DESIGNING AND CALIBRATION OF A LOW-COST MULTI-POINT SOIL MOISTURE MONITORING SYSTEM FOR PRECISION AGRICULTURE
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REALIZAREA ȘI CALIBRAREA UNUI SISTEM, CU COSTURI REDUSE, DE MONITORIZAREA UMIDITĂȚII SOLULUI IN MAI MULTE PUNCTE PENTRU AGRICULTURĂ DE PRECIZIE

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ABSTRACT
Soil moisture monitoring and control are essential aspects for precision agriculture. The paper presents the designing and calibration of a low-cost soil moisture monitoring system. The system includes 28 capacitive sensors, connected to an Arduino based data acquisition system, allowing simultaneous multi-point measurements. The calibration process was conducted on six reference points within the moisture content range of 0–25%. The calibration results indicate a non-linear variation and reveal a significant deviation between the sensors leading to the determination of individual variation curves for each sensor.

REZUMAT
Monitorizarea și controlul umidității solului sunt aspecte esențiale pentru agricultura de precizie. Lucrarea prezintă dezvoltarea și calibrarea unui sistem ieftin de monitorizare a umidității solului. Sistemul include 28 de senzori capacitivi, conectați la un sistem de achiziție de date bazat pe placă Arduino, permițând măsurători simultane în mai multe puncte. Procesul de calibrare a fost realizat pe șase puncte de referință în intervalul de umiditate de 0-25%. Rezultatele calibrării indică o variație neliniară și arată o abatere semnificativă între senzori, ceea ce a condus la determinarea unor curbe de variație individuale pentru fiecare senzor.

INTRODUCTION
In recent decades, concern for sustainable agriculture, social sustainability, environmental protection, and sustainable utilization of natural resources has grown in importance over time. Irrigation is an important aspect of agriculture (*Chartzoulakis et al., 2015*) as it provides a reliable source of water for crops, ensuring their growth and productivity. Irrigation helps to mitigate the effects of drought (*Wang et al., 2021*) and ensure crop yields even during periods of limited rainfall.

Efficient irrigation systems can also help to reduce water (*Umair et al., 2019*) waste and prevent soil erosion, preserving the land and water re-sources for future generations. Energy-efficient irrigation systems can help reduce energy consumption and protect the environment. Also, energy production releases an important amount of air polluting gasses, which, law makers are trying to reduce (*Chereches et al., 2018*).

Soil moisture is one of the most important characteristics of total soil fertility, as it directly affects plant growth and crop yield and quality (*Sharma et al., 2018*). Optimum soil moisture can improve crop yields and reduce irrigation costs, while low water content can lead to crop loss and considerable damage to farmers. Therefore, it is essential to monitor soil moisture levels and make well-informed choices regarding irrigation control and crop management as well for researching new irrigation systems (*Mircea et al., 2019*).

Overall, a soil moisture sensor integrated in monitoring system (*Shamshiri et al., 2022*) provides valuable information about soil conditions and helps to optimize water usage in various applications. There are several methods for determining soil moisture content: gravimetric, nuclear, electromagnetic, tensiometric, hygrometric, remote sensing, satellite technology and aerial image processing (*Gheorghe et al., 2019; Susha et al., 2014*) enable indirect quantitative and qualitative soil moisture evaluation.

Literature shows a high interest in developing, testing and calibration of low-cost soil capacitive (*Aringo et al., 2022*), resistive (*Kandwal et al., 2021*) or newly designed, innovative (*Segundo et al., 2011*) moisture sensors usually combined with Arduino-based data acquisition systems. These low budget sensors can be easily integrated in IoT based (*Placidi et al., 2020; Wu et al., 2023; Marino et al., 2023; Ndjuluwa et al., 2023*), wireless (*Schubert et al., 2017*) networks for automated soil moister monitoring (*Nagahage et al., 2019*) or irrigation control (*Dhatri et al., 2019; Sarmphim et al., 2022*) in agriculture or animal husbandry (*Micle et al., 2021*). Due to low energy consumption (*Dhatri et al., 2019*) this monitoring system are suitable for solar powered solutions (*De Melo et al., 2023*). Measurements with low-cost sensor provide a medium accuracy, in some cases show good correlation with traditional soil testing, usually being compared with high end commercial sensor (*Aringo et al., 2022; Schwamback et al., 2023*). However, to provide more accurate measurements (*Domínguez-Niño et al., 2019*), calibration and laboratory or field testing (*Hrisko, 2020*) at different depth and positions for specific soil types (*Kulmány et al., 2022; Adla et al., 2020*) from different geographic areas is mandatory for low-cost sensors (*Bovolenta et al., 2020*). Also, individual calibration (*Bogena et al., 2017*) is recommended as significant deviation and sensor to sensor variability (*Nolz et al., 2013; Nieberding et al., 2023*) has been reported in the same testing conditions. The gravimetric procedure is the most used calibration method to obtain specific linear (*Souza et al., 2020*) or polynomial regression equations.

In this paper, the design and calibration of a data acquisition system based on capacitive soil moister sensors and an Arduino board will be presented.

The proposed system can make determinations of soil moisture content, over a wide range of moisture levels, even outside the range normally encountered in agriculture, using a single acquisition board and 28 sensors arranged in the same plane.

This type of data acquisition system and sensors positioning aims to provide valuable information regarding the efficiency of different irrigation systems in combination with diverse types of soils. It can be used to determine the propagation of water in the soil following irrigation with any type of irrigation system.

MATERIALS AND METHODS

The experiment design consists of two major steps: the system development (design and realization of data acquisition system) and system calibration.

The soil sample used consists of a total of 5000 g of sand (with determined initial moisture content of 0.31%, bulk density 1556 kg/m3, granulometric fractions clay 3.9%, silt 1.4%, fine sand 87.3%, coarse sand 7.3%, other physical characterizations described in (*Fechete-Tutunaru et al., 2019*).

Water used for the experiment was tap water with electric conductivity varied between 70 and 100 µS/cm, the maximum legal limit being <2500 µS/cm.

The capacitive soil moisture sensors used: SKU: CE09640 (Figure 1) are made of a corrosion-resistant material and have the following characteristics: operating voltage: 3.3 ~ 5.5 VDC, output voltage: 0~3.0 VDC, operating current: 5 mA, weight: 15 g, Interface: PH2.0-3P, size: 98mm x 23mm, operating voltage 3.3 - 5.5 V. It has 3 connecting pins. The electronic circuit was manually protected with two-layer sprayed rubber films.

Fig. 1 - Capacitive soil moisture sensor

The moisture content of soil can be assessed by measuring the capacitance between two electrodes inserted in the soil and observing its impact on the dielectric constant. The probe is stimulated with a frequency to facilitate the measurement of the dielectric constant. However, the probe's readout is affected by the soil's type and temperature, and the relationship between water content and the readout is not linear.

The data acquisition system for soil moisture is composed of an Arduino Mega 2560 board, 2 analogue multiplexers with 16 channels CD74HC4067 (**** Datasheet, 2003*), the 28 capacitive analogue soil moisture 2 electrical strips (one for each polarity), connection cables and the power supply provided via the USB cable connected to a laptop (5V). The system diagram is presented in Figure 2.

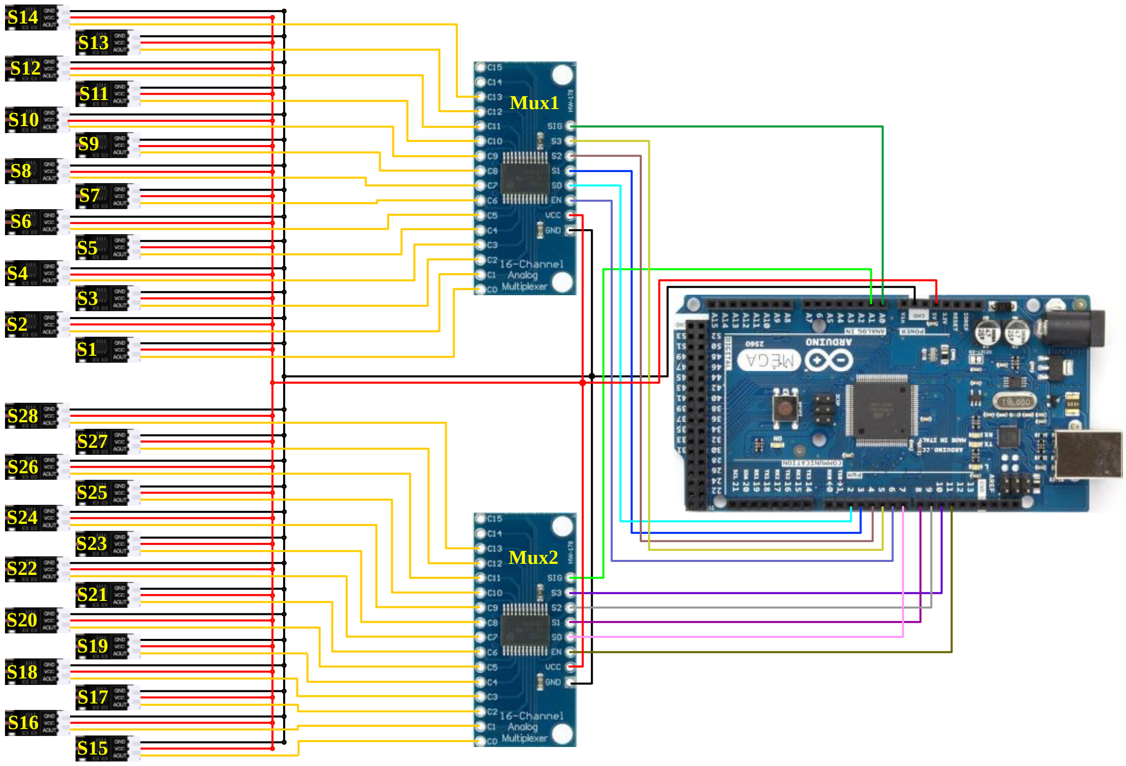


Fig. 2 - The connection diagram of the data acquisition system: S1…S28 – sensors; Mux1, Mux2 - multiplexers

The code for this data acquisition system was written in C++ programming language, which is commonly used for programming microcontrollers like the Arduino, connected to 28 capacitive moisture sensors through two 16 channels multiplexers to increase the number of sensors that can be read by the microcontroller.

The first code lines define the pins that are used to connect to the two multiplexers and the various sensor inputs. The first multiplexer is connected to pins 2-5, and the second multiplexer is connected to pins 7-10. The output enabled pins for the two multiplexers are connected to pins 6 and 11. The moisturePin and moisturePin2 correspond to the analogue inputs connected to the two multiplexers, which read the moisture levels from the sensors.

It is important to multiplex the signals from the soil moisture sensors to reduce the number of input pins needed on the Arduino board. In this code, two 16-channel multiplexers are used to multiplex the signals from the 28 soil moisture sensors.

In the loop function, the code first reads the current time using the getCurrentTime function and prints it to the serial monitor. Then, it loops through each sensor index and reads the moisture value using the selectSensorInput function to select the appropriate input on the multiplexer.

Soil moisture values are stored in a .xls file by using a dedicated software. This allows us to track soil moisture levels over time and have a better understanding of its evolution. Alternatively, a network connection can be used to access data from the real-time soil moisture monitoring system.

After all the sensors have been read, the code loops through each sensor again, with a 1 Hz frequency.

Finally, the code waits for a specified delay using the delay function before starting the loop again.

After the data is collected and stored, specialized software may be used to analyse the data. This allows us to identify patterns in the data and make informed decisions about land management and water resource use.

Overall, this code provides a simple and efficient way to read moisture values from multiple sensors using an Arduino board and to detect moisture distribution.

Analogue capacitive soil moisture sensors produce an electrical voltage between 0 and 5 volts that is proportional to the capacitance of the sensor. This electrical voltage is then measured by an analogue-to-digital converter (ADC) built into the Arduino board, which converts it into a digital value.

All the experimental part took place at room temperature ranging from 20 to 23 ^{0}C.

As a first step a two-reference point calibration step was considered by determining the raw values for dry (in air calibration) and wet conditions (in water calibration, tap water – with conductivity between 70 and 100 µS/cm).

The next step for calibration was to define these values for each sensor, individually, in the written code. Thus, the initial values are transformed into soil moisture percentages and displayed as such.

Aiming for mor precise results, a different, more complex calibration was employed. There are several standards for determining soil moisture, the most common standards for determining soil moisture are ISO 11465:1993 - Soil quality - Determination of dry matter and water content on a mass basis - Gravimetric method. This method involves drying a soil sample at a specific temperature in an oven and measuring the mass of the dry and wet soil to calculate the moisture content; ASTM D2216 - Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mas; ASTM D4643 - Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating, ISO 11461 - for the determination of soil water content on a volume basis. The authors went on using the procedure described in ISO 11465:1993 - Soil quality standard (*** *ISO-11465-1993, 2016*).

The sand was dried in a thermostatically controlled oven at a temperature of 105 ^{0}C. The procedure consisted in drying a container with lid at 105 ^{0}C and then cooling it, in a desiccator for 60 minutes (Figure 3). Determination of the mass of the wet soil m_{wet} with an accuracy of 10 mg. Then, the container and soil are put in an oven at 105 ^{0}C until constant mass is reached. When constant mass was achieved, the container is cooled with the lid closed, in a desiccator for 60 minutes. The cooled container is immediately measured to determine the mass of the dried soil m_{dry}, with an accuracy of 10 mg.

Fig. 3 – Soil samples in the oven and excicator

During the soil drying procedure and after the procedure was completed, according to (*** *ISO-11465-1993, 2016*), the moisture content of the soil was verified using the AXIS AG120 (*** *Datasheet AGS*) high precision moisture analyser (0.01% moisture and 0.001g mass resolution). The result presented in Figure 4, 0.05%, show that the moisture level was even less than 0.1% mentioned in soil quality standard.

The formula used for determination of water content on a dry mass basis (w_{H2O}), expressed as percentages by mass, to an accuracy of 0.1% (m/m):

$$w_{H_2O} = \frac{m_{wet} - m_{dry}}{m_{dry}} * 100 \tag{1}$$

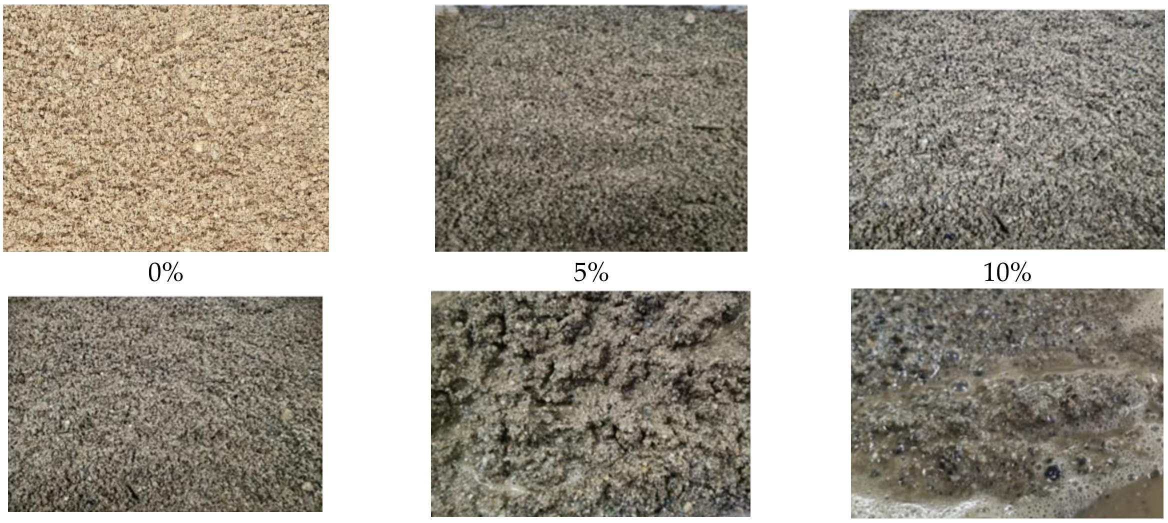
where:

m_{wet}- represents the mass, in grams, of the wet soil,

m_{dry}- represents the mass, in grams, of the dry soil.

Fig. 4 – AXIS AG120 high precision moisture analyser

Calibration procedure steps include preparing 5000 g of dry soil, preparing soil samples (Figure 5) with soil moisture to 5, 10 … 25% reference values and taking calibration measurements.



0% 5% 10%

15% 20% 25%

Fig. 5 – Sand samples - different moisture levels

All sensors were calibrated at the same time in the same container at distinct levels of soil moisture and placed at a dept of 70 mm, as can be seen in Figure 6.

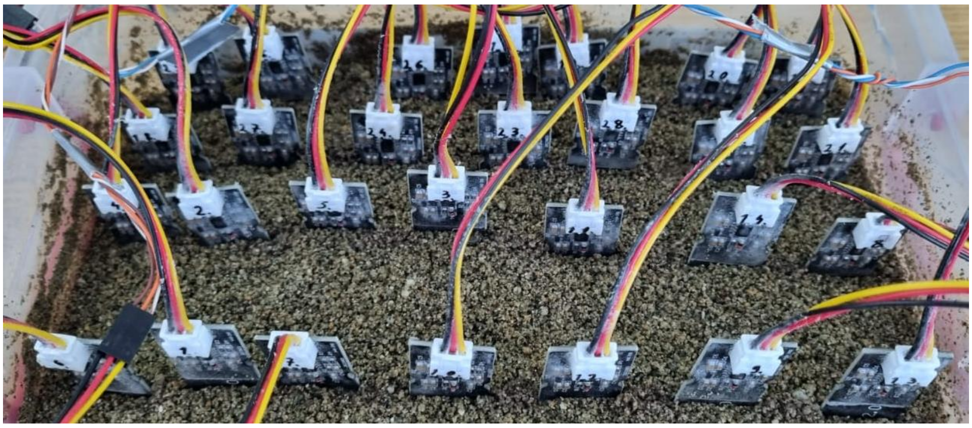


Fig. 6 – Simultaneous sensor calibration step

It is important to specify that the positioning of the sensors and the contact between them and the soil to be analysed required increased attention, because a less good contact between the sensors and the sand produced large variations in the values generated by the sensors.

RESULTS

The values obtained from the 28 capacitive sensors, in all calibration conditions (air, water, and sand at different moisture levels) are plotted in Figure 7. All measurements took place with all 28 sensors inserted in soil (sand) at once and placed at a dept of 70 mm. An average of ten sessions of measurements were produced for each situation (air, water, and sand at different moisture levels), at room temperature (22 ^{0}C). Each session generated at least 15 values for each sensor in every situation (different moisture levels – one measurement per second).

The results of soil moisture sensors calibration measurements, statistically processed, (average, minimum, maximum, standard deviation) are presented in Table 1. The results show a maximum value of 514 Hz for dry and 216 Hz for wet, a minimum of 483 Hz for dry and 190 Hz for wet, an average of 500.35 Hz for dry and 204.71 Hz for wet. The maximum and minimum values are obtained after the stabilization of the measurements. The standard deviation is 9.30 Hz for dry conditions and 6.13 Hz for completely wet conditions.

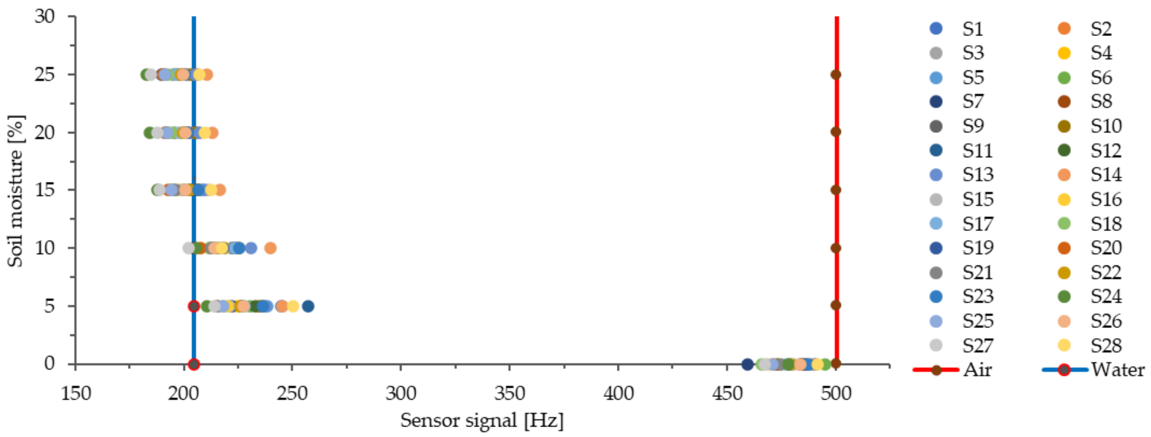


Fig. 7 – Correlation for calibration mean values from 28 sensors – in water, air, and sand (0, 5, … 25% water content)

Table 1

Statistical analysis of calibration results – all sensors average

Analysis	Moisture – signal output [Hz]							
	air	water	0%	5%	10%	15%	20%	25%
Minimum	483	190	459.72	210.90	202.15	187.91	184.43	182.78
Maximum	514	216	495.14	257.17	239.00	216.50	213.08	210.52
Average	500.35	204.71	480.58	230.02	217.65	201.10	198.52	196.45
Standard deviation	9.302	6.133	9.26	11.81	9.48	7.11	6.86	6.68

As can be seen, the initial calibration produces high deviations compared to the precision calibration, thus the values obtained for the initial calibration in air are even higher than in the case of the precision calibration using sand with 0% moisture and in the case of full immersion in water the values obtained are approximately equal to the values obtained in the case of precision calibration at a moisture content of about 15%. This is the reason only on the data obtained by the more accurate method will be relied on.

To assess whether significant differences exist between the mean values of sensors at various soil moisture levels, statistical processing using Analysis of Variance (ANOVA) was employed. The ANOVA test results are presented in Table 2, wherein it is observed that the p-value corresponding to the F-statistic of the one-way ANOVA is less than the standard 0.05 value, indicating that one or more treatments exhibit statistically significant differences.

Table 2

ANOVA test results – only sand samples (0, 5, … 25% soil moisture).

Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	1737505	5	347501	4763.085	8.9E-174	2.26996
Within Groups	11819.05	162	72.95712			
Total	1749324	167				

The p-value corresponding to the F-statistic of one-way ANOVA is lower than 0.01 which strongly suggests that one or more pairs of treatments are significantly different. For the six levels of moister levels the post hoc Tukey test was applied to pinpoint the statistically significant difference of the 15 pairs of soil moisture samples, Table 3.

The results of the Tukey test indicate that significant differences are observed in most cases, except for pairs corresponding to high soil moisture levels (15–25%). In these cases, sensor sensitivity is reduced, and the recorded signal values for this range of soil moisture are less accurate. Nonetheless, situations where soil moisture exceeds 15% in the case of sandy soil are uncommon and less suitable for agricultural purposes.

Table 3

Tukey test results - only sand samples (0… 25% soil moisture).

Treatments pair	Tukey Q statistic	Tukey p-value	Tukey interference (p<0.01)
0% vs 5%	155.0361	0.001005	significant
0% vs 10%	162.6855	0.001005	significant
0% vs 15%	172.4872	0.001005	significant
0% vs 20%	174.2527	0.001005	significant
0% vs 25%	175.2995	0.001005	significant
5% vs 10%	7.6493	0.001005	significant
5% vs 15%	17.451	0.001005	significant
5% vs 20%	19.2166	0.001005	significant
5% vs 25%	20.2634	0.001005	significant
10% vs 15%	9.8017	0.001005	significant
10% vs 20%	11.5673	0.001005	significant
10% vs 25%	12.614	0.001005	significant
15% vs 20%	1.7656	0.787353	insignificant
15% vs 25%	2.8123	0.353876	insignificant
20% vs 25%	1.0467	0.899995	insignificant

In the pursuit of regression equations several types of variation curves were explored, in Figure 8 the exponential – Asymptotic fit is plotted.

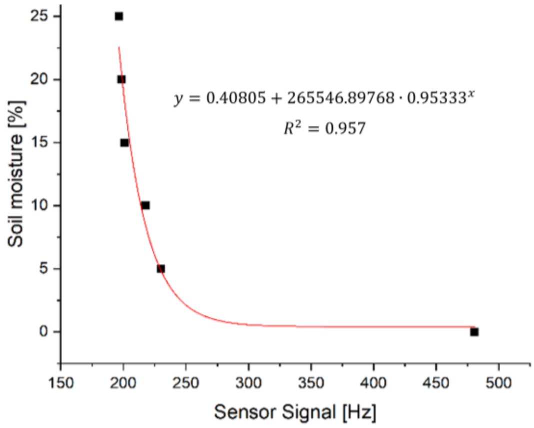


Fig. 8 – General calibration regression curve: Exponential – Asymptotic fit

However, upon the implementation of these equations within certain analysis intervals, substantial deviations were observed as presented in Table 4, where “x” represents signal values and “y” represents the soil moisture. These discrepancies were primarily driven by the elevated variability in sensor-generated data, even though the sensors were procured in a single acquisition. It is worth noting that the batch from which these sensors originate displayed increased variability. Consequently, the analytical domain was partitioned into three distinct intervals: 0–5%, 5–15%, and 15–25%. As a result, the general regression curve obtained across the entire calibration domain was divided into three segments corresponding to the three value intervals, as depicted in Figure 9 along with the corresponding average linear equations.

Table 4

Regression equations analysis

Function	Equations	R^2	Deviation from reference values (predicted values [%] - reference values [%])					
			0 %	5 %	10 %	15 %	20 %	25 %
Linear	$y = 28.08446 - 0.061343 \cdot x$	0.537	1.40	8.97	4.73	0.75	4.09	8.97
Polynomial	$y = 1237.055885 - 13.1996257 \cdot x +$ $+0.04512982 \cdot x^2 - 4.790 \cdot 10^{-5} \cdot x^3$	0.953	0.01	0.70	1.84	3.15	0.48	2.49
Exponential	$y = 0.40805 + 265546.89768 \cdot 0.95333^x$	0.957	0.41	0.13	1.54	3.17	0.50	2.41
Linear: three intervals	$y = 449.91 - 2.1561 \cdot x, x \in [480.3, 230]$	0.978						
	$y = 86.284 - 0.3518 \cdot x, x \in (230, 201.9]$	0.991	0.01	0.01	0.53	0.31	0.83	0.53
	$y = 9.5955 - 0.02 \cdot x, x \in (201.9, 197.3]$	1.000						

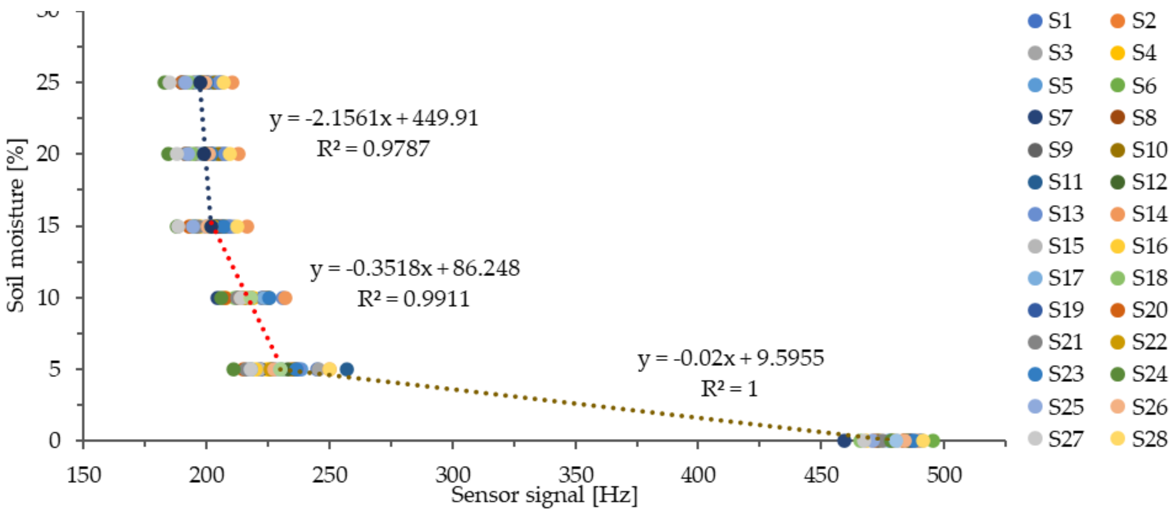


Fig. 9 – General regression curve defined by three linear segments with specific regression equations

However, after subjecting the general linear regression equations to testing for each sensor, a significant deviation from the values obtained during calibration became evident. For these reasons, linear regression equations were determined individually, for each sensor.

The linear regression equations were individually applied to transform the signal values read by each sensor into soil moisture values.

Due to the variation in values generated by different sensors for the same situation (high variability), also proven by the ANOVA test, the p-value corresponding to the F-statistic of one-way ANOVA is lower than 0.01 which strongly suggests that one or more pairs of calibration point references are significantly different.

For the six levels of moisture levels the post hoc Tukey test was applied to pinpoint the statistically significant difference of the 15 pairs of soil moisture samples. The results of the Tukey test show significant differences in most cases, except for calibration point references corresponding to high soil moisture levels (15–25%). In these cases, sensor sensitivity is reduced, and the recorded signal values for this range of soil moisture are less appropriate. Nonetheless, situations where soil moisture exceeds 15% in the case of sandy soil are uncommon and less suitable for agricultural purposes.

The application of a single regression equation results in significant deviations within certain intervals. For these reasons, it was chosen to divide the entire measurement range into three segments (0–5%, 5–15%, and 15–25%) and then calculate individual regression equations for each of the 28 soil moisture sensors, resulting in a total of 74 regression equations. The variation in measured values within the 0–5% range is notably high, leading to significant deviations when applying linear regression across the entire measurement interval (0–25%).

CONCLUSIONS

The paper presents the development and calibration of a multi-point, low cost, soil moisture monitoring system based on 28 capacitive soil moisture sensors connected to a single Arduino board.

Implementing a system like the one presented in the current article requires a heightened degree of attention on calibration. Opting for an expedited calibration will strongly impact the accuracy of measurements, as has been observed. For the best results, it is desirable to conduct an individual calibration process for each sensor, thus minimizing deviations, although it is a time-consuming process.

The available technical equipment and the desire to perform precision calibration directed us towards the mass determination of soil moisture, managing to fit very well within the limits provided by the standards. The use of a quick calibration method, using two extreme environments such as atmospheric air and water, is fast but generates significant deviations, which is why it is not recommended. In line with the water retention capacity of sand, it has been decided that the analysis range should be set between 0% and a maximum of 20% soil moisture, as above 20% the water retention in sand is not possible.

Based on calibration test a polynomial regression curve of the 3rd order or an exponential curve can, in general, produce quite precise values (maximum deviations 3.17%); to have an even higher precision (maximum deviation 0.83%), the 0-25% interval was divided into 3 segments and the linear regression was applied on each of these segments.

This monitoring system should be used to investigate subsurface drip irrigation systems (*Montoya et al., 2022*) and in future articles, the water distribution method for irrigation through several types of soil will be explored and recommendations regarding the suitable irrigation system for different situations will be provided.

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