A Wireless Passive Soil Water Content Sensor Tag

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ABSTRACT

This paper describes the working principle of a low-cost, passive, contactless impedance-based sensor tag and a hand-held readout device for measuring soil water content. Laboratory tests with first prototypes in earthenware pots containing compost, show good repeatability with a resolution of 1 on a scale of 10. Measurements are possible at distances up to 2 cm between tag and reader. The system can easily be used for irrigation management practices. On-going research aims at additional measurement of electrical conductivity and inductance, improving accuracy to 1:100, and increasing reading distance. Developments are on-going to print the full sensor on a plastic card. Besides soil water content, possible other applications are sensors for measurement of temperature, pressure, gas composition etc.

Keywords: contactless, battery-less, RF tag, soil water content, moisture, Electrical Conductivity

1 INTRODUCTION

Irrigated agriculture plays a key role in economic development and poverty reduction [1]. Soil water content sensors are used to optimize irrigation quantity and timing in agriculture, which leads to large water savings and better crops [2]. In spite of this, wide-spread introduction in practice is hampered by high costs of such sensors [3]. Generally, Frequency Domain sensors have lower costs compared to TDR [4], and many of such sensors have come to market. But, even in Dutch high-tech greenhouse industry, where for instance about 1500 growers annually produce 4 billion potted-plants, water need is still estimated by hand which is labour intensive and inaccurate. Use of soil water sensors demands high-level skills and knowledge. World-wide, many poorly trained, small-scale horticultural farmers, having hardly access to fresh water sources, cannot afford such innovative and costly tools, which impedes their possibilities to enhance water use efficiency and crop productivity. In order to get a good estimate of soil water variability, many sensors are needed. As these sensor systems are yet quite expensive (roughly over 70 euro per sensor), this is not very economical for growers. Available soil water content sensors have cables attached to them, which is unpractical. For every sensor an interface or a read-out unit for multiple sensors is needed. Therefore, suppliers of soil moisture sensors add wireless sensor networks at extra cost (over 500 euro). Some sensors incorporating a wireless system are described [5,6], but until now commercialization failed due to the fact that production costs of the needed electronics are still too high and batteries are needed.

There is a need for simple, practical and low-cost wireless water content sensors. Such sensors can be constructed without the need for batteries or signal processing on board, using an LC-resonance circuit. Many suggestions for such sensors are reported in scientific work, e.g. in [7]. Such sensors use a wide range of frequencies to sample the resonance curve. So far, commercialization of such sensor failed, because allowed radio-frequency bands are narrow [8]. A new approach, called the *AquaTag,* is described in patents [9,10]. It has the potential of having ultra-low production costs, and is based upon an RF-technology and an interrogation algorithm that allows for narrow-band communication with the tag. This opens possibilities to use many sensors in the field in order to obtain a good estimate of average soil water content. Expected accuracy of the *AquaTag* is lower than for high-end FD-sensors, normally around 1-5%. However, when soil water spatial variability is high, an acceptable good estimate of average soil water content of a field, may even be obtained with less accurate sensors, as long as variability is larger than the accuracy. E.g., for a grassland watershed near Chichaska (Oklahoma, USA) a standard deviation for water content is reported up to 8.3 m^3/m^3 [11]. This leads to less strict design criteria for the accuracy of these sensors, offering possibilities to further lower production costs.

Our aim was to develop a low-cost, passive, contact-less sensor tag for measuring soil water content, which can easily be used in irrigation management practices in a large variety of crop production systems. The targeted accuracy for it is 1 on a scale of 10. This paper describes such a sensor and the results of evaluation in laboratory of first prototypes. We present a novel approach and demonstrate well-working sensors tags and a simple hand-held reading device.

2 MATERIALS AND METHODS

2.1 AquaTag working principle

Water content is a function of soil electrical capacitance. It is measured using two electrodes, with an AC-signal at a frequency between $10 - 200$ MHz. This approach is commonly referred to as the Frequency Domain (FD) method [12]. The *AquaTag* [13] is a resonance type impedance sensor and is based upon this measurement principle (Fig 1.).

Fig. 1: *The AquaTag system, with reader and sensor tags.*

It contains a resonance circuit (Fig. 2.) that can be interrogated with a reader to obtain the unknown electric impedance (*Z*). Electrodes are connected to a printed loop antenna (*L*) and a tuning capacitor (*C*), together forming a resonance circuit for 27 MHz. The resonance frequency changes as the electric impedance between the electrodes changes. Any substrate, like soil or other growing media, that changes its impedance (capacitance, resistance or inductance) as a function of some physical parameter such as moisture or fertiliser content, can be attached to the electrodes. With electrodes in free air, the resonance circuit is tuned slightly above the 27 MHz band. With electrodes in water, the resonance frequency drops slightly below the 27 MHz band.

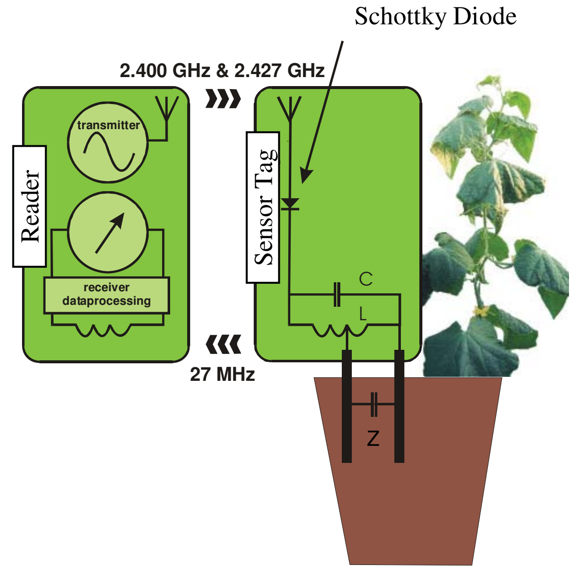

Fig. 2: Block diagram of the content sensor system.

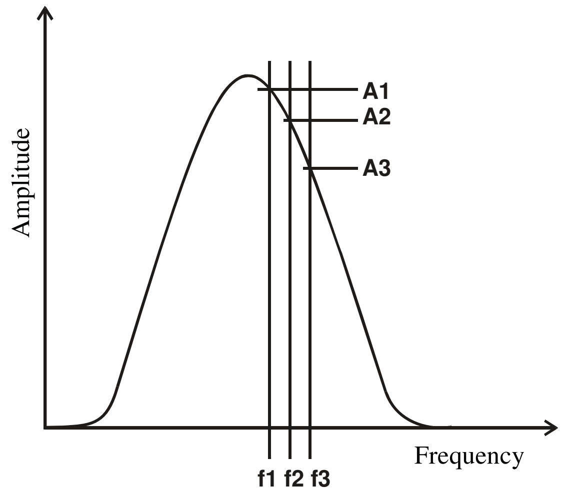

Fig 3. Resonance curve for the AquaTag.

The resonance frequency and Q-factor of the resonance circuit can be acquired by interrogating the tag at — at least — three frequencies within the 27 MHz band (f_1, f_2, f_3) = (27.0 MHz, 27.1 MHz, 27.2 MHz). For this, the reader unit must measure the returned signals very accurately. Since the tag is passive, emitting only weak signals, the reader cannot excite and measure at the same time. For excitation it uses a much higher frequency in the 2.4 GHz band. The reader contains two 2.4 GHz transmitters separated 27 MHz in frequency, built around the CC2500 from Texas Instruments, and a 27 MHz receiver built using discrete components. Besides the LC-resonance circuit, each tag contains a 2.4 GHz antenna and a Schottky diode connected to the electrodes. While the reader activates the passive tag, the two 2.4 GHz signals are mixed by the diode. This invokes a 27 MHz measuring signal, which is fed to the LC-resonance circuit. One transmitter has a fixed frequency of 2.4 MHz, the other switches its frequency to 2.4270 GHz, 2.4272 GHz and 2.4274 GHz. Amplitudes are measured (A_1, A_2, A_3) at the slope of the resonance circuit (Fig. 3.). From these, the electrode capacitance and resistance is calculated, assuming the inductance L is known. To control the transmitters and the receiver, to compute electrical impedance and to convert it into readable units for soil moisture content, the reader contains a micro-processor.

The sensor tag is made of a standard 3 mm Printed Circuit Board (45 × 74 mm^2), with a few copper tracks forming two antennas (27 MHz and 2.4 GHz), a Schottky diode, and a tuning capacitor. It is covered with a plastic cap and has two gold-plated pins (5 × 66 mm^2). In principle the tag can be printed on plastic film, reducing production costs to a few cents.

2.2 Water content measuring algorithm

Though there are numerous publications of resonance type impedance sensors, none of them can be sold, because they use a bandwidth too large to comply with international radio frequency regulations. One needs to work in the allowed ISM frequency bands for RFID tags. These bands are rather small, compared to the width of an LCR-resonance curve. Further, the maximum power allowed in these band is limited. So smart technology is needed to analyse the weak 27 MHz signals from the tag.

The tag itself is passive and has no chip on board. Therefore, the reader firmware contains all intelligence of the system. To compute capacitance and resistance the three measured amplitudes need to be very accurate and at frequencies as far as possible from each other. For this, the 27 MHz band (Band C: 26.957 – 27.283 MHz) was chosen because it is the broadest ISM band available between 10 − 200 MHz as defined by the International Telecommunication Union [8]. The 27 MHz measurement signal is derived from the two stable 2.4 GHz oscillators, yielding an accuracy of better than 400 Hz.

For calculating capacitance, resistance and signal strength, straight algebraic solutions for the equations are being used, requiring amplitudes to be exact. However, in practice, there will always be some noise in the measured amplitudes, in particular at low signal strengths at a large reading distance or at high soil electrical conductivities (EC). If measured values differ just a little, fitted curves may vary largely from reality. As an example (Fig. 4, left), the three amplitudes are shown as dots at the peak of the resonance curve. The striped curve is the result from a simple linear regression on the three measurements including noise. This regression yields a far smaller resonance curve than the actual one according to the model (Fig. 4, right).

To reduce noise, normally multiple measurements are taken and averaged. Measurements are taken by hand, so some motion between measurements cannot be avoided. Such reader displacement also introduces noise, and affects measurements. Therefore, to avoid motion blur, twenty snapshots are taken for each individual amplitude in less than 1 ms. These measurements are averaged after eliminating outliers. This process is repeated a number of times. Observations are averaged again, and then used in an iterative non-linear least squares regression algorithm to fit the model in good agreement with the observations. The capacitance and resistance of the resonance circuit comes out after a few iterations. This approach yields a better fit, as can be seen from the light dotted curve in Fig. 4.

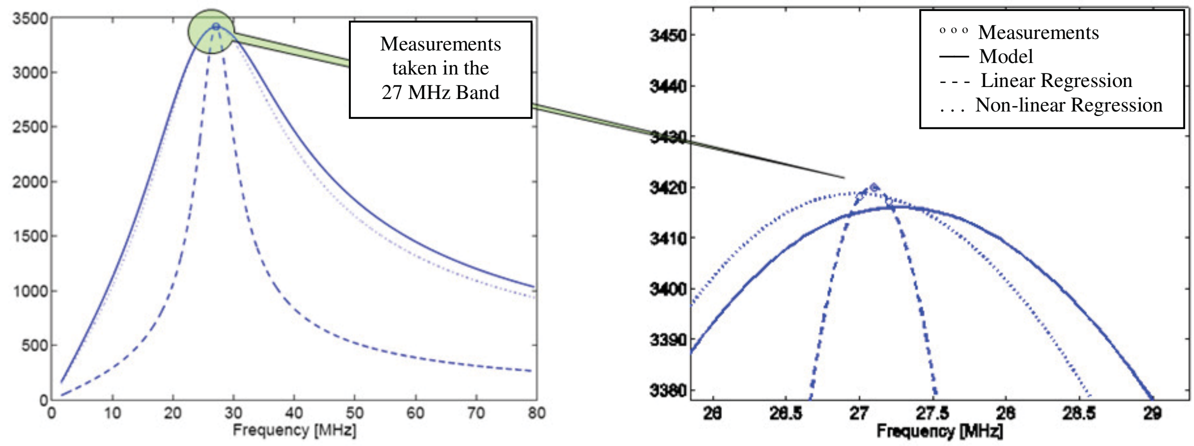

Fig. 4: *Model and fitting results for the resonance curve (left), and detail (right).*

Actually there are three unknowns: capacitance, resistance and a factor that incorporates the total of gain, attenuation, mixing efficiency and distance between the tag and the transmitter. This factor is calculated in the same way. In this work, only capacitance is used as a measure for water content. In future work, the resistance and the factor will be taken into account to obtain extra parameters like for instance soil electrical conductivity, or to enhance accuracy of the tag.

2.3 Sensor accuracy experiment

To get an impression of accuracy, the sensor was tested in a pot with compost at different water contents, while the compost was drying out. A plastic pot has the disadvantage that water evaporates only at the top, creating a moisture profile in the pot. Therefore, an earthenware pot was used, making it possible to let water evaporate evenly on all sides of the pot. The pot was filled to the rim with compost, and then by hand lightly pressed to about 1 cm under the rim (Fig. 5, left). Pot volume to 1 cm below the rim was

980 cm^3, which was measured by filling the pot with water. First, compost in the pot was wetted until saturation, by putting it in a container with water filled up until the water level rose to 1 cm below the rim of the pot. Then the pot was sealed with plastic film to prevent evaporation, and left over night. The following day, water was replenished something. After removing the pot from the water, it was allowed to drain for 15 minutes until no more water ran out of the pot. At that time, water content is the maximum that compost can hold when water is supplied from below, from a saucer. This water content was taken as reference for saturation (100%). The sensor was inserted vertically from above in the pot up until the lower edge of the sensor body touched the compost. It remained there until the pot was "oven-dry" (Fig. 5, right). Weight difference between oven-dry and saturation gives the volume of water the compost may contain, assuming that the specific gravity of the water in the pores is about 1. The whole pot filled with compost including the sensor were then weighed, allowed to stand overnight at room temperature and dry out, weighed the next morning, etc. After each weighing, ten measurements were taken and averaged. This cycle was repeated 3 times. In the last cycle another sensor was used as the first sensor was broken. Distance between reader and sensor tag was kept around 3 cm for all measurements. Values were normalised, expressed as a percentage, relative to the capacity at saturation and oven drying. Weights were normalised as well, taken from the weight at saturation and oven-dry.

Fig. 5: *AquaTag sensor in earthenware pot with compost (left) and detail (right).*

2.4 Reading distance experiment

The AquaTag was designed to be a non-contact sensor and to be readout manually with a reading device from close distance. In principle an operational distance from 0 – 1 cm is sufficient for this purpose. However, the distance from the reader to the tag affects total gain of the system, and may lead to erroneous capacitance readings when it becomes too large for the tag to be operated in its working range. As such, it is important to know to what distance the tag can be read-out having a not too large error. For this a sensor was placed first in a pot filled with dry sandy soil. Next, the soil was saturated with tap water, resulting in a bulk EC of about 0.4 – 0.5 mS/cm. For each, 20 measurements were taken and averaged. The difference was used as the maximum water content range. Next, for the wetted soil, the tag was readout 3 times, at different horizontal distances with 1cm intervals from 0 to 5 cm. Averaged values were normalised to 100% for the maximum range.

3 RESULTS

Figure 5 shows the results of the sensor calibration. There are 20 measurements done in three cycles, wherein each measured value is, in turn an average of 10 readings. The measurements were fitted with a 2^{nd} order polynomial, which gave a good correlation ($R^2 = 0.99$). Deviation from this curve stays within a range from -4.8 to 10.4, having a standard deviation of 3.74. This result was obtained with a tag and reader that stayed in place between readings. Static seen, accuracy is about 1 on a scale of 10 ($P = 0.99$). However, in two cases, standard deviation of each set of 10 readings was 12.5 and 19.5 relative to a scale of 100. This was for measurements at 90% and 100% respectively. These two standard deviations were higher than is desirable. In all other cases the standard deviation was smaller than 5 by a measurement above 50% and smaller than 2 for measurements below 50%, which is acceptable or even very good. For compost normally, desired water contents are around 70%.

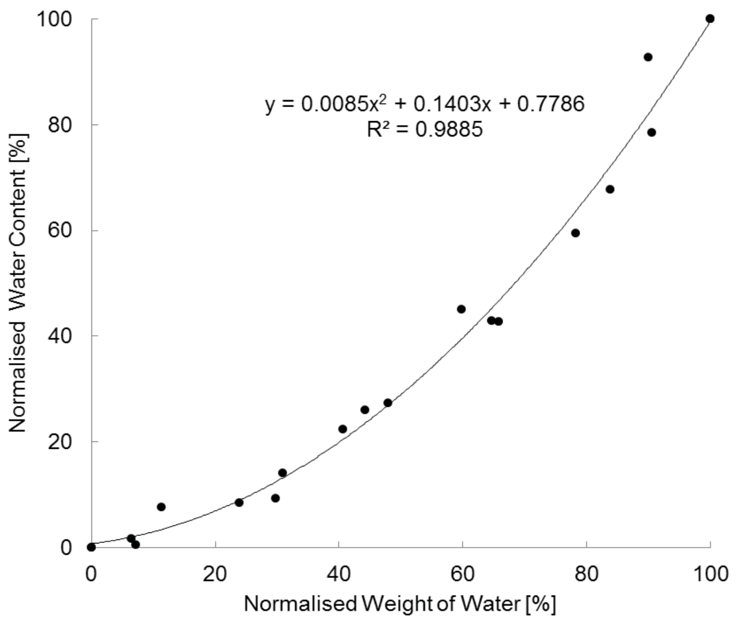

Fig. 5: *Water content measurements taken with the AquaTag in pots with compost, compared to gravimetrically obtained weight of water in the pots.*

Because of a higher water absorption of the pot compared to the compost, even though the compost dried, the pot remained long saturated during the drying experiments. Because the sensor measuring field was smaller than pot volume, the sensor measured the actual water content of the compost. The pore water of the pot itself contained 66 g of water, which was considered negligible for a total weight of 1276 g for the oven-dried pot containing compost and sensor. Remarkably, is was not easy to obtain "oven-dry". It takes a very long time to dry-out the earthenware pots completely. The best approach was to place the pot alternately one hour in the oven at 105 ^{o}C and then at room temperature until it had cooled, and to repeat this a number of times. Then water content decreased more rapidly. However, oven drying was stopped when no considerable weight loss was observed anymore. Measurements were done at room temperature.

The results for the distance test are shown in Fig. 6. For this soil and at this EC, the error is at maximum 3.5%, for all distances up until 5 cm. This is lower than the overall found accuracy in the first experiment. A lower deviation (<0.5) is found for distances up to 3 cm.

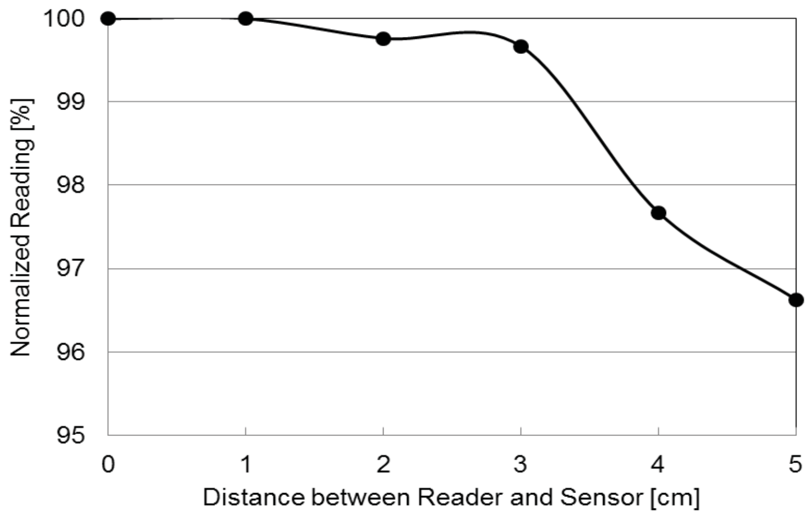

Fig. 6: *Normalised reader output for a varying horizontal distance between reader and AquaTag, obtained for a saturated sandy soil.*

4 DISCUSSION

Although the sensor is capable of measuring EC as well, the evaluation so far focussed only on water content. The achieved accuracy of 1 on a scale of 10 is good. However, accuracy becomes lower as either the water content or reading distance is very high, leading to weak signals. High EC may lead to a flat resonance curve. If the signal is weak or the resonance curve is less sharp, the filtering of unwanted signals is worse. On-going research aims at improving accuracy to 1:100, increasing the reading distance and additional measurement of resistance and inductance.

Influence from EC and temperature are not yet fully investigated. It is expected that they will affect overall accuracy. Since EC can be measured as well, water content readings may be corrected for EC. Temperature corrections may be done for water content and EC according to literature, but this might not include the direct solar radiation effect on the sensor housing and electronics when sensors are placed in open field under arid conditions. The sensor cannot measure temperature itself, so to perform a correction, temperature must be obtained from another source.

Reading distance and angle directly affect overall gain. Only horizontal displacements are investigated so far. The observed reading distance of about 2 – 3 cm, is sufficient for the application. When the reader is placed e.g. direct vertically above the sensor, the coupling of transmitter and tag is low, and the system might go out of its working range. When the tag is used in automated systems and sensor-reader orientation is not fixed, so the reading distance varies largely, it is needed to extend the read-out distance to maybe 5- 10 cm. Research must focus on algorithms to obtain an estimate for the gain, and compensate capacitance and EC for variations therein.

At the Technical University of Delft, experiments are going on to print the full sensor on a plastic card. Since there is not yet a printable Schottky diode available for 2.4GHz, and with a sufficient low threshold voltage, this work includes the development of such a diode as well.

Besides soil water content, possible other applications are impedance-based sensors, such as for temperature, pressure, and gas composition.

5 CONCLUSIONS

The working principle of a low-cost, passive, contactless impedance-based sensor tag and a hand-held readout device for measuring soil water content is described. Laboratory tests with first prototypes in earthenware pots containing compost, show good repeatability with a resolution of 1 on a scale of 10. Measurements are possible at distances up to 2 cm between tag and reader. The system can easily be used for irrigation management practices. On-going research aims at additional measurement of electrical conductivity and inductance, improving accuracy to 1:100, and increasing reading distance. Developments are on-going to print the full sensor on a plastic card.

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