Testing the Variation in Performance of a Coil-Based Soil Moisture Sensor with Soil-Core and Air-Core Deployments

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Abstract*— Soil moisture monitoring is crucial for irrigated and rainfed crops. Multiple sensor solutions have been proposed in the last decades, and recently, coil-based sensors have been proposed. In this paper, we evaluate the hypothesis that the performance of a coil-based sensor with an alternative setting will not diminish its performance. This new setting supposes an easier deployment in which the core of the coil is not filled by soil but with air. The tests were conducted on a sensor composed of two copper coils with 40 and 80 spires. The sensor has been calibrated with two settings, with the core filled with air or with soil. For the calibration, four different soil moistures were included. Calibration models were obtained for each of the settings. The following metrics are considered for each regression model to evaluate the performance of the two sensors' settings: correlation coefficient, R2, and p-value. The results indicate small differences between both sensors; R2 were 0.95 and 0.93 for soil-core and air-core sensors. Additional tests and metrics have been considered to compare the performance. A T-student test of paired data indicates that there are no significant differences between data gathered with air-core and soil-core sensors. Finally, the coefficients of variation between multiple data gathered in the same conditions were 0.43 and 0.25 % for air-core and soil-core sensors. The obtained results indicate that even though the performance is slightly lower in air-core sensors, the simplicity of the deployment justifies this slight reduction since its impact on the measurements is almost null.

Keywords-Coil-based sensor; Precision Agriculture; Conductivity Sensor; Digital Agriculture.

I. INTRODUCTION

Soil moisture is essential to numerous ecological and agricultural processes, making it a key component in understanding and managing the environment. Recent research has underscored its importance in studies related to climate change, agricultural productivity, and ecosystem health. As a vital indicator of climate change, soil moisture is utilized by researchers to examine patterns and predict future developments [1], [2]. In agricultural environments, precise soil moisture monitoring allows for timely irrigation, minimizing water waste and reducing plant stress [3]. Additionally, soil moisture content greatly affects the formation of condensation water, which can serve as a vital water source in arid regions [4]. The relationship between soil moisture and vegetation also influences surface-air temperature, shaping local climate patterns [5]. Innovative methods, like transfer learning and remote sensing, are being developed to enhance soil moisture forecasting and improve measurement accuracy [6], [7].

Recent breakthroughs in biological humidity sensing have created new and innovative opportunities for moisture detection. Recent studies showcased the detection of relative humidity, presenting different, promising methods [8]. Many recent advances, highlight the increasing interest in utilizing biological systems for humidity measurement, potentially providing benefits in sensitivity, biocompatibility, and environmental sustainability [8], [9].

On another note, progress in humidity sensing technologies has broadened the methods for precise and dependable moisture measurement. Optical sensors, including the ones using optical fibers with adjustable temperature and humidity sensitivities, present promising options for accurate humidity detection [10]. Another study revealed that the use of metal ions-based sensors, have shown selectivity in sensing relative humidity, opening new possibilities for material-based methods [8]. Additionally, incorporating humidity sensors into Internet of Things (IoT) systems and smart building applications has facilitated distributed measurement networks for thorough environmental monitoring.

Another approach to evaluate soil moisture is the use of coils as humidity sensors. Humidity sensing technology has investigated the use of coils as effective measurement devices. Coil-based humidity sensors provide benefits in sensitivity, response time, and durability over traditional methods [9]. These sensors generally rely on changes in the coil's electrical properties, such as impedance or resonant frequency, to detect variations in ambient humidity levels [11]. Some other designs use hygroscopic materials coated on the coil surface to improve sensitivity and selectivity [12].

Soil-filled coils pose distinct challenges in scientific research and engineering. The heterogeneous nature of soil can result in uneven electromagnetic properties within the coil, impacting its performance and dependability [13]. Moreover, changes in soil moisture content can lead to fluctuations in the coil's inductance and quality factor over time [14]. There are not many studies that specifically focus on the problems that coils have when measuring the soil, nevertheless, it is known that the measuring instruments suffer variations when samples are taken within a difference of minutes [15], [16].

The aim of the study is to test whether the performance of the soil sensor proposed in [14] is affected by the reduction in the volume of sensed soil (soil-filled coil or air-filled coil). We have based our study in one of the prototypes previously developed and tested in [14]. To evaluate the variation in the performance, we have compared the results of a calibration conducted with a soil-core and an air-coil sensor. The calibration was conducted, including four soil moisture values. Commercial organic substrates have been used as soil with different water volumes. Multiple metrics and tests are considered to evaluate the loss in performance due to the new setting.

The rest of the study is divided into five sections. Section II details the most relevant reported studies, whereas Sections III and IV describe the proposal and the used materials and methods. The results are presented in Section V, followed by a conclusion and future perspective in Section VI.

II. RELATED WORK

This section summarizes the current use of sensors to measure the moisture of the soil and their benefits and limitations.

Recent studies on moisture sensors have aimed to enhance their accuracy, affordability, and suitability for different soil types and moisture levels. In 2023, Schwamback et al. [17] compared low-cost and commercial soil moisture sensors, examining the balance between price and precision. Their research emphasized the promise of automated, inexpensive sensors for broad agricultural applications. The following year, in 2024, Nandi et al. [18] assessed the performance of both low-cost and high-end soil moisture sensors across various moisture levels and soil textures. Their study offered important insights into the accuracy and reliability of sensors in different environmental conditions, supporting the ongoing effort to create more versatile and affordable moisture-sensing technologies.

In a field study, Marković et al. [3] assessed the performance of low-cost capacitance and resistance-based soil moisture sensors in an irrigated apple orchard. They observed that although the sensors generally followed soil moisture trends, discrepancies emerged between sensor readings and gravimetric measurements, especially at higher moisture levels. The authors stressed the need for proper sensor calibration and positioning to ensure accurate readings. According to what was studied in the previous article, Kim et al. [19] compared soil moisture variations based on different sensor installation positions in Korean orchard soils. The study revealed that sensor placement relative to irrigation emitters and tree roots influenced readings, with sensors nearer to emitters showing greater variability. Their findings underscore the importance of strategic sensor positioning for accurate soil moisture monitoring. Both articles are proof that due to the heterogeneity of the soil, and its properties, moisture measures can fluctuate in the space where the sample is taken.

Another study in 2021, Basterrechea et al. [20] discusses the design and calibration of a soil moisture sensor using inductive coils and electromagnetic fields. The prototypes, which vary in coil characteristics and wire dimensions, were tested in commercial and agricultural soils providing a significant voltage difference between wet and dry soils. While it is useful to differentiate between dry and wet soils, this study does not clarify what would happen if the soil entered the coil's core differently, thus not proving other ways of measuring the electromagnetic field.

III. PROPOSAL

In this section, the details of the soil moisture sensor are included. First of all, the sensor is characterized. Then, the signal conditioning circuit, which has been used to allow the sensor to operate in microcontrollers, is described. Following, the circuit used to power the coil and the test to seek the peak frequency of the proposed system is presented. Finally, the two possible deployments of the system, air-core and soil-core, are explained.

A. Description of the assembly and operation of the conductivity sensor

The conductivity sensor consists of two coils, the primary coil with about 80 turns and the secondary coil with about 40 turns, as shown in Table 1. This consists of a signal generator feeding the primary coil with a sinusoidal signal, generating a variable magnetic field. From this, the secondary coil is induced with this field where, depending on the medium in which the coil is located, it will be one voltage or another due to changes in soil moisture. With this principle, we can calibrate the sensor to detect changes in the medium depending on the amplitude of the signal obtained. The magnetic field obtained is solenoidal since the coils are mounted on a tube with a diameter of 25 mm. Given the direction of the ascending current, a magnetic field is generated in an anticlockwise direction. It must be noted that this coil-based sensor is one of the prototypes previously studied in [14].

TABLE I. TABLE OF CONDUCTIVITY SENSOR MOUNTING CHARACTERISTICS

Features	Secondary coil	Primary coil
No. of coils	40	80
Layers	1	1
Copper diameter	0.4 mm	0.4 mm
Covering	Epoxy	Epoxy
Ratio	2	0.5
Coil diameter	25 mm	25 mm

B. Signal conditioning circuit description

The process for filtering the signal of the values obtained in the sensor consists of the rectification of the AC-DC signal. The first step is transforming the Vin signal, where the V1 signal is received. The second step is rectifying the signal from alternating to direct using a diode bridge. The third step is the filtering of the lobulation signal of the V1 signal so that it is a signal with a more stable amplitude over time. The fourth step is regulating V3 of the signal in direct current to provide further stability to the already filtered signal V2. Finally, the voltage obtained from the Vout regulation stage is captured to process and send to the server, as seen in Figure 1.

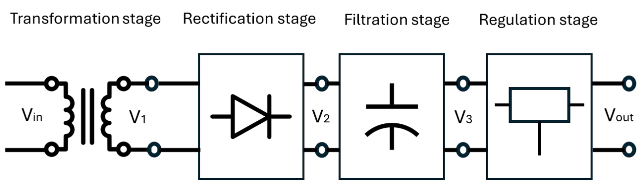

Figure 1. Diagram of signal filtering stages.

Figure 2 illustrates the electrical circuit integrated into the node to support the aforementioned stages. It is important to note that the input signal to the primary coil is supplied by a signal generator, which provides a sinusoidal signal. This allows the primary coil to generate a varying magnetic field, inducing an electric current in the secondary coil.

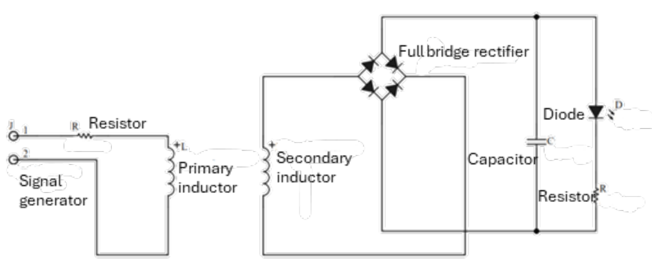

Figure 2. Sensor circuit diagram.

C. Peak frequency and sensor power supply

As mentioned earlier, the primary coil is powered by a function generator, providing a consistently stable sinusoidal signal with an amplitude of 9 volts. The signal frequency is chosen based on the coil's resonance peak. A frequency sweep, as shown in Figure 3, is conducted to determine this peak.

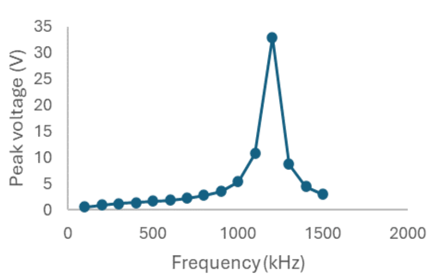

Figure 3. Arrangement of the coil in the ground with or without earth in the core.

The primary coil is supplied with a wide frequency range, with the resonance peak being identified at 1200 kHz, a crucial value in our process of determining the resonance peak frequency.

D. Deployment of the coil in the ground with or without soil in the core

As shown in Figure 4, a detailed arrangement of how the conductivity sensors would be in the proposals can be seen, in our case, by introducing earth into the core of the coil that we can measure or not.

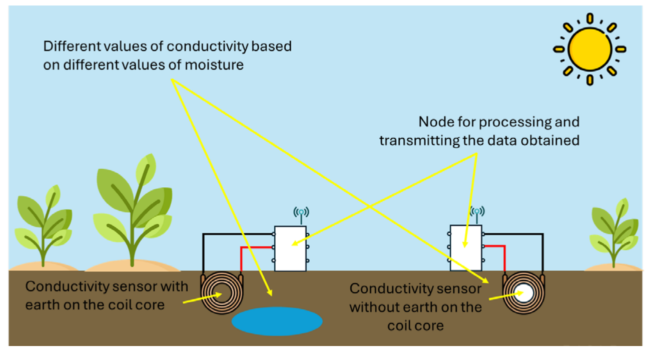

Figure 4. Explanatory drawing of the sensor settings.

Another aspect is that the sensors are placed underground, and through wired transmission devices, we send the data to nodes that process and transmit the collected values. When the coils are inserted into the soil, they detect varying conductivity levels caused by different moisture content (the amount of water per volume of soil in a given area) over time.

IV. MATERIALS AND METHODS

In this section, all the elements and procedures for conducting the tests aimed at evaluating the performance of the sensor are described. First of all, the materials, including the soil, water, and pots, are identified. Then, the different soil moisture concentrations and their generation are characterized. Finally, the employed mathematical methods and metrics to evaluate the performance of the two sensor configurations are explained.

A. Used Materials

The materials used to conduct the tests include pots, soil, water, beakers, laboratory balance, and the soil moisture sensor.

The used tapered pots have a variable diameter, are narrower at the base, and expand towards the top. The pots were made of polypropylene, measuring 13 cm in height, 9 cm in minimum diameter and 13 cm in maximum diameter. Three pots are used in order to have experimental repetitions of the results.

The used soil was commercial soil composed of peat and manure. The soil was a universal organic substrate, widely sold in gardening stores, composed of German peat, enriched with NPK fertilizer and perlite, and suitable for a broad range of plant species mainly used for horticulture and gardening purposes. This soil is characterized by a high water-retention capacity, a pH of 6 and 97 % of organic matter. In each pot, we included 700 g of commercial soil, which constituted 10.5 cm of soil. The amount of soil was measured with a laboratory balance Series 5161 (NAHITA BLUE). This balance has a precision of 0.1 g and a capacity of 5000 g.

Water was added to the pots to generate a variable range of soil moisture values. The used water was deionized water. A crystal beaker was used to weigh the water with the above-described laboratory balance. The beaker from Fisherbrand (Waltham, MA, USA) has a capacity of 250 mL.

B. Generated samples

The generated samples aimed to represent different irrigation regimes or different soil moisture levels in rainfed crops. Four soil moisture levels were considered in the experiments that were conducted.

The moisture levels range from adding 0 to 100 mL of water to the pots. Since organic soil was stored in an open bag for a long time, it is possible to assume that this soil is characterized by 0 mL of added water. Besides this, 50, 75, and 100 mL of water were added to each one of the pots. We can also express the added water as a Gravimetric Water Content (GWC) (% weight or % mass), Volumetric Water Content (VWC), and centimetres of water per meter of soil (cm or mm). All these different options are summarized in Table 2.

TABLE II. TABLE TYPE STYLES

Added water (mL)	**GWC (%)**	**VWC (%)**	**Liters of water per meter of soil (L/m^2)**
0	0.0	0	0
50	7.1	5.2	3.7
75	10.7	7.8	5.6
100	14.3	10.4	7.5

C. Data gathering system

This experiment was based on a prototype in which we constructed two coupled coils to measure changes in soil moisture by detecting variations in conductivity through the induced electromagnetic field. The coils were attached to a tube and connected to a rectifier circuit, which was linked to an Arduino Analog-to-Digital Converter (ADC). From there, we obtained readings of environmental changes. Under natural conditions, if it were necessary to prevent soil from entering the tube, the core would be sealed with two plugs.

D. Data gathering procedure

For data gathering, the sensor was introduced in the pot to ensure that the soil covered the total height of the sensor. The sensor's core was filled with soil in the data gathering of a soil-core sensor. Meanwhile, to obtain data on the air-core sensor, the core of the sensor was left empty. In real conditions, plastic taps are used to seal the core of the soil full of air to ensure that no soil falls into the air core.

After the sensor was exposed to each soil moisture, data was gathered. The sensor gathered data every 45 seconds. In each pot, an average of 5 data sets were gathered and stored in an Excel file for processing. These kinds of data allow us to generate additional results linked to the noise in the signal.

E. Data processing and used metrics

First of all, two regression models were generated with averaged data from each experimental repetition for the air-core and coil-core sensors. For this analysis, the metrics used to compare the results are the correlation coefficient and the adjusted R2. Moreover, the p-value for the regression model is also considered as a metric.

A paired samples t-test was conducted to determine whether there were significant differences between the soil moisture sensor readings in the two settings. This test is commonly used to compare the two series of data with a common origin to determine the magnitude of differences. The metric used in this case is the p-value. The comparison was conducted using the averaged data.

Additional analyses include the comparison of data gathered with the two settings by means of paired data tests. In this case, the employed metric will be the p-value of a T-student test. Finally, and with the aim of evaluating the differences between replicas, the data were compared using the coefficient of variation.

F. Statistical analyses

In order to compare the gathered data with the two alternative uses of the sensor, the following statistical methods are used. First of all, regression models for each calibration process are extracted, and metrics to compare the results include the correlation coefficients, the R2, the p-value and the coefficients of the models a and b values that define the slope and the y-intercept. The generated models corresponded to linear regression models and were obtained with Statgraphics Centurion XVIII [21]. For the generated models, confidence and prediction intervals are identified. Then, to confirm if the behaviour of both ways of using the sensors is comparable, a test of paired data, using the T-student test, is conducted. Finally, the coefficients of variation of gathered data are compared to compare the performance of both calibration tests.

V. RESULTS

In this section, the results obtained were gathered to analyze the performance of soil-core and air-core coils are presented. First of all, a comparison of the calibration for both sensors is analyzed.

A. Comparison of calibration curves

In this subsection, the calibration curves obtained with soil-core and air-core sensors are compared. On the one hand, Figure 5 depicts the calibration of the soil-core sensor, which is the version of the sensor currently used in [14]. The calibration curve follows a linear regression model. In Figure 5, the confidence is shown in dotted green, and the prediction intervals in dotted grey. On the other hand, Figure 6 portrays the calibration when the core of the sensor is not filled with soil. As in the previous case, the presented calibration follows a linear regression model. The metrics for these calibrations, as well as the values of a and b in the mathematical model, are summarized in Table 3. Besides the two calibration models, an additional model has been added, including data for both settings.

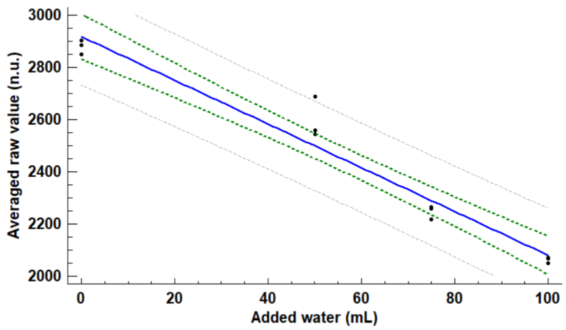

Figure 5. Calibration curve of the sensor with soil-core.

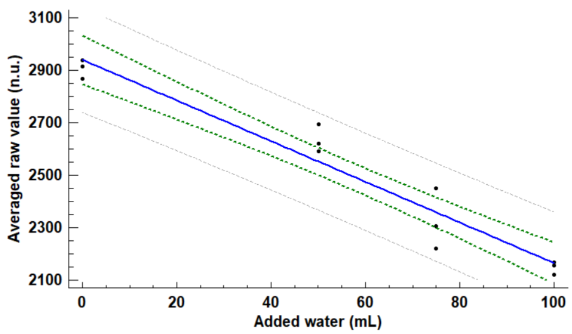

Figure 6. Calibration curve of the sensor with air-core.

TABLE III. DATA OF CALIBRATION REGRESSION MODELS

Data	Correlation coefficient	Adj. R2	*p-value*	*a*	*b*
Soil-core	-0.977	95.03	<0.0001	2918	-8.38
Air-core	-0.969	93.31	<0.0001	2940	-7.76
All data	-0.968	93.51		2929	-8.07

After analyzing the obtained data of the calibration models, it is possible to conclude that even though the metrics are a bit inferior with the air-core sensor, the simplicity of its deployment can justify accepting lower metrics. It must be noted that in this calibration, special efforts have been conducted to ensure that the soil density remains similar in the surrounding soil to that of the core of the sensor by avoiding compacting the soil in the core. Nevertheless, in real deployments, this cannot be ensured due to the difficulties of installing sensors without affecting the surroinding soil. The decrease in the accuracy can be explained by the diminution in the portion of the sensitive volume of the sensor covered by the monitored soil.

B. Comparison of paired data

The result of the T-student test was a p-value equal to 0.002, which indicated that there are no significant differences between both pairs of data. Thus, we can confirm that the use of air to fill the core of the sensors does not alter its performance, and the data obtained can be compared with data gathered with the soil-core.

C. Comparison of differences between gathered data in each pot

The result of comparing the standard deviation between the three experimental replicates of both air-core and soil-core sensors is presented in the following paragraph. We focus on the coefficient of variation for the averaged value of data collected for individual pots considering the pot repetitions for each treatment. This information represents the variability of data due to the experimental replicas. The results can be seen in Figure 7. As in the previous case, the coefficient of variation is very similar, with an average value of 0.8 % in both cases. Nevertheless, in the air-core sensor, it has been possible to achieve values lower than 0.5 % in some of the treatments.

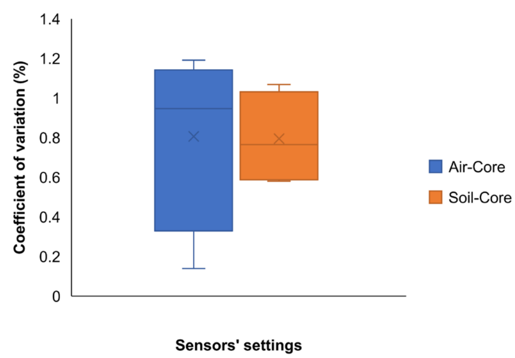

Figure 7. Coefficient of variation of the 3 experimental replicas.

Initially, and considering the gathered data, we can confirm that with the new sensor' settings, it has been possible to achieve similar variability in gathered data. Moreover, some individual results indicate that there is a potential to achieve lower variation in gathered data, but additional experiments are required to confirm this tendency.

CONCLUSIONS

In this paper, we have assessed the performance of an existing soil moisture sensor with an alternative setting. While the original sensor was previously used and completely buried in the soil, in this paper, we propose the fact of not filling the core of the sensor with soil due to the problems encountered in the past. This new form of using sensors has the potential to facilitate their use by users who are not experts or have limited experience.

The results indicated that even though a portion of the sensor's sensing volume has been filled with air, the sensor's performance is similar to that of soil-core sensors. We have evaluated multiple metrics, including the ones linked to the calibration regression models and coefficient of variation. While the R2 of the regression model for the soil-core sensor was 0.95, the one for the air-core sensor was 0.93.

In future work, and with the aim of testing the effect of filling the core of the sensor with soil, the sensors will be buried and unearthed multiple times to evaluate the coefficient of variation of gathered data in these cases. Moreover, the experiments will be conducted with different soils. Finally, the impact of roots in the data gathering will be assessed.

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