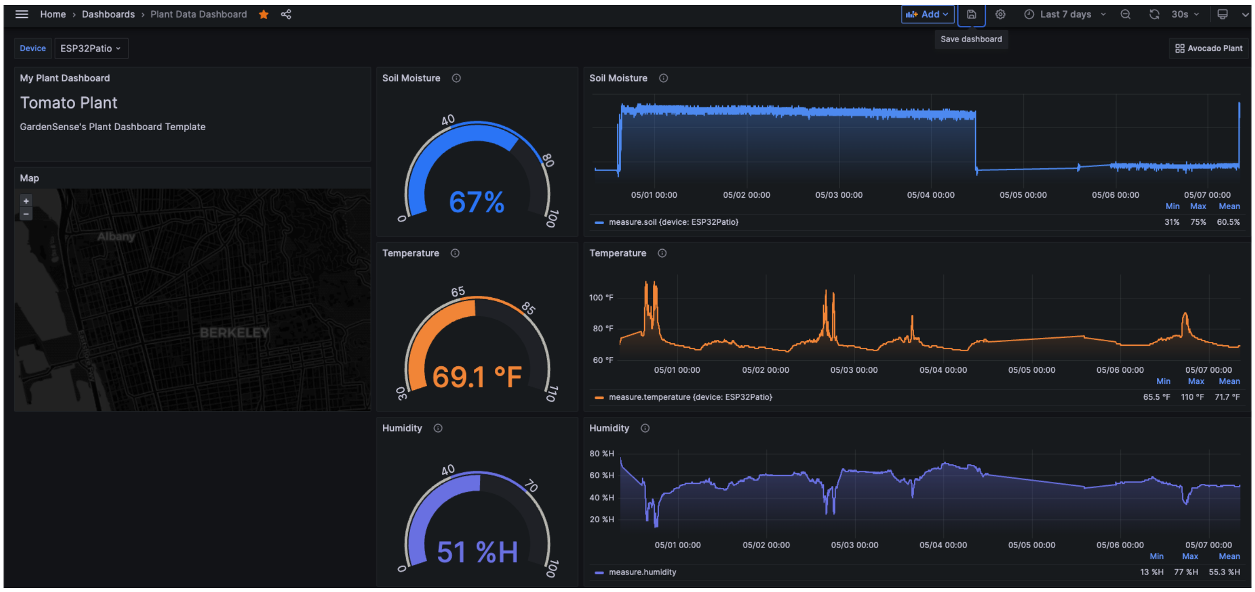


Figure 5: System Architecture

Once the information has traveled through MQTT and parsed through InfluxDB, we then pass it to our Grafana dashboard which can provide advanced analytics on a user's sensor or plant, depending on how they configure their sensor tracking in their gardening system. Some users may opt to have one sensor per plant, others may want one sensor per plant box, and some may want sensors placed in various locations throughout their land unattached to any one plant or crop. The goal behind the visualization is to offer modularity in their visualizations and information gathering.

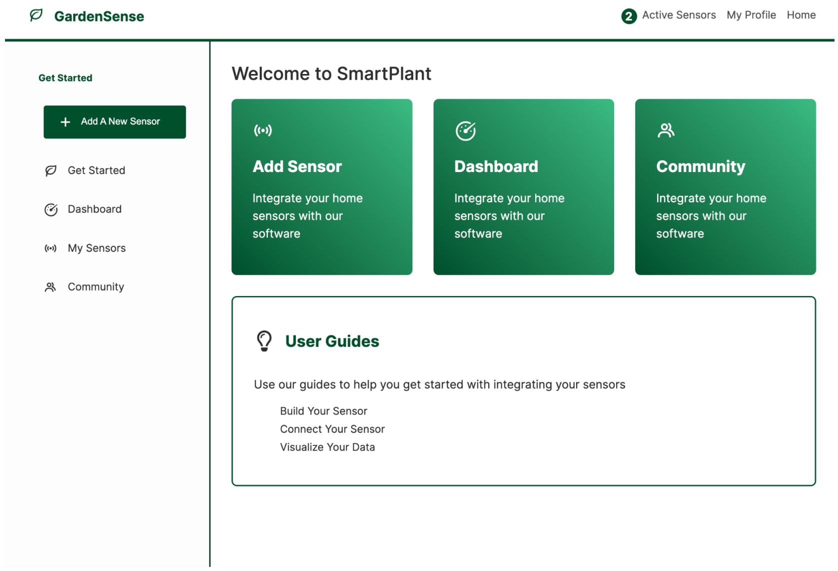
3.4 Dashboard



3.5 Interactive Front-End Prototype

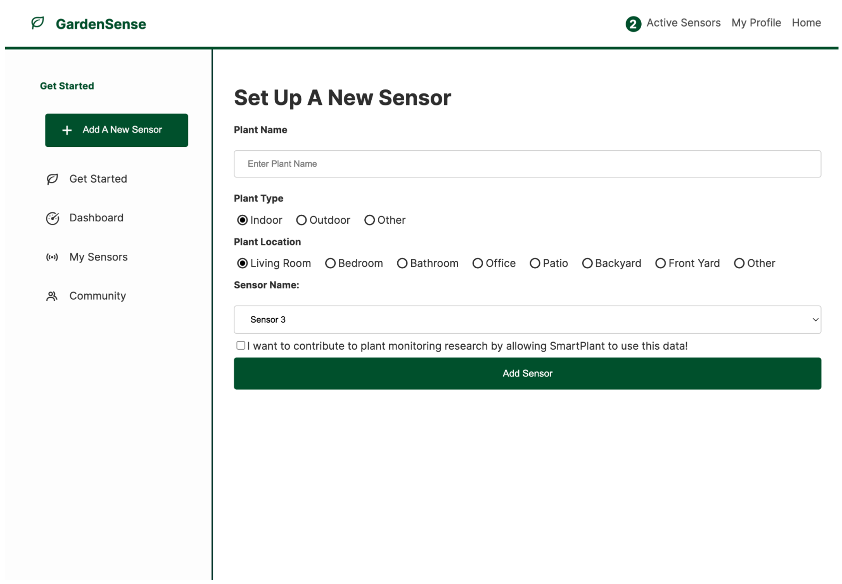
Demo Link: https://poetic-semolina-65f468.netlify.app/

In order to expand the capabilities and collect more information from our users, we created an interactive application for plant growers and farms of any size to use. This prototype offers users the ability to add new plants to a sensor or create groups of sensors for more than one plant or crop. The ultimate goal is to offer users modularity in the way they configure their data collection setup.



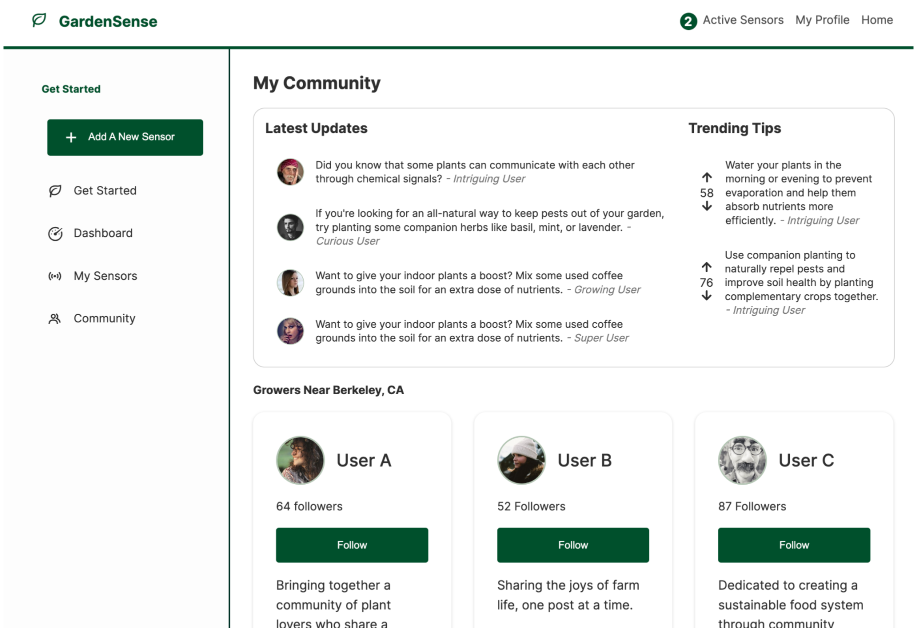
1.0. Welcome Page

Upon entering the prototype, a user is presented with a welcome screen with three different areas to explore. These areas include a place to connect a sensor, visualize the dashboard, and access the community experience. This page gives a user a quick introduction on how to interact with the application, as well as offers areas for the user to explore and pursue what interests them.



2.0. Add Sensor

The Add Sensor experience presents the user with a form for them to connect a new plant to a sensor on the network.



3.0. Community

As part of increasing engagement and learning more about how gardening and farming users might want to establish strong connections, we built a community feed that can show users the latest news from friends and followers. Through this engagement, we want users to share information on how to best care for their plants based on their own successes, and even find ways to share data.

4. Future Work

Many opportunities exist for future work and improvements to the GardenSense hardware and software platform. This section will discuss opportunities for improvement in the sensors themselves, data transmission methods, advanced visualizations and machine learning, and user experience improvements to the user front-end platform.

4.1. Sensor and Data Transmission

One limitation of our current sensor unit is it is limited to two types of data transmission via WiFi and mobile hotspot. WiFi is perfectly adequate for at-home use or small gardens with Wifi connectivity, and the personal hotspot compatibility is great for systems that use mobile hotspots throughout a given sensor area. We would also like to propose an improvement to automate connection to the internet via the devices. Right now, a user would need to manually edit the microcontroller code to add in necessary WiFi or mobile hotspot username and password credentials. One potential solution would be to print QR codes on each device. Once taking a picture of the QR code, the user would be presented with a module that searches for devices in their current network and connects that device to their network. This is an area that likely needs more software research to accomplish.

4.2 Advanced Visualizations and Machine Learning

Place content here

4.3. Front-End Interactive Prototype

As it exists today, the front-end application is in an alpha prototyping phase. There is some interaction in adding plants and viewing plants, however, user authentication and proper news feed social media interactions are lacking. Most of this can be solved by integrating cloud data solutions to improve the flow. For users interested in viewing sensor data on the prototype, improvements can be made to the inclusion of specific data and charts. At the moment, there is a single link to an external dashboard hosted by Grafana.

With the addition of user data storage and proper user authentication, this front-end application could be launched and user-tested on a wide user base.

5. Project Summary

Our project team set out to create a sensor data system and interactive web application to share plant and garden information. We started off first through research into user needs, low-cost sensors, and the latest in database technologies. We finished having built an interactive dashboard that can display sensor data in meaningful ways, a frontend application for users to save their own sensor and plant information, and guides on how to build some sensors for your own use.

With the current status of our project, we expect more people to use the application and sensor dashboard and provide feedback on their experience. We plan to continue the development of new features as well as talk to more gardeners and small business farmers about what they would like to see.

We believe that gardeners and small business farmers alike want to share plant information with their broader community and find new ways to monitor the health of their plants. Whether it is a single plant, home garden, community garden, or small farm, our system provides real-time data visualizations and social tools for users to be an expert in their craft.

6. References

[1] J. Campbell, “History and Scope of Remote Sensing” in *Introduction to Remote Sensing, Fifth Edition.* The Guilford Press, 2011, pg. 3

[2] Number of Connected Devices Worldwide from 2019 to 2021, with forecasts from 2020 to 2030, Statista, https://www.statista.com/statistics/1183457/iot-connected-devices-worldwide/

[3] https://www.precedenceresearch.com/remote-sensing-technology-market

[4] https://www.marketsandmarkets.com/Market-Reports/internet-of-things-market-573

[5] S. Khanal, K. KC, J. P. Fulton, S. Shearer, and E. Ozkan, “Remote Sensing in Agriculture—Accomplishments, Limitations, and Opportunities,” Remote Sensing, vol.12, no. 22, p.3783, Nov. 2020.

[6] "Watering Houseplants," University of Vermont Extension Department of Plant and Soil Science, https://pss.uvm.edu/ppp/articles/watering.html

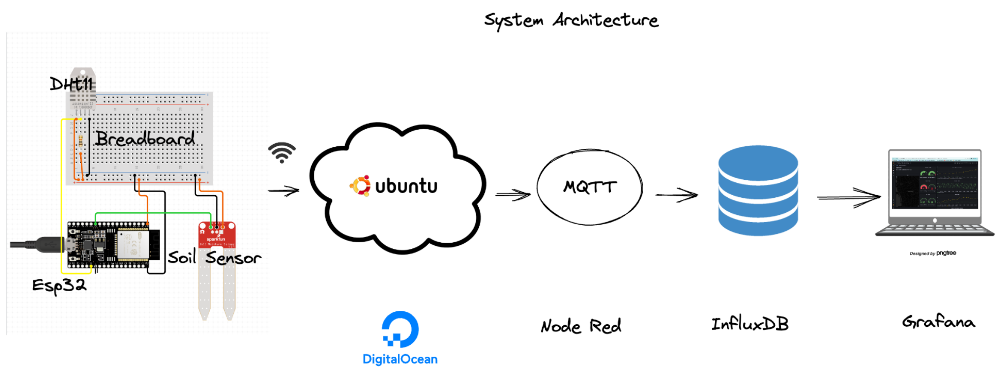
[7] Rogers, D., Bosch, D., & Famiglietti, J. (2017). Adoption of soil moisture sensors in the United States. Journal of Irrigation and Drainage Systems Engineering, 143(4), 04017003

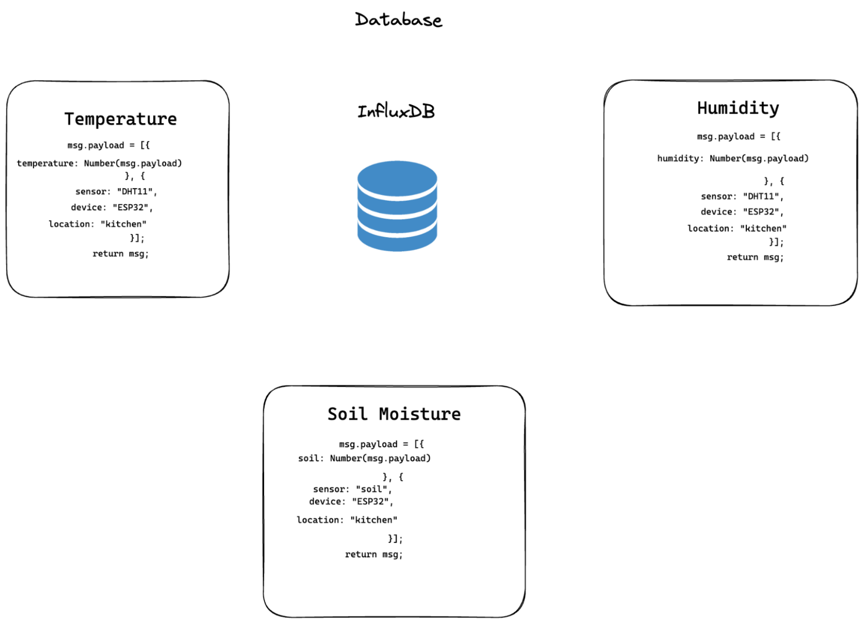
7. Appendix

7.0. Interesting Learnings

The most common reason house plants die is due to overwatering. House plants need a soil moisture level between 20-60% [6]. When testing the sensors, we found one set of plants had a soil moisture rating of around 70%. After watering a new house plant using the provided instructions and a measuring cup, the plant went from 50% moisture to an elevated 75% moisture. This makes house plants prone to root rot, especially in the Bay area which has higher humidity than average. The plants had this elevated soil moisture percentage despite using potting soil which is designed to drain excessive water away from plant roots. It is estimated that half of commercial farmers use soil sensors but that number is concentrated on the largest farms [7]. In the future, this should be repeated on a commercial farm to see if farmers also overwater their plants. If so, a wider adaptation of soil monitoring systems could result in conserving water.

7.1 System Diagram



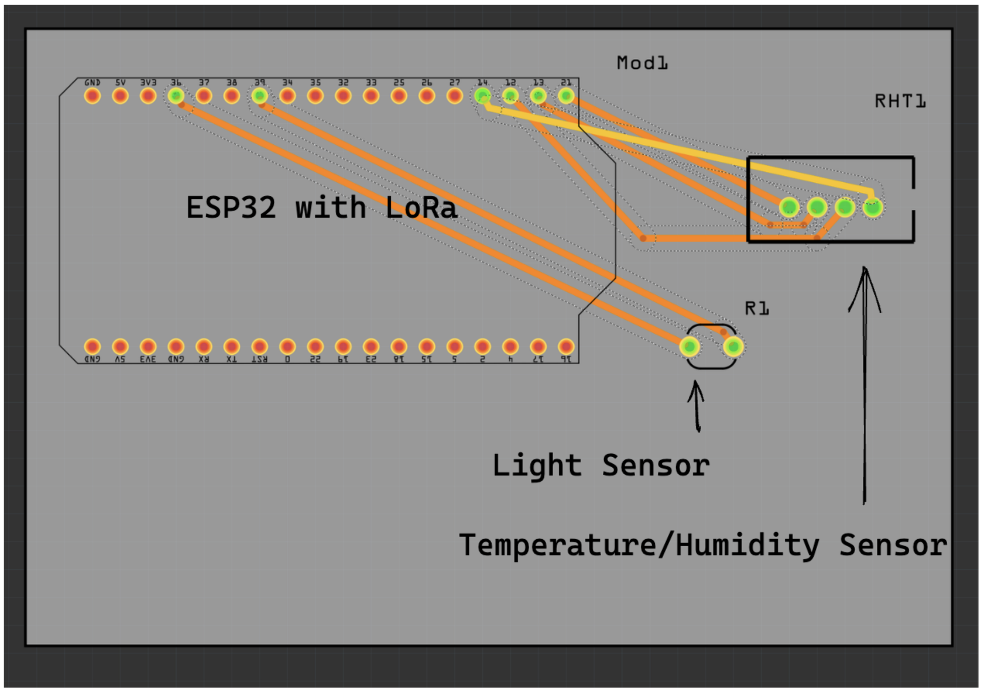


7.2 Deployed System

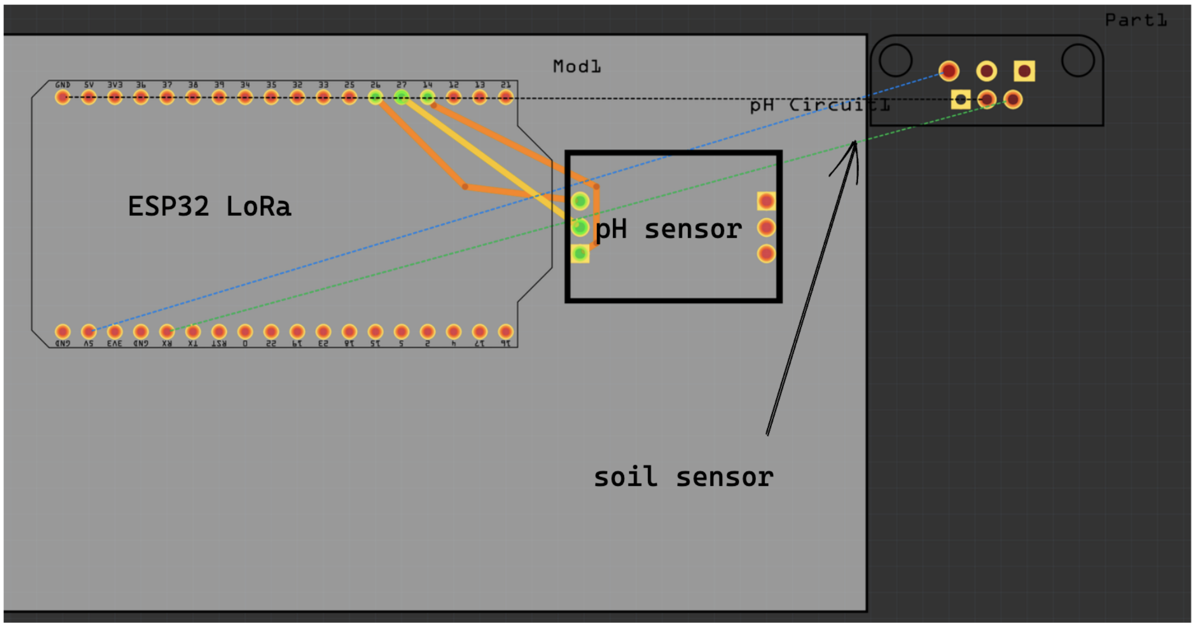
Component	URL
Interactive Front End Alpha Prototype	https://poetic-semolina-65f468.netlify.app/
NodeRed MQTT Flow	https://nodered.smartplant.live/
InfluxDB	https://influxdb.smartplant.live/
Grafana	https://grafana.smartplant.live/

7.3 Sensor Prototypes

Prototype One

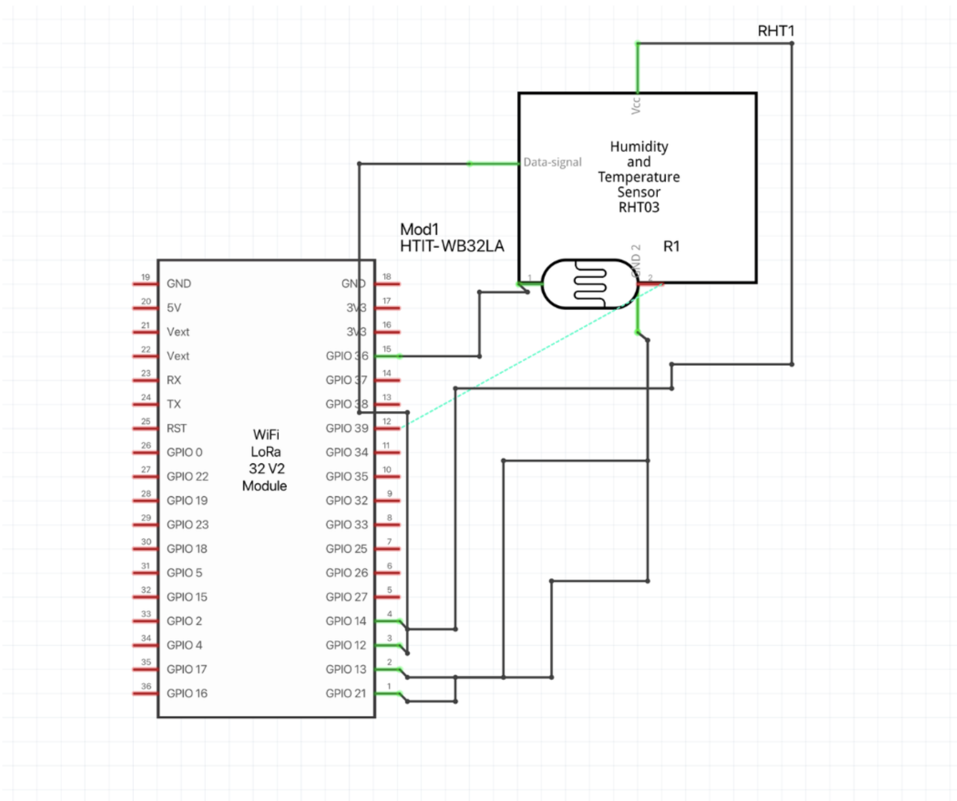


Prototype Two



7.4 Prototype Schematics

Prototype One Schematic



Prototype Two Schematic