Wireless Soil Moisture Sensor Based on Fringing Capacitance

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***Abstract*—A soil moisture sensor was developed which was based on fringing capacitance and the increase in dielectric constant of a soil-water mixture with water content. The frequency shift of an RC oscillator connected to the capacitance sensor electrode was measured by a microcontroller. The data, in IEEE 1451 format, is communicated by a built-in RF transmitter (433MHz) to a receiver or base station for logging and display. This battery-operated sensor/transmitter is expected to have an operational life of several years.**

I. Introduction

Soil moisture measurements provide useful information for agriculture, such as grape growers, soil stability monitoring, dam monitoring and construction activities. Wireless sensor data monitoring is much less labor intensive than periodic sampling by workers for most applications. Updates need be done only infrequently (e.g. daily), and only with moderate accuracy, but monitoring is often needed over a wide area and for long periods. An array of widely dispersed battery-operated wireless sensors is ideal for that application. To conserve battery power and lower costs, brief intermittent RF transmission is employed.

A capacitance sensor to measure soil moisture has been developed. It has good resolution and reproducibility, which allows trends in moisture changes to be tracked.

We believe that the data format should conform to an open standard and we have used the IEEE 1451.4 standard for the sensor/transmitter which is converted to IEEE 1451.5 format at the receiver.

II. FRINGING CAPACITANCE MOISTURE SENSORS

The dielectric constant of materials or mixtures containing water increases markedly with moisture content because the dielectric constant of water (about 80) is 10 to30 times higher than the common materials in which it is adsorbed or mixed, as discussed in more detail below. A capacitor with a mixture as the dielectric will display a significant, and proportional, capacitance increase with moisture content. However, the dielectric constant, and thus capacitance, is a non-linear function of the moisture content (usually expressed as a percent by volume) at least in soil, grain and other lossy materials.

Rather than use the well-known parallel plate capacitance configuration, a fringing field capacitance (Fig. 1) is used in order to project the sensing electric field into the surrounding material [6]. Its equivalent circuit (C_s) is a capacitance (C_X) proportional to the material dielectric constant in parallel with a fixed capacitor (C_0), which is due to the portion of electric field lines, which do not pass through the material.

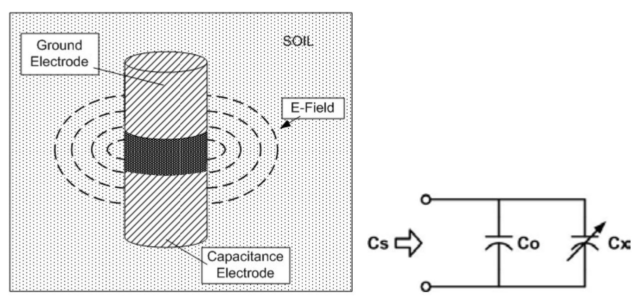

Figure 1. Capacitance Sensor Fringing Electric Field and Equivalent Circuit

III. Dielectric Constant Dependence

The dielectric constant of soil, and other materials which are mixtures of particles and water (including organic materials such as grain and wood), have been modeled theoretically [3,4,5]. The results are summarized in Fig. 2 and Fig. 3. The dielectric constant (ε) increases with water content (by volume), but is non-linear (Fig. 2) and also depends on these three other factors: frequency, conductivity and particle size. Soil conductivity is due mostly to the salt concentration (as well as water content) of the soil.

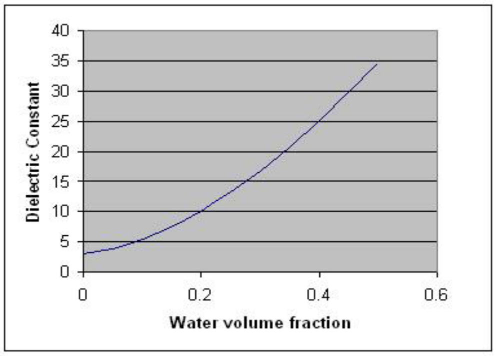

Figure 2. Dependence of Dielectric Constant of a Mixture on Water Content

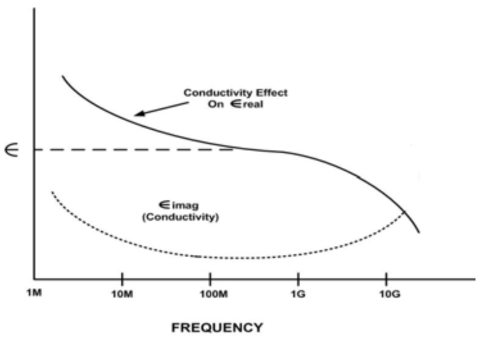

Figure 3. Typical Dependence of Dielectric Constant on Frerequency

The influence of conductivity on the dielectric constant (real part) is much greater at lower frequencies and thus a higher sensor operating frequency (5 to 500 MHz) is desirable. At higher frequencies the contribution of conductivity becomes small but for larger sample sizes, which are needed for soils with large aggregates, inductive effects can cause significant errors, at least with fringing capacitance sensors. To avoid these errors, we have chosen an operating frequency of 10 MHz even though some conductivity effects remain.

Because of the various soil-dependent parameters, the curves relating dielectric constant (and thus capacitance and frequency shift) to moisture content will vary with soil type so that calibrations for specific soils will be needed for high accuracy.

IV. FREQUENCY SHIFT OSCILLATOR

Sensor capacitance changes can be conveniently and accurately measured by a frequency shift oscillator [1]. This approach was used in an older paper on frequency shift soil moisture sensors [2] where it was pointed out that, to avoid the adverse effects of the high loss (or high conductivity) of soils on the oscillator circuit, a T-coupling network is desirable, if not necessary. This is also used here (Fig. 4). The capacitance change at the output (oscillator side) is an order of magnitude less than the input (soil side), but the conductivity change is two orders of magnitude less (the desired effect). Even this smaller capacitance change, and thus frequency shift, can easily be measured precisely with a standard microcomputer.

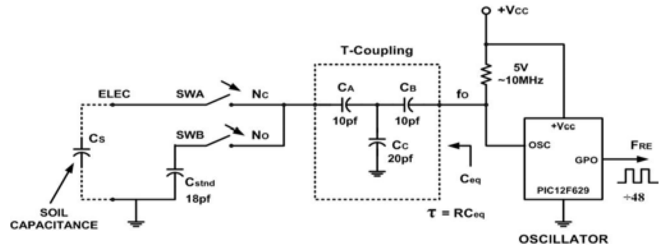

Figure 4. Frequency Shift Oscillator Circuit with Capacitance T-coupling Network

Rather than use a conventional LC oscillator (e.g. Colpitts), we have chosen to use a small microcomputer RC oscillator for simplicity, low cost, and ease of interfacing to a readout microcomputer. The oscillator frequency (F_o) is inversely proportional to capacitance and is nominally 10.5 MHz. An internal frequency divider by 48 (software) produces an output (FRE, nominally 218 kHz) which is proportional to Fs. Its frequency shift, which is proportional to the sensor capacitance change, is measured by the second microcomputer. Frequency shifts (ΔFs) are typically in the 2 to 8% range.

Because of temperature effects and component variations, the oscillator frequency will drift with time. To compensate for this, an analog switch (SWA) disconnects the capacitance sensor so that the oscillator base (or zero) frequency Fob can be determined. When the sensor is connected, the resulting frequency Fos is converted to a frequency shift $\Delta Fs = Fob - Fos$. Typically, ΔFs range is +5 to +50 KHz. The calibration process if further refined by comparing a precision (1%) standard capacitor (C_{stnd} = 18 pfd) in place of the sensor (SWA off, SWB on). The results frequency shift is ΔFc and all sensor readings are normalized as:

$$Y = \frac{\Delta Fs}{\Delta Fc} = \frac{Fob - Fos}{Fob - Foc} - Yo$$

Where Y is the sensor response in air (rather than in soil). Thus for a sensor capacitance (Co + Cs) equal to $C_{stnd,,}$ then Y = 1.0.

V. MAIN MICROCONTROLLER

The main microcontroller (12F675 [8]) controls the two analog switches, read in the oscillator frequency, calculates the frequency shifts, encodes the data, and controls the RF transmitter (Fig. 5). It also sends the TEDS or ID information (see IEEE 1451), controls the sleep mode, and monitors the battery voltage.

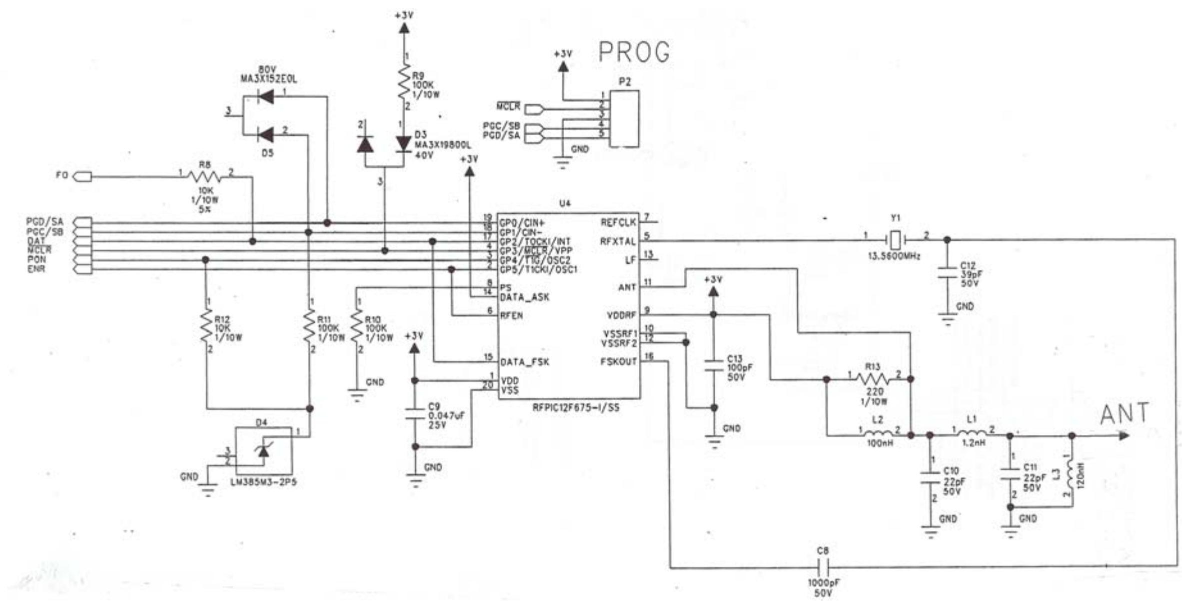

Figure 5. Microcontroller with RF Transmitter Circuit Diagram

Specifically the value of Y is calculated and transmitted. It is converted to % moisture by volume at the receiver.

VI. Wireless Transmitter and Receiver

The RF transmitter is the RF part of the Microchip (RF-PIC). It is configured for FM at 433 MHz. Data is Manchester encoded at about 9600 bits/sec. The receiver section (part of a CC1000 transceiver) converts the FM data to digital form. It is converted further to RS232 serial format by a microprocessor (16F873) which is connected to a standard PC for display.

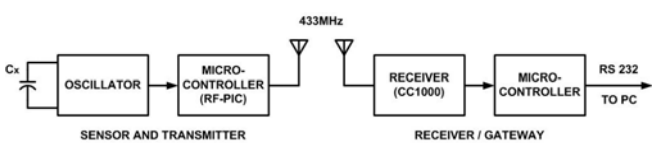

Figure 6. Block Diagram of Transmitter and Receiver

The transmitted data has the following format (each character is one byte):

PPPPPPSSIIAADDDDQ

where P is a preamble, S a sync character, I an identification, A an address, D the data (e.g. Y) and Q a trailer.

Upon power up, the TEDS information is sent instead (see IEEE 1451 section).

VII. Sensor Probe Construction

The sensor electronics consists of the oscillator and the microprocessor with RF transmitter are constructed on a long, thin circuit board (Fig. 7) which is placed inside a stainless steel tube (5/8" or 15.9 mm dia). At one end is the capacitance sensing electrode, specifically a separate section of the tube with an insulating gap between it and the rest of the grounded tube. The fringing field is across the gap between the end electrode and grounded case (Fig. 1). At the opposite end is an antenna jack (SMA). The antenna (433 MHz quarter wave) may be connected directly to the jack or through a coax (required for fully buried sensor). Between the jack and circuit board within the tube or case are two AAA batteries to provide the power.

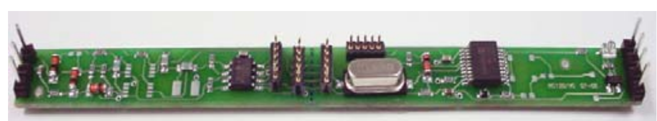

Figure 7. Sensor Printed Circuit Board

A photograph of the completed sensor is shown in Fig. 8.

Figure 8. Photo of Soil Moisture Sensor in Case

VIII. IEEE 1451 TEDS and Data Protocol

An IEEE 1451.4 (Dot4) format Transducer Electronic Data Sheet (TEDS) was used for the identification except that another UUID (MAC address) replaces the 1-wire type usually used. An example of the code is shown in Fig. 9.

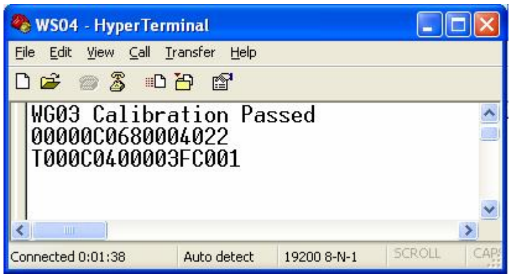

Figure 9. TEDS Display

The Dot4 standard [9] does not specify the data format. A standard 4-byte IEEE floating point format was used for the frequency shift data (Y).

Within the receiver or gateway, the data (optimally) is converted to the more capable IEEE 1451.5 format for re-transmission [10]. An Internet (via Ethernet) gateway was also demonstrated.

IX. TEST RESULTS

The measured frequency shifts, normalized as the parameter Y (relative to the standard capacitor shown in Fig. 8) for a specific soil. It did follow the expected response (Fig 2) but it should be recognized that the sensor must be calibrated to fit specific soils.

The range of the RF is 30 to 100 meters, depending on the antenna.

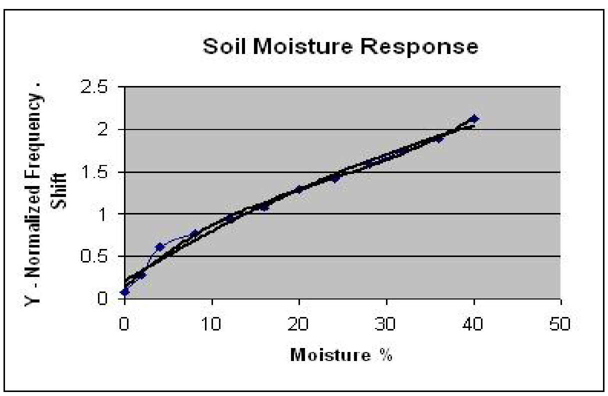

Figure 10. Sensor Response

X. SUMMARY AND CONCLUSION

The frequency shift capacitance sensor was shown capable of measuring soil moisture over a wide range (0 to 45% by volume) with good reproducibility. The moisture data was transmitted wirelessly (433 MHz) using an IEEE 1451 compatible format, received by a gateway and display on a computer.

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