# Individual Research, Design, and Implementation:
# Soil Moisture Sensing Subsystem

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## 1. Abstract

Our team, CloudGarden, is working to develop a wirelessly connected outdoor soil moisture sensor requested and supported by Daniel Cambron of Lexcelon, LLC, for home gardeners and hobbyists who want to simplify their daily gardening routine or may not be able to check on their crops with great frequency. Implementation of consistent and accurate soil moisture sensing is essential to the project because it is the main environmental measurement that is desired and reported from our devices to our target audience. This report provides details concerning the research, design, and testing of a non-contact soil moisture sensing system which I have undergone to find a solution that fulfills our engineering requirements or design constraints. Through research, I investigated and fleshed out the commercial and research processes through which capacitive soil moisture sensing has been implemented in the past to create a functional decomposition for my subsystem. Design and implementation of PCB capacitor prototypes alongside a systematic comparison of waterproofing techniques led to the conclusions that a parallel plate PCB capacitor pattern and silicone waterproofing will be implemented for the outdoor soil moisture sensor. A custom PCB was created and tested to compare methods of waveform generation, but the PCB capacitor section was flawed so I have decided to enable utilization of both hardware and software defined waveform generation. Exploration of how my part meshes into the greater whole of CloudGarden's outdoor soil moisture sensor was detailed within this report alongside testing procedures for the final integrated device.

## 2. Problem Statement

### 2.1 Need

Daniel Cambron, our project sponsor, recently acquired some land in Mercer County and after a couple of weeks of gardening, quickly realized that he wanted a way to keep track of what was going on with his plants remotely. Currently, to check the soil moisture content of his plants, a gardener like Daniel would have to walk all the way to his plant and evaluate it physically while still running the risk of over or under watering it. With our wirelessly connected outdoor soil moisture sensor, home gardeners or hobbyists can conveniently and reliably check whether they need to water their plants without having to leave their house or significantly invest in an industrial system. Through reliable and consistent soil moisture measurements, the end user will be able to check whether they need to water their plants without having to leave their house, physically picking the pot up, or sticking their finger into the soil surrounding it. Because of our project's intended use, reliable and consistent soil moisture measurement is essential to the effective functionality of our product as having to second guess or verify the moisture readings negates the purpose of the device. Soil moisture sensing is one of the most important aspects of the project as everything else is built around either powering, processing, or communicating the soil moisture measurements to the user.

### 2.2 Objective

My individual research and design revolve around non-contact soil moisture sensing including the PCB capacitor, waveform generation for estimating capacitance, the processing and thresholds between various levels, and the recalibration of the soil moisture baselines. Because we are not directly measuring the moisture content or the amount of water in the soil, the measurements that we derive will not have units and thresholds will be determined to dictate relative soil moisture levels such as dry, very dry, wet, very wet, etc. Since the PCB will inevitably contain the electronics for the radio, energy storage, and control subsystems, I also need to keep waterproofing of the device in mind as it effects the contacts on the PCB and any electronics used for capacitive moisture sensing which otherwise would be directly susceptible to water. The result of this subsystem will be the initial or chosen PCB intended for capacitive soil measurement, an algorithm for soil moisture measurement processing and calibration, a method for waterproofing, and verification of usable readings or values for soil moisture measurement from my device or selection.

### 2.3 Background

Maintaining the necessary amount of water within a plant's soil is essential for its growth and survival. Concerning soil absorbance, field capacity is the upper limit for plant soil moisture, permanent wilting point is the lower limit of plant soil moisture, and available water capacity is the range in between when water can be absorbed by the plant through its roots in the soil [1]. If field capacity is surpassed, the roots can rot, potentially killing the plant and if the available water is below the wilting point, nutrients cannot travel through the plant, starving it of what it needs to survive [2]. The goal of soil moisture sensing is to ensure plants stay within the middle ground or available water capacity. Widely available soil moisture sensors typically resistively estimate the approximate amount of water in the soil using direct contact with the soil [3]. As the sensor is meant to be placed and left outdoors direct contact or exposure of an electrical contact to soil could corrode the sensor prematurely, leading to less accurate readings over time. Numerous papers have presented a non-contact capacitive method of soil moisture sensing, using PCBs to track changes in the surrounding medium's permittivity due to moisture absorption [1, 4, 5]. Commercial capacitive moisture sensors are limited to products such as the Adafruit STEMMA Sensor [6], DFROBOT Gravity: Analog Capacitive Moisture Sensor [7], and generic sensors available on Amazon [8] which use wires to communicate measurements, significantly limiting their range; and are designed to be used with external microcontrollers, making them difficult to use for people lacking a technical background.

The other individual research projects within my team involve Wireless Data Transmission, Hub Processing and Presentation, Power Sourcing and Sensing, and Controls and Timing. Seth Smith is handling Wireless Data Transmission which defines how measured data will be transmitted from our distributed devices back to a central hub for user access. Ben Smith is designing the Central Hub which receives, processes, and presents the measured data in a way that is easily accessible for home gardeners or hobbyists. Sam Mousharbash will implement the Power Sourcing and Sensing for the deployed soil moisture sensor, ensuring that we have enough energy to power the device for its intended lifetime and the current percentage of battery life. Joshua Music is focusing on the Controls and Timing for the soil moisture sensor, selecting a microcontroller which can decode signals with an ADC and transmit them over Seth's radio while mitigating energy losses through implementation of a deep sleep mode and subsystem activation control. The mechanical assembly and enclosure of our device will be determined based on the resulting size of Sam's power sourcing investigation, the physically largest subsystem, alongside the shape of the PCB sensing circuit, determined as a result of my individual research.

## 3. Requirements

### 3.1 Marketing Requirements

Following our initial meeting with our sponsor, Daniel Cambron of Lexcelon, LLC, we determined 12 Marketing Requirements (MR) describing the function and intended use of the device. The marketing requirements in Table 1 are a subset that are relevant to my sub-project concerning the development of soil moisture sensing.

*Table 1: Marketing Requirements*

| # | Marketing Requirements | Relevance |
|---|---|---|
| 1 | The device shall sense the relative moisture content of surrounding soil. | Defines the necessity of soil moisture measurement for the device |
| 2 | The device shall hourly measure and wirelessly transmit all measurements. | Specifies the rate of sampling wherein soil moisture sensing must be effective |
| 3 | Reported data shall be remotely accessible and easy to interpret for a home gardener. | Necessitates relative soil moisture sensing output for increased readability |
| 4 | All measurements shall be consistent and reliable. | Ensures that soil moisture sensing sustains effectiveness for its intended lifetime |
| 5 | The device shall have a long battery life. | Places power constraints on the soil moisture sensing subsystem |
| 7 | The device shall be waterproof. | Waterproofing protects the soil moisture sensing system from water damage |
| 8 | The device should be compact | Constrains the shape and design of the PCB capacitor for soil moisture sensing |
| 9 | The device should be low cost and easily replaceable. | Places budgetary constraints on the soil moisture sensing subsystem |
| 12 | The device's soil moisture sensing shall be able to be recalibrated for varying environments | Defines functionality necessary for establishing relative soil moisture evaluation |

### 3.2 Engineering Requirements

The marketing requirements were broken down into specific and technical Engineering Requirements (ER) which have a single definite meaning; specify what the system will do, can be demonstrated or measured; and can be traced back to marketing requirements. The engineering requirements shown in Table 2 are a subset of the engineering requirements that are relevant to the soil moisture sensing sub-project.

*Table 2:Engineering Requirements*

| # | Engineering Requirements | Rationale (MR derived from) | Relevance |
|---|---|---|---|
| 1 | The device shall measure soil moisture and report soil moisture percentages or levels of soil moisture. | 1 & 3 | Describes the main functionality of the capacitive soil moisture sensing subsystem and describes the intended presentation of data to the user since the measurements are unitless |
| 2 | Soil moisture readings shall be taken without direct electrical contact to the soil | 1 | Protects the soil moisture sensing from reduced accuracy because of corrosion or related water damage |
| 3 | Soil moisture sensing reliability shall not degrade over time. | 1 & 4 | Restriction on the soil moisture sensing circuit to ensure that the user does not have to second guess of physically verify moisture content measurements |
| 5 | Measurements on the device shall be taken every hour | 2 | Defines that whichever method of soil moisture measurement is chosen, it must be repeatable within the sampling period |
| 12 | The device shall have a battery life greater than 2 years. | 5 | Constrains the soil moisture sensing circuit's power draw and creates a focus on power draw minimization |
| 14 | The device's electronics shall be enveloped within an enclosure. | 7 | Defines one of the protection systems and requires compatibility for the soil moisture sensing circuit and associated PCB |
| 15 | The device's enclosure shall have a waterproofing rating of IP-54 or greater. | 7 | Defines the level of waterproofing necessary for the soil moisture sensing circuit and PCB along with the testing to verify its effectiveness |
| 16 | The device should be no larger than 10" long, 2" wide, and 5" deep. | 8 | Restricts the size of the soil moisture sensing subsystem along with the rest of the device to ensure it can fit inside of pots |
| 17 | The total parts cost for one device shall not exceed $30. | 9 | Budgetary constraint on the deployable device including the soil moisture sensing subsystem |
| 19 | The device's electrical components shall be off-the-shelf or available online. | 9 | Ensures that the device can be reproduced easily without constructing components or pieces by hand |
| 20 | The device shall be able to be recalibrated to report relative soil moisture levels or percentages. | 12 | Recalibration ensures that levels or percentages can be determined using air and water range endpoints for capacitance and deal with variations in water composition |

## 4. Commercial Product Analysis

With my individual research focus defined, I began by focusing on the basic idea of a capacitive soil moisture sensing using the mixture of webpages, papers, and articles that we had already acquired through searching for background information earlier within our project's definition. While other methods of non-contact moisture sensing exists like seismic wave propagation, neutron probes, gamma ray probes, time domain reflectometry, GPS reflection, ground penetration radar, and microwave remote sensing, capacitive soil moisture sensing doesn't possess a health risk, is simple to implement, and cheap [4]. I ordered a capacitive moisture sensor from Amazon to ensure that I would have something to test by the time I had performed my literature review concerning the capacitive soil moisture sensor background.

To my surprise, the 5 pack of Capacitive Soil Moisture Sensors labelled SKU: SEN0193, developed through a non-descript manufacturer, arrived within days so I immediately examined the construction of the cheap commercial sensing unit visually using a multimeter to check connectivity. Immediately, the pattern used for the capacitive moisture sensing was evident, shown in Figure 1, as a plane passed through the middle of the component, connected to ground, and a plane traced around that which was the capacitive section tied to a larger voltage. The board lacked waterproofing and had a flimsy wired connector on the edge which turned almost 45 degrees when I attempted to insert the cord. My initial assumptions, later found to be false, were that the device operated through a diode fed from the PCB capacitor to the timer in the middle of the PCB which would time the speed of the discharge from the capacitive section.

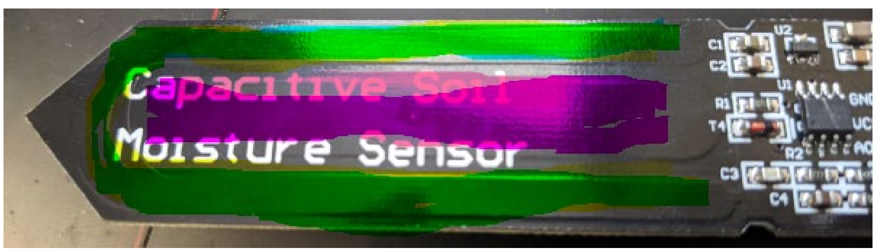



*Figure 1: Commercial Capacitive Soil Moisture Sensor with Highlighted PCB Portion*

Having had no prior experience with the analysis or creation of circuits with timing IC's, my analysis of the circuit, shown in Figure 2, reinforced this assumption. Visual inspection of the two IC's on the board, a voltage regulator with a label of "662K" and a 555 timing IC with a label of "TLC555C" led to inspection of their equivalent data sheets. For the voltage regulator, I found that it was a constant 3.3V source which would provide a stable reference for the timing IC with capacitors on either side to ensure a robust voltage supply [9]. The 555 chip features very low power consumption and, according to the data sheet, has an input for a timing capacitor to output to which then could output a high timer output signal [10]. The lack of waterproofing was disappointing as it is easy to destroy in its intended deployment environment and meant that I would have to source a method of waterproofing before long duration or outdoors testing. After a waterproofing process had been applied to the device, in this case, liquid electrical tape, I was able to test the device as described later within this report.

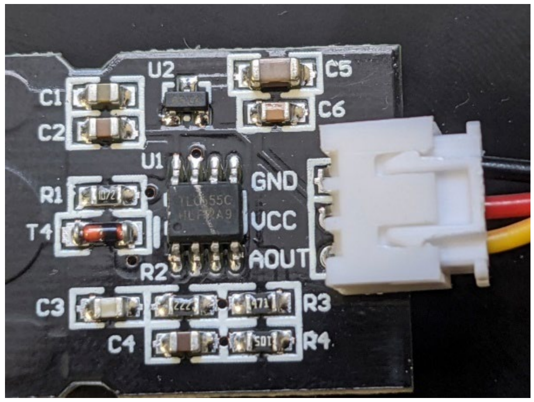



*Figure 2: Commercial Capacitive Soil Moisture Sensor Waveform Generation*

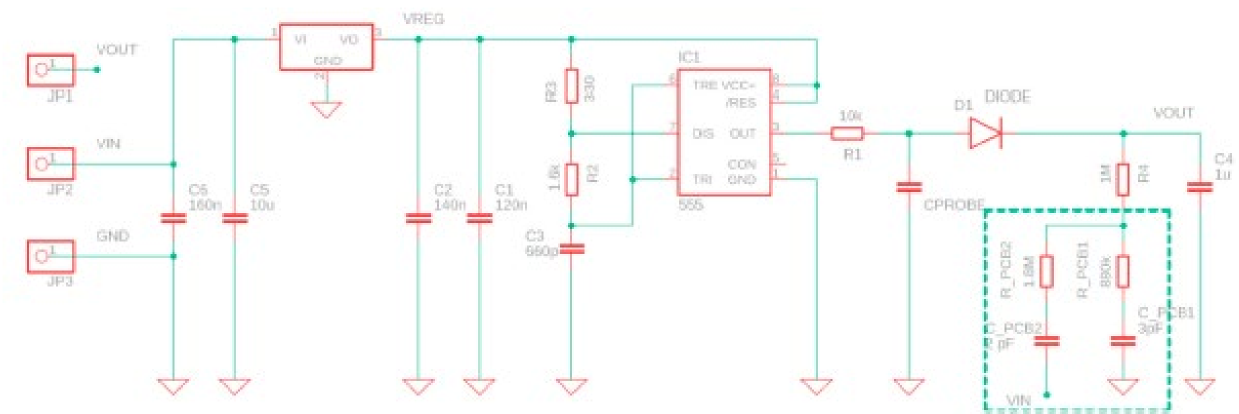
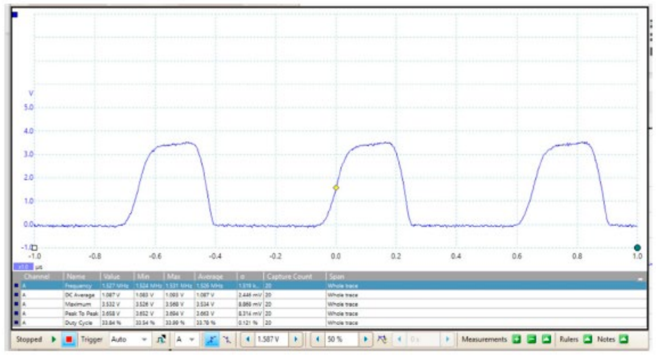


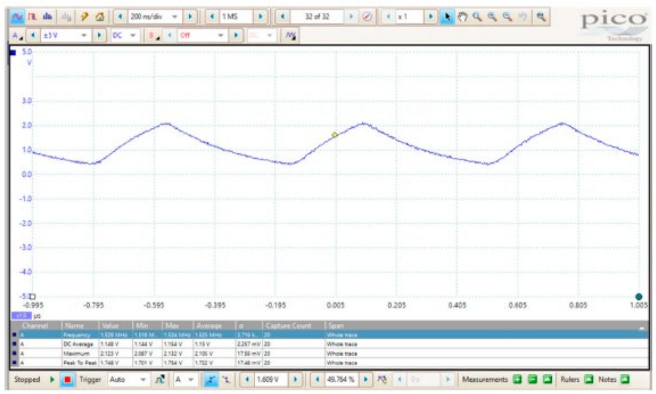

*Figure 3: Commercial Capacitive Moisture Sensor Schematic*

While making my way through various academic papers, I stumbled upon a paper that revolved around the analysis of the commercial low-cost capacitive coplanar soil moisture sensor that I had bought, clarifying the purpose of the hardware defined 555-timer circuit [8]. Shown in Figure 3 is the timing circuit which was reverse engineered by the authors of the paper through removal of the silkscreen protecting the copper traces and tracking the routes of the copper through visual inspection [8]. (Note: the section connecting to R4 is flawed in the version of the product I have and should be tied to ground through remedial soldiering) The IC labeled IC1 in the middle of the schematic is the 555 timer, whose output is pushed through a lowpass filter containing the PCB capacitor to an ADC.

The huge realization provided by this paper is that the TL555I or 555 IC is used to generate a waveform and not to time the discharge of the capacitor, changing the entire functionality of the circuit. My assumptions concerning the device's operations were corrected as follows: the voltage regulator supplies the 555 IC, producing a stationary sawtooth double-exponential waveform that is passed into the low pass filter containing the PCB capacitor, indicated as "CPROBE" and a known resistance [8]. According to [8], the higher the operating frequency, the lower the effect of losses related to the imaginary part of the permittivity so operating frequency of the waveform generator should be maximized to minimize these losses. The capacitance of the PCB capacitor varies as the dielectric constant of the soil changes, creating different output voltage values to be read by an ADC. Figure 4 is an example of the waveforms developed and analyzed by the authors of the paper with the top waveform being what is fed into the low pass filter and the bottom waveform being what is output to the microcontroller [8].



(a)



(b)

*Figure 4: Capacitive Sensing Waveforms before and after RC Circuit*

The description and analysis of the commercial capacitive soil moisture sensor also laid down the basics of capacitive moisture sensing from an electromagnetic level. The capacitive moisture sensor's capacitance and output voltages varies depending on changes to the complex relative permittivity of the surrounding soil medium [8]. The permittivity of the dielectric, $\varepsilon_r^*$, is dependent on the frequency used for measurement or waveform generation alongside the moisture, salinity, and ionic content of the surrounding soil [4]. Within Equation 1, the permittivity of the soil, represented by $e_r^*$ , alongside the geometric factor, $G_0$, which varies depending on the shape of the capacitor, directly impact the overall capacitance of the device [8]. This means that alongside the method of waveform generation, the geometric factor or design of the PCB capacitor pattern greatly effects the capacitance of the device as soil moisture changes around it.

$$C = \varepsilon_r^* \varepsilon_0 G_0$$

*Equation 1: Capacitance Calculation using Medium Permittivity*

To summarize what I found through visual inspection and with the assistance of the paper which analyzed the same device, the commercial capacitive soil moisture sensor uses a waveform generator alongside a PCB capacitor in a low pass filter to approximate moisture changes in the surrounding medium. The frequency of the waveform generator and geometric factor of the capacitor greatly affect the resolution of measurement as large capacitive values allow for smaller changes. The method of waterproofing also effects the device as innate vulnerability of electronics to the local environment needs to be mitigated to ensure proper functionality. Because of this, I pivoted to the investigation of the waveform generation method, device waterproofing, and PCB capacitor pattern as the main design focuses for my individual research.

## 5. Functional Decomposition

Functional Decomposition was used to aid in the translation from the technical concept of capacitive soil moisture sensing to a solution that satisfies the system requirements laid bare by the Marketing and Engineering Requirements. To communicate the functionality and interfaces for subsystems in the design, function decomposition starts at the highest level of abstraction which is further refined with each ascending level. Shown in Figure 5 is Level 0, the functional requirement of the capacitive soil moisture sensing system. At the most basic level, what is expected is that a black box or subsystem is powered by Sam's chosen energy storage system and produces an variable voltage output that can be used to determine a percentage and relative soil moisture levels. This voltage output will be read by Josh's ADC, transmitted over Seth's radio communication, and processed by Ben's hub. The system needs to respond predictably to the modification of moisture on the surrounding soil medium to enable approximation of nearby soil moisture levels.

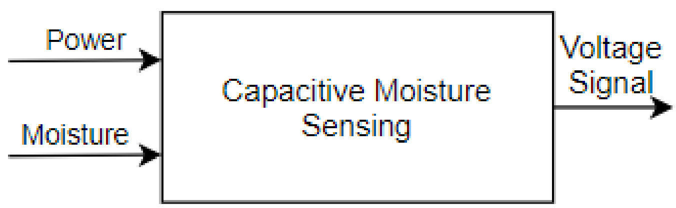



*Figure 5: Level 0 Capacitive Moisture Sensing Functional Decomposition*

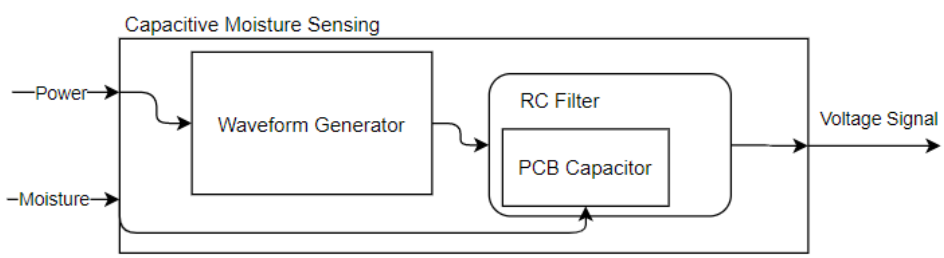



*Figure 6: Level 1 Capacitive Moisture Sensing Functional Decomposition*

Based on how the Commercial Capacitive Moisture Sensor worked, the implementation of such a device could be broken down one more step into a Level 1 Functional Decomposition, shown in Figure 6. The power supplied to the capacitive moisture sensing circuit is specifically used to power the waveform generator which creates a pulsed waveform that is pushed through an RC filter. The RC filter contains the PCB capacitor whose capacitance changes because of the variable permittivity of the surrounding medium, changing the decay time of the waveform as it passes through. Using the known resistance, resulting voltage can be converted into a digital signal by Josh's microcontroller and processed in Ben's hub to compare the value to calibrations representing water and air, the two end points of the soil moisture spectrum or available water capacity. Using the two calibrated end points, the percentage or soil moisture level can be determined, logged, and displayed for the user through the central hub. Calibration will occur by prompting the user to hold the sensor in air and in groundwater prior to deploying it in the field and pressing a button on the central hub to save the values as part of the soil moisture sensing object.

Figure 7 depicts the relative importance of waveform generation, PCB capacitor pattern and sourcing, and waterproofing when it comes to the creation of the Soil Moisture Sensing subsystem. The most abstract or category level rankings were determined using systematic comparison aided by AHP Table 8 in the Appendix. Through this systematic comparison, it was found that the PCB capacitor pattern and sourcing is the highest priority during the research and design phase as it defines the effectiveness of capacitive moisture sensing, is the hardest to change compared to waveform generation and waterproofing, and essential to the integration of our respective subsystems. If we were to design or source PCBs that turned out to not be effective, it would greatly dampen the effectiveness of our soil moisture sensing. Waterproofing was the second highest priority because if water were to seep into our device, it could corrode, degrading the measurements, or fail completely. Since the device is meant for outdoors operations, waterproofing is vital to our system's overall performance whether it is my soil moisture sensing subsystem or Josh's, Seth's, and Sam's which all exist on the deployed device. Waveform generation was ranked least important because of the availability of waveform generation circuits, definition and customizability of hardware-defined waveform generation, and the potential for software-defined waveform generation meant that this could be easily altered after the initial design phase if proven ineffective.

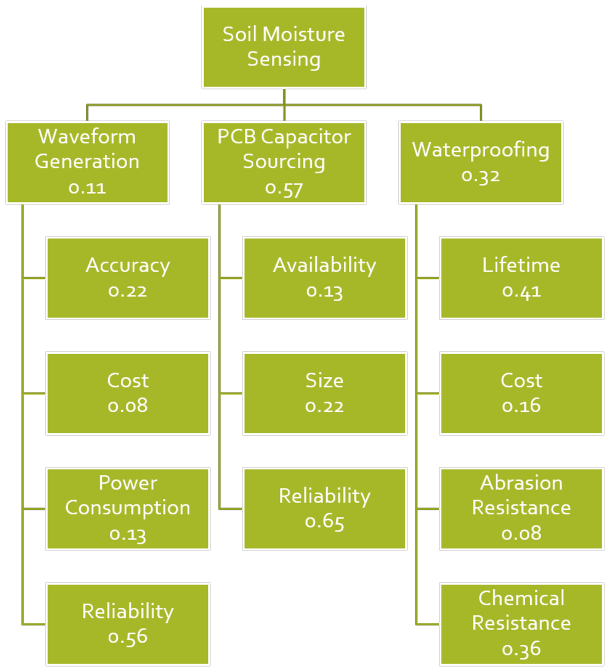



*Figure 7: Soil Moisture Sensing Objective Tree*

## 6. Research

### 6.1 Waveform Generation Schemes

Concerning the waveform generation scheme for what is passed through the low pass filter containing the capacitor, I have found numerous papers describing types of circuits or methods for waveform generation including the hardware defined circuit found in commercial capacitive moisture sensors and software defined algorithms highlighted in papers surrounding the subject. I created an AHP table, displayed as Table 9 within the Appendix, to allow for systematic decision making concerning the waveform generation schemes. Within this table, the main parameters or focuses for the project include the difficulty of implementation, accuracy or resolution of the resulting ADC value, cost of implementation, power consumption of the scheme, and reliability or consistency over time. Budgetary cost and power consumption were the least important parameters because they are the costs associated with increased accuracy and both have tight restrictions within our project but if small increases in both can gain better consistency and accuracy, it would be worth it for the increased effectiveness. Reliability and accuracy are the two most important factors. If the sensing system is not reliable or accurate at approximating soil moisture, then the benefits of the device to remotely monitor soil conditions is negated due to the need to physically verify. Moving forward into the research of waveform generation schemes, the AHP breakdown shows that consistency and accuracy are the most important parameters for waveform generation as this decides whether the approximate soil moisture value can be trusted and the device itself is useful to the intended user.

Hardware defined circuits, described earlier, utilize a 555 timer to implement waveform generation as showed in Figure 4. 555 timer IC's, shown to a greater detail in Figure 8, are precision timers which can be used as a relaxation oscillator, circuits that repeat through the charging and discharging of a capacitor to produce strings of stabilized waveforms [11]. Within the circuit defined in Figure 3, the two resistors and capacitor are connected across the terminals to generate a fixed pulse train using the time constant of the RC network and a path for discharging the capacitor [11]. The maximum frequency of hardware defined waveform generation is therefore dependent on the maximum frequency of the 555 IC chosen for the circuit. At the beginning of a cycle, the capacitor's voltage increases as energy is stored until it reaches the voltage reference supplied to the IC. At this threshold, the output of the RC circuit to the trigger and threshold pins reset the internal flip flop, driving an output voltage. As the output voltage is driven, it drives the discharge to ground, dumping the voltage stored within the capacitor, ending the cycle, and beginning it again. Knowing how the 555 IC works is essential for effective recreation of the circuit and manipulation of the voltage used to generate waveforms to increase resolution by tying the supplied voltage to the ADC reference.

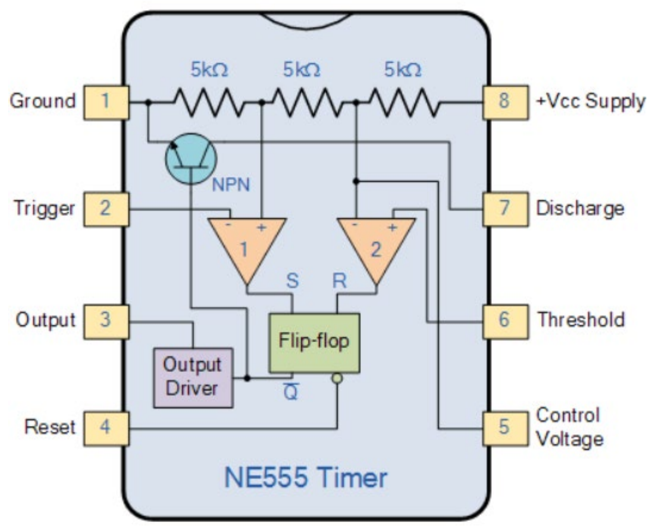



*Figure 8: 555 Timer Diagram*

Shown in Figure 9 and Figure 10 are two implementations of software defined circuits which measure capacitive responses to generated waveforms. Within Figure 9, the capacitor is represented by interdigitated finger copper track and fed a voltage signal, with the op amp on the left acting as a buffer to reduce parasitic capacitance, before being output to a plug delivering the capacitive sensing signal alongside a voltage signal from the thermistor on the right [1]. In Figure 10, the system focuses solely on creating a single waveform and measuring the RC filter response or how long it takes the capacitor's voltage to decay [5]. Within both systems, constant frequencies are pulsed to evaluate the time required to discharge from a high voltage to a low voltage was measured using a direct microcontroller interface and, using a known resistance, calculate capacitance from its known behavior using Equation 2 [1]. A commercial soil sensor also uses what seems to be a similar method of direct microcontroller waveform generation [6] but outside of the paper's basic descriptions, no information is given for how to implement this system within software.

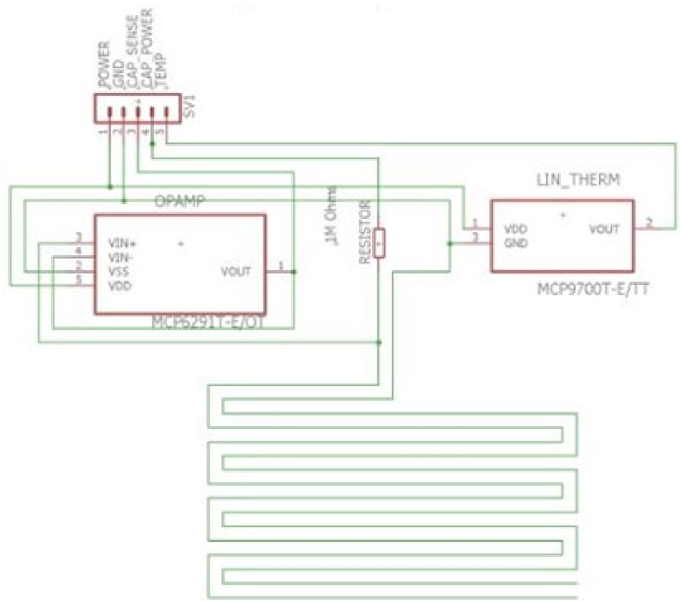



*Figure 9: Microcontroller Direct Interface Example with Op Amp Buffer*

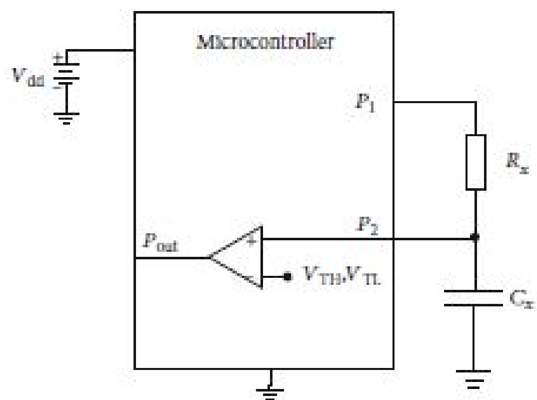



*Figure 10: Direct Microcontroller Interface with Comparator Diagram*

$$t = RC \ln\left(\frac{V_h}{V_l}\right)$$

*Equation 2: Capacitance Calculation using Voltage Threshold Comparison*

According to [5], this method is flawed in that it has low resolution at low capacitance values and frequencies. To fix this, it proposed an alternative method which counts the number of discharge cycles during a fixed period. This altered method, shown in Figure 11, charges the capacitor almost instantaneously before counting the number of discharge cycles during the fixed time and monitoring voltage output [5]. Using the time value gathered from the known value of the reference capacitor, the discharge time for the unknown capacitor is used to calculate the unknown capacitance by setting the ratio of times equal to the ratio of capacitances.

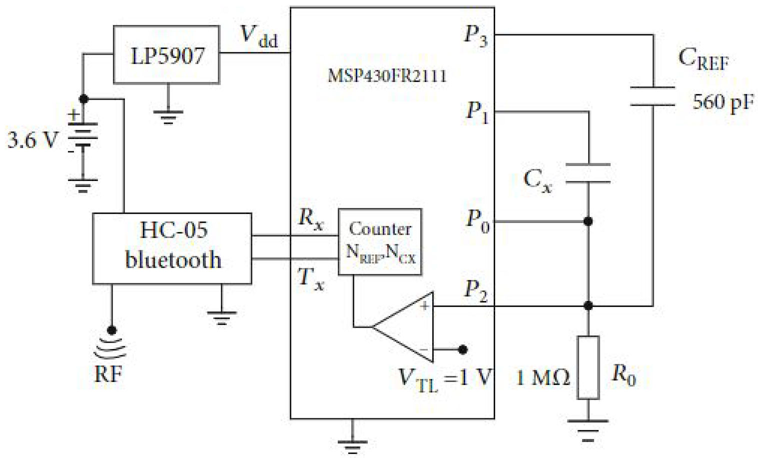



*Figure 11: Direct Microcontroller Interface for Counting Discharge Cycles*

As indicated within the Soil Moisture Sensing AHP, Table 8 in the Appendix, deciding which waveform generation scheme was of the lowest priority because it can be easily adjusted within software or the voltage division and capacitors used for the waveform generation can simply be replaced. However, since I could not find commercial devices with the same pattern but different waveform configurations for waveform generation comparison, I designed and created my own PCB with a set PCB capacitor pattern containing the option to either use the hardware defined circuit from [8] or a software defined method of waveform generation. Sadly, I did some testing and found that the new device is so long that I cannot test it in pots because the length of the capacitor needs to be submerged within the soil or the fringing field will be biased towards the air value or porosity by however much it's sticking out.

Since I was unable to fairly test and compare both methods using technical results, I decided upon a systematic comparison of both options using AHP Table 9 concerning the Waveform Generation Method to decide which one would be the focus of integration and technical design. Using the weights determined through Table 9, I ranked hardware defined and software defined waveform generation in Table 3 on a performance scale of 1 to 5 with 1 being poor, 2 being marginal, 3 being acceptable, 4 being good, and 5 being excellent.

*Table 3: Waveform Generation Decision Matrix*

| Waveform Generation | Accuracy | Cost | Power Consumption | Reliability | | |
|---|---|---|---|---|---|---|
| Weights | 0.22 | 0.08 | 0.13 | 0.56 | Geometric Mean | Normalized Value |
| Hardware Defined | 5 | 3 | 3 | 5 | 3/4 | 0.50 |
| Software Defined | 4 | 5 | 4 | 3 | 3/4 | 0.50 |

To explain the performance ratings given within the Table 3, I will walk one by one through the metrics that were compared or ranked. Since the hardware defined circuit is configurable, not severely dependent on the resolution of the ADC, and can reach higher frequencies of waveform generation, I believe that it has better accuracy than the software defined circuit. Since the hardware defined circuit requires purchasing of supplementary components such as resistors, capacitors, and a timing IC, I ranked it as acceptable due to the low cost but the software defined circuit's cost is better because it requires only needs a resistor and capacitor. The power consumption of the hardware defined solution is worse than the software defined solution since it works in parallel with the power used for the microcontroller but the software defined solution would make the microcontroller stay on longer which could also consume more power depending on the length of time. Concerning reliability, I considered the hardware defined circuit to be more reliable because it is used in commercial products and known to function and is not entirely dependent on the timing of the microcontroller programming. As shown in the final column, both methods tied within the systematic comparison, so I have decided to add the solder jumper used in my custom board to our integrated prototype and leave traces or connections for the hardware defined circuit. This will enable us to either use the hardware defined circuit or the software defined circuit depending on which copper pads are bridged, allowing the development and testing of either waveform generation type.

### 6.1.1 Calibration Methods

During our initial meeting with our sponsor, I asked whether the soil moisture sensors would need to be recalibrated to sustain effective operation within different soil types. Our sponsor did not know and our initial investigation into capacitive soil moisture sensing did not prove one way or another concerning calibration. Through the investigation into methods of waveform generation and analysis, I have found that calibration is necessary but does not vary significantly between soil types. Code provided within [7], [12], and [13] for the implementation of soil moisture sensing on hardware defined circuits insists upon calibration to be able to describe soil moisture in levels or percentage calculations . For each example, the user is instructed to read the analog values and print them across the serial channel with the device either submerged in air and water to record these as the end points for relative analysis. While [1] and [5] suggested calibration for each type of soil composition due to additive components, since water has a permittivity of approximately 80 and soil has a permittivity of around 5, changes in moisture have a much larger impact on permittivity than the different soils so it could be considered negligibly different [1]. For this reason, calibration should be undergone to key in the water differences rather than the differences between various soil types.

Other methods of calibration were explored in [14] and [15] but they involved external measurements from devices such as a digital scale or tensiometer to verify the measurements. Another paper suggested using multiple capacitors as references for the calibration of charge and discharge to ensure that the correct trendline was applied to soil type being used [1]. These methods are impractical for our project because they either require expensive equipment, external capacitors applied by the user, or a full week to dry soil for volumetric water content calculations. The technical knowledge required for these calibration techniques is outside of what we expect to be our target audience so we intend to use the calibration implemented by commercial devices as it is simple and can be integrated into the central hub and processing interface.

## 6.2 PCB Capacitor Utilization

As described within Equation 1, the geometric factor or pattern of the PCB capacitor effects the overall effectiveness of the device as it effects the overall capacitance of the system and size of potential variation. The geometric factor scales the capacitance as it interacts with the permittivity of air and the surrounding soil medium. Following with the idea that the highest capacitance would allow greater variation in voltage values, I searched for multiple forms of PCB capacitor patterns and the equations that modeled their capacitance Using the approximation of these equations along with examples of PCB capacitors within the commercially developed sensors and academic papers, I constructed numerous potential patterns for high capacitance values for testing described later on.

The most popular pattern within the papers covering soil moisture sensing was an interdigitated copper electrode or interdigitated "finger" pattern, shown in Figure 12 [1] and Figure 13 [4]. Represented by Equation 3, the geometric factor is a ratio of the product of the number of fingers, thickness of copper, and finger length to the distance between two fingers [5]. Shown in this equation and defined in [16], having the width of the tracks equivalent to the space between fingers maximizes the capacitance output by an interdigitated finger capacitor pattern and the total number of electrodes or fingers effects overall capacitance. The contribution of finger number within the product is the main benefit of the interdigitated finger, allowing for larger capacitance with the same area allocation as other patterns. Two released patents on the use of this pattern for capacitive sensing of soil moisture cover the intended implementation of our soil sensor with an interdigitated finger capacitor pattern, WO2009066992A2 [17] and US20150338363A1, although this patent was abandoned [18].

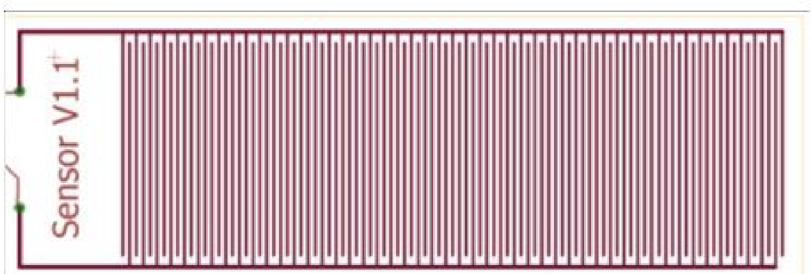



*Figure 12: Interdigitated Finger Capacitor Example*

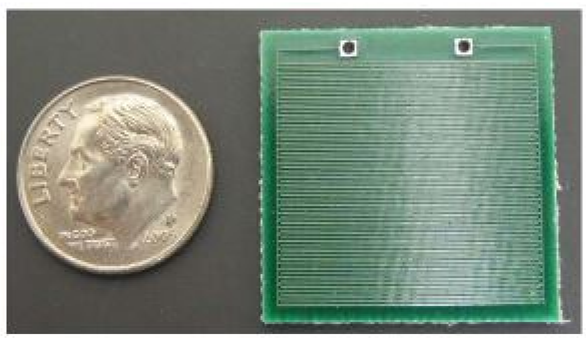


*Figure 13: Patented Interdigitated Finger Capacitor Example*

$$C = \varepsilon_0 \varepsilon_r \frac{nlh}{d}$$

*Equation 3: Interdigitated Fingers Capacitance*

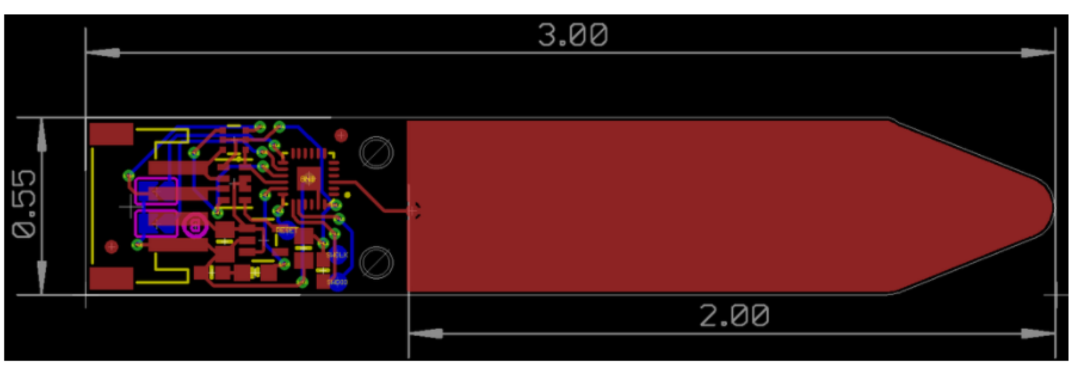



*Figure 14: Stemma Soil Sensor Schematic*

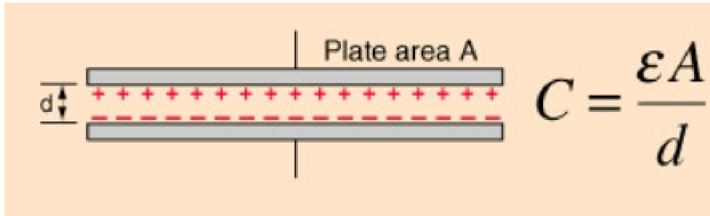



*Figure 15: Parallel Plate Capacitance*

After stumbling upon the Stemma Soil Sensor, pictured in Figure 14, I decided to explore the possibility of using a simpler parallel plate pattern for the PCB capacitor pattern [6]. As shown in Figure 15, the overall capacitance is dependent on the area of the parallel plates which can be maximized along the length of the capacitive sensing section [19]. Usage of this pattern allows for greater utilization of the chamfered portion used to assist insertion into other soil medium than other patterns. During my research, I found tips from others who had made their own capacitive PCBs and suggested various tips for performance improvement. These included maximizing trace length and proximity to increase capacitance, aligning traces on both faces of the PCB and maximizing probe length to ensure sufficient soil depth [13]. Based on the example from the commercial Capacitive Soil Moisture Sensor and these tips, I also wanted to test a version with two parallel coplanar strips and the respective equation is shown in Equation 4 [20]. To maximize capacitance, I believe a capacitor with this area would need to maximize strip width and minimizing the distance between strips from my interpretation of the equation.

| | | |
|---|---|---|
| **Two parallel coplanar strips**[13] | $\varepsilon\ell\dfrac{K\left(\sqrt{1-k^2}\right)}{K(k)}$ | $d$: Distance<br>$w_1$, $w_2$: Strip width<br>$k_m$: $d/(2w_m+d)$<br>$k^2$: $k_1k_2$<br>$K$: Elliptic integral<br>$\ell$: Length |

*Equation 4: Parallel Coplanar Strip Capacitance*

There was contention between papers on whether to have the back of the PCB electrically floating or tied to ground.  According to [4], using the backside of the PCB as an electrically floating copper pad dealt with the possibility of erroneous backside fringing fields. By having copper on both sides led to a smaller change in capacitance between air and water because the interaction of the water with backside fringing fields was reduced [4]. Meanwhile in [1] and [13], tracks were printed on both sides of a PCB and connected to the same electrode to minimize internal capacitance of the device for an interdigitated track pattern. Building off of this, my own prototype capacitive PCBs had electrically floating copper pads on the bottom of the PCB except for the parallel plate capacitor because it required both sides of the copper PCB to be connected to function as a capacitor. Since the capacitive values of various PCB capacitor patterns can be tested and quantified for comparison, a decision can be made for one pattern over others depending on its capacitive value. I tested PCBs with different patterns and tested their capacitance with LCR meters carrying the assumption that the largest capacitance is the best because it allows for greater variability or change in voltage and time values.

The other decision concerning PCB capacitors was whether to integrate commercial products or create my own custom PCB from scratch. While commercial soil moisture sensing PCBs are readily available and tested for prior to marketing and sales of the product, they lack customizability, require sourcing for reproduction of the product, have defined size, and more than likely do not have the mixture of waveform generation and PCB capacitor pattern that we find to be the most effective. Custom PCBs allow for easier customization, redesign, and integration of the product and are easier to source and reproduce but are not verifiably functional until our own testing is completed. I created Table 10 within the Appendix through the AHP decision making process to allow a fair comparison of both methods. The main parameters compared were the availability of the PCB capacitor and size of the PCB capacitor. Reliability, in this instance, is the verification of PCB capacitor effectiveness at approximating soil moisture changes and was determined to be the most important aspect of PCB capacitor selection. The size followed closely behind as the size of the PCB capacitor impacts the size of the overall device, shaping the essential component that all other parts are integrated with.

*Table 4: PCB Capacitor Sourcing Decision Matrix*

| PCB Capacitor Sourcing | Availability | Size | Reliability | | |
|---|---|---|---|---|---|
| Weights | 0.13 | 0.22 | 0.65 | Geometric Mean | Normalized Value |
| Commercial PCB | 2 | 2 | 5 | 1 4/7 | 0.49 |
| Custom PCBs | 4 | 5 | 4 | 1 5/8 | 0.51 |

Using the weights determined through Table 10: AHP Matrix for PCB Capacitor Sourcing's AHP matrix, I ranked commercial PCBs vs custom PCBs in Table 4 on a performance scale of 1 to 5 with 1 being poor, 2 being marginal, 3 being acceptable, 4 being good, and 5 being excellent. The commercial PCB rated higher in reliability assuming it had long term testing so it would be verifiably functional when received. The custom PCB rated higher in availability and size because the size can be configured during initial design and the design can be freely altered and accessed for reproduction but still requires manufacturing from a PCB mill. Using this scale and evaluation, custom PCBs will be the method of capacitive PCB implementation for the project moving forward.

### 6.2.1 Porous Material

It was indicated that a porous material could be added to the capacitive moisture sensor to mitigate inaccurate or false results caused by airgaps between the PCB and the soil [16]. Since sensitivity of the capacitive measurement is dependent on the distance between the copper fingers and the measured medium, adding a porous material would maintain a constant proximity between the capacitor and the water [5]. While not explored by the papers, I believe porosity would be the biggest difference within soil types, reducing effectiveness in soils with large sand content and increasing it in soils with large clay content due to their porosity. To analyze the effect of such an addition, a porous ceramic was bonded to a PCB in [16] which added a delay time of 10 to 20 minutes as water had to be absorbed into the porous material but allowed for more accurate measurements. However, the porous material would have to be added or bonded to the outside PCB for the length of the entire capacitive sensing section to increase accuracy and is difficult to source for larger sizes. I chose not to pursue this route because implementation would double the cost of the system and the difficulty of finding large spear shaped porous materials when the entire measurement is relative or dependent on calibration anyways.

## 6.3 Waterproofing

To ensure the safety of our device's electronics while deployed within weather condition, we need to waterproof the device to satiate an IP-54 rating as specified by our sponsor and defined in the Appendix. To initialize the systematic comparison of waterproofing methods, I created Table 11, an AHP ranking the ideal waterproofing parameters to rank its most important aspects. The main parameters for ranking were the lifetime of the waterproofing, cost of waterproofing application, abrasion resistance or resistance to physical deformation, and the chemical or solvent resistance. The lifetime and chemical resistance were determined to be the two most important parameters because they determine the effectiveness of the waterproofing, assuming the waterproofing methods considered all seal the electronics or devices fully. Susceptibility to chemicals or a short lifetime could endanger the electronics of the device due to unknown groundwater composition. Cost was the second lowest rank because the cost for one applicator of water proofing could be divided down into the number of devices it can be applied to with that applicator, reducing the cost per device. Abrasion resistance was the least important because while things could gradually wear it down, the enclosure will help protect the water proofing from deteriorating due to collisions, etc.

*Table 5: Waterproofing Decision Matrix*

| PCB Capacitor Sourcing | Lifetime | Cost | Abrasion Resistance | Chemical Resistance | | |
|---|---|---|---|---|---|---|
| Weights | 0.41 | 0.16 | 0.08 | 0.36 | Geometric Mean | Normalized Value |
| Silicone | 5 | 4 | 5 | 5 | 1 2/3 | 0.40 |
| Liquid Electrical Tape | 2 | 3 | 5 | 5 | 1 1/2 | 0.30 |
| Acrylic Conformal Coating | 5 | 2 | 1 | 1 | 1 2/5 | 0.15 |
| Nail Polish and Heat Shrink | 1 | 5 | 2 | 1 | 1 1/5 | 0.15 |

Numerous papers and websites mentioned different ways for waterproofing commercial soil moisture sensors or the sensors they had developed themselves. Shown in Table 5, is a decision matrix comparing waterproofing methods based on descriptions given in various references and the weights from the AHP table on a performance scale of 1 to 5 with 1 being poor, 2 being marginal, 3 being acceptable, 4 being good, and 5 being excellent. Acrylic conformal coating suffers from poor abrasion and chemical resistance [21] which could lead to a drastic reduction in waterproofing effectiveness and the nail polish method has a very short lifetime [22]. Liquid electrical tape was a close second but because it is more expensive per device due to a minimum of 2 coats for a proper seal and has life time of about a year before breaking, it is a backup or quick fix solution available if necessary [23]. Silicone reigned supreme in comparison to the other types as it boasts a long lifetime, excellent abrasion resistance, and excellent chemical resistance while being affordable [24].

## 7. Design

### 7.1 Initial Testing Results

Using the commercial Capacitive Soil Moisture Sensor that I had purchased alongside code that I had found for its operation; I underwent a short test of the stability of the soil moisture sensor's readings. To do so, I integrated the following two code examples together to provide a percentage and moisture level estimate of values read from the soil moisture sensor. The first snippet of code, shown in Figure 16, is an example of the steps taken to initially calibrate the capacitive soil moisture sensor [7]. The voltage value is read from the analog output from the capacitive moisture sensor to the microcontroller's ADC.

The digital representation of this signal is then reported over the serial connection to allow for acquisition of the air and water signal values to serve as available water capacity end points.

Figure 17 is an example of constructing thresholds or levels using the established calibration range [7]. Within this code, the air and water values, having previously been calibrated, are saved, and used to create intervals or levels for the evaluation of soil moisture level. As the analog values given by the capacitive soil moisture sensor are read, the program determines whether they are within certain levels and prints out the current level to the serial monitor or, in our case, the user. I modified this code as shown in Figure 18 to output a time in seconds and the digital soil moisture value so I could monitor the variation in the measured soil moisture over time after water was added to the system to analyze the system's effectiveness.

Calibration | Arduino 1.8.13

File Edit Sketch Tools Help

Calibration

```
void setup() {
  Serial.begin(9600); // open serial port, set the baud rate as 9600 bps
}
void loop() {
  int val;
  val = analogRead(0); //connect sensor to Analog 0
  Serial.println(val); //print the value to serial port
  delay(100);
}
```

*Figure 16: Calibration Code Example*

```
const int AirValue = 520;   //you need to replace this value with Value_1
const int WaterValue = 260;  //you need to replace this value with Value_2
int intervals = (AirValue - WaterValue)/3;
int soilMoistureValue = 0;
void setup() {
  Serial.begin(9600); // open serial port, set the baud rate to 9600 bps
}
void loop() {
soilMoistureValue = analogRead(A0);  //put Sensor insert into soil
if(soilMoistureValue > WaterValue && soilMoistureValue < (WaterValue + intervals))
{
  Serial.println("Very Wet");
}
else if(soilMoistureValue > (WaterValue + intervals) && soilMoistureValue < (AirValue - intervals))
{
  Serial.println("Wet");
}
else if(soilMoistureValue < AirValue && soilMoistureValue > (AirValue - intervals))
{
  Serial.println("Dry");
}
delay(100);
}
```

*Figure 17: Soil Moisture Threshold and Level Example Code*


```
const int AirValue = 564;   //you need to replace this value with Value_1
const int WaterValue = 293;  //you need to replace this value with Value_2
int soilMoistureValue = 0;

unsigned long curSeconds = 0;

void setup() {
  Serial.begin(9600); // open serial port, set the baud rate to 9600 bps
}
void loop() {
soilMoistureValue = analogRead(A0);  //put Sensor insert into soil
curSeconds = millis()/1000;
Serial.print(curSeconds);
Serial.print(" , ");
Serial.println(soilMoistureValue);
delay(250);
}
```

*Figure 18: Basic Soil Moisture Value Code*

Assuming water moves through soil differently depending on whether there is a plant within proximity, I used a succulent, potted with potting soil, as my first test subject. To begin, I started the sensor, without waterproofing it, and the serial monitor to record values for the air and water calibration. As this initial calibration indicates the range of values, I noticed that the range was a lot smaller than the full range of the ADC, about one half of the full available range. I assume increasing the capacitance or tying the reference of the timing circuit to the reference of the microcontroller could increase the range or resolution of this measurement.

After inserting the moisture sensor into the soil, adding water resulted in a large transient spike from which it took about 10 to 15 minutes for the value output from the sensor to settle around a constant or linear trend line. The depth of the sensor also greatly changes its effectiveness as having less geometric area in the soil reduced the voltage output, assumedly by reducing the capacitance. To analyze this, I would need to waterproof the device and go for a longer testing duration with added data logging capability.

## 7.2 PCB Capacitor Pattern Testing

To test the effectiveness of multiple PCB capacitor patterns, I worked with Ben to design and create four different PCB prototypes, shown in Figure 19, for testing using the University of Kentucky Innovation Center. Since the depth of PCB insertion into the soil drastically effects the effectiveness of the devices, I created long spear-like shapes meant to maximize the overlap between PCB capacitor area and soil coverage. The first PCB was a copy of the commercial soil moisture sensor I had purchased in terms of the pattern but with longer depth. The second PCB is an interdigitated finger form which is patented but suggested to be the best pattern for PCB capacitor creation and featured in multiple papers [18]. The third PCB is a simplified version with two large coplanar copper traces parallel to one another on one plane which I had imagined and created myself based on Equation 4. The fourth PCB had two parallel plates based on the Stemma Soil Sensor whose schematic is shown in Figure 14 [6] but is not shown in Figure 19.

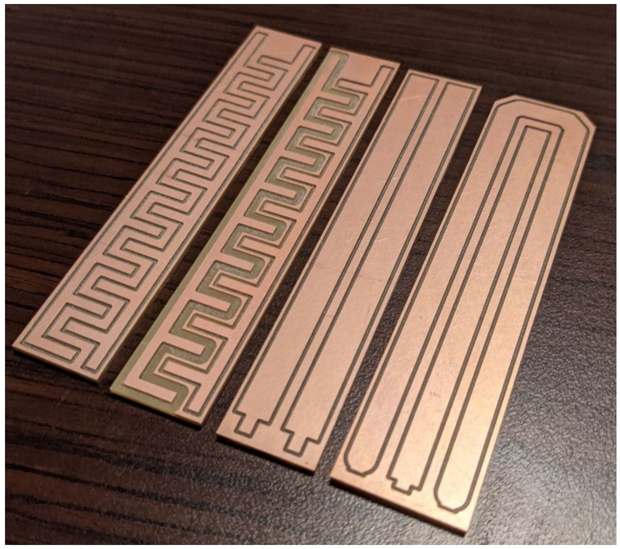


*Figure 19: Custom PCBs made for Capacitance Testing*

I searched for ways of determining the capacitance of the two copper plates assuming that with a larger capacitance smaller changes could be measured from the output of the RC filter. To test my design, I utilized the SR715 LCR meter at the UK Solar Car garage with a voltage peak of 1V and a frequency of 10kHz as was done to measure PCB capacitance in [4]. Ideally, we would want as high of a frequency as possible to acquire as much of a real component to measure [8] so we used 10kHz, the maximum of the LCR meter. I soldered wire leads to the power and ground of each copper board and inserted them into the LCR device as shown in Figure 20. I measured the capacitance and dissipation factor of each PCB capacitor using the C +D option on the LCR meter with the results shown in Table 6. Dissipation factor, according to the LCR's manual [25], is the ratio of the real part of the impedance to the imaginary part. For the microcontroller ADC, we want as much of a real part as possible to be able to approximate capacitance, so the Parallel Plate PCB pattern seems superior in both Capacitance and Dissipation factor as measured by the LCR.

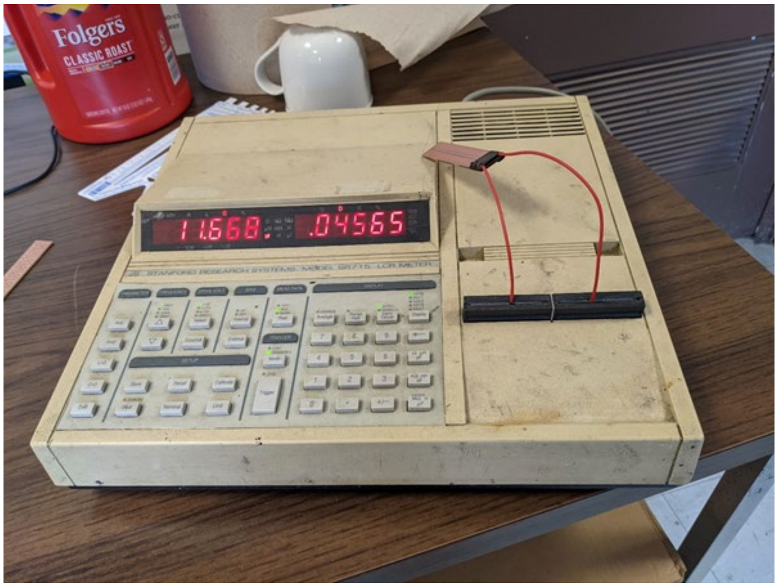


*Figure 20: LCR Capacitance Measurement Example*

*Table 6: Results of PCB Capacitor Testing*

| PCB Style | C | D |
|---|---|---|
| Interdigitated Fingers | 9.78pF | .04585 |
| Parallel Traces | 11.713pF | .04542 |
| Circle Around (Large Area) | 13.150pF | .04478 |
| Circle Around | 7.4389pF | .04662 |
| Parallel Plates | 54.836pF | .06174 |

### 7.3 Software

To enable longer tests and look at general trend lines for soil moisture sensing, I developed code, shown in Figure 21, that would be able to log the data values into CSV format using PuTTY, a downloadable serial monitor program. Manipulating the code once more from my previous example, the code begins by establishing the three headers for the data collection and initializing the serial port along with the calibrated air and water values. For each period or sample, the time in seconds, soil moisture raw voltage, and relative soil moisture percentage are output over the serial port or USB connection in csv or comma separated form. Using the logging function of PuTTY, shown in Figure 22, I was able to capture the serial logs or data within a *.csv file type as it came to my computer over USB into a form. I then was able to convert the .csv file to a .xlsx file containing the data points and allowing for finer manipulation and analysis of the resulting data as shown in Figure 24's plot.

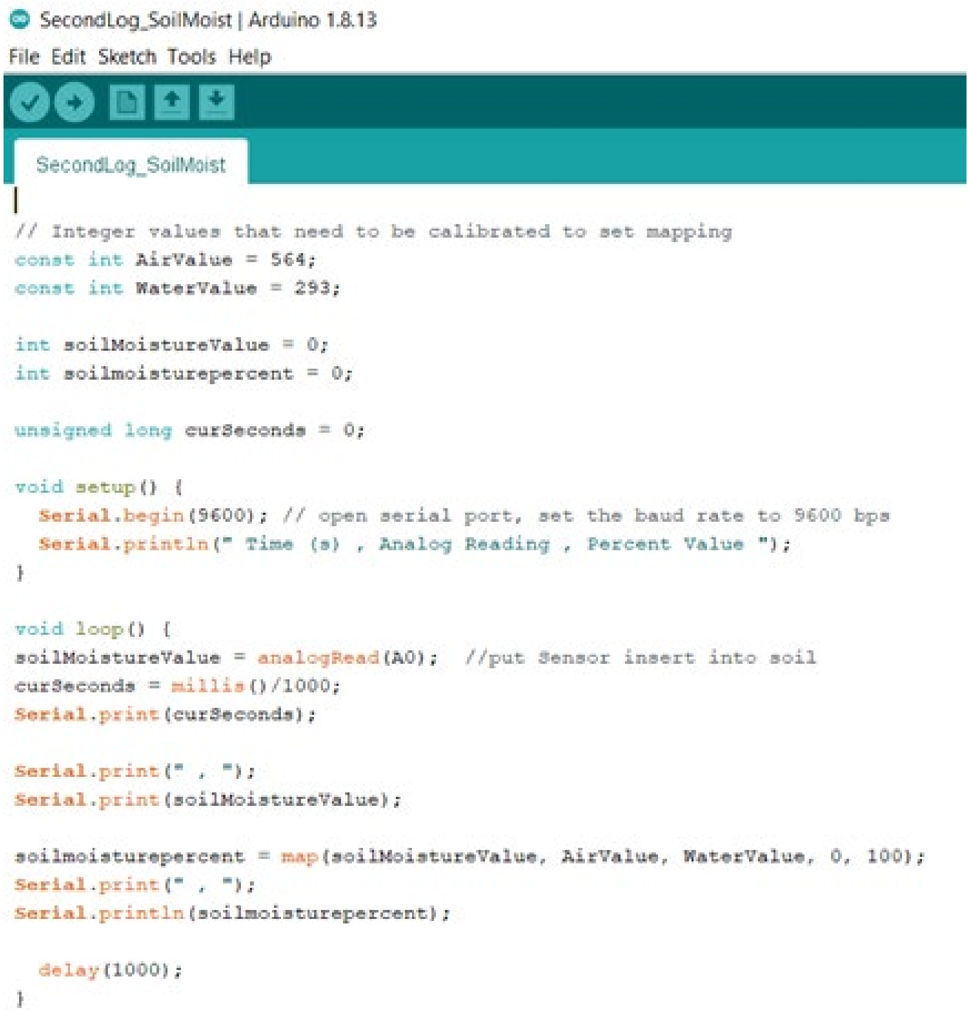



*Figure 21: Logging Soil Moisture Code*

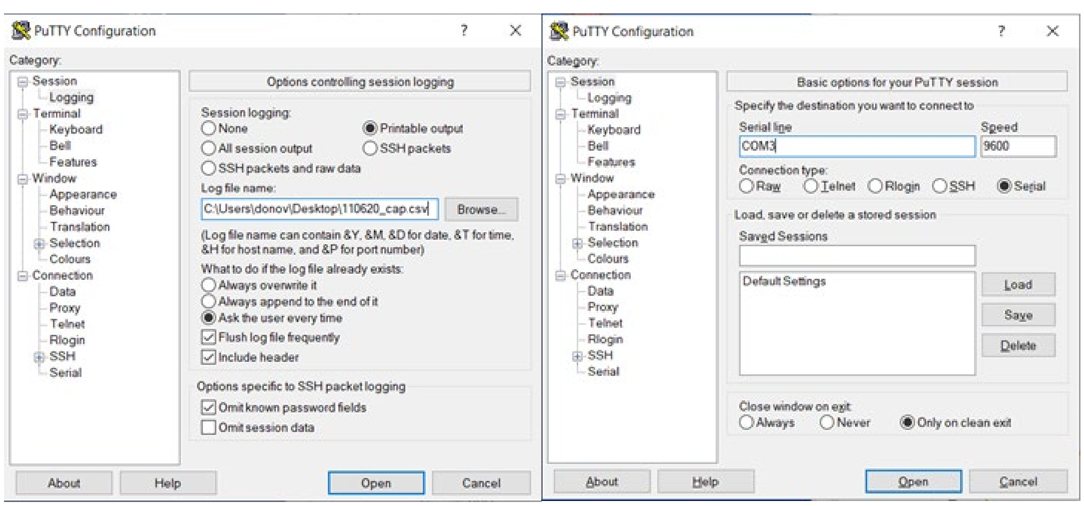



*Figure 22: PuTTY Logging Example*

### 7.4 Commercial Test with Logging

I waterproofed a sensor using liquid electrical tape and verified that water was unable to seep into the electronics on the board. After application, I put the device within UK Solar Car's aloe plant, Kevin, shown in Figure 23, and poured water directly into the center while logging data with PuTTY. Leaving the device within the plant, I recorded over 30,000 data points over a period of almost 8 and a half hours to analyze the variability of the measurement over time. I failed to realize that soil moisture does not change second to second and that I would record so many data points over the 8 hour time period but it proved useful for analyzing the variation in the linear trend of soil moisture. Figure 24 is a graph of the resulting soil moisture measurements with the analog reading or ADC output in orange and the left y-axis and the percent value in blue with the right y-axis.

*Figure 23: Commercial Capacitive Soil Moisture sensor deployed for long-term testing*

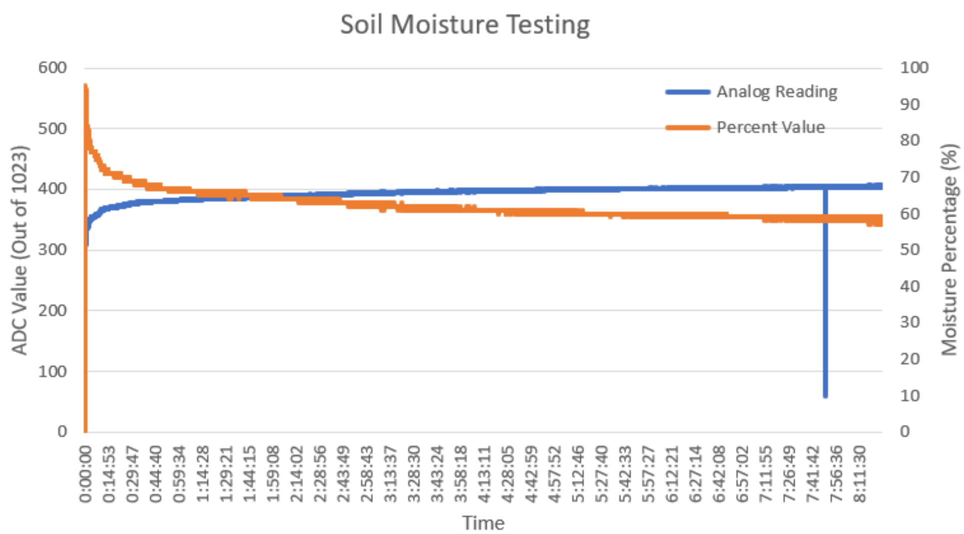



*Figure 24: Soil Moisture Testing Results*

The behavior that I had noticed with my initial/preliminary testing is that the measured moisture level spikes when water is added but drastically reduces soil moisture level within 15 to 20 minutes of the initial exposure. Within the above plot, this is shown as the initial spike in moisture percentage spikes before the rate of decay in percentage moisture slows down greatly to a steady decline. This transient spike makes sense as the readings are closest to a pure water state which is the highest percentage of the moisture mapping. With a sampling rate of one hour, this is not a huge deal as the likelihood of acquiring data at the peaks or when water is added, is low. The downward spike around the 8 hours mark is currently unexplained as I was not next to Kevin when the voltage spike occurred. Overall, the commercial capacitive moisture sensor trend seemed very consistent over the 8-hour period. Future testing should occur for longer time periods but should have a lower sampling rate as soil moisture does not drastically change over a period of one second and this would allow for easier processing

### 7.5 Custom Designed PCB

Figure 25 showcases the Autodesk Eagle schematic for the custom PCB I have ordered to compare waveform generation techniques. Majority of the hardware defined circuit is transferred from the hardware defined circuit found in [4] with R4 correctly tied to ground. This consists of a voltage regulator that changes voltage inputs of up to 16V down to 3.3V, a voltage divider circuit and reference to create the waveform generator, and an RC low pass filter and diode to supply the resulting voltage to an ADC for measurement. The main alteration, inspired from boards I am developing for the UK Solar Car Team, is the addition of a solder jumper that can be used to switch between outputting from the capacitor to a hardware defined circuit or directly to a microcontroller. This allows for a comparison of the two methods side by side while maintaining the same area and PCB capacitor pattern.

The physical design of the board, shown in Figure 26, is the Autodesk Eagle custom PCB translation of the previous schematic. A 6-pin Molex Microfit connector is used to allow for easy yet stable connection to the board with a connections specifically made for comparison of the microcontroller direct interface and the hardware defined circuit as well as a voltage input for the hardware defined circuit that bypasses the voltage regulator. Mounting holes around the boundary between the electronics and PCB capacitor section enables the creation of an enclosure to protect the electronics. The red plane represents the PCB capacitor section used to measure approximate soil moisture and a blue plane hidden beneath is the other parallel plate, tied to ground. I increased the overall length of the PCB because the larger the area or coverage of the soil, the more I assumed that capacitance would change as soil moisture did.

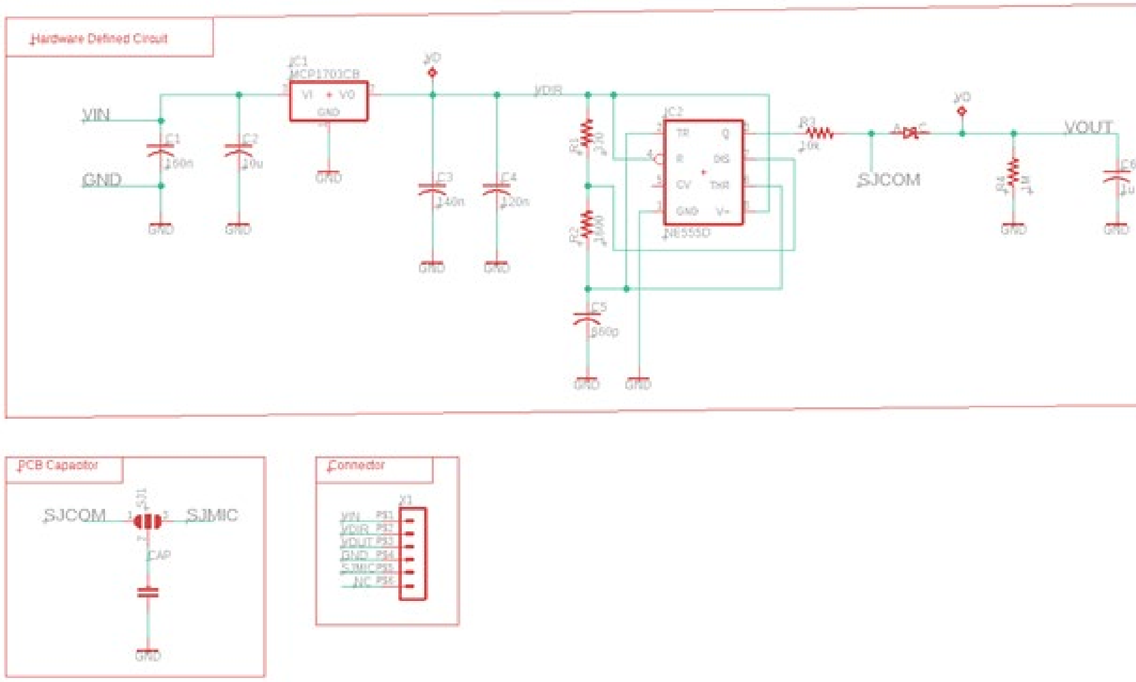



*Figure 25: Custom PCB Schematic*

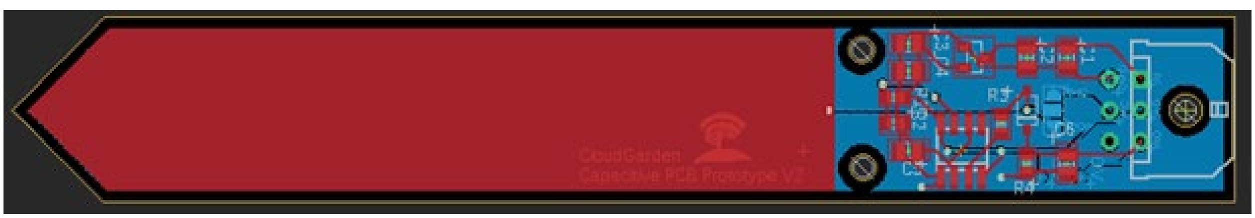



*Figure 26: Custom PCB Board Drawing*

Upon starting the initial population of the PCB, I realized that I did not have the resistors or capacitors specified within the EAGLE schematic for the timing of the waveforms produced by the 555 Timer IC. Delving into the datasheet for the Timer IC, I found multiple equations, shown in Equation 5, for the derivation of the high time, low time, period, frequency, and duty cycle of the generated a stable oscillator waveform [10]. Using these equations, I used the resistances and capacitance I copied from the commercial hardware defined circuit to calculate a frequency of 619,000 Hz or a duty cycle of 54.67%. Using what capacitors and resistors I had around, I found resistors of 270 Ω and 1500 Ω for R1 and R2 and a capacitor of 560 pF which created a frequency of 788,000 Hz with a duty cycle of 54.13% as shown in Table 7. To allow for greater utilization of the ADC range, I also tied the ADC's to an external voltage reference of 3.3V and modified the program to only log every minute to allow for easier analysis, shown in Figure 27.

*Equation 5: RC Equations for the 555 IC Oscillator Circuit*

$$t_H = 0.693(R_A + R_B)C$$

$$t_L = 0.693(R_B)C$$

Other useful relationships are shown below:

$$\text{period} = t_H + t_L = 0.693(R_A + 2R_B)C$$

$$\text{frequency} \approx \frac{1.44}{(R_A+2R_B)C}$$

$$\text{Output driver duty cycle} = \frac{t_L}{t_H + t_L} = \frac{R_B}{R_A + 2R_B}$$

*Table 7: 555 IC Capacitance and Resistance Results*

| | R1 (Ω) | R2 (Ω) | C (F) | Th (s) | Tl (s) | Period | Frequency | Duty Cycle |
|---|---|---|---|---|---|---|---|---|
| Commercial | 330 | 1600 | 6.60E-10 | 8.83E-07 | 7.32E-07 | 1.61E-06 | 6.19E+05 | 54.67% |
| DIY | 270 | 1500 | 5.60E-10 | 6.87E-07 | 5.82E-07 | 1.27E-06 | 7.88E+05 | 54.13% |

MinuteLog_SoilMoist | Arduino 1.8.13

File Edit Sketch Tools Help

MinuteLog_SoilMoist

```
// Integer values that need to be calibrated to set mapping
const int AirValue = 684;
const int WaterValue = 434;

int soilMoistureValue = 0;
int soilmoisturepercent = 0;

unsigned long curSeconds = 0;

void setup() {
  Serial.begin(9600); // open serial port, set the baud rate to 9600 bps
  Serial.println(" Time (m) , Analog Reading , Percent Value ");
  analogReference(EXTERNAL);
}

void loop() {
soilMoistureValue = analogRead(A0);  //put Sensor insert into soil
curSeconds = millis()/60000;
Serial.print(curSeconds);

Serial.print(" , ");
Serial.print(soilMoistureValue);

soilmoisturepercent = map(soilMoistureValue, AirValue, WaterValue, 0, 100);
Serial.print(" , ");
Serial.println(soilmoisturepercent);

  delay(60000);
}
```

*Figure 27: Minute Logging Soil Moisture Code*

*Figure 28: Custom PCB Testing*

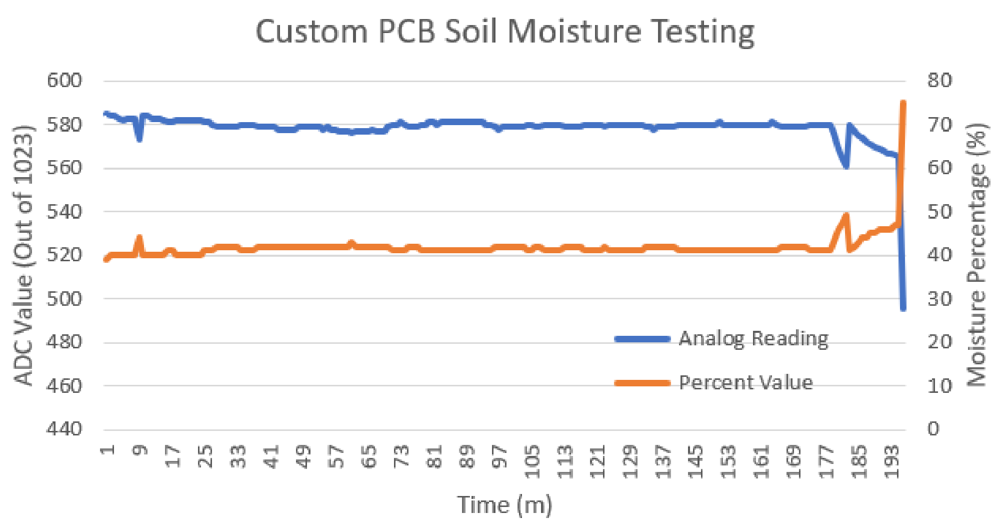



*Figure 29: Custom PCB Soil Moisture Testing Results*

Having newly populated the custom PCB, I intended to test by creating one PBC with a hardware defined circuit and one using the software defined method of waveform generation then comparing the resulting data logs from both over a period of 8 hours to analyze their variability and measurement resolution. What I discovered 3 hours into testing was that the moisture percentage was increasing overtime rather than decreasing and the variation with additional water was incredibly small, as shown in Figure 29. I added a significant amount of water to the middle portion of the plant where the custom PCB was located at around 81 minutes and there was little to no change in the measured moisture value. However, putting my thumb or finger on the top portion of the PCB capacitor sticking out of the soil led to the large jump in percent value to around what I would expect with the amount of water that I added.

My assumption for what caused this variation is that the increased length of the PCB capacitor section was too long for the pot I tested it within and the ground plate on the back side of the board was considerably longer than the plate on the front side of the board. Since the ground plane reached into the electronics portion, there was not an easy way of submerging the PCB capacitor fully into dirt or soil assuming an enclosure would block or cover this section because it contains solder jumpers used to switch between waveform generation methods. The capacitance measurement was largely skewed towards the fringing field or capacitor value from the air calibration and the return to normal or expected readings only occurred after I blocked the air from reaching the top half of the PCB capacitor. Since this test was inherently flawed due to variable capacitance, I have chosen, through the decision matrix in Table 3 and AHP Table 9, to include a similar implementation of solder jumpers into our final prototype to enable usage of a software defined or hardware defined waveform generation method. Rather than making the PCB capacitor as long as possible, moving forward I should keep the use case in mind, whether it is in a potted plant or staked outdoors, or keep the PCB capacitor short to enable usage in both cases as the length greatly alters overall effectiveness.

## 8 Integration

Interfacing of my subsystem into others involves the synthesis of the radio systems, microcontroller and power control, and energy storage systems into the custom PCB used for capacitive soil measurement. Waterproofing is also an essential concept to integrate to protect our system from the elements. For this purpose, a cover will be 3D printed to provide an enclosure for the device's electronics like created in [26] due to its simplicity and effectiveness alongside the silicone chosen through my independent research. My project's effectiveness is dependent on the success of Ben, Josh and Sam's portions concerning the central hub processing and the outdoor soil moisture sensor's microcontroller and energy storage circuits. The interaction of electromagnetic fields from Seth's radio system antenna could alter the fringing field measurement of the PCB capacitor but the systems would not function at the same time and any variance would be adjusted for during device calibration [4].

As the main focal point of central hub development and processing, Ben deals with the logging and processing of measurement data through a database. Using my knowledge of the custom PCB capacitive moisture sensor we develop; I will instruct Ben on how to best interpret the digital signal transferred to the hub from the device. I will also work with Ben to ensure the successful implementation of the calibration UI and saving necessary for the development of soil moisture percentages and levels which is essential for effective usage and data communication to the end user. Outside of soil moisture sensing processing, I will work hand in hand with Ben concerning the design of the 3D printed enclosure for our integrated device and the implementation of waterproofing to seal our electronics from the elements.

The microcontroller and timing algorithm that Josh selects will decide the effectiveness of my circuit in terms of when to power the input to waveform generation and the precision of our measurement is defined by the voltage reference and resolution of the microcontroller's ADC. The control algorithm used for Josh's microcontroller also plays a big factor in the determination of waveform generation schemes, between hardware and software defined systems. Examples of other integrated systems used microcontrollers such as the D1 Mini used in [26] and [27] or the Arduino Pro Mini used in [28] and [13]. Both microcontrollers are Arduino based with Deep Sleep options, low power consumption, and ADCs connected to I/O ports.

The energy storage systems selected by Sam will determine how large of a focus will be on the power consumption of my system. If the energy storage system does not provide sufficient current for my planned system within the defined battery life requirement, my design may pivot towards software defined waveform generation. This would reduce my system's power draw but add to the complexity of Josh's control algorithms hosted on the microcontroller. The addition of solar panel power generation, akin to what I found within [26] and [29], in Sam's subsystem would allow for greatly reduce the limits imposed through a focus on low power consumption.

Budget and time constraints on the design of the soil moisture sensing circuit mostly concern the IC's or components used on the PCB and leaving ample time for functional testing. Since I have already defined majority of the PCB capacitive moisture sensing systems, created a prototype, and intend to test to define the last section of the system, the research and design of my subsystem is mostly complete and ready for integration with the other systems. Some timing constraints to keep track of however is the amount of time it takes to receive PCBs from manufacturers as the most expensive and quickest option still only leads to arrival within 4 business days and the time necessary to test soil moisture sensing from wet soil to dry is significant, having to collect data for multiple days per session [14]. We could also purchase ultra-precise waveform generator or 555 timer IC's for the hardware defined circuit if that is deemed superior, but this is limited by the small budget for the deployed device ($30). Preliminary calculations based on my talks with other team members suggests that we may already be running against the cap on budget for a single device which means saving costs wherever possible will help in meeting our sponsor's specifications.

## 9 Testing Procedure

To validate the integrated soil moisture sensing subsystem's effectiveness in delivering upon the constraints and goals relevant to non-contact soil moisture sensing, I have developed a series of tests for each engineering requirement. To ensure that the device is able to measure and decide between levels of soil moisture without reliability degrading over time as described in ER 1 and 3, 5 trials will be performed consisting of insertion of the device into soil in proximity of a plant while recording measurements and verifying physically every 8 hours over a period of 3 days. The physical verification of soil moisture will serve as the control that the measurements will be compared against to ensure correct determination of soil moisture percentages and levels. Verification that soil moisture readings are taken without direct contact or exposure of electrical contacts to the soil to comply with ER 2, physical inspection and waterproofing trials will ensure that none of the bare copper is potentially exposed to water during measurement. Waterproofing trials, or verification of ER 14 and 15, are described by the IP-54 rating requested by our sponsor. A rating of IP-54, described in the Appendix and in Figure 30, indicates that a device can be splashed with water from all angles and covered in sand without either water or sand being able to move into the device's enclosure. Soil moisture sensing recalibration described in ER 20 will be tested using 2 different water compositions and soil types within potted plants and ensuring that the device can accurately predict their soil moisture level after undergoing software recalibration.

To verify that soil moisture measurements can be consistently measured hourly in accordance with ER 5, a software defined testing mode will be made to increase the sampling rate and report the time value recorded on the microcontroller alongside the soil moisture measurement. Verification will take place at the central hub, comparing the time of message reception with the sent clock value. This ensures that we can effectively control the sampling time of measurements taken on the device without large time delays between measurement acquisition and transmission. Verification of the component sourcing and budgetary constraints for ER 17 and 19 will be completed through preliminary summing of the cost of all parts and inspection of component's origins. In terms of the custom PCB, this means ensuring we hold control of the CAD files necessary for creation of the device and verify that it can be made by current PCB manufacturers. Verification that the device is smaller than the size constraints in accordance with ER 16, the integrated device will be measured with a dial caliper or size will be estimated within the PCB CAD software used for the final PCB. Verification that the device has enough battery life as requested in ER 12 current draw will be measured through one hour of operation using the final integrated product and whether or not the energy storage system can supply that amount of current for 2 years continuously will be computationally estimated.

## 10 Conclusions

Overall, through research into the academic and industrial implementations of capacitive soil moisture sensing, I have found solutions for the main concerns facing my subsystem. Through production and LCR meter testing of PCB capacitor pattern prototypes, I have concluded that the parallel plate PCB capacitor pattern is the best because it has the largest capacitance due to its utilization of the PCB area and minimal distance between copper plates. Investigation into coding algorithms utilizing calibration and testing employed by academic papers reassured me that calibration is necessary for the relative measurement of soil moisture levels and percentages. The intended testing with the prototype PCBs for both hardware and software waveform generator functionality failed due to a flaw in my PCB capacitor plane length so through systematic comparison, I have decided to include a solder jumper to enable the utilization of either form of waveform generation in the final prototype. Systematic comparison of the parameters impacting waterproofing methods and a decision matrix comparing their features led to the conclusion that Silicone is the best waterproofing method for our purpose, providing a waterproof seal around the electronics. Having found and tested solutions for my individual subsystem, planned tests for integration, and with full understanding of the dependence of my project on other’s subsystems, I can firmly say that I am prepared and ready for the gradual integration of the other subsystems onto a custom PCB to create the final intended product.

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# 12 Appendix

## 12.1 AHP Decision Making Process

To make decisions concerning the soil moisture sensing subsystem, I systematically compared the relative importance of categories and grouped aspects to one another using decision matrixesque tables. In each AHP table, the categories are listed as the rows and columns of the matrix with two extra columns added for calculation of the weights. After grouping like terms together and using the following scale from the senior design textbook, I used pairwise comparison between each row's value to that of the column.

- 1 = equal
- 3 = moderate
- 5 = strong
- 7 = very strong
- 9 = extreme

Values above 1 designate the importance of the row criteria over the column criteria and values below 1 show the importance of column criteria over the row criteria. A value at 1 means the row and column are of equal importance. To deal with innate inconsistency, the geometric mean of each row was recommended for calculation to reduce the bias in the skewed data. The ratio of each criteria's geometric mean to the sum of means was used to create the relative importance rankings.

*Table 8: AHP Matrix for Soil Moisture Sensing*

| Soil Moisture Sensing | Waveform Generation | PCB Capacitor Pattern | Waterproofing | Geometric Mean | Weight |
|---|---|---|---|---|---|
| Waveform Generation | 1 | 1/3 | 1/5 | 2/5 | 0.11 |
| PCB Capacitor Pattern | 3 | 1 | 3 | 2 | 0.57 |
| Waterproofing | 5 | 1/3 | 1 | 1 1/5 | 0.32 |

*Table 9: AHP Matrix for Waveform Generation*

| Waveform Generation | Accuracy | Cost | Power Consumption | Reliability | Geometric Mean | Weight |
|---|---|---|---|---|---|---|
| Accuracy | 1 | 3 | 3 | 1/5 | 1 1/6 | 0.22 |
| Cost | 1/3 | 1 | 1/3 | 1/3 | 4/9 | 0.08 |
| Power Consumption | 1/3 | 3 | 1 | 1/5 | 2/3 | 0.13 |
| Reliability | 5 | 3 | 5 | 1 | 3 | 0.56 |

*Table 10: AHP Matrix for PCB Capacitor Sourcing*

| PCB Capacitor Sourcing | Availability | Size | Reliability | Geometric Mean | Weight |
|---|---|---|---|---|---|
| Availability | 1 | 1/3 | 1/3 | 1/2 | 0.13 |
| Size | 3 | 1 | 1/5 | 5/6 | 0.22 |
| Reliability | 3 | 5 | 1 | 2 1/2 | 0.65 |

*Table 11: AHP Matrix for Waterproofing*

| Waterproofing | Lifetime | Cost | Abrasion Resistance | Chemical Resistance | Geometric Mean | Weight |
|---|---|---|---|---|---|---|
| Lifetime | 1 | 5 | 3 | 1 | 2 | 0.41 |
| Cost | 1/5 | 1 | 5 | 1/3 | 3/4 | 0.16 |
| Abrasion Resistance | 1/3 | 1/5 | 1 | 1/3 | 2/5 | 0.08 |
| Chemical Resistance | 1 | 3 | 3 | 1 | 1 3/4 | 0.36 |

## 12.2 Waterproofing Standards: IP-54

The following information has been obtained from [30] and describes IP54 enclosure protective ratings: International (or Ingress) Protection IP ratings systems define an enclosure's protective capacity. The code labels the enclosure's IP followed by two numbers: The first showing the extent to which equipment is protected against particles, and the second digit indicating the extent of protection against water. IP54 means a high level of protection against particles and a fair amount of protection against water and sports the following characteristics:

- Protection from dirt, dust, oil, and other non-corrosive material
- Protection from contact with enclosed equipment
- Protection from splashing water

In Figure 30, retrieved from [30] the IP rating of 54 correlates to 5 for solids or dust protection with limited ingress of dust and equipment interference for 2 to 8 hours. For water, this correlates to protection against water splashes from all directions and limited permitted ingress. Ingress, in this context, means the act of entering the enclosure surrounding vulnerable electronics. So for testing of the device, we should verify it is IP-54 water resistant by splashing the deactivated device with water from all angles and covering it in sand then verify that neither was able to move into the device's enclosure.

*Figure 30: IP Ratings Guide*