Capacitive Soil Moisture Sensor Theory, Calibration, and Testing

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1 Introduction

Soil moisture can be measured using a variety of different techniques: gravimetric, nuclear, electromagnetic, tensiometric, hygrometric, among others [1]. The technique explored here uses a gravimetric technique to calibrate a capacitive-type electromagnetic soil moisture sensor. Capacitive soil moisture sensors exploit the dielectric contrast between water and soil, where dry soils have a relative permittivity between 2-6 and water has a value of roughly 80 [2]. Accurate measurement of soil water content is essential for applications in agronomy and botany - where the under- and over-watering of soil can result in ineffective or wasted resources [3]. With water occupying up to 60% of certain soils by volume, depending on the specific porosity of the soil, calibration must be carried out in every environment to ensure accurate prediction of water content [4]. Fortunately, the accuracy of measurement devices has been increasing while the cost of the sensors has been decreasing. In this experiment, the Arduino platform is used to program a microcontroller to read the analog signal from the capacitive sensor, which in turn outputs a voltage. The inverse of this voltage can be linearly fit to approximate volumetric soil moisture content via gravimetric methods. This is done by measuring the volume and weighing dry and wet soil across a range of moistures. This is the process carried out in this paper.

2 Capacitance as a Proxy for Soil Moisture

Capacitance is defined as the amount of charge a material can store under a given applied electrical potential [5]. Commonly, capacitors are visualized as parallel-plate configurations similar to that shown in Fig. 1. In equation form, capacitance can be written as the ratio between charge and potential:

$$C = \frac{Q}{V} \tag{1}$$

where C represents capacitance, Q is electrical charge, and V is the electrical potential. Using Gauss's law and electrical potential, capacitance can be more broadly defined in differential form as follows:

$$C = \frac{\oint_s \epsilon \mathbf{E} \cdot ds}{\int \mathbf{E} \cdot dl} \tag{2}$$

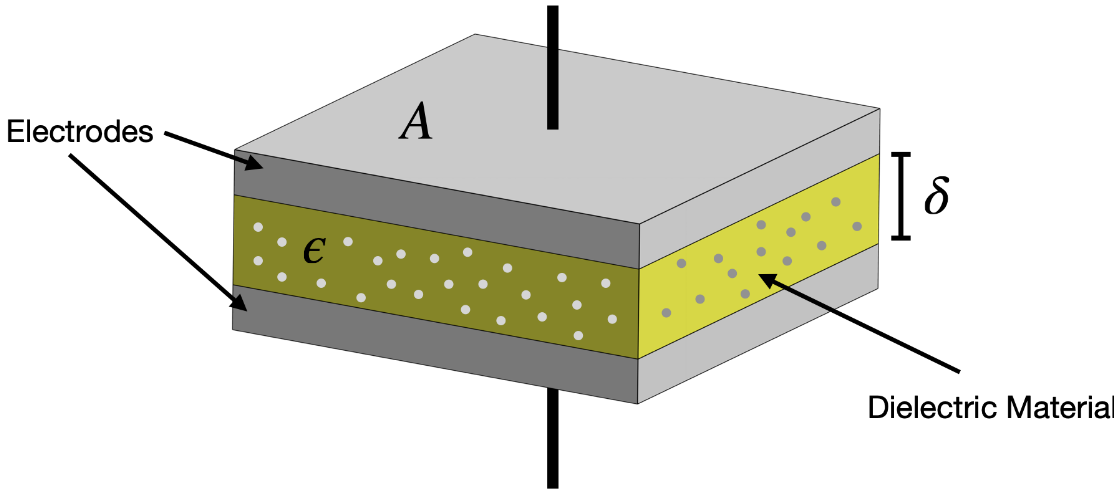

Figure 1: Parallel plate capacitor showing the standard components used to calculate capacitance for a given material and electrical potential.

where ϵ represents the dielectric permittivity of the material between the electrodes, $\mathbf{E}$ is the electric field, and ds and dl are the surface and line integral differentials, respectively.

For the idealized parallel plate capacitor, Eqn. 2 can be simplified by requiring uniform charge across the capacitor plate areas, and the electric field maintains a uniform path between plates:

$$C = \frac{\epsilon E A}{E\delta} = \frac{\epsilon A}{\delta} \tag{3}$$

This is the classic result for a parallel plate capacitor, which states that capacitance, or the storage of energy, is related to the area, dielectric material properties, and distance between plates.

If the capacitor plates are not parallel, the integral is much more complicated [6]. The surface and line integrals require much more nuanced approaches, where an infinite line is assumed for the length of each electrode along with assumptions of symmetry [7]. The complete theoretical dive into solving the integrals is outside the scope of this paper, so the results will be presented and if the reader is interested, they can follow one of the aforementioned references for full and partial derivations.

Figure 2 shows a coplanar capacitor, which treats its exposed area as the dielectric material, thus, allowing the measure of the dielectric constant, which is much higher for water than most soils. This allows the sensor to approximate water content in a soil based on the change in capacitance.

The theoretical approximation of capacitance for the setup in Fig. 2 is given as two different equations throughout the literature [7, 8]:

$$C = \frac{\epsilon L}{\pi} \ln\left(1 + \frac{b}{a}\right) \tag{4}$$

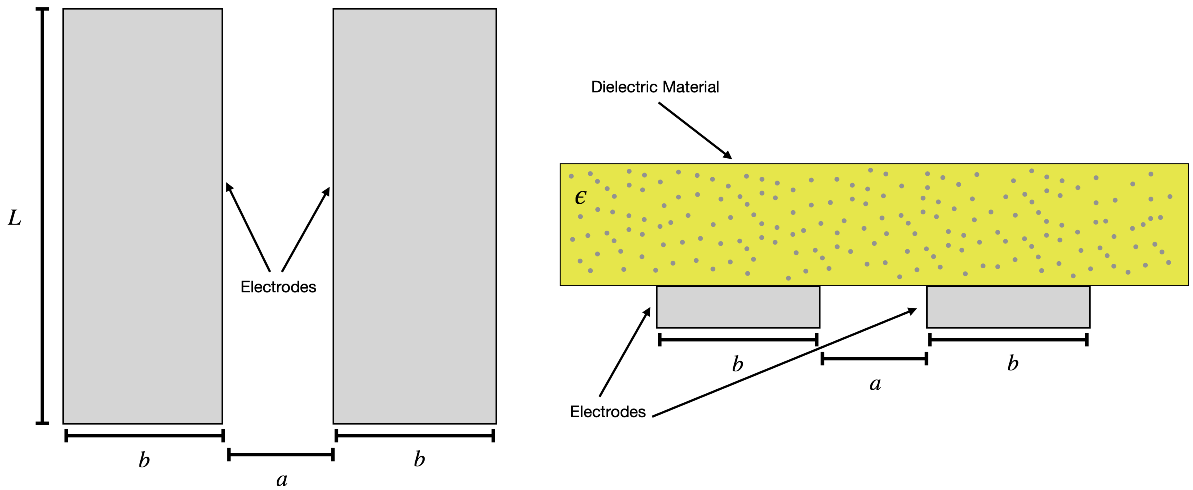

Figure 2: Drawing of coplanar capacitor showing the exposed material as the dielectric (soil + water).

$$C = \frac{7}{40} \cdot \epsilon \cdot L \left(\frac{b}{a}\right)^{\frac{2}{\pi}\arctan\left(\frac{a}{L}\right)} \cdot \left(1 + \frac{L}{b}\right)^{\frac{1}{3}} \cdot \left(\frac{a}{b}\right)^{-\frac{2}{3}} \tag{5}$$

where the geometries play a major role in the calculation of capacitance. It is easy to see that both relationships determine the capacitance linearly by dielectric constant, which is an important result, as accurate measurement of the dielectric constant will be essential for approximating water content in a soil. Consequently, it can be stated that the dielectric constant of a material is directly proportional to the capacitance and a constant that accounts for the unchanging geometry of a sensor [9]:

$$\epsilon = f(C, g) \tag{6}$$

where g represents a geometric scaling factor based on the device being used. This result is particularly important because it will simplify the relationship between the amount of water in a given soil and the measurement recorded by the capacitor.

The capacitance is an important parameter to be measured, however, capacitance is rarely measured directly. Instead, it is common to place the capacitor in either series or parallel with other components in order to read the resonant frequency of the circuit [10]. The resonant frequency for an inductive, capacitive circuit is given as:

$$F = \frac{1}{2\pi\sqrt{LC_t}} \tag{7}$$

where F represents the resonant frequency of the system, which is measurable, L is the inductance of the system, and C_t is the total capacitance of the system. Kelleners et al. [9] use several empirical relationships to carry out an approximation for total capacitance based on the resonant frequency. Thus, the approximation of dieletric constant for a capacitive soil moisture sensor can be loosely written as [11]:

$$\epsilon = f(F) \tag{8}$$

And this result has been observed many times over: the dielectric property of the medium is a function of resonance frequency of the capacitor. This is the first mention of an easily measurable quantity being related to the property of an exposed material (unlike the closed feature of a standard capacitor). This is the working principle for a capacitive soil moisture sensor.

A given soil is comprised of several materials that range in relative dielectric permittivity from 2 - 6 when dry [2]. As a reference, the dielectric constant for air is roughly 1 (i.e. the same as vacuum space). However, the dielectric constant for water is around 80 for standard temperature and pressure. This high permittivity allows electricity to flow more freely, which increases the capacitance, and results in a lower value of resonance. This is why capacitance is a good measure of soil moisture, because of the relative impact of water on electrical permittivity in materials present in soil.

Direct quantification of soil moisture is not a simple procedure. It requires knowledge of soil properties such as density and dielectric constant, and with the introduction of water - it becomes even more complicated. This is why calibration is required for varied sets of soil. The water content for a selected soil can be approximated by separating the soil content into two parts: dry soil and water content. This can be done by looking at a mass of soil over a given volumetric sample:

$$\theta_g = \frac{m_w}{m_d} \tag{9}$$

where θ_g is the gravimetric water content defined as the mass of water per mass of dry soil [12], m_w is the mass of the water present in the soil sample, and m_d is the total mass of the dry soil sample. The gravimetric water content can be rewritten as an apportionment of moist and dry soil as follows:

$$\theta_g = \frac{m_w}{m_d} = \frac{m_s - m_d}{m_d} \tag{10}$$

where the mass of moist soil has now been defined as m_s. Another method for determining water content is the volumetric water content (VWC), which is defined as the volume of liquid water per volume of soil:

$$\theta_v = \frac{V_w}{V_s} \tag{11}$$

This is perhaps the most common definition of water content. It relates the volumetric content of liquid water, V_w, to the total volume of moist soil, V_s. Volumetric water content can be related to gravimetric water content using density and mass:

$$\theta_v = \frac{\frac{m_w}{\rho_w}}{\frac{m_d}{\rho_d}} = \theta_g \frac{\rho_{d,s}}{\rho_w} \tag{12}$$

where ρ_w is the density of water (often ignored, as it is close to 1), $\rho_{d,s}$ is defined as the mass of dry soil divided by the soil sample volume (not necessarily the same as dry soil density). Thus, when making calculations for dielectric constant, the volumetric water content is used to partition the calculation into two types: soil dielectric constant and water dielectric constant.

The dielectric partitioning is computed as follows [13]:

$$\epsilon = (1 - \theta_v)\epsilon_s + \theta_v \epsilon_w \tag{13}$$

There are much more complicated partitioning schemes involving soil, water, and air, however, for simplification reasons, only the linear relationship between soil and water are considered here. This again allows us to arrive at the final proportionality statement, which relates the volumetric soil moisture for soil to the frequency response of a capacitive soil moisture sensor:

$$\theta_v = f(\epsilon) \rightarrow \epsilon = f(F) \tag{14}$$

$$\therefore \tag{15}$$

$$\theta_v = f(F) \tag{16}$$

Now, the specifics of how the volumetric water content (VWC) is related to the frequency response of the capacitive sensor is very complicated and surely outside the scope of this paper, however, it is important to note that this relationship has been noted and studied to great length throughout the literature on capacitive soil moisture sensors [14, 15, 16, 17].

3 Instrumentation

Figure 3 shows a drawing of the sensor used in the calibration and analysis. U.S. patent #US7170302B2 is an example of a similar type capacitive probe as the one used here [18]. The capacitive moisture sensor employed here uses a 555 timer integrated circuit to convert its resonance frequency to an analog signal, which will be read by an Arduino board. This analog signal will be calibrated to create an empirical relationship between the soil moisture and the output analog signal of the sensor.

The Arduino board being used is an Arduino Uno, which has a 10-bit ADC that is capable of operating at 3.3V using its external reference. The capacitive sensor being used operates at 3.3V, but is only valid between roughly 1.5V - 3.3V. This means that we really only have an operable range of about 50%. With the 10-bit ADC, an operable range of 1.5V - 3.3V, and a VWC measurement range of 0% - 100% - this gives a VWC resolution of about 0.5%, which is the lower limit on resolution for the measurement setup. A higher resolution ADC would result in higher resolution in measurement, but 10 bits suffices for the current analysis.

The wiring diagram for the Arduino and sensor is given in Fig. 4. The parts used in this experiment will need to capture the two basic principles used in calibrating soil moisture sensors: measuring the volume and weight of soil, both moist and dry. Thus, along with the capacitive soil moisture sensor, a digital scale will be necessary, as well as a container or sampler to measure the volume of soil. The parts list used in this paper are given below, for reference:

- Capacitive Soil Moisture Sensor
- Arduino Uno Board
- High Resolution Digital Scale
- Calibration Mass(es)
- 250ml Graduated Container

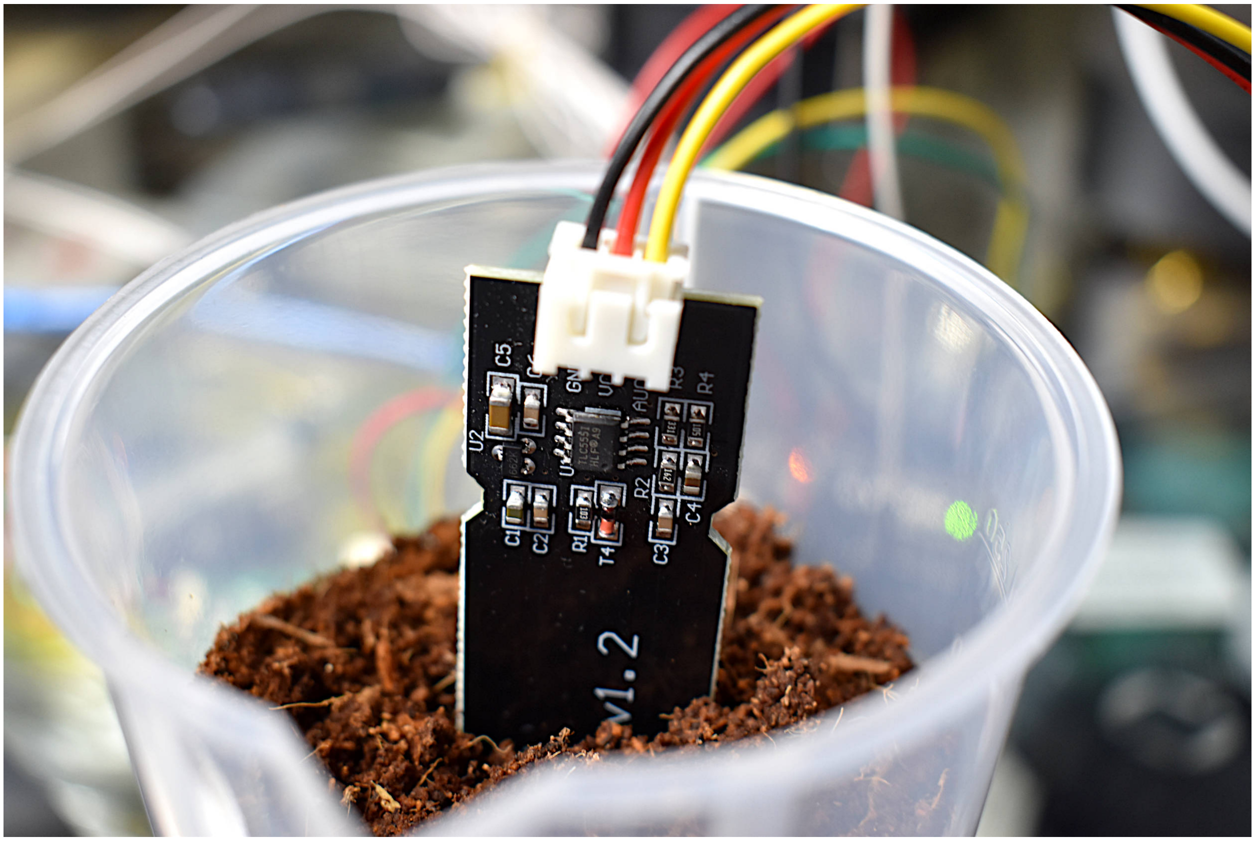

Figure 3: Capacitive soil moisture sensor inserted into the test soil. It operates at 3.3V, uses a 555 timer integrated circuit, and outputs an analog signal proportional to the resonance.

- Soil Sample
- Mini Breadboard

The soil samples referenced above can be any other type of soil. The soil in our case was a dried coconut coir, however, this is not necessary as the soil needs to be moistened to expand to a usable volume anyway. Therefore, it is recommended that a soil type be used that is somewhat dried already, and still loose enough to pack in a sensor. This will make the experimentation process much more straightforward.

The Arduino code for reading the analog signal from the capacitive sensor is given in Code 1. The Arduino code uses the analog pin A0 to read the signal from the capacitive sensor every 100 milliseconds. The Arduino reads the signal in bits, so this is converted to voltage by dividing by the 10-bit resolution of the Arduino Uno, and multiplying by the 3.3V input reference. The capacitive sensor should read a voltage close to 3.15V once Code 1 is uploaded to the Arduino board. This should serve as a verification that the sensor is functioning properly.

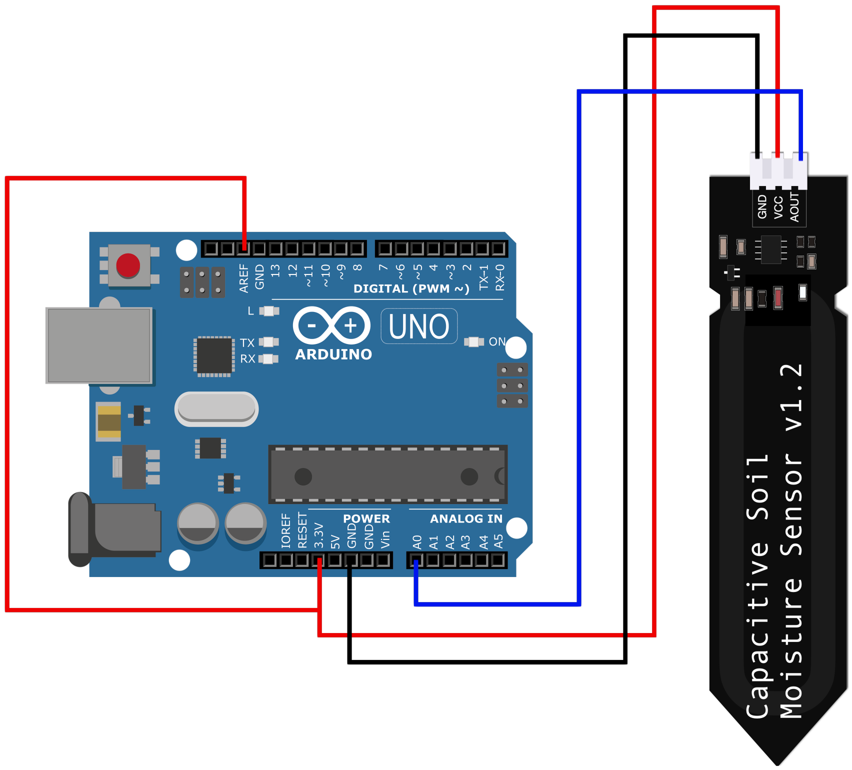

Figure 4: Capacitive soil moisture sensor wiring to Arduino Uno board.

4 Calibrating the Capacitive Soil Moisture Sensor

The volumetric water content, as defined in the first section, is the ratio of volume of water to volume of soil contained within a sample. Therefore, if the instantaneous water content in a soil sample is to be calculated, the volume and mass of each sample must first be measured. Every time water is added to the soil, the mass of the sample will change. Soil moisture is consistently approximated by keeping the volume of each sample the same every time water is added, while also measuring the mass of every sample. The way this is done is by using one of the 250ml containers with graduated markings and making sure the soil level reaches the same level each time water is added to the soil.

Returning to the definition for volumetric water content in Eqn. 12, it is easy to see how each component factors into the experimental process:

$$\theta_v = \left(\frac{m_s - m_d}{m_d}\right)\frac{\rho_{d,s}}{\rho_w} \tag{17}$$

where each of the terms above can be measured or derived using the graduated container and the digital scale. The four components involved in approximating the volumetric water content in the soil are explicitly defined as:

- $m_s \equiv$ measured mass of the wet soil

Code 1: Arduino code to read analog voltage from capacitive soil moisture sensor.

```
//Simple code for Measuring Voltage from
//Capacitive soil moisture sensor
//
int soil_pin = A0; // AOUT pin on sensor

void setup() {
  Serial.begin(9600); // serial port setup
  analogReference(EXTERNAL); // set the analog reference to 3.3V
}

void loop() {
  Serial.print("Soil Moisture Sensor Voltage: ");
  Serial.print((float(analogRead(soil_pin))/1023.0)*3.3); // read sensor
  Serial.println(" V");
  delay(100); // slight delay between readings
}
```

- $m_d \equiv$ measured mass of the dry soil
- $\rho_{d,s} \equiv$ bulk density of soil (mass of dry soil divided by sample volume)
- $\rho_w \equiv$ density of water

In reality, only one of these measurements is measured after each loop: the mass of the wet soil. The soil should be completely dry at the start of the experiment. The best way to determine this is to take a few measurements of the assumed dry soil over a few hours. If the mass keeps changing significantly, then there is still water contained in the soil that will continue to evaporate. Once the mass is consistent over a few measurements, this can be taken as the dry soil mass, m_d. This takes care of one of the four variables in Eqn. 4. The density of water is widely known and can be considered around 997 kg$\cdot$m^{-2}. Lastly, the bulk density of the soil can be approximated by taking a sample volume of the soil of interest, drying the soil, weighing it and using the weight of this soil divided by the original volume [19]. This is the 'bulk density' which often is quite different from the dry soil density, but is the standard nonetheless.

Calculation of the bulk density also gives the dry soil mass, and thus results in calculation of three out of four parameters in the volumetric water content of a soil. As stated above, only one parameter is to be measured during each iteration of the calibration process, and that is the mass of the wet soil, m_s. Below is the general procedure for calibrating the capacitive soil moisture sensor via gravimetric methods:

1. Take a soil sample from the ground
2. Dry the soil sample
3. Measure the mass of the soil sample container
4. Wet the soil with 10ml of water (this is 5% water content, but any higher percentage suffices)

Table 1: Example data output from the capacitive soil moisture sensor calibration procedure. The data presented here is sufficient for deriving the relationship between soil properties and the response of the capacitive sensor, resulting in an approximation of volumetric water content, θ_v.

Container Mass [g]	Soil + Container Mass [g]	Sensor Reading [V]
22.75	62.78	2.96
Sensor Reading in Air [V]	71.51	2.90
3.15	82.41	2.94
Density of Water [k$\cdot$gm^{-3}]	96.94	2.78
997.0	109.22	2.43
Mass of Dried Soil from 200ml [g]	132.37	2.08
26.33	138.9	2.04
Bulk Density of Soil [g$\cdot$ml^{-1}]	159.02	2.01
0.13165	186.76	1.81
Soil Volume [ml]		
200		

5. Mix the wet soil around to ensure the water is evenly distributed, then refill the container to 200ml and ensure the soil is packed similar to the original sample

6. Measure the mass of the wet soil

7. Repeat steps 6., 7., 8. until the soil is saturated and starts to seep water

8. Once the procedure of watering has reached saturation, lay the 200ml of soil out on an array of wax paper to allow it to dry out again

9. When the soil is dry, measure the mass of this dry soil - this is the mass of the dry soil used for the soil bulk density

The above procedure can take up to 7 days, when factoring in the drying procedure. The experimental process can take roughly 10-minutes per measurement (packing, watering, settling), and with about 6-10 measurements per experiment - the actual work can be 1-2 hours. Thus, after the initial few days of drying the soil, plus 2 hours of experiments, along with a few days of drying the soil out - the full-scale experiment takes about 7 days. The way to ensure the fastest experimentation is to lay the soil out very thinly on the wax paper. This will give about 7 days per soil calibration. It is also recommended that a spreadsheet be used to log all of the values as they are being measured, similar to the one shown in Table 1. This will facilitate easy calculation and input to analysis software for visualization and numerical calculations.

A note on capacitive sensor settling time: the capacitive soil moisture sensor can take some time to equalize and give a steady reading, so be sure to wait approximately 1 minute after the sensor settles to a given value. It should settle in 1-5 minutes, depending on the saturation level of the soil and how well the wet soil was mixed. Under the assumption of a successful calibration, the data can be taken and analyzed.

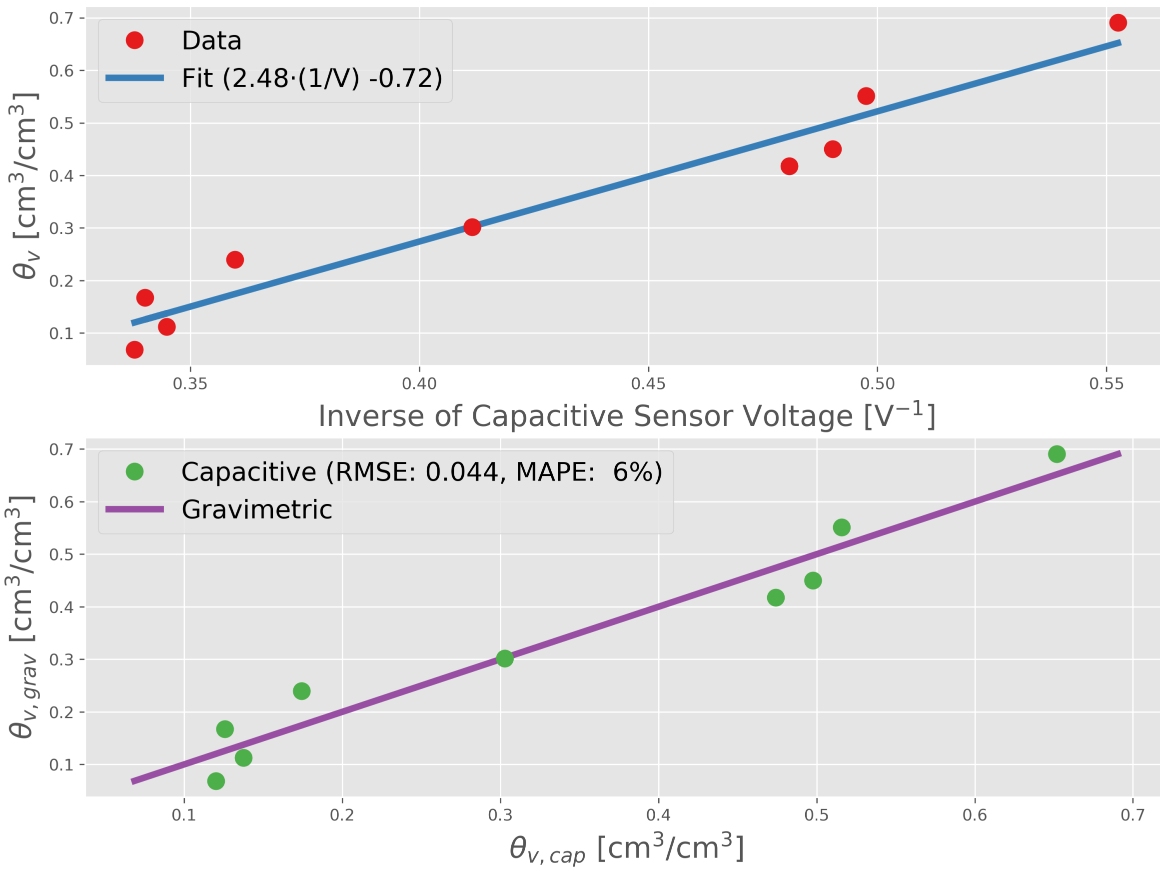

Figure 5: Linear fit between the inverse of the voltage readings and the gravimetric calculation of volumetric water content.

Figure 5 shows the results of the calibration procedure and the linear fit between the inverse of the voltage reading from the capacitive sensor and θ_v derived by gravimetric methods. The inverse of the voltage reading was fitted via least-squares regression, which resulted in the following relationship between the capacitive sensor and θ_v:

$$\theta_v = \frac{2.48}{V} - 0.72 \tag{18}$$

Equation 18 demonstrates a root-mean square error of roughly 0.044, meaning that the volumetric water content for the soil used in this study can be approximated to within roughly 6% of a given reading. This error is in the vicinity of similar devices that have been extensively calibrated as well [20].

5 Conclusion

The theory, calibration, and operation of a capacitive-type soil moisture sensor was introduced here as a way to predict volumetric water content in soils in an efficient and reliable manner. Using an Arduino board and digital scale, the real-time measurement of both the mass of the soil and the readings from the capacitive sensor were recorded. By adding water to dry soil, the mass of the soil changes across the same volumetric sample. This gives users the ability to approximate the water content in soil by measuring the weight against a dry sample of the soil - giving an instantaneous approximation of soil moisture content. The voltage was then linearly correlated to the gravimetric moisture approximations, to give an effective relationship between the reading from the capacitive sensor and the water content in the soil. The method used here produced an error of about 6% for readings, indicating a fairly good approximation of the water content in the soil used in our case (coconut coir). This calibration procedure demonstrated that low-cost capacitive-type soil moisture sensors are capable of predicting the water content in soils to a high degree of accuracy, with little required outside of the device itself, which is in direct contrast to the time it takes to traditionally measure the water content in soils. This low error suggests that the long-term stability of these types of capacitive probes may be beneficial for botanists, agronomists, and water resource managers as a low-cost, efficient, and reliable method for monitoring and predicting water content in soils.

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