Minimised wireless water content and conductivity soil sensor system

Cristina Rusu, Anatom Krozer, Christer Johansson, Fredrik Ahrentorp, Torbjörn Pettersson, Christian Jonasson, John Rösevall, Dag Ilver, Mattia Terzaghi, Donato Chiatante, Antonio Montagnoli

A R T I C L E   I N F O

Keywords:
- Miniaturised soil sensor
- Multi-parameter electrical impedance
- Soil water content
- Soil water conductivity
- Easy calibration soil sensor

A B S T R A C T

Obtaining more data for the research/studies of plants growing may be easier realized when suitable non-destructive detection methods are available. We are here presenting the development of a miniaturised, low-power, real-time, multi-parameter and cost-effective sensor for measurements in mini plugs (growth of seedling). The detection technique is based on measurement of electrical impedance at two frequencies for sensing two soil parameters, water content and water conductivity (dependent on e.g. total ions concentration). Electrical models were developed and comply with data at two frequencies. An easy and efficient calibration method for the sensor is established by using known liquids’ properties instead of various soil types. The measurements show a good correlation between the sensor’s readings and the traditional soil testing. This soil sensor can easily send data wirelessly allowing for spot checks of substrate moisture levels throughout a greenhouse/field, and/or enable sensors to be buried inside the soil/substrate for long-term consecutive measurements.

1. Introduction

Measurement of soil parameters (Bandyopadhyay et al., 2012) and evaluation of seedling growth rate (Rahaman et al., 2015; Montagnoli et al., 2016) for pre-cultivation nurseries/cabinets are generally done manually. For example, soil water content can be determined by gravimetric method which is time consuming and destructive (Reynolds, 1970; Shukla et al., 2014). In the case of pH and ions concentration measurements, usually a sample of soil is collected and sent to the laboratory to be evaluated. Therefore, there is a need of small size soil sensors that fit in mini plugs, capable of cost-effective real-time monitoring, and with possibility of easily assembly in a sensor network (see Future trends section in Visconti and De Paz, 2016; Sirregar et al., 2018; Nwabueze et al., 2019).

There are various of methods to monitor the moisture properties in soil (Zermeño-González et al., 2012; Munoz-Carpena, 2004; Aniley et al., 2018). Electromagnetic techniques, especially measuring the electrical impedance in a specific excitation frequency range, at a single frequency or measurements in the time domain, for in-situ measuring soil water content is becoming more exploited due to its relative simplicity and ease of adaptation (Umar and Setiadi, 2015; Gaskin and Miller, 1996, Chen et al., 2019; MacDonald, 1987; Kaatze and Hübner, 2010). The monitoring of water content in these systems is done by determining the effective permittivity of the soil (from the impedance readings) that effects the capacitance between two electrodes inserted in the soil (Robinson et al., 2003; Kupfer et al., 2000; Will and Gerding, 2009). Nutrients in the soil are taken up in an ionic form and by measuring soil electrical conductivity (also from the impedance measurement) information of the amount of ions dissolved in water can be provided (Samouélian et al., 2005).

In the last 10 years, new soil sensors have become available due to rapid technological development in the micro and nanoelectronics industry (Artigas et al., 2001; Zhang et al., 2002; Kuang et al., 2012; Dias et al., 2016). The capacitance-type sensors measure the electrical capacitance between two electrodes that uses soil as a dielectric and the soil water content is determined by measuring the capacitance of the ‘soil’ capacitor since the soil water content changes the effective permittivity of the soil (Topp et al., 1980). Commercial soil water sensors can measure one- or multi-parameter (www.netafim.com; www.decagon.com; www.delta-t.co.uk; www.imko.de; www.phytech.com) but these are usually of big size (sensor itself is bigger than 10 cm × 3.2 cm × 0.7 cm; without electronics and power supply) and
quite expensive (few hundreds of euro). They do not fit in small soil pot less than 3–4 cm diameter and few cm heights that are standard utilized for growing seeds (e.g. forest plant production).

We have developed a miniaturised and simple to use sensor for measurement of two soil parameters, total water content and electrical conductivity, by measuring the electrical impedance between electrodes where the capacitance and conductivity of the soil can be determined (MacDonald, 1987). For our soil sensor, in order to simplify electronics and energy consumption, we do measurements at two frequencies for estimation of the two soil properties simultaneously. By measuring the soil capacitance, the effective dielectric constant of the soil is measured which depends on the water content of the soil, and by measuring the soil resistance, the electrical conductivity which is related to the total ion content, is measured.

This soil sensor contains the electrodes and detection electronics in one small size unit. Preliminary measurement shows that a sufficiently precise calibration of this sensor is obtained by simply using only liquids of known dielectric constant and electrical conductivity. For research and development work, there is a big advantage of having many cost-effective sensors and with easier calibration. Of course, more complex calibration can be performed if higher accuracy is needed.

2. Detection method design and principle

The electric properties in the soil can be electrically considered as a resistance (R) and capacitance (C) network connected in parallel with each other (Meehan and Hertz, 2013; Rinaldi and Francisa, 1999). In this case the amplitude of the impedance (Z) can be expressed by:

\[
|Z| = \frac{R}{\sqrt{1 + (\omega RC)^2}}
\]

(1)

where, \(\omega = 2\pi f\), \(f\) is the frequency, the capacitance \(C = \varepsilon C_0\), with \(C_0\) being the capacitance of the electrodes in vacuum (in practice – in air), the relative dielectric constant (permittivity) of the soil, \(\varepsilon_r\), an effective soil dielectric constant dependent on the water content that will affect the capacitance. The inverse of the resistance, \(R\), i.e. \(\frac{1}{Z} = G\) where \(G\) is the electrical conductance will be used further in the report (calibration chapter 3.3). By measuring the amplitude of the impedance at a few frequencies (at least at two frequencies) in a frequency range that influences both the resistive and capacitive soil properties, it is possible to determine the soil resistance, \(R\), and capacitance, \(C\). \(R\) and \(C\) can be determined by implementing the RC network (equation (1)) in an electronic circuit that works at (at least) two frequencies and where the amplitude of the impedance is measured (will be further discussed in chapter 3).

Considering the total electrical properties (e.g. the electrical impedance) between electrodes inserted in the soil, the electrode interfacial electrical properties due to a charge double layer at the electrodes must also be taken into account in order to fully describe the electrical properties in the whole excitation frequency range. Thus, when two electrodes are entered in the soil the total impedance between the electrodes can be described by a resistance (R) and capacitance (C), a RC-network for the soil itself and an electrode interfacial impedance in series with the RC soil network, both for low and high excitation frequency range of the electric field between the electrodes. The interfacial electrode impedance can be modelled by a constant phase element (CPE) (Rinaldi and Francisa, 1999; Sun and Liu, 2019; MacDonald, 1987). CPE is an element that can be used to describe the interface effect between electrodes and an ionic liquid (the CPE component is a “mixture” of a capacitance and a resistance) where the impedance of the CPE element is described by:

\[
Z_{\text{CPE}} = \frac{1}{Q(i\omega)^n}
\]

(2)

where \(Q\) is the admittance of the element, \(i = \sqrt{-1}\) and \(n\) is a number that describes the electrical character of the element. We have tested to describe the total impedance between electrodes, both at low and high frequencies with a parallel RC network (that describes the soil impedance) and a CPE element in series that takes into account the electrodes interfacial properties. The obtained result when comparing with experimental data is very good in the whole frequency range for different wetness in soil. We have measured the soil electrical impedance at different water contents in a large frequency range in order to electrically describe the soil in detail and fitted the data to the RC network model including the CPE element, see Fig. 1, Fig. 2.

![Fig. 1. Amplitude of soil impedance versus frequency for volumetric water content of 41% (red) and 66% (black), measured by the commercial impedance measurement system. The solid lines (blue) is the fit of the data using a RC network for the soil impedance and a CPE element in series as described in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image)

At low frequencies the impedance between the electrodes in the soil is sensitive to the electrode interface to the soil (the charge double-layer) and can be seen in Fig. 1 as an increase in impedance below about 10 kHz, that can be described by including the CPE element. For frequencies above about 10 kHz, the electrode/soil interface effects are small but can be seen as a small slope of Z vs frequency (see Fig. 1). In order to fully incorporate any electrode effects, we have also included the simplified Randles circuit model approach (Harris et al., 2015) by adding a resistance in series, \(R_s\), with the CPE element and the RC network. The result of fitting the impedance data to this total circuit gave very low values of \(R_s\). This seems reasonable from observing the small values of the extrapolated impedance at high frequencies (in the range of 100 MHz) in Fig. 1 since at high enough frequencies the impedance levels out to the \(R_s\) value when using the simplified Randles circuit model. However, all these electrode effects are ignored (i.e. we neglect the CPE and \(R_s\) elements) in the final soil sensor system analysis and, as we will see later, this is a good assumption. In the final sensor system, we have decided only to use the amplitude of the impedance at two frequencies (in the range between 100 kHz and 10 MHz, one frequency before and one after the cut-off frequency of the RC network). These two points are the minimum number of measurements that must be carried out in order to determine the capacitance and resistance of the soil, and in this way the complexity, power consumption and dimensions of the electronic unit will be reduced. This means that we cannot use the total RC/CPE network since this somewhat more complicated model demands more measured data points in the frequency span as there are more unknown parameters in this model. This is the reason why we adopt the simpler RC model that only contains two unknown parameters (R and C). From a measurement statistics point of view, it is advantageous to measure the complex impedance (real and imaginary parts of the impedance) or the amplitude of the impedance at several frequencies in order to decrease the uncertainty in the measurement data. From the fitting result using the equation for the absolute value of the impedance (equation (1)) and the data shown in
Fig. 1 (for wetness 65.6%), the determined resistance and capacitance values are 364 Ω and 37.9 pF using N = 157 datapoints in the fitting process and 368 Ω and 38.2 pF using only N = 8 data points. The result of the fitting is shown in Fig. 3. The obtained resistance and capacitance values of using the minimum number of data points (N = 2 at 100 kHz and 10 MHz) are 367 Ω and 38.6 pF. The obtained R and C values from the RC model are in good agreement with the obtained fitted resistance and capacitance values using also the CPE element (R = 341 Ω and C = 37 pF). Thus, there is a small variation in the resistance and capacitance values after fitting the data to the simplified RC network, when changing the number of measurement frequency points (N), even when using the minimum number of data points (N = 2) and also consider the RC network in series with the CPE element. The standard deviation (uncertainty) increases when decreasing the number of data points.

Fig. 2. Measured impedance amplitudes (black data points) and fitted (orange continuous lines) to the RC-model in equation (1) using two different number of data points, N, for a wetness of 66% as shown in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. (a) Results from FE-analysis (COMSOL); simulated impedance as a function of frequency for different values of soil conductivity, \( \sigma_{\text{soil}} \), and fix relative permittivity \( \varepsilon_{\text{soil}} = 40 \) (left) and different values of soil relative permittivity and fix conductivity, \( \sigma_{\text{soil}} = 40 \text{ mS/m} \) (right). (b) Geometrical layout (left) and electrical field lines and potential (V) at 8.5 MHz from FE analysis (right) of two metal, flat electrodes, considering the dielectric properties of the substrate.
points due to the decrease in statistical significance of the measured data. However, the resistance and capacitance values at low number of data points are almost the same as compared with larger number of data points.

Thus, from our electrode measurements on soil with different wetness we have found that the obtained R and C values are not significantly affected by the choice of the number of frequency data points as long as they cover a large frequency range including data below and above the cut-off frequency of the RC network. This also shows that our RC model works reasonably well in soil impedance measurements. However, in order to have good accuracy of the obtained RC values it is crucial to choose at least one of the frequency points somewhat above the cut-off frequency of the impedance response curve and one data point below the cut-off frequency.

We are considering a parallel RC concept for the electrical properties of the soil where the electrodes can be modelled as a capacitance with an effective soil dielectric constant (permittivity) that will affect the capacitance, and a soil conductivity that will contribute to the resistance in the RC network.

In order to describe the soil in more detail the amplitude and the phase of the soil electrical impedance were measured in a large frequency range (few kHz up to 50 MHz) with an impedance analyser (HP 3243) connected to the two electrodes that are used in the soil sensor system. We are using non-coated electrodes (metal is in direct contact with the soil) that are positioned directly in the soil.

To further verify the RC model, we have used Finite Element (FE) analysis to simulate the absolute value of the impedance between the two electrodes surrounded by a conductive and dielectric media (simulating the soil) and obtained the results shown in Fig. 3. The result shows that the FE simulated response from the electrodes can be well described by our RC-model over the whole frequency range (Fig. 3a). The effect of changing the soil conductance can be seen in the lower frequency range where the impedance response is dominated by the real part (resistivity, R). On the other hand, a change in the permittivity of the soil (dielectric constant, \( \varepsilon_f \)) mainly affects the high frequency response. The cut-off frequency which ranges from about 5 to 30 MHz in Fig. 3a is dependent on both the permittivity and the conductivity of the soil, according to \( f_c = 1/(2\pi RC) \). From the decrease in the response at about 8 MHz seen in Fig. 1 we deduce that this is the cut-off frequency of the measured soil RC network. From the FE analysis we also note that the RC product is independent from electrode area or from the distance between the electrodes. We also note that changing the electrode area/length will not affect the cut-off frequency because it depends on both resistance and capacitance, which both will change due to the changes in dimension and the effect will be cancelled out.

Thus, mainly the soil properties, effective dielectric constant and electrical conductance play an important role for the soil electric response as can be seen Fig. 1. From the FE analysis results we also have plotted the electric field lines between the electrodes in order to estimate the measuring zone distance. The result is shown in Fig. 3b by using the following simulation parameters:

- **Electrodes**: Cu, 3 mm wide \( \times \) 0.2 mm thick \( \times \) 30 mm long,
- **Substrate**: (Quartz glass) 15 mm wide \( \times \) 50 mm long \( \times \) 2 mm thick, \( \varepsilon_{\text{quartz}} = 4.2, \sigma = 10^{-14} [/m] \),

We have used several dimensions of the electrodes in order to study the dimension and distance dependence of this method. We have also tested to electrically isolate the electrodes but found that this will give a very high isolation resistance between the electrodes that will complicate the conductivity analysis in the soil. The dielectric constant of the soil can be measured in this way but since it will be difficult to determine the conductivity we proceeded with non-insulating electrodes. From our measurements we found no degradation of the Cu electrodes, both visually and from changes in the measured data.

3. Results and discussions

3.1. Materials

The utilised ‘soil’ is Jiffy Preforma, a peat-based propagation material designed to work with seeds (http://www.jiffygroup.com/). The comparison of measurements between our miniature sensor and the commercial sensor were performed in bigger soil pots because the smallest commercial soil sensor does not fit in the mini-pot volumes smaller than 30 cc (e.g. QP D 104 VW 3).

For sensor calibration, NaCl solutions of known electrical conductivity were used and their conductivity was measured with CDMD210, Radiometer Copenhagen. Five various liquids with different dielectric constants were used; polyethylene glycol (\( \varepsilon = 12.4 \)), ethanol (\( \varepsilon = 24.3 \)), methanol (\( \varepsilon = 33 \)), glycerol (\( \varepsilon = 42.5 \)) and tap water (\( \varepsilon = 80 \)), their properties were taken from literature 4.

The soil sensor was manufactured on PCB, standard FR4, 1.6 mm thick (Cogra Pro AB, Sweden). The copper electrodes are covered by 3 \( \mu \)m layer of gold to prevent the electrode surface from oxidizing when subjected to the moisture and water of the soil. FR4 is a hygroscopic material, thus the entire surface was coated with a 0.5–1 mm thick layer of polyurethane PCB coating (Kontak Chemie, Plastik 70).

All the soil measurements were done at controlled temperature and humidity; 20 °C and 30% relative humidity in climate chamber Heraeus Vötsch VCL 6010. The watering of the pots is done by pot immersion into water.

3.2. Electronics

3.2.1. Detection electronics

The impedance of the soil is characterized by determining the capacitance and resistance of the low-pass filter that the soil forms between the two excitation electrodes and the GND electrode (Fig. 4); three electrode design was chosen for easier signal generation and increased reliability. An excitation signal of known amplitude is applied to voltage divider nets, and the signal amplitudes at the electrodes are determined by a peak detector. The peak detector creates a DC signal proportional (theoretically) to the amplitude of the AC response of the soil electrodes. The microprocessor digitalizes the response and transfers via UART interface to the communication module.

We have calibrated the electronic unit with R and C values corresponding to the soil wetness range. We have studied the signal path in each frequency branch, so we can describe the signal path with a transfer function from the input to the output of the electronic unit that helps in the calibration of the electronic circuit. The accuracy is in the range of 1% of the measured resistance values. Using constant capacitance values and measure the resistance gave accuracy in the range of 1.6%.

The power consumption is about 57 mA for 5 s at 3.3 V during the data acquisition cycle and the current drops to below 5 \( \mu \)A when the device goes into idle state. The “5s” is the actual data acquisition cycle during which 5 measurements are taken the average value is displayed. Data readings reported in this paper are obtained after a steady state of the soil moisture content and data values had been established.

3.2.2. Data reading

The data from the soil sensor can be read from a PC or wireless with Bluetooth low energy. The physical connection to PC is a USB-FTDI cable (TTL-232R-3 V3 from FTDI Chip) and the USB-port also powers the soil sensor. A graphical user interface was developed in LabVIEW.

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4https://www.engineeringtoolbox.com/liquid-dielectric-constants-d_1263.html
The soil sensor capacitance readings can be translated into soil volume water content (ratio of volume of water in the soil and the total soil volume) from the measured soil permittivity. The soil conductivity, \( \sigma \), and volume water content, \( \theta \), is related to \( R \) and \( C \) according to:

\[
R = \frac{A}{\sigma} \quad (3)
\]
\[
C = \varepsilon_r C_0 \quad (4)
\]

\[
\sqrt{\varepsilon_r} = b_0 + b_1 \theta \quad (5)
\]

where \( A \) is a calibration parameter, \( \varepsilon_r \) is the relative permittivity of the soil, \( C_0 \) the capacitance between sensor electrodes in air (\( \varepsilon_r = 1 \)), and \( b_0 \) and \( b_1 \) are calibration parameters. To calibrate, the water content measured by a commercial sensor [4, (https://www.delta-t.co.uk/product/wet-2-horticulture)] was plotted versus the permittivity and the calibration constants \( b_0 \) and \( b_1 \) (see Eq. (5)) [1, (Topp et al., 1980)] were determined. The result of this calibration can be seen in Fig. 7.

Since both the conductivity and dielectric constant (permittivity) may change during a measurement or calibration, we tested the developed sensor system against any interference effects between the measured resistance and capacitance values. In order to investigate this, we used known values of resistances and capacitances (components) connected in parallel to the electrodes and we found that we independently can measure the resistance and capacitance without any interference. Further, we also tested effects on interference using real calibration samples and we found no effect of coupling between conductivity and permittivity.

### 3.4. Sensor evaluation

#### 3.4.1. In liquids

##### 3.4.1.1. Hoagland solutions

The Hoagland solution is a hydroponic nutrient solution widely used and considered to be suitable for supporting growth of a range of different plant species [5, (Hoagland and Arnon, 1950)]. Electrical conductivity of the soil sensor was tested by comparing measurements in distilled water and three different concentrations of Hoagland solution (1/4, 1/2, 1), with the results determined by a commercial conductivity meter (Hanna Instruments HI 8733). Soil sensor readings were well related (\( R^2 = 0.9983 \); linear regression) to the conductivity meter readings with distilled water (Fig. 8a).

##### 3.4.1.2. Liquid extract from Jiffy soil media with Hoagland solution

Further, the electrical conductivity of the soil sensor was tested by comparing measurements of liquid extracted from Jiffy media (1:5 Jiffy-liquid, g/g) watered with distilled water and three different concentrations of Hoagland solution (1/4, 1/2, 1), as obtained with the conductivity meter. The liquid was extracted from the Jiffy media through the Saturated Media Extract (SME) method [6, (Landis and Dumroese, 2006)]. Conductivity of liquid extract from Jiffy media watered with distilled water was around 80 mS m\(^{-1}\). The soil sensor readings were well related (\( R^2 = 0.9679 \); polynomial regression) to the conductivity meter reading when the conductivity was lower than 200 mS m\(^{-1}\). At higher conductivities the soil sensor readings deviate from the conductivity meter since the soil sensor was calibrated specifically for Jiffy soil media with a conductivity range of 0–200 mS m\(^{-1}\) (Fig. 8b).

##### 3.4.2. In Jiffy soil media

#### 3.4.2.1. Soil water content in Jiffy media with distilled water

The soil sensor SWC readings were tested in potted Jiffy soil media by comparing with different known volumetric soil water contents (SWC) as shown in Fig. 9a, with a good correlation (\( R^2 = 0.97 \)). Maximum detectable value was measured with SWC of 73% when the soil media was fully saturated, and no more water was retained.

#### 3.4.2.2. Electrical conductivity and actual SWC in Jiffy media with distilled water

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Electrical conductivity of Jiffy substrate was measured at different SWC obtained with distilled water. The measured electrical conductivity increased with increasing of SWC showing a good correlation ($R^2 = 0.98$; Fig. 9b). A maximum electrical conductivity value of 32.81 mS m$^{-1}$ was measured with a SWC of 70%.

3.4.2.3 Electrical conductivity in Jiffy media with Hoagland solution. The soil sensor was also tested by measuring the electrical conductivity of Jiffy media, at a constant SWC of 0.6 (cm$^3$ cm$^{-3}$) with distilled water and at three different concentration of Hoagland solution ($\frac{1}{4}$, $\frac{1}{2}$, 1). The result showed that the electrical conductivity increases with increasing Hoagland solution concentration (Fig. 10). In addition, in this case, the electrical conductivity measured with Jiffy media watered only with distilled water is higher than zero value due to the influence of the soil. The highest electrical conductivity values (above 73 mS/m) was measured when Jiffy media was watered by a two-fold concentration of Hoagland solution. These results highlighted the buffer effect of Jiffy media on the electrical conductivity which resulted in inaccurate reading when the same concentration was measured in liquid and in liquid extract from Jiffy media. Furthermore, these results demonstrated that adding a very high concentration of Hoagland solution in Jiffy media, the electrical conductivity are still detectable by the soil sensor system.
4. Conclusions

Miniaturized soil sensor measuring simultaneously the soil water content and electrical conductivity (dependent on total ions concentration) has been successfully developed for ‘mini-plug’ soil pot by measuring the frequency dependent electrical impedance of the soil using two electrodes working at only two frequencies. The easier calibration method of this sensor allows for faster integration into experiments and straightforward studies of the growth of seedlings and the connection with the properties of their soil in the ‘mini soil plugs’ (green-houses) up to sensors network on the field. The detection method makes this sensor cost-effective, low-power and portable system that can be deployment throughout the greenhouse/field in arrays and/or distributed.

The soil sensor can be easily connected wirelessly to data loggers/ WSN allowing for spot checks of substrate moisture levels throughout a greenhouse/field, and/or enable sensors to be buried inside the soil/substrate for long-term consecutive measurements. Several of these soil sensors can be interfaced with a greenhouse/nursery climate computerized controller unit and used for controlled irrigation systems.
automation. However, dielectric and conductivity sensor performance requires substrate-specific calibration because each soil/substrate presents specific dielectric and conductivity properties.

Declaration of Competing Interest

All authors explicitly state that there are no competing interests, and no financial and personal relationships with other people or organizations that could inappropriately influence (bias) the work reported in this paper.

Acknowledgement

This work is partially funded by EU-FP7-ENV grant Zephyr – Zero-impact innovative technology in forest plant production (grant agreement No 308313) and by ECSEL JU grant AFarCloud – Aggregate Farming in the Cloud (grant agreement No 783221).

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