Design and Characterization of a Low-Power Moisture Sensor from Commercially Available Electronics

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***Abstract*—This paper discusses the design and development of a custom soil sensor made from off-the-shelf electronics. The output of this sensor is correlated to the water content in two types of agricultural soil: sandy and loamy. Two popular industrial soil sensors are used to determine if the repeatability and accuracy of this custom sensor fall within commercial standards. Experimental results indicate that the custom sensor performs similarly to the commercial sensors in terms of repeatability and accuracy but consumes approximately 10x less energy per measurement. This custom sensor will eventually be used in conjunction with a wireless power transfer system for underground *in-situ* moisture measurements.**

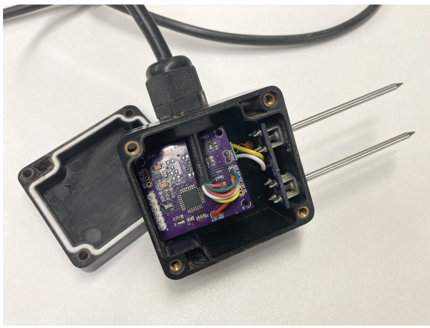
***Index Terms*—Soil moisture, moisture sensor, energy-efficient sensor.**

I. Introduction

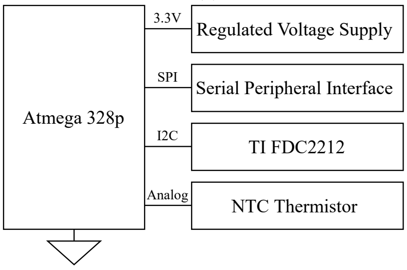
Global shortages in freshwater resources have driven the agricultural sector to use historically uncommon water sources such as reclaimed and coastal water reservoirs [1]. These water supplies often raise concerns over how unknown factors such as contaminants and excess salts affect soil quality. Given the lack of data on these water sources, it is essential to monitor how each source impacts soil health before long-term crop yields can be significantly affected. One proposed solution to this need for monitoring is to install underground *in-situ* soil condition sensors. Fully underground sensors are desirable because they are not damaged during field operations as often as sensors with protruding wires and antennas. However, given the problems associated with powering underground electronics [2], these sensors should consume very little power while maintaining accuracy and economic feasibility. The following work reports on the development of a low-power soil moisture sensor made from commercially available electronics. This sensor will eventually be incorporated into an underground *in-situ* sensor network that is wirelessly powered.

Most high-accuracy soil sensors operate by measuring changes in the dielectric permittivity of soil samples [3]. Since the difference in relative permittivity between minerals ($\epsilon_r \approx 6$) and water ($\epsilon_r \approx 80$) is so large, any additional water content in a soil sample causes the dielectric constant of the soil to increase significantly. Sensors often differ in their approach (time-domain reflectometry, impedance, solid-state sensors, etc.), but almost all fundamentally measure changes in the dielectric properties of the soil. The Utah custom soil sensor (Fig. 1) introduced in this work is built around a commercially available capacitance-to-digital converter, the TI FDC2212. This device operates by measuring how the sensor input shifts the natural frequency of an RLC oscillator circuit. In the custom soil sensor, the operating principle of the FDC2212 is utilized to measure soil moisture by connecting the sensor inputs to two stainless steel probes. These probes can then be inserted into a soil sample to measure the capacitance and, therefore, the dielectric permittivity of the soil. The custom sensor also includes an on board NTC thermistor to help compensate for the effects of temperature on the output of the capacitance sensor. Capacitance and temperature data are processed in the custom sensor using an Atmega328p, a microcontroller popular in the Internet of Things (IoT). Both the FDC2212 and Atmega328p can be run with low current during active use (2.1 mA and 10 mA, respectively) and have low-power modes to which the sensor can default during periods of inactivity. However, given the novel application of the FDC2212 as a soil sensor, it is necessary to evaluate its performance against soil sensors currently in use: the Delta-T ML3 ThetaProbe and the Acclima TDR-310H. The Delta-T ML3 measures moisture using soil impedance measurements and reports an accuracy of $\pm 1\%$. Meanwhile, the Acclima TDR-310H operates using time-domain reflectometry but also reports an accuracy of $\pm 1\%$. This work examines the custom sensor's performance (i.e., accuracy and repeatability) using field soil samples and compares that performance to the output of the two commercial soil sensors.

The rest of the paper is organized as follows: Section II discusses the methods used to characterize the custom sensor, Section III presents experimental results, Section IV provides a discussion of these results including how they compare to commercial soil moisture probes, and Section V discusses future works.



(a)



(b)

Fig. 1. Custom soil sensor: (a) photograph and (b) high-level design schematic.

(a)

(b)

(c)

(d)

(e)

Fig. 2. Custom sensor embedded in sandy soil: (a) 0.98%, (b) 10.73%, (c) 30.6%, (d) 40.2%, and (e) 44.8% water by volume.

II. Methods

The methods presented in this paper are largely an adaptation of the procedure discussed in [4]. Sensor performance was examined in sandy (74% sand; 12% silt; 14% clay) and loamy (25% sand; 50% silt; 25% clay) soil testbeds. Soil composition values were provided by Utah State University Analytical Labs. Each soil sample was processed using a 2 mm ISO test sieve (ISO 565) to achieve a more uniform particle size and filter any impurities. The sieved soil samples were then left to air dry for several days (three and seven days for the sandy and loamy, respectively) on two large, flat pallets.

After air drying, 3000 mL of loose, sandy soil was packed into a large testbed. A cylindrical core sampler was then used to collect two 6 mL samples of soil from the top of the soil wall. Each core sample was weighed and stored for later use. The probes of the custom capacitance sensor were then pushed vertically into the top of the packed soil. An additional 1000 mL of soil was then packed on top of the sensor. After taking several moisture measurements, the top 1000 mL of soil was removed, the sensor was inserted into a different location, and the sensor was buried again. This process was repeated three times for each of the three sensors (custom, Delta-T, and Acclima). Since the Delta-T sensor reports an estimate for mineral and organic heavy soils, both values were processed. The soil was then moved to a larger mixing bucket and mixed in with 400 mL of deionized water. Using deionized water prevents the salinity of the soil from changing significantly. The entire process of obtaining core samples, packing the soil, and making moisture measurements was then repeated at this new moisture level. In total, five moisture levels were tested. Each new moisture level introduced an additional 400 mL of water to the soil sample. Fig. 2 shows the sandy soil volume at various moisture levels. By the final iteration of water addition, the sandy soil became completely saturated. An identical procedure was used to test the loamy soil sample. Once all measurements had been completed, the core samples were baked at 70°C for three days. The baking process removes all water from the soil. The 6 mL soil samples were then weighed to estimate the actual volumetric water content of the samples by dividing the change in the sample's mass with the density of water ($1\ \mathrm{g} \cdot \mathrm{cm}^{-3}$).

After the samples had been baked and weighed, the data obtained from the sandy and loamy tests were used to generate a best-fit relationship that maps the custom sensor's output to the moisture content of the soil. The best-fit relationship was then tested by repeating the measurement process on a new mass of sandy soil (74% sand; 12% silt; 14% clay).

III. Results

Fig. 3.a shows the output of the custom soil sensor as a function of volumetric water content for both soil types. The sensor demonstrated consistent performance despite changes in soil type and bulk density (Fig. 3.b). Bulk density is an indicator of soil compaction. In the sandy and loamy tests, the bulk density of the soil increased since the soil became easier to compress at higher moisture levels. Although additional tests across different soil types will need to be performed, the data from this correlation study is sufficient to create a cubic best-fit relationship between the sensor output (x, as a proportion of the full-scale range) and the moisture level (θ_v, in percent volume) of the soil:

$$\theta_v = 101.0 - 4.74x + 0.0685x^2 - 0.000332x^3 \tag{1}$$

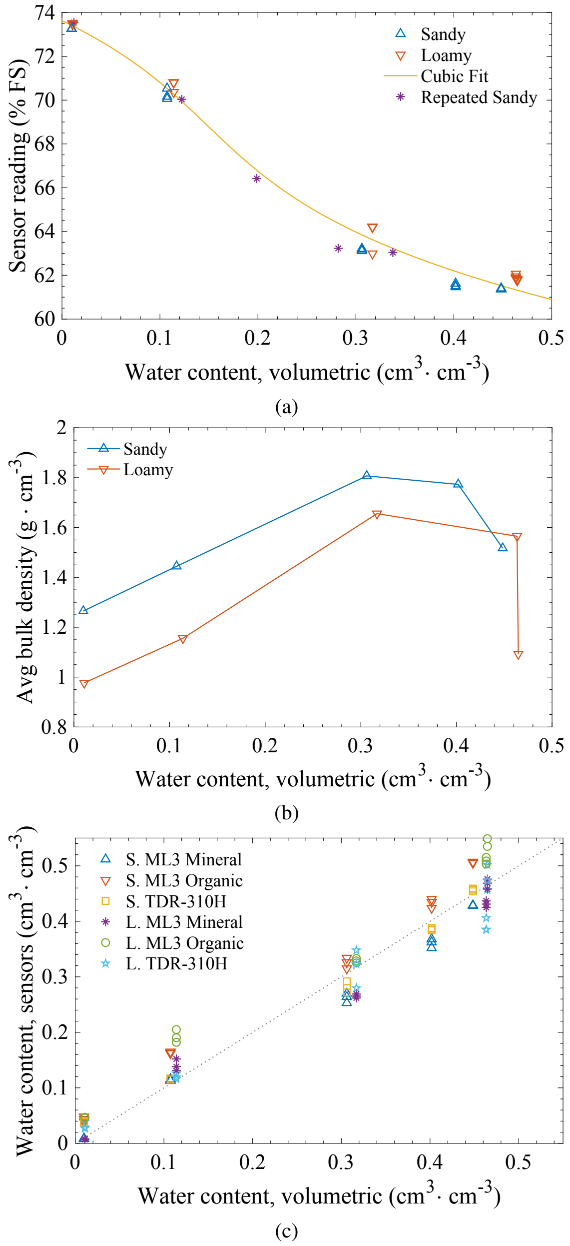


Fig. 3. Test results: (a) custom sensor output, (b) soil bulk densities, and (c) commercial sensor readings in sandy (S.) and loamy (L.) soils as functions of volumetric water content.

Using the relationship from (1) and the second sandy soil study results, the custom sensor predicted the soil's volumetric water content within 1.745% (0.01745 $\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$) of the value recorded by baking and weighing the soil samples.

IV. Conclusions

Table 1 shows the average variance and error calculated using the data in Fig. 3.a and Fig. 3.c. The average variance is calculated by averaging the variance in sensor readings (as a proportion of the full-scale range) at every moisture level in both soil types. The average error is calculated by subtracting the measured soil moisture level (in percent volume, measured by baking and weighing the samples) from the sensor readings (in percent volume) provided by the ML3 and 310H sensors. Similarly, the mean error for the custom sensor is calculated by inserting the sensor readings from the second sandy soil trial into the best-fit curve and comparing the output to the measured water content. Overall, the custom sensor shows similar performance to the commercial sensors. The spread of output data from the custom soil sensor remained tight at every moisture level in both sandy and loamy soil. However, the variance of the custom sensor appears artificially low in this comparison because the sensor only used 12% of its full-scale range, while the commercial sensors used roughly half their full-scale ranges during these tests. From the values posted in Table 1, the error of the custom sensor is similar in magnitude to the commercial sensors. The error of the custom sensor will likely improve as more data are collected and incorporated into the best-fit relationship used to predict volumetric water content (1).

Throughout these tests, the power consumed by the custom soil sensor was monitored using a digital multimeter. At no point during testing did the sensor draw more than 12 mA (at 3.3 V) with a mean conversion time of 150 ms. Given these sensor characteristics, each measurement should only consume 6 mJ per measurement. Therefore, the energy consumed by this custom sensor is at a minimum 13x less than the TDR-310H (80-120 mJ [5]) and 7.5x less than the ML3 ThetaProbe (45-252 mJ [6]) in their most efficient configurations. This drop in energy consumption represents a significant improvement over the commercial soil sensor. A more energy-efficient microcontroller could further reduce the energy consumed by the sensor.

TABLE I
Average Variance and Error Values for ML3 Mineral (M.), ML3 Organic (O.), Acclima TDR-310H, and Custom Soil Sensor Readings in Sandy (S.) and Loamy (L.) Soils.

Average	ML3 M.	ML3 O.	310H	Custom
S. Variance	0.350	0.413	0.261	0.01451
S. Error	2.20%	4.00%	1.790%	1.745%
L. Variance	0.557	0.743	1.217	0.1143
L. Error	2.32%	5.06%	2.66%	NA

V. Future Work

The largest improvement that can be made to the current iteration of the custom soil sensor involves making better use of the low-power functions on both the microcontroller and capacitance-to-digital converter. These software improvements will help reduce the active and idle power consumed by the custom sensor. Likewise, future iterations of the custom soil sensor will include hardware modifications to further reduce power consumption. In addition to improvements in the custom sensor's software and hardware, additional correlation and characterization studies need to be conducted with the custom sensor across different soil types, temperatures, and salinity levels. Lastly, the improved sensor will be used in conjunction with the wireless power transfer system developed in tandem with this device for *in-situ* soil condition monitoring.

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