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Application of an Intelligent Dielectric Sensor for Soil Water Content, Electrical Conductivity and Temperature

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Abstract - ***This paper describes prospective applications of an intelligent dielectric sensor for measuring water content, electrical conductivity and temperature in soil. The sensor incorporates an application specific integrated circuit for dielectric measurement. It has an embedded micro-processor which handles calibration, data processing, control and communication as well as rewritable memory for storing calibration data. The sensor can be used in agricultural practices for continuously monitoring water related parameters in soil and growing substrates in which field-busses or digital networks are used to read-out multiple sensors. A prototype of the sensor was tested in a LONWORKS® network environment.***

Keywords - ***Intelligent dielectric sensor, soil water content, electrical conductivity, calibration, field-bus.***

I. INTRODUCTION

Recently, the **WET**-sensor came available on the market[1]. This sensor is meant to be used for agricultural practices to monitor water content (**W**), electrical conductivity (**E**) and temperature (**T**) in soil and growing substrates. The availability of this sensor opens a way for automatic irrigation and fertigation of crops, by using it in a feed-back control loop [1]. However, a large number of sensors are needed to monitor soil parameters sufficiently accurate, due to soil variability.

For the WET-sensor, a hand-held meter is available to read-out single sensors (Fig. 1). For research purposes, some sensor multiplexers have been built, but for practical application, and to interconnect a large number of sensors with computer systems, its better to use field-bus systems rather than to use extensive wiring schemes. In the agricultural field, most systems work with analogue input circuitry, but recently applications incorporating field-busses are penetrating this sector. Therefore, the demand for information on how to incorporate the WET-sensor into new digital networks is becoming stronger and stronger.

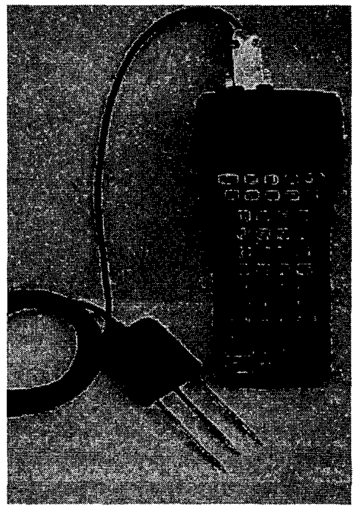

Fig. 1. The WET-sensor, connected to a PSION-Workabout palm-top computer containing read-out software.

The WET-sensor, using a dielectric measuring principle, was tested under research and practical circumstances for many years and has proven its value [2]. It incorporates an application specific integrated circuit (ASIC) for dielectric measurements to obtain a low sensor price at large-scale production [3]. This ASIC has a digital interface with an RS232-output, meant for connecting it directly to a micro-processor or onto a digital network, which makes it suitable for smart sensor applications [4], [5]. To full extend, [6] describes all computational actions needed to convert rough sensor data to actual dielectric and soil property data. In spite of all this, no WET-sensors are implemented into new irrigation systems. The reason for this is that the diversity of irrigation management systems is very large and each company uses its own, non standardized equipment. This problem focuses on the complex interfacing nature of the ASIC and more specifically the dielectric data handling, the storage of specific sensor and soil type calibration data and the general hardware and software interfacing procedures of the sensor.

[1]The WET-sensor and SigmaProbe are trademarks from Delta-T-devices Ltd. (UK). LONWORKS® and ECHELON are registered trademarks of ©2000 Echelon Corporation. This work was funded by the EC project WATERMAN (FAIR1 PL95 0681), the Dutch DWK research program on Water and Nutrient Management, Delta-T-Devices Ltd. (UK) and Cultilène (NL). The work on the LONWORKS application was supported by the Dutch Ministry on Economic Affairs, and performed by Halin and E.I.E. B.V. Veldhoven (NL).

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This paper proposes a different approach. By embedding the dielectric measuring ASIC as well as a micro-processor and a calibration data memory into the sensor housing, all complex data handling can be performed at the front end. In this way, this – intelligent – sensor can output its calibrated values directly over a serial bus, which relieves application engineers of extensive hardware development and software programming and makes the process of interfacing the sensors fairly straight forward and cost effective.

II. MATERIALS AND METHODS

ASIC for dielectric measurements

Dielectric measuring principles observe to what extend electrically polarized particles like molecules, ions and cells, can follow an alternating electric field. By measuring the dielectric properties (electric capacitance and conductance) of a specific solid or liquid material, one is capable of telling more about the individual constituents of the material. Since water is a polar molecule, and therefore has a high dielectric constant, water content is one of the major material properties that is analyzed with this method [7], [8].

There are applications known that measure water content, ion-concentration and electrical conductivity in soil and growing substrates [9], or even soil contamination [10]. Others [11] and [12], report on applications for on-line monitoring cell concentration in milk and yeast [13] or even hardness of concrete [14]. Dielectric measurements are useful in a broad range of agricultural, as well as environmental and industrial processes for on-line monitoring [15].

For many years Time Domain Reflectometry, based on pulsed excitation, was used to measure soil water content [16]. TDR involves extensive and expensive equipment. Recently, the Frequency Domain method, which uses a single sine wave excitation, became available [17]. The dielectric measuring ASIC is based upon this method, and makes it possible to build simple, cheap and accurate sensors for on-line monitoring applications. Based on this ASIC, also a pore water conductivity sensor, called SigmaProbe[1], is available. This sensor involves an automatic correction algorithm to compensate for water content and bulk electrical conductivity [18].

The ASIC comes in a standard 44-pin PLCC package. It has a TTL-level, RS232-output and operates from a single 5 V power supply at a supply current of 35 mA. It connects directly to a microprocessor. The ASIC contains a 4-channel vector-volt meter that measures complex electric impedances (phase and magnitude) at a fixed frequency in the range of 10 up to 30 MHz. One of its channels is used to connect a pair of measuring electrodes via a set of coupling capacitors that block any DC current to prevent from electrolysis. To compensate for most of the internal errors and external parasitic impedances, two channels are used to measure a known reference capacitor and resistor. To facilitate a temperature correction algorithm, the chip has an additional single ended analogue input to which a temperature sensor is connected.

The ASIC contains a synchronous detector with a multiplier and low pass filter (LPF), an AD-converter and interfacing and controlling logic, as shown in the simplified functional block diagram of Fig. 2. Four impedances (Z_1...Z_4) are measured at four differential inputs. A stabilized oscillator (OSC) generates a sine wave current (i_z), at a frequency f_0 determined by an externally connected crystal. It develops a voltage (u_Z) across the unknown impedances that are successively selected by S_1.

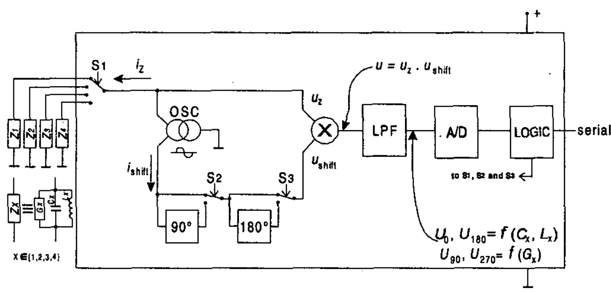

Fig. 2. Simplified functional block diagram of the ASIC.

This voltage is fed to an input of the analogue multiplier. A second current (i_{shift}), equivalent to i_z, also comes from the oscillator. Its phase is shifted by respectively 0°, 90°, 180° and 270°, controlled by the switches S_2 and S_3. The voltage u_{shift} developed across the phase shifter is fed to the other input of the multiplier. The output of the multiplier (u) consists of a DC and an AC term with frequency $2 \cdot f_0$. The DC term ($U_{0°}$, $U_{90°}$, $U_{180°}$ or $U_{270°}$) is found at the output of LPF. In case of a 0° or 180° phase shift ($U_{0°}$ or $U_{180°}$), it is a measure for the capacitance (C_x) or inductance (L_x), and in the case of a 90° or 270° phase shift ($U_{90°}$ or $U_{270°}$), it is a measure for the conductance (G_x) of the unknown impedance (Z_x). The output of LPF is fed to an analogue-to-digital converter and next converted into a serial output by logic circuitry (LOGIC). In order to compute the unknown Z_1 ... Z_4, this serial data must further be processed by a micro-computer.

As soon as the ASIC is powered, it starts repeating its measuring cycles and outputs its data at the SERIAL pin. Each measuring cycle involves several measuring states. During every state, the ASIC outputs a 6-byte serial ASCII-pattern that reflects the measured value for that state including the state number. The serial pattern contains 1 start bit, 7 data bits and 1 stop bit for each character. No parity is used. The serial data is sent in packages that start with an @-character followed by the state-identifiers: A, B, ... U, V and is ended with a ↔-character. Every state-identifier is followed by a 5-digit BCD number that is in the range of 0 to 99999, but typically around 10000. Data values are relative, and there is a near linear relation with the measured values. A typical data package would look like a repeated string of: @A09976B10952....V10047↔. Every package contains 134 characters ($22 \times 6 + 2$). Table I gives an overview of all the states.

There are 22 measuring states, incorporating the 16 states for the four impedance channels Z_1 ... Z_4. Each takes 100 ms of measuring time. This time, as well as the baud rate of 1220 is related to the 20 MHz crystal frequency. Six other states are used for three additional analogue inputs of which one is used for temperature (state 1 and 22) and two for internal zero-reference (state 2 and 21). The temperature is measured at the beginning and at the end of a measuring cycle, to be able to compensate for a possible warming up of the ASIC.

Table I

Measurement state overview (n are BCD-digits).

state	ASCII-characters	Comments
start	@	No measurement
01	Annnnn	Analogue input 3
02	Bnnnnn	Offset before measurement
03	Cnnnnn	Analogue input 1
04...07	Dnnnnn ... Gnnnnn	$U_{0°}$, $U_{90°}$, $U_{180°}$, $U_{270°}$ for input Z_1
08...11	Hnnnnn... Knnnn	$U_{0°}$, $U_{90°}$, $U_{180°}$, $U_{270°}$ for input Z_2
12...15	Lnnnnn... Onnnn	$U_{0°}$, $U_{90°}$, $U_{180°}$, $U_{270°}$ for input Z_3
16...19	Pnnnnn... Snnnn	$U_{0°}$, $U_{90°}$, $U_{180°}$, $U_{270°}$ for input Z_4
20	Tnnnnn	Analogue input 2
21	Unnnnn	Offset after measurement
22	Vnnnnn	Analogue input 3
stop	↔	No measurement

Dielectric calibration procedure

The sensor contains several parasitic elements like electrodes, input circuits and internal ASIC circuitry, that all contribute to the overall measured impedance. Therefore the sensor must be calibrated, to measure the dielectric properties permittivity (ε), conductivity (σ) and temperature (T) accurately. Fig. 3 gives a simplified model of the total input circuitry of the sensor. Besides the unknown G_x and C_x there is a series inductor L_s and resistance R_s to model the electrical path length of the electrodes and a parallel capacitor C_p and resistor R_p that model the input circuitry of the sensor. R_{ref} and C_{ref} are used to compute C_p and R_p. The values of L_s, R_s, C_p and R_p need to be obtained through a calibration procedure and are typically for each individual sensor. The internal offsets in the ASIC are compensated for by subtracting the measured values from two states, each shifted 180° from each other. The readings of the temperature sensor need to be linearized with a 3rd order polynomial and an offset is used for calibration. Data collected with this calibration routine can be stored into memory as dielectric calibration data.

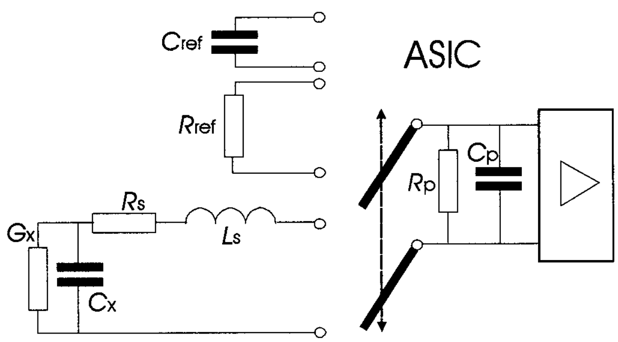

Fig. 3. Simplified electric model for the sensor measuring rods (R_s,L_s) and ASIC input circuitry (R_p,C_p).

Data processing

Data coming out of the ASIC must be processed before water content, pore water conductivity and temperature are available. A low power, multi-purpose microprocessor will perform this task. All firmware for this will be stored in an embedded ROM. The working principle, as shown in Fig. 4., involves the following steps:

Input routine

The micro-processor acquires the ASCII-data string from the ASIC (INPUT ROUTINE). It has also access to dielectric calibration data for the individual sensor, stored in embedded non-volatile and rewritable memory.

Computation of dielectric properties

From the ASCII-data the complex impedances of the individual channels (Z_1...Z_4) are computed (TOTAL IMPEDANCE) with a standard formula containing a minor linearization algorithm [19]. Since these values include the impedance of electrodes, connectors and wiring, the next step is to perform a correction to yield the exact Z_x (CORRECTION). From Z_x

the dielectric properties ε and σ can be computed (DIELECTRIC PROPERTIES).

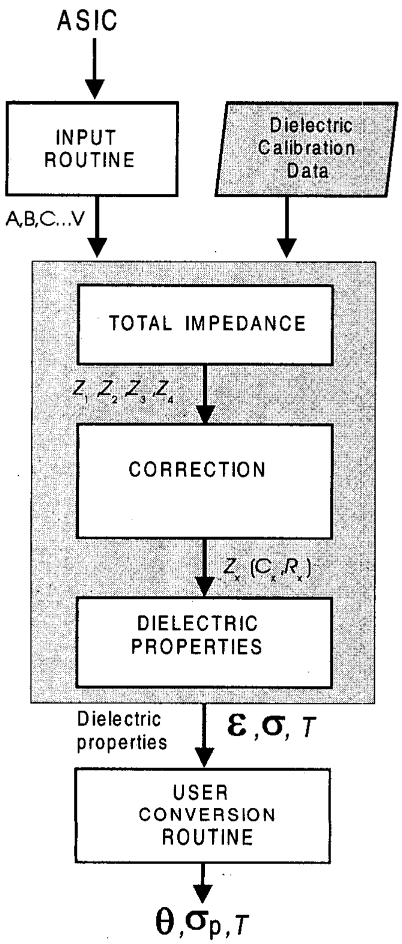

Figure 4. Dielectric data processing.

User conversion routine

The relationship between the dielectric properties permittivity (ε) and conductivity (σ) and the soil related parameters like water content and pore water conductivity, strongly depends on the soil type in which the sensor is used. To obtain accurate measurements a soil-sensor specific calibration is needed.

For soil volumetric water content (θ), general calibration curves for standard soils can be used [20]. These calibration curves depend on σ, soil type (sand, silt and clay fraction), density, and temperature [1]. Topp acquired these calibration curves for a broad range of soil classes using the TDR-principle [16]. These curves can be approximated with a third order polynomial equation as follows:

$$\varepsilon(\theta) = 3.03 + 9.3\,\theta + 146\,\theta^2 - 76.7\,\theta^3. \quad (1)$$

Fig. 5 shows this curve for sand, taken at 150 MHz. This curve deviates only slightly from the curves found for the FD-method at 20 MHz.

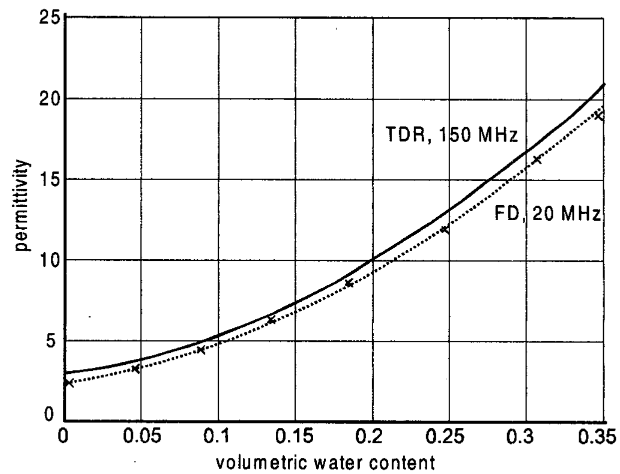

Fig. 5. The Topp calibration curve for sand, in which the permittivity (ε) is given as a function of the volumetric water content (θ), for the TDR-method (150 MHz) and the FD-Method (20 MHz).

Actually, the sensor measures the total or bulk soil conductivity (σ). But, non-dissolved soil fractions contribute to this value too. Since plants only deal with the in water dissolved components, farmers are only interested in the conductivity of the water that can be extracted from the soil. This pore water conductivity (σ_p) is dependant on σ and ε [18], and can be obtained from:

$$\sigma_p = \frac{\varepsilon_{water} \cdot \sigma}{(\varepsilon - \varepsilon_{\sigma=0})}. \quad (2)$$

Herein, ε_{water} refers to the permittivity of water at the temperature of interest ($\varepsilon_{water} \approx 80$ at 21 °C), and $\varepsilon_{\sigma=0}$ is the intercept with the y-axis of the line ε versus σ. Note that this is not the value for ε at $\theta = 0$. This offset value can be calculated from ε and σ values measured at two arbitrary free water content values. In general one could use a fixed value for $\varepsilon_{\sigma=0}$. For this, a calibration could be performed once, but on-site calibration is preferred to achieve a higher accuracy. As a rule of thumb the model applies for most normal soils and growing substrates, like mineral wool, for $\theta > 0.10$.

Conductivity depends on temperature, which makes it difficult to handle this parameter in practical situations. Growers normally use the conductivity given with reference to a predefined temperature. It is a custom to take 20 °C as the reference temperature (T_{ref}) and to use the temperature coefficient (2.25% per °C) of water salted with NaCl as the default. This method may be used for both bulk and pore water conductivity. As described in [1], this referenced conductivity (σ_{Tref}) can be computed from:

$$\sigma_{Tref} = \sigma\,(1 - 0.0225 \cdot (T - T_{ref}))\,. \qquad (3)$$

User calibration routine

The user calibration can be handled interactively by a specific routine embedded into the sensor. The obtained user soil calibration data, like the constants from the Topp-curves, can be stored into the embedded memory. Re-calibration at the user site is possible when rewritable memory is used.

Output routine

The output routine transfers the soil property parameters onto the field bus. This procedure depends on the system or network in which the sensor should operate. Fig. 6. Shows the user data conversion and output routines.

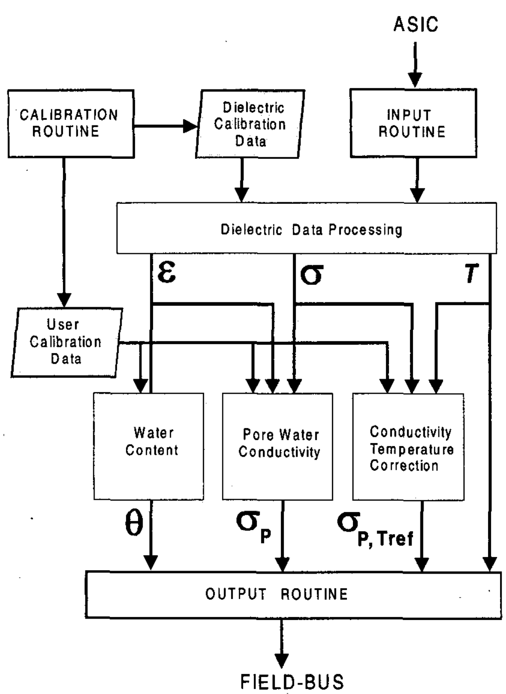

Fig. 6. Schematic overview of the micro-processor firmware.

III. RESULTS

Sensor electronics

For evaluating the concept of the intelligent sensor, a PCB containing the front-end electronics around the dielectric chip was developed. A simplified schematic, incorporating the ASIC, is given in Fig. 7. Only a few external components such as a crystal (XTAL), an Op-Amp (MAX480), a reference resistor R_{ref} and a reference capacitor C_{ref}, and resistors R_1, and R_2 for automatic gain control are needed. A set of measuring rods is connected to the sensor via the capacitors C_1 and C_2, used for DC-blocking. Fig. 8 shows the developed printed circuit boards containing the ASIC.

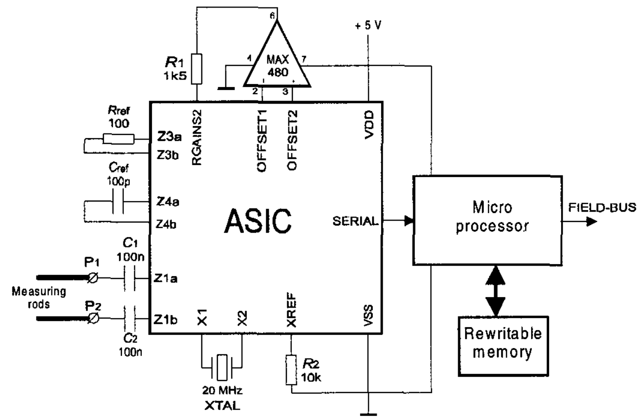

Fig. 7. Simplified schematic of sensor electronics.

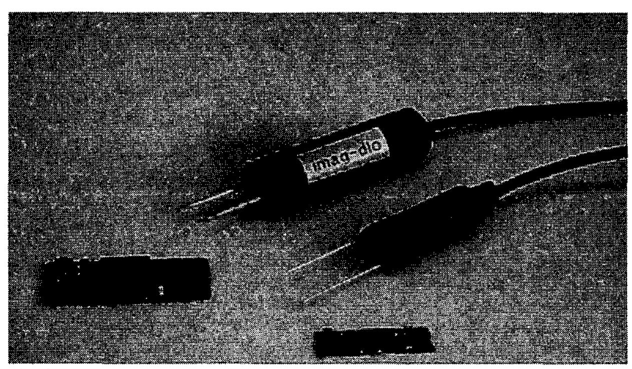

Fig. 8. Mounted PCB-board with ASIC (left) and smaller version (right), with a glued and sealed non-packaged die version of the ASIC, together with the encapsulated sensors.

The operation of the data processing and the calibration routines were emulated and tested with a PC in a simple RS232 multiplexed network set-up. To test the field-bus application, a LONWORKS® based application was developed in which the ECHELON processor served as the embedded processor.

Sensor Calibration

The sensor was calibrated by determining the ε and σ scales and the electrical path length compensation parameters by measuring impedances with reference values of air and tap water ($\sigma \approx 0.0017$ S/m) and with water of two other conductivities (0.1 S/m and 0.2 S/m). The permittivity scale is calibrated between $\varepsilon = 1$ for air and $\varepsilon = 80.3$ for tap water at 20 °C. Permittivity scaling data shall be independent of σ. The conductivity scale is determined for $\sigma = 0$ in air and $\sigma = 0.2$ S/m in water. The series inductor for the electrical length compensation is found from the measurements in water at $\sigma \approx 0.0017$ S/m and $\sigma = 0.2$ S/m. Water with a value of 0.1 S/m is used to adjust the series resistor such that the capacitance readings for the three conductivities are equal. The calibration procedure was guided by PC-software, which yields the dielectric calibration data that can be downloaded into the embedded memory.

Sensor validation showed that permittivity can be measured with an accuracy of ± 0.5 on a scale of 1–80. The resolution is even better. The accuracy for soil water content depends on the user calibration, the variability of the soil and the density. For some typical soils used in horticulture, the accuracy for the soil volumetric water content found was ± 5%. After calibration for a specific soil like sand, ± 1% is achievable. The range for conductivity is 0 – 0.2 S/m for soil and 0 – 0.5 S/m for mineral wool. The resolution is ± 0.01 S/m, within a temperature range of 0 to 50 °C.

In small micro-processor applications, for instance when using 8-bit routines, the accuracy of mathematical computations is low. The firmware for the micro-processor was altered in such a way that truncation effects were minimized.

IV. CONCLUSION

It was shown that an intelligent dielectric sensor for soil water content, conductivity and temperature which interfaces with a computer system through a field-bus could be built. The sensor incorporates an application specific integrated circuit to measure dielectric properties, a micro-processor and calibration data memory. The theory of its operation, and the hardware and firmware involved were described briefly. Several prototypes of the sensor were tested. A LONWORKS network application was built. It is possible to implement the sensor in agricultural, environmental and industrial monitoring and control applications in a fairly easy way.

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