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Method for Calibrating an Arduino-based Soil Moisture Sensor Using van Genuchten's Equation

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Instructions on building a do-it-yourself soil moisture sensor using Arduino microcontrollers abound on the Internet. These do-it-yourself soil moisture sensors are favorite projects by both plant and microcontroller enthusiasts because the parts are affordable and the end product is functional. In the absence of proper calibration, these soil moisture sensors cannot generate usable information on the status of plant-available-water in the soil. This research demonstrates the calibration of an Arduino-based soil moisture sensor using the soil moisture characteristic curve of a clay loam soil. Van Genuchten's model was used to generate an equation and various parameters specific to the soil. An acceptable correlation was achieved between the soil volumetric moisture content and raw sensor value, with an R^2 = 0.63. A highly significant result was achieved on the correlation between the actual and predicted soil moisture tension with a Mean Absolute Percentage Error (MAPE) of 7.5% and a *p*-value of less than the alpha value of 0.05. It is recommended that the technique demonstrated in this research be used by other researchers working on a similar setup.

Keywords: SWRC, SMT, lipa clay loam soil, microcontroller, R Software, low cost

INTRODUCTION

Do-it-yourself soil moisture sensors using low-cost microcontrollers are popular among plant hobbyists and microcontroller enthusiasts. Current trends in low-cost, home-made soil moisture sensor developments utilize the Arduino board (Kumar et al. 2016). These devices output raw values that necessitate soil-specific calibration (Kargas and Soulis 2012; González-Teruel et al. 2019). A previous study by Kojima et al. (2016) even suggests that measured soil moisture values exhibited the influence of individual sensor differences. The Arduino board is powered by an Atmel chip microcontroller and has several input and output terminals where the soil moisture probe can be attached.

The calibration of a low-cost soil moisture sensor involves two steps. The 1st step involves the calibration of raw sensor values using the thermo-gravimetric method (oven-drying). The thermo-gravimetric technique is widely used for measuring soil moisture content and has been employed as the standard reference for determining soil moisture (Lekshmi et al. 2014). The result of this step, often expressed in percent, is insufficient to gauge whether moisture is available to the plant or not. The 2nd step is the calibration of soil moisture content, expressed as either gravimetric or by volume, to the soil moisture tension (SMT) value, soil moisture characteristic (SMC) curve, soil moisture retention (SMR) curve, or soil water retention (SWR) curve. The SMR curve is used to predict soil moisture storage, field capacity, and permanent wilting point, which are useful information for irrigation purposes (Lekshmi et al. 2014). The SMT value is the most usable information for water management as it not only tells whether soil moisture is available to the plant or not but also provides a quantitative measure of the level of available soil moisture. In the past, low-cost soil moisture sensors employ the use of a gypsum block with two electrodes inside and a multimeter. The range of resistance readings, in ohms, in the multimeter is calibrated with the moisture content of the soil (Fowler and Lopushinsky 1989).

Soil moisture tension is the energy state at which water is being held by the soil. Plant-available soil moisture ranges from 1/3 – 15 bars SMT, with the former considered as the field capacity and the latter the permanent wilting point. Soil moisture tension values reflect the level of soil moisture in the soil and is consistent across different soil textures and structures. At the same soil moisture tension, the gravimetric moisture content of a fine-textured soil is higher than that of a coarse-textured soil. Furthermore, at low tension levels, soil moisture is affected not only by soil texture alone, but also soil structure.

Van Genuchten's Model is a closed-form equation often used to describe the soil water retention curve (Ghanbarian-Alavijeh et al. 2010) by fitting experimental data with a proposed soil-water retention model (van Genuchten 1980). Comparing van Genuchten's equation with the Brooks-Corey equation in model fitting of SWR data, a high correlation was achieved for the field capacity and permanent wilting point values compared to Gardner's equation (Pan et al. 2019). Estimation using van Genuchten's model is implemented using R Statistical Software (de Sousa et al. 2020) through the soilphysics package. The soilphysics package facilitates curve-fitting using an automatic non-linear least squares estimate function, taking advantage of all the power of R for dealing with extensive algorithms and for building high-quality graphics (de Lima et al. 2016).

Recent literature search on the use of Arduino as a soil moisture sensor listed numerous applications of this technology in automation and the Internet-of-Things. These recent researches lack the calibration of their soil moisture sensor to their specific soils and applications. This research gap may be addressed by demonstrating the process of calibration of an off-the-shelf Arduino-compatible soil moisture sensor. This study is novel for the following reasons: (1) this research takes the calibration process a step further by incorporating van Genuchten's Equation in the process, which gives added value to the results, and (2) this research has never been done in the Philippines, using the set of hardware mentioned in this document. Researchers who use a similar set of hardware but use uncalibrated probes will get less accurate and less precise results. Calibrating an Arduino-based soil moisture sensor to a soil moisture characteristic curve of a soil is necessary to get meaningful results that would indicate the availability of water to the plant through soil moisture tension values. This study aimed to demonstrate a method for calibrating Arduino-based soil moisture sensors. The specific objectives were as follows: (1) to create a computer program that would interface the soil moisture sensor with the Arduino and display information on the computer; and (2) to utilize the open-source statistical software R in the curve fitting process.

MATERIALS AND METHODS

The soil utilized for this study is Lipa Soil Series, with a texture of clay loam. Soil samples were gathered, air-dried, and were passed through a 2-mm sieve. Around 800 g of soil were placed in 21 plastic pots, with holes at the bottom for drainage of excess water. The pots were saturated with water and allowed to naturally dry through evaporation. Moisture readings, using the Arduino-based soil moisture sensor, were made and soil samples were taken for gravimetric moisture determination every day for a month. Four replications of moisture readings and soil moisture determination through thermo-gravimetric means were made.

An Arduino-based soil moisture sensor was built by connecting an off-the-shelf soil moisture probe with three prongs to a gizDuino microcontroller board. Each stainless-steel prong is 12 cm long and 2 cm apart. The gizDuino microcontroller board is an affordable clone of the Arduino Uno board that uses the same Atmel micro-controller chip and therefore functions similarly to the original. The microcontroller board is connected to a computer, with a Windows operating system, via USB connection (Fig. 1). The soil moisture probe that was used was of the resistive type that captures data in analog format and converts it to digital format. Do-it-yourself soil moisture probes compatible with Arduino are the resistive type. As of this writing, capacitive-type soil moisture probes for Arduinos are not available in the market. The probe outputs in 10-bits (digital) values, where the minimum value is 0 and the maximum is 1023. An Arduino Software Integrated Development Environment (IDE) running on the computer was utilized to upload programs to the Arduino microcontroller board. Soil moisture readings were displayed on the computer screen.

Linear regression between the measured volumetric moisture content of the soil and raw Arduino soil moisture sensor readings was performed to generate an equation and establish their degree of relationship (Fig. 2). To convert the measured volumetric moisture content value to SMT, the SMC curve of clay loam soil was used,

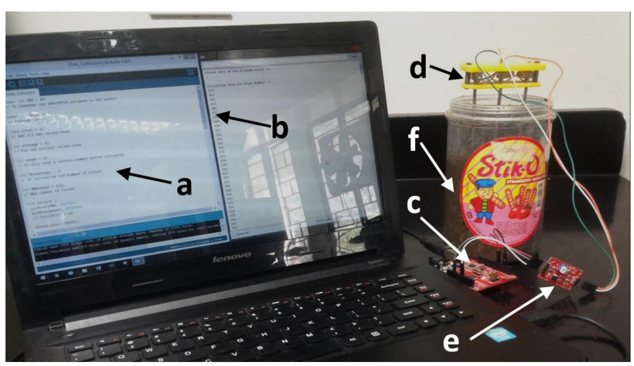

Fig. 1. Arduino-based soil moisture sensor setup. (a) Arduino Software IDE, (b) soil moisture readings, (c) Arduino microcontroller board, (d) three-pronged soil moisture probe, (e) soil moisture probe controller, and (f) soil sample.

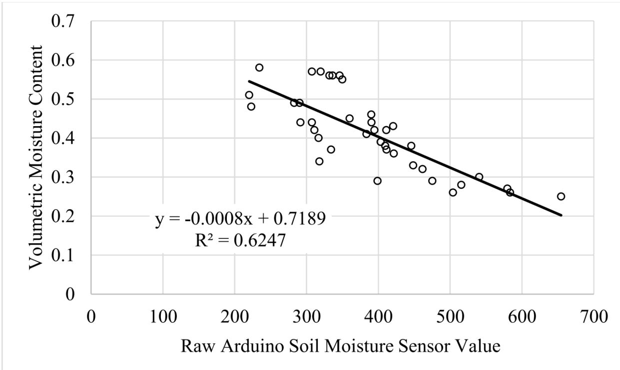

Fig. 2. Regression analysis between Arduino-based soil moisture sensor raw values and volumetric moisture content of clay loam soil.

lifted from instructional materials of the Soil Physics Laboratory, Division of Soil Science, Agricultural Systems Institute, College of Agriculture and Food Science, University of the Philippines Los Baños (2019). To establish a working equation for the soil moisture sensor, the volumetric moisture content was fitted using van Genuchten's Equation to establish its various parameters. Modeling using van Genuchten's Equation was performed in R Statistical Software with the aid of the soilphysics Library. Van Genuchten's Equation (Equation 1) describes the relationship between volumetric moisture content and SMT.

$$(\theta - \theta r) / (\theta s - \theta r) = (1 + (\alpha\ |h|)^{n})^{-m} \qquad \text{(Eq. 1)}$$

where, θ is the volumetric soil moisture content, θ_r is the residual soil moisture content, θ_s is the saturated moisture content, h is the soil moisture tension, cm H_20, α is van Genuchten's scale parameter, n is a dimensionless parameter related to the curve's shape, and m is taken as $(1 – (1/n))$, this is Mualem's (1986) restriction.

RESULTS AND DISCUSSION

A linear trend was observed on the correlation between the Arduino-based raw sensor values and the volumetric moisture content (Fig. 2) with an R^2 of 0.63. The equation of the best-fit line is shown in the graph. High raw sensor value readings were observed for low volumetric moisture content and low raw sensor value readings were observed for high volumetric moisture content.

Model fitting in R Statistical Software using the soilphysics Library resulted in the van Genuchten parameters shown in Equation 2. Fig. 3 shows the graph of volumetric moisture content and soil moisture tension. The predicted curve of the soil moisture tension is based on van Genuchten's Equation. A very narrow range of raw soil moisture sensor values between field capacity (1/3 bar or 340 cm SMT) and permanent wilting point (15 bar or 15 296 cm SMT) was observed. At field capacity, the raw soil moisture sensor value is 520 and at permanent wilting point, 650. Close to saturation (SMT is 0 bar), the raw soil moisture sensor value is 235.

Based on statistical tests, a high correlation between the measured and predicted soil moisture tension values was observed. *T*-test for correlation, with Pearson's Statistic, yielded a probability value of 1.179 x 10^{-10}, a value much less than 0.05 (5% probability). A correlation coefficient value of 0.993 was achieved, above the critical value of 0.549. Based on these statistics, there is no significant difference between the actual and predicted soil moisture tension.

Combining Equation 1 and the equation in Fig. 2 yields the final equation (Equation 2) that takes raw soil moisture sensor value and computes for SMT.

$$h = \frac{\sqrt[n]{\sqrt[m]{\dfrac{\theta s - \theta r}{(-0.0008v + 0.7189) - \theta r}} - 1}}{\alpha} \qquad \text{(Eq. 2)}$$

where v is the raw sensor value, h is the soil moisture tension, θ_s = 0.558163, θ_r = 0.062622, α = 0.014639, n = 1.229330, and m = 0.813451.

Using Equation 2, the relationship between raw soil moisture sensor values and the soil moisture tension is established (Fig. 4) for a clay loam soil. This equation has a Mean Absolute Percentage Error (MAPE) of 7.5%. Such a level of error is acceptable because it is below 10%. As a rule of thumb, the lower the MAPE value, the better the prediction. A MAPE of less than 10% means a highly accurate forecast (Lewis 1982). Research by Duarte et al. (2021) on the use of Arduino to monitor soil moisture, conducted in Brazil, yielded a MAPE of 9%. A MAPE of 7.5 also means that the soil moisture sensor and the model is 92.5% (100% – 75%) accurate, quite acceptable for the known limitations of resistive-type sensors.

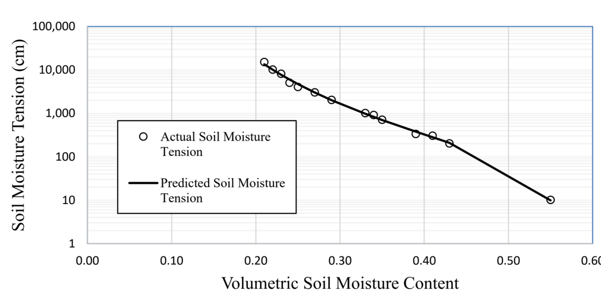

Fig. 3. Relationship between volumetric soil moisture content and soil moisture tension for a clay loam soil.

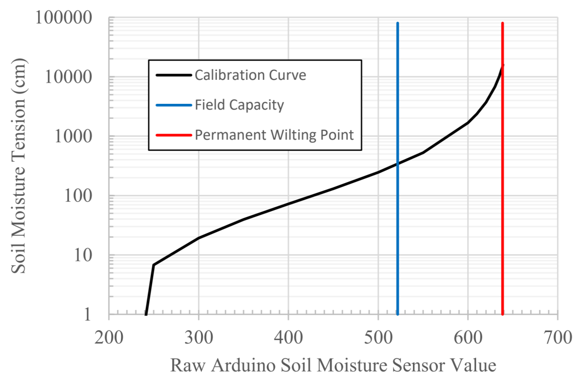

Fig. 4. Relationship between raw Arduino-based soil moisture sensor values and soil moisture tension values of clay loam soil.

Given the Arduino soil moisture sensor setup described in this research, the graph in Fig. 4 can be used to determine the availability of moisture to plants on Lipa Clay Loam soil and other soils with similar texture. The field capacity, designated in Fig. 4 by the blue line, with a soil moisture tension of 1/3 Bar or about 340 cm of water has a raw soil moisture sensor value reading of about 520. This sensor reading corresponds to about 30.3% volumetric moisture content. The permanent wilting point, designated in Fig. 4 by the red line, with a soil moisture tension of 15 Bar or 15 296 cm of water has a raw soil moisture sensor value of about 650. This sensor value corresponds to about 19.9% volumetric moisture content. Thus, plant available water (moisture content between 1/3 Bar and 15 Bar) is between the raw Arduino Soil Moisture Sensor values of 520 and 650.

CONCLUSION

This research demonstrated a procedure for calibrating a home-made Arduino-based soil moisture sensor through calibration with van Genuchten's Equation using the open-source R Statistical Software. To interface the Arduino board with the soil moisture probe, a computer program was made. The Arduino-based soil moisture sensor performed at an acceptable level based on statistical tests, with an Absolute Percentage Error (MAPE) of 7.5%. This study went a step further by incorporating van Genuchten's Equation into the development process, giving added value to the results and the entire process. Van Genuchten's Equation is familiar to most researchers in the field of soil and water and the resulting equation becomes easily modifiable, adaptable, and transportable due to its ubiquity. Although the calibration curve developed only applies to the set of hardware described in this study and to clay loam soil, this product can still be used by farmers to monitor the soil moisture in their fields. A balance between ease of use, affordability, and an acceptable level of accuracy are needed to achieve adoption. Since this study aimed to establish a set of protocols for the assembly and use of do-it-yourself Arduino-based soil moisture sensors, researchers and digital agriculturists who are developing similar products are advised to follow or improve upon the calibration method described in this research as well as expand its use to incorporate other soils of various textures and conditions.

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APPENDIX

Computer code to interface soil moisture probe to an Arduino or Arduino clone:

```
void setup() {
  Serial.begin(9600);
}

void loop() {
  int AnaVal = analogRead(A0);
  int DigVal = digitalRead(3);

  Serial.print("ANA= "); Serial.print(AnaVal);
   Serial.print("  DIGITAL = ");Serial.println(DigVal);
}
```