# Detecting Soil Moisture Utilizing Low-Cost Mesh Technologies

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***Abstract*—Everyday more people are beginning to grow plants in their backyards, personal greenhouses, or even at their desks at work. The overall indoor farming market is significantly increasing every year, and with it the rate of personal farming. To address this growing demand for people who are unable to detect soil moisture or determine when to water their plants, we have developed a low-cost soil moisture sensor which uses a wireless Wi-fi mesh to communicate with multiple soil moisture sensors simultaneously. These sensors will be connected to a server which will host a website along with collecting soil moisture data as well, from which levels of soil moisture can be tracked throughout the day and a determination can be made when soil must be watered for maximum crop yield and minimum water usage necessary.**

## I. Introduction

### A. Motivation & Market

There is a new trend of indoor growing which is expanding across the United States and the rest of the world. There are several different kinds of indoor farms which consist of protecting crops from the outdoors. Examples of this are: greenhouses, hoop houses, vertical farms, container farms, and even some home growing systems. Many people believe that vertical farming is the boundary of the indoor farming market and this is a huge misconception. Vertical farms are in a fully enclosed box and use artificial light to grow crops. The existing market for these farms is small but growing. While vertical farms are a small part of the industry today, they will play an important role in driving technological innovation and industry awareness. There are over 40,000 farms growing crops indoors in the United States alone. This accounts for over 1 billion square feet of growing area. These farms produce a market value of \$14.8B annually. The break down for this can be seen in the table below [1]:

| | No. of Farms | Square Footage | Market Value |
|---|---|---|---|
| Aquatic Plants | 277 | 1,642,080 | $ 20,756,332 |
| Bulbs | 193 | 1,306,346 | $ 72,766,990 |
| Cuttings, seedlings, liners, and plugs | 1,114 | 35,627,552 | $ 585,066,367 |
| Floriculture | 18,724 | 873,290,590 | $ 5,888,527,346 |
| Flower Seeds | 212 | 368,593 | $ 32,378,251 |
| Greenhouse fruits and berries | 673 | 7,950,774 | $ 28,976,671 |
| Greenhouse Tomatoes | 6,323 | 55,180,582 | $ 400,286,262 |
| Other greenhouse vegetables | 5,268 | 42,816,149 | $ 234,199,741 |
| Sod Harvested | | | $ 1,011,490,194 |
| Mushrooms | 740 | 37,416,059 | $ 1,127,007,448 |
| Nursery stock crops | 4,883 | 258,498,855 | $ 5,104,694,108 |
| Tobacco transplants | 447 | 4,487,277 | $ 11,442,846 |
| Vegetable seeds | 555 | 4,801,257 | $ 155,216,334 |
| Vegetable transplants | 1,942 | 21,527,367 | $ 165,845,977 |
| | 41,351 | 1,344,913,481 | $ 14,838,654,867 |

Source: https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/st99_1_041_042.pdf

**Figure 1:** Breakdown of Market Value for Indoor Farming by Sector

With the growth of the general indoor gardening market, there is a proportional rise in the personal gardening market. Approximately 20% of the population age 18-34 reports gardening as a leisure pursuit. Millennials are far more interested in protecting the environment than most previous generations, with a greater interest in organic foods. Many millennials live in the city with limited time to garden and limited space to pursue this hobby. This lends them to be a generation looking for simple solutions to help them determine when their plants should be watered. Baby Boomers are also becoming more interested in gardening with 40% reporting gardening as a leisure pursuit. Since these are longtime homeowners, they are already fans of gardening and can be enticed to purchase tools which can reduce their effort while maximizing their yield. The below graphic demonstrates the large capitalization of the home garden and its growth in the coming years:

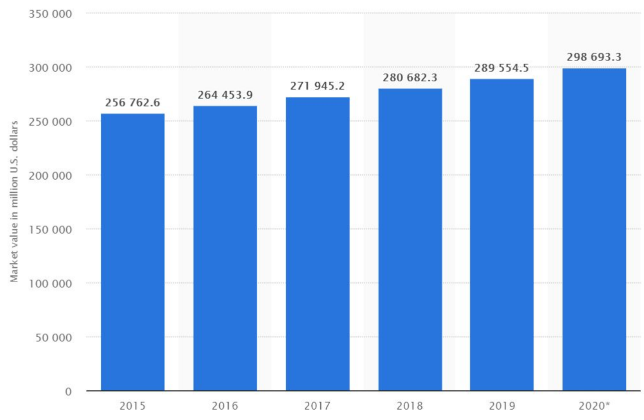


**Figure 2:** Growth of Home Garden Market [2]

When analyzing the need for a solution, it is important to look at the habits and income demographics of people who garden. By looking at figures 3 and 4 we can determine what these trends are. In figure 3 we see that the average income of those who garden is around $30,000, indicating a need for low-cost solutions to facilitate their gardening needs. In figure 4 we see that the average time spent on gardening is about 6-7 hours per week, indicating a need for a solution which can reduce time spent gardening even further since people are not spending a great deal of time on this endeavor today.

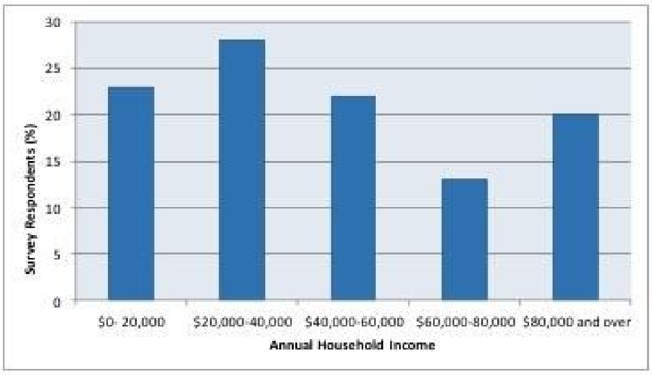


**Figure 3:** Average Income of People who Garden [3]

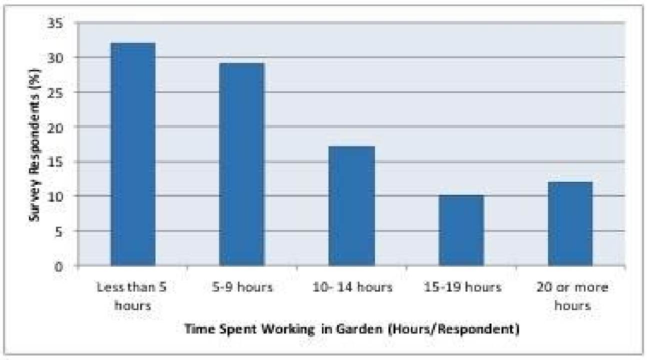


**Figure 4:** Average Time Spent on Gardening [3]

## B. Current Solutions

There are a great deal of smart agriculture solutions on the market from a variety of different vendors, start ups, and conglomerates. These solutions offer not only soil moisture detection but a host of other features such as frost, humidity, leaf moisture, pesticide detection etc. Many of these larger offerings come with a variety of sensors, cameras, and applications (web and mobile) to track these various statistics and in many cases automate farming of large greenhouses and increase crop yield.

The biggest downside of these current solutions is that they are built for large scale farms (outdoor and indoor) and do not have products that cater to smaller gardens, indoor plant growing in homes, or even small greenhouses. Many of these solutions are too sophisticated for the average grower who wants limited information such as when to water their plants. For these individuals there is no holistic solution which provides a low-cost sensor, server, and website to view all their data over time. Most solutions on the market are sensors which display the soil moisture on a small display which is on the device itself, but do not post anything to a website or a sensor with no display and an application tracking capability. The single sensor with a display averages about $25 per sensor and the single sensor with application capabilities averages around $100. Both of these price points are too high for the average gardener or consumer for the market we are targeting.

There are two major downsides to current solutions on the market for soil moisture detection: most solutions are designed for large farms or greenhouses and the cost point is outside the range of what the average gardening/indoor plant growing consumer can afford. This is the niche which our product can dominate in. By providing a low-cost solution for gardening with analytic capabilities, we can allow the average gardener to have more accurate reports for their needs.

## C. Our Contribution

Our solution to this problem is to provide a simple and holistic device which allows someone to detect the moisture of the soil in which their plants are growing. There will be a simple processor which will be attached to the sensor and send this information to a central server which displays the information on our website so the user can determine when the plant went below the threshold soil moisture level. This entire set up including 5 processors, sensors and batteries costs $ 130 with current materials cost and could probably be reduced to $40 if mass produced. That makes the average price per sensor only about $8. The most expensive cost is currently the battery, which can be easily reduced when mass quantities are ordered. We are also implementing a wireless Wi-fi mesh which will allow us to expand and increase the range of our solution to eventually support larger projects moving forward. By using the mesh, we can expand not only the efficiency of our communication between devices, but can also increase its range so that someone could use multiple sensors all over their home and garden and thus only need one server for the entire house. This also provides them the flexibility to move their plants around their home based on light and other factors. By providing a mesh network, we are able to reduce the requirement of an access point which would further reduce costs from our overall product and offering.

## D. Results

4 ESP32 devices were attached to 4 soil sensors and 2000mAh batteries. 1 ESP32 acted as the root server and was wired to a direct connection. The 4 ESP32 devices created a mesh and routed messages towards the root server which concurrently handled the mesh and HTTP server. Without using a deep sleep, the 4 ESP32 devices ran out of power within 10 hours. By adding a sleep signal, battery was conserved for a significant amount of time and was able to run for 125 hours.

Our results show that a single ESP32 has the power to act as the root in a mesh, store messages, and run an HTTP server. This is a big step towards creating ad-hoc wireless networks that do not need a connection to a central AWS server or more power device (such as a raspberry pi).

## II. Design and Implementation

### A. Our Proposal

Our proposed solution involves using a mesh network to connect all the available moisture sensors and their respective boards. One node periodically collects the sensor data from the rest of the mesh devices and serves it to the site which displays the readings. The values are displayed in a simple fashion where graphs display the fluctuating moisture values and effectively display any trends in moisture changes. This solution is more adequate for any current home gardeners because it is both low-cost and its simplicity makes it user-friendly and easy to use. As opposed to more expensive and sophisticated soil sensor technology currently out in the market, our mesh allows for multiple sensors to be connected. This makes our solution even more robust because gardners can place these sensors in different locations of their garden, both indoors and outdoors, and have all of the metrics easily viewable on one site. Furthermore, gardeners can continue to add sensors to their mesh network to meet the size requirements of their home gardens.

### B. Solution

The board we chose to use are the NodeMCU ESP-32S. These system-on-chip microcontrollers provide a robust design along with low-power consumption. Additionally, the ESP32 boards come with a hybrid Wifi-Bluetooth chip, providing us with ample potential for interfacing with other systems. For moisture detection, we are using simple hygrometers for humidity detection. These moisture sensors are relatively cheap and easily connect to the boards.

We chose to use a library called painlessMesh to handle the mesh network. Essentially the library takes care of creating an ad-hoc network where no central node or router is required. There is no need for a central router or controller for the mesh to work - all that is needed is enough hardware to construct the mesh. This provides us with an additional benefit: it allows any prospective user to add more devices to the mesh and meet moisture-sensing needs of even larger greenhouses. This number however, is only limited by the amount of memory allocated in the heap for other connections. This limit has not been tested yet as our prototype has only involved up to 7 sensors. Nonetheless, due to the simplicity and elegance of the mesh design, we believe the system would be able to house a high number of nodes.

Figure 5 is an example of what a broader network such as ours would look like if expanded. We were able to construct a mesh network using our 5 devices. One of these devices acts as not only a passive clients in the network, but also a server. The server is able to run HTTP on port 80 as one of it’s tasks. This allows it to not only record data which it receives from the soil sensors, but is also able to host a website as an HTTP server along with being able to receive samples from all clients to populate the graphs on the website.

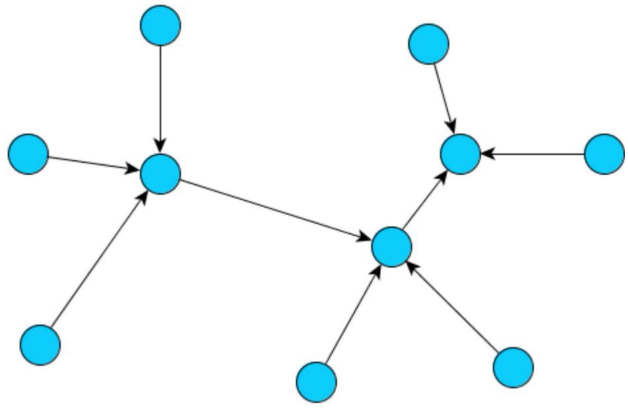

**Figure 5: Mesh Link Between ESP32s Clients and Server**

It is also important to explain the architecture of the overall system. As can be seen in Figure 6, the overall architecture is quite simple. It starts with the soil sensor, which is placed into the soil. This sensor will communicate with an ESP32 client which will gather the data from the soil sensor every 2 hours. These ESP32 clients will communicate with an ESP32 client/server which will collect all of the data and use this to populate the website. The website will be hosted on this server and will be used to monitor the plants over time and determine when the plants should be watered.

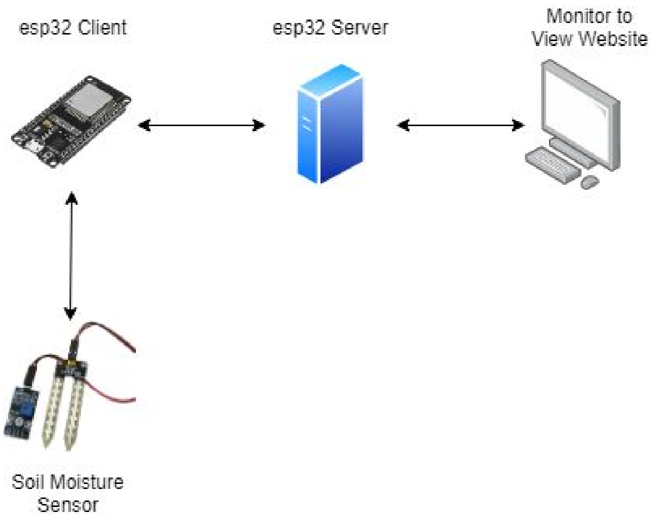


**Figure 6: Architecture of System**

We created a simple website as can be seen in Figure 7. It is a single page display that does not require login information or extra security because the website is hosted locally in the mesh since the server is also a part of the mesh. The data which is being collected is also not extremely sensitive, so adding extra security over the TCP would just be unnecessary overhead to the system. The server itself also has password protection for extra security measures for those gardeners who wish to secure their own data.

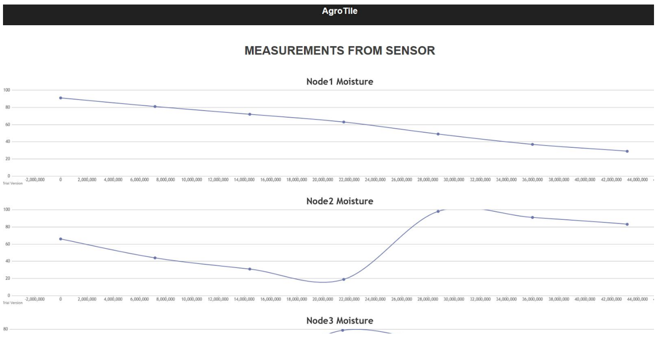


**Figure 7: Website to Show Data Over Time**

## III. RESULTS & ANALYSIS

The mesh protocol worked well and was able to quickly connect and update topology as more nodes were added or removed. Data was sent throughout the mesh to the server; however, nodes situated between the server and edge devices ran out of power significantly quickly due to having to route messages to the server. In order to deal with heavy power consumption, we decided to give the server the ability to turn off the mesh after a specific amount of time. Essentially, the server would collect the data from the nodes, and then send a sleep signal to all nodes which would then sleep for the time specified in the message. During this time, the server would wait for new connections and continue hosting the webpage. Once all the nodes woke up, they would continue to communicate their readings to the server until receiving a new sleep signal. By changing the sleep time to a long duration (2-6 hours), battery usage was significantly decreased.

The ESP32 server was able to handle maintaining a mesh and hosting an HTTP server. However, the server could not maintain many open TCP connections while also maintaining the mesh. It works best with only one device accessing the server. In the future, it would make sense to have a single embedded device showing the server results on a screen so that multiple devices do not need to access the server. This result was impressive and shows that a single ESP32 has the power to act as a web server and mesh root node concurrently.

## IV. CONCLUSIONS

### *A. Future Work*

While the team was able to achieve a great deal with our current implementation, there is still much we can do to further optimize and improve our design. Below is a list of items which we plan to implement in the next iteration of our device:

a. Bluetooth Low Energy (BLE) Mesh: The team was not able to implement a BLE mesh for our current iteration of our project because we wanted to experiment with hosting a website on our edge devices to remove the total number of devices in the system and reduce the overall cost of the project. It also made sense to use a wi-fi mesh for the first iteration since the target will be mostly indoor gardening and home gardening where it is much easier to gain access to a power source to run the device. There are several BLE mesh libraries that currently exist on the market for Arduino; however, we were primarily interested in mqtt over Bluetooth because we are already implementing the same structure over wifi. We want to implement a BLE mesh as a power saving mechanism given the high-power consumption mentioned earlier in the paper for our wifi mesh. BLE can also help increase the overall range of a system such as this and would definitely be something to be considered once larger greenhouses are observed as a target market for this product

b. Temperature and Humidity Detection: Just knowing the moisture of the soil is not enough to get a completely holistic picture of the health of plants and the conditions which warrant them receiving water at specific intervals. By including sensor readings such as temperature and humidity, we could provide far more holistic readings to a consumer and provide them with more complete data about not only the health of their plants, but the conditions under which their plants can thrive (more covered for this under next point). For this, we would implement the ST Electronics Tile processor which has the capability to detect temperature, humidity and soil moisture with its built-in on-board sensors. The reason we could not implement the ST Electronics board in this iteration was the upfront cost of acquiring the boards and the lost time in receiving the boards. Although the increased cost would increase the overall cost of the system, with mass production and an expanded feature set, the price jump can be justified.

c. Machine Learning: There are many things that could be done with implementing a machine learning algorithm on the data gathered from the devices. This capability would allow us to preemptively detect when soil moisture might be getting too low and send a notification to the user to give them notice that they need to water the plants. It would also be possible for users to specify what plant they are using the sensor for and based on that plants' watering needs send notifications for when the plants should be watered. By combining three different pieces of information, (soil moisture, humidity and temperature) it becomes possible to predict when a plant should be watered not based solely on the moisture of the soil but also based on the time of year, temperature outside, the level of humidity in the gardening environment etc. This would be a huge value add for consumers since they would not only track different statistics for their plants over time, they would also be able to make more informed and educated decisions based on multiple factors. Consumers would also be able to take a great deal of guesswork out of when to water plants with our intelligence driven notifications and could provide this information to house sitters/friends who would come to water the plants for someone else.

d. Building software from scratch: It was extremely helpful to use many of the inbuilt libraries which Arduino had to offer when writing our code; however, many of these libraries are outdated and fraught with bugs. When trying to flash our code onto the ESP32s we had so many problems occur involving race conditions, library collisions, exceptions and configuration errors. It would be much more prudent to write the code we need from scratch and import only those libraries which we are familiar with and trusted. This would allow us to tailor our solutions to fit the specific device we are building and be able to modify it with more ease in the future. By building the code base from scratch, we could also take energy efficiency far more into account since we know that these devices need to be able to last years.

e. Including a dedicated server: Since the primary goal of this first iteration was to create a low-cost device which would work over small distances, we decided to not include an external server which would process all of the data. In our second iteration, we want to expand our solution to include a low-cost and low-power Raspberry Pi device which would receive the readings from all sensors in the mesh, aggregate the data and post it to our website. This would improve the energy efficiency of the ESP32s since they would no longer be required to host the website or any other server activities further improving the overall efficiency of the entire system. If we added more nodes to the system, this would probably kill our current client/server node's battery life much faster, which also necessitates the need for a dedicated server which could be connected to a persistent power source.

f. Persistent Database: In our current implementation, if the server powers off, all of the data collected would be lost, which is not ideal in the case of a power outage or temporary disconnection. It would thus be prudent to implement a persistent database which could store all of the data even if the server is switched off. This would allow us to show larger and longer historical graphs with data that persists over years so gardeners can see trends in the soil moisture of their garden. It would also be helpful to have persistent data to run machine learning applications for predictive information on watering plants and general plant health.

g. Lightweight Communication Protocol: Given that the average HTTP header is on average 700 to 800 bytes in size, it is extremely inefficient for a solution such as ours where we only need to sample a small amount of state change data every two hours. A solution such as CoAP would be much more suitable solution given it's header size which ranges between 10-20 bytes. Since CoAP is still able to reference REST API request and responses, this would not require a major pivot in our current solution as long we have a persistent server which can host the website for the client.

### *B. What We Achieved*

We have shown that a single ESP32 can act as the root of a wireless mesh, store mesh node messages, and maintain an HTTP server. A large part of this project was aimed towards seeing how much power we could squeeze out of a single $10 ESP32. These results show that ad-hoc ESP32 networks can serve as an entire IoT system by communicating, hosting, and storing messages without the need for more expensive equipment such as a raspberry pi or AWS server. We were able to take the lifetime of the device from only 10 hours and were able to extend the life to 5 days which is a great achievement when utilizing heavyweight protocols such as HTTP. All of our contributions provide a robust solution for home gardening where you do not need to be technologically proficient to get a holistic view of all the plants in your house to save time spent gardening with more accurate results.

## Acknowledgment

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