Cost-Oriented Prototyping of a Soil Moisture Sensor for Precision Agriculture

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Abstract. The fourth industrial revolution is based on the production process's digitisation to promote traceability, reduction of waste and decision support. This transition from the physical to the information domain requires, besides the process's digital representation, sensors and transducers capable of capturing the system states. In the case of agricultural processes, due to the heterogeneity of production conditions, as well as the large area in which it takes place, physical characterisation often requires a large number of sensors spread over several hectares. This fact makes the economic costs associated with the digitisation of agriculture a very relevant aspect. In particular, if robust and precise sensors are to be deployed. Within this reference frame, this paper describes the approach taken to develop low-cost sensors capable of measuring soil moisture at three different depths. Robustness is achieved through the use of materials with high mechanical strength and corrosion resistance and both accuracy and repeatability are accomplished by using a signal conditioning strategy based on a programmable analogue front-end. Details about the methodology used are presented throughout the article.

1 Introduction

The first evidence of agricultural activity date back to around 10,000 BCE during the Neolithic period [1]. From that point on, farming has shaped human evolution and forms the backbone of any society without which everything else collapses. Indeed, at the time this article is being written, the war in Eastern Europe has disrupted agri-food exports from that region. The shortage of those products has contaminated, vertically, many countries and is responsible for serious economic problems.

Due to its importance, agricultural processes have been subject to modernisation in order to increase yield and improve efficiency. Historically, there have

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been periods where changes in agricultural methodologies proved to be decisive. However, the major disruptions in this activity took place just during the last 150 years or so. For example, agriculture mechanisation, introduced in the late XIX century, has allowed the cultivation of large areas while promoting the reduction in manual labour. The mid-20th century introduced new high-yield crop varieties and promoted the use of both fertilisers and pesticides to enhance crop growth and pest control. These innovations were fundamental to sustaining a rapidly growing global population.

At present, and for some years now, fusion between information technologies and farming, has paved the way for the rise of precision agriculture. Precision agriculture is a broad concept supported by many different technologies: drones and sensors allows farmers to collect data on their crops and computers, allied to new, and more powerful, machine learning algorithms, are pushing the envelope and shifting the place where decision-making is carried out. Complex data models can be used to accurately represent process dynamics leading to digital twins where different scenarios can be simulated. With the addition of those technological layers, more suitable decisions are made about when and how to plant, fertilise, irrigate and harvest.

This digitisation paradigm is being driven, not only at the agriculture level but over industry and services in general. However, pushing agriculture processes to the information age is particularly challenging due to several reasons. On one hand, agriculture takes place along a very large area. On the other, production happens in environmental conditions which are very hostile to technology. Regarding the latter, high-temperature amplitudes, humidity, dust, and frequently the lack of both power distribution lines and information communication infrastructures are challenges that must be overcome.

Digital twins, which support digitisation, require the ingestion of different types of data. Some are hand forwarded from the farmer, or third-party stakeholders, to the digital system. Other variables must be acquired locally using cameras and/or an array of distinct sensors. To properly characterise the chemical, physical and even biological conditions of a production area, sensors must be deployed in the field using geographical sampling. The heterogeneity that comes from different production conditions such as soil types, and the need to achieve a given spatial data resolution, forces the use of a large number of sensors. Moreover, due to the above-enumerated environmental conditions, the life span of any sensor is severely reduced when compared to its use in other contexts where they are shielded from adversarial conditions. For those reasons, sensors to be used in agriculture only make sense if they are robust and inexpensive.

In agriculture, there is a broad range of variables which are very pertinent. One such variable is soil moisture which directly impacts the availability of nutrients and many physical properties such as soil structure and porosity. Furthermore, the cycle of nutrients and decomposition deeply relies on water. Hence, being able to accurately represent the soil's water content distribution is essential. Even if this type of information can be provided, indirectly, using hyperspectral imaging, a more widespread method resorts to sensors.

Soil moisture sensors can be based on different technologies. Nevertheless, low-cost commercial solutions frequently are of the capacitive type and contain a signal conditioning circuit that exhibits poor sensitivity, limited operating range and lack of repeatability. This paper presents a different approach to soil moisture capacitive sensors signal conditioning by relaying this role to an analog integrated front-end manufactured by Renesas Technology. Moreover, a different approach to the sensor structure will be presented that enables the measurement of soil moisture at different depths. This aspect of the work will be examined during Sect. 3. Section 2 offers an outline of the technologies presently used for measuring soil moisture. Also, during Sect. 3, the procedure employed for signal conditioning will be described. Finally, in Sect. 4, the principal conclusions are presented, also indicating future research directions.

2 Soil Moisture Measurement Technologies

In agriculture, assessing soil moisture is essential due to its influence on nutrient availability and on the crop's absorption mechanism. In laboratory facilities, the relative soil moisture can be calculated by taking the ratio between the mass of water in a soil sample and its total mass. This approach, which relies on extracting and measuring the amount of water in a soil sample, is defined as a direct measurement method. Although direct methodologies are precise, they take time and human resources to perform [2].

In contrast, indirect measurement techniques involve finding the soil's water content by measuring physical properties that are correlated with the water concentration in the soil. These methods utilise sensors which can be permanently attached to the soil and feature continuous monitoring [3]. In general, such methods require repeated calibrations for matching different types of soil.

Indirect measurement methods count on many different technical methods. For example, the use of the heat pulse is based on the principle that the thermal properties of soil are influenced by its water content [4]. In this framework, a heat pulse is applied to the soil surface, and the resulting changes in temperature are measured to estimate the soil moisture content. Using the soil's heat capacity and thermal conductivity, the soil moisture content is indirectly obtained. It is worth noticing that, despite its simplicity, this approach can be affected by many factors such as soil texture, organic matter content, and soil temperature.

Further indirect measurement techniques rely on the changes in the soil's electrical conductivity [5]. The measurement is typically made using two metal probes inserted into the soil to a specific depth. Then, an electrical current is injected and the resistance between the two electrodes is measured. This resistance is proportional to the soil moisture content in the sense that higher resistance is proportional to soil dryness. Albeit straightforward, the accuracy of such a measurement method is highly dependent on soil salinity, temperature, and many others.

Another method that is also based on the injection of an electrical signal in the soil is the time domain reflectometry [6]. In particular, this technique involves sending an electromagnetic pulse through a soil sample and measuring the time for the pulse to reflect back to the transmitter. This time delay is correlated with the soil's electrical permittivity which, in turn, is dependent on the soil's moisture content. Besides the cost of the equipment, this measurement technique is sensitive to several soil conditions such as soil compaction and salinity. Moreover, the measurement depth is limited to the region near the transceiver.

Radioactivity can also play a role in measuring the soil's water content. The use of neutron probes is an example of such an approach [7,8]. The working principle is based on the detection of the number of neutrons emitted from a radioactive source. This method enables the measurement of soil moisture content over a relatively large depth range and has a high level of accuracy. However, they require a radioactive source, which can pose a health risk and requires expensive specialised equipment.

Another class of soil moisture devices are known as granular matrix sensors (GMS) [9]. The consists of a matrix of small granules of ceramic or polymer materials deployed in the soil. The dielectric characteristics of the granules matrix change according to the water absorbed.

All the measurement methods previously described require the deployment of a sensing device in the soil. On the other side of the spectrum, remote sensing methods are able to collect information about a process without direct physical contact. In practice, this is achieved through images provided by different types of cameras such as hyperspectral which are able to capture data across hundreds of narrow spectral bands. Such methods can be applied to soil moisture measurement by measuring the spectral reflectance of vegetation in the visible and near-infrared wavelength ranges. The use of vegetation indices has several advantages such as the fact that are non-invasive and can be used to estimate soil moisture content over large areas [10,11]. On the other hand, it exhibits low accuracy and is strongly dependent on the relationship between vegetation growth and soil moisture which, in turn, depends on the type of vegetation cover.

At present, many other soil moisture methodologies are the subject of active research such as using nanotechnology, MEMS and microfluidics [12–14].

Despite this broad range of measuring processes and techniques, commercially most soil moisture sensors are capacitive and based on the soil's electrical permittivity change as a function of water concentration. Unlike GMS sensors where the dielectric change is observed over a third-party material, capacitive moisture sensors rely on the soil as the dielectric material. In practice, capacitive soil moisture sensors consist of two or more electrodes, acting as the capacitor armatures, buried in the soil. As the soil moisture content increases, the soil's electrical permittivity also increases, which leads to a corresponding increase in capacitance. To demonstrate this method's popularity, Table 1 present a set of examples for commercially available dielectric-based soil moisture sensors.

The list of manufacturers provided in this table is, in no way, exhaustive. The choice to include or not a given brand name was taken according to the online availability of the metrological characteristics regarding their products. For this reason, very popular capacitive sensors, such as the DFRobot's SEN0308, were not included in the list but, in the alternative, presented in Table 2.

Table 1. Commercial soil moisture sensor that relies on dielectric measurement

Reference	Manufacturer	Characteristics
WaterScout SM100	Spectrum Technologies, Inc	Accuracy = 3% Range = [0, 100]% Communication: proprietary
VH400	Vegetronix	Accuracy = 2% Range = [0, 50]% Communication: voltage
CS655	Campbell	Accuracy = 3% Range = [0, 100]% Communication: SDI12
SM150T	Delta T Devices	Accuracy = 3% Range = [0, 70]% Communication: voltage
SMT100	Truebner	Accuracy = 3% Range = [0, 60]% Communications: RS485/SDI12
Teros 10	Meter Group	Accuracy = 3% Range = [0, 70]% Communication: voltage
HydraPROBE	Stevens	Accuracy = 5% Range = [1, 80]% Communication: SDI12

The prices of most of the devices presented in Table 2 are not disclosed by the manufacturers without asking for an explicit quotation. In general, the price values of such sensors can be up to one order of magnitude higher than the average value of those presented in Table 2. On the other hand, lower-cost sensors exhibit poor repeatability, unknown accuracy, not IP rated and limited mechanical robustness. Moreover, most of them have severe technical problems associated with the signal conditioning circuit. For these reasons, low-cost sensors are unsuited for real-world deployment. But, since better sensors are also

Table 2. List of commercial, lower-cost, soil moisture capacitive sensors.

Reference	Manufacturer	Interface	Price
Grove	Seeedstudio	Analog	5.96€
SoilWatch 10	Pino-Tech	Analog	23.41€
Plantmate	Plantmate	Analog	8.86€
SEN0308	DFRobot	Analog	16.83€
Stemma	Adafruit	I2C	6.88€
TH10/16	Sonoff	N/A	19.90€
Edupon	STEMinds	Analog	3.99€

more expensive, and due to the large amount needed to describe the soil conditions in real applications, instrumentation for precision agriculture is usually only available at one or two points along the production area. For those reasons, the sensor's price is an important factor to be taken into account but, at the same time, accuracy and repeatability must not be overlooked. Hence, this paper explores an alternative way to implement a capacitive-based moisture soil sensor where the signal conditioning is performed through the Renesas ZSSC3230 analog front-end. The following section will provide details regarding the sensor's mechanical construction and signal conditioning.

3 Materials and Methods

Figure 1 presents the regular format seen for capacitive soil moisture sensors. The two plates that comprise the capacitor are engraved over a printed circuit board (PCB). Usually, the sensor has a length of around 20 centimetres and a width of 20 millimetres. This sensor must be buried in the soil at some maximum depth. The two conductors are co-planar and lead to different capacitors. C_A is a capacitor whose armatures have a length equal to the segments that are not buried in the ground and the capacitor C_S is associated with the buried parts of the armatures and its permittivity depends on the soil's moisture contents. Hence, the equivalent capacitance between points A and B can be represented as:

$$\begin{aligned} C_{eq} &= C_A + C_S \\ &= C_{\text{parasitic}} + C_{\text{air}} + C_{\text{soil}} \end{aligned} \tag{1}$$

Each capacitance will rely on the armature's shape and on the dielectric constant of the medium. For example, the dielectric constant of air is 1 and the one of dry soil can range between 2 to 7 [15,16]. On the other hand, water has a dielectric constant of 80.

If the capacitor geometry is constant, the buried conductors lead to a capacitance of [17]:

$$C_{soil} \propto \alpha \cdot \varepsilon_{\text{water}} + (1 - \alpha) \cdot \varepsilon_{\text{dry soil}} \tag{2}$$

where α denotes the percentage of water in a given volume of regular soil. The soil's dielectric constant depends also on the conductivity and the soil's particle size and is a non-linear function of the water volume fraction.

This arrangement, despite being popular, has two main weaknesses. First, the parasitic capacitance is a function of the sensor depth and second, the layout is not suitable to be employed at distinct depths. For those motives, a distinct method was assessed in this work as can be noticed from Fig. 2, The mechanical layout was designed using materials that can be found in regular hardware stores can be seen in Fig. 3.

The frame is made using $\frac{1}{2}$ inch PVC pipe segments and the capacitor armatures are built using two metallic alloy threaded fittings. A total of three pairs of such fittings are installed along the pipe creating three capacitors located at different depths. The lumped model for each one of those capacitors is illustrated in Fig. 4.

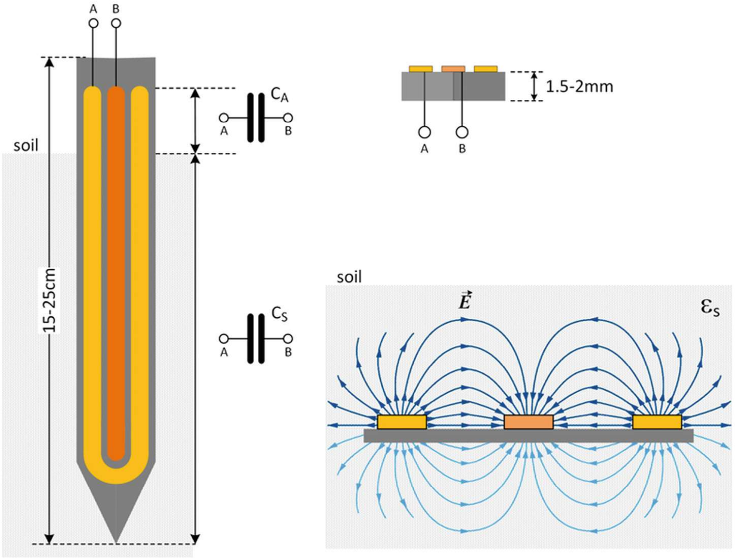

Fig. 1. Format and lumped electrical model for a common dielectric-based soil moisture sensor.

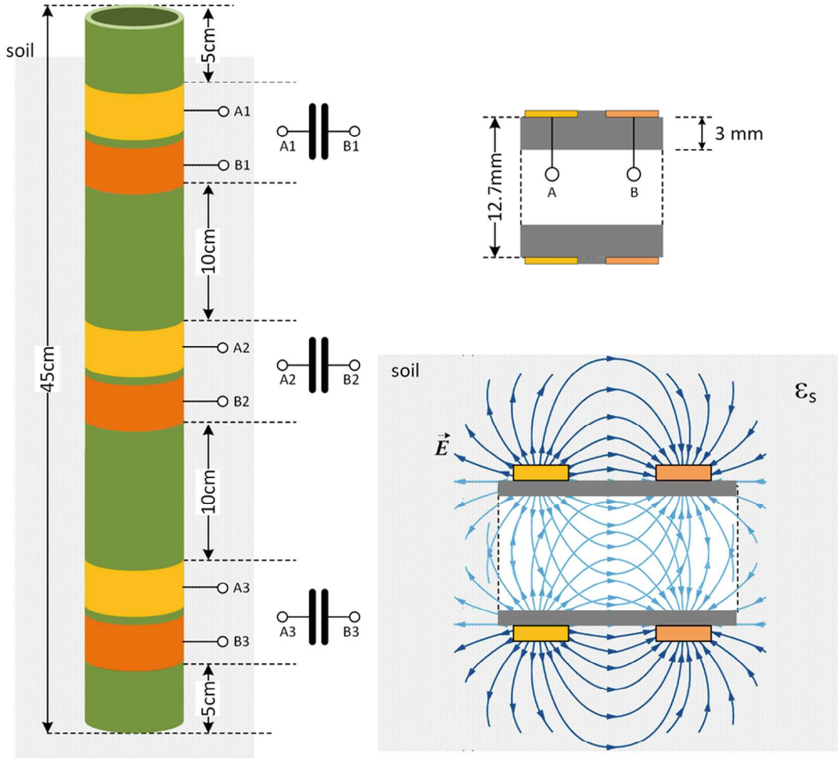

Fig. 2. Electrical equivalence of the newly developed capacitive soil moisture sensor.

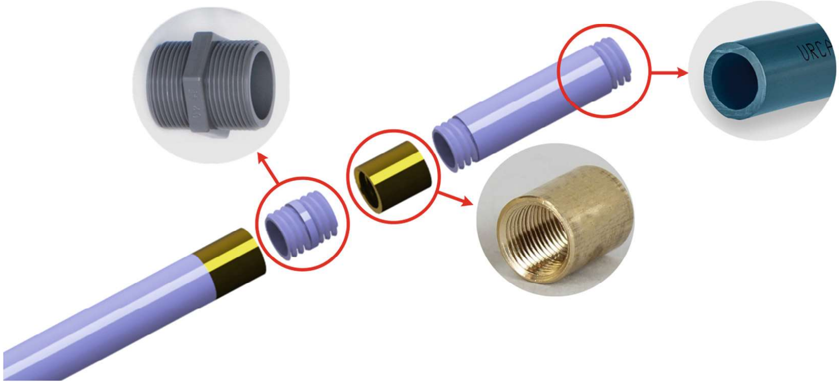

Fig. 3. Detail regarding the materials employed in the prototype construction.

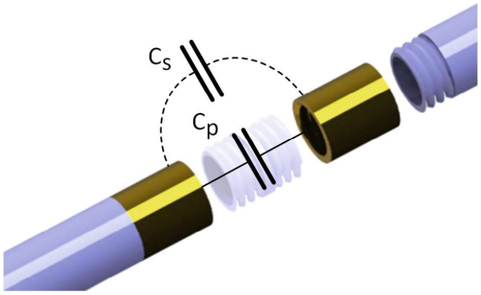

Fig. 4. Lumped parameter model for each of the three capacitors.

The total capacitance can also be split into two capacitances: a parasitic, produced by the cross-section of each fitting and the PVC spacer and the soil-based capacitance between the metal faces and the soil. The value of C_P is approximately equal to 2 pF and C_S is a function of the soil's permittivity. The values of C_S are very low and care must be taken to select the signal conditioning methodology.

Signal conditioning for soil moisture capacitive sensors is done by integrating them into an oscillator which generates a signal whose frequency is proportional to the capacitance of the sensor. The selection of the oscillation frequency is essential since larger values will reduce the effect of the soil conductivity but will lead to increasing the effects of parasitic inductances. High-end sensors use frequencies that go as high as 70 MHz but lower-cost sensors, like many of those listed in Table 2, depend on a <2 MHz oscillator made using the NE555 or TLC555 integrated circuits. In those cases, a square wave is generated by the integrated circuit and applied to a low-pass RC filter where the capacitance is provided by the sensor. The last stage of this signal conditioning circuit is a peak detector used to demodulate the filtered signal. Although simple and cheap, this circuit exhibits poor frequency stability and repeatability. Moreover, the dynamic measuring range is strongly limited.

To circumvent those problems, an alternative signal conditioning strategy was employed by using the ZSSC3230 analog integrated circuit manufactured by Renesas, Inc. This device is fully programmable and provides digital offset compensation.

4 Conclusions and Further Work

Digitisation in agriculture presents many operational problems that are not easily fixed. The large area of land used in the farming processes means that a large number of sensors must be deployed which leads to economic costs. For example, to get correct information about the spatial soil moisture distribution, several sensors must be employed. Currently, there are several commercial systems that allow the measurement of this quantity. However, equipment with good metrological and robustness characteristics are expensive and those that are low-cost do not provide the necessary quality to be used in serious production processes. For this reason, this work is based on the development of a soil moisture measurement sensor that is expected to be a middle ground between the two extremes. The next research steps include testing and calibrating the measurement system and validating it in the field.

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