A Reconfigurable Multi-Sensor Based on Printed Circuit Board Technology for Measuring Moisture Content and Temperature in Stored Grain

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***Abstract*—We present the design and fabrication of a reconfigurable smart-sensor for measuring moisture content and temperature in grains stored in silos, using a capacitance fringing field interdigitated sensor and a using a Resistance Temperature Detector (RTD), both implemented on a single conventional printed circuit board. The sensor was tested in laboratory, using corn kernels with percent moisture content (MC) in the range of $MC = 8\%$ to $MC = 32\%$ and, using a simple relaxation oscillator and a frequency-to-voltage converter, we measured a capacitance variation of $\Delta C = 4.99$ pf, with a sensitivity $S = 0.21\,\mathrm{pF}/\%\mathrm{MC}$. The RTD sensor, which uses the copper resistance of the PCB tracks, was characterized in the $10\,^{\circ}\mathrm{C}$ to $50\,^{\circ}\mathrm{C}$ temperature range, and the measured results presented a very linear behavior ($R^2 = 0.99888$) when compared to the measured temperature values using a commercial sensor (LM135). A modified bridge circuit was developed, where a linear behavior of the differential output was obtained. The developed configuration allowed for the independent adjustment of both the offset and the gain in the output voltage V_{out} of the bridge. The bridge signal processing circuit was calibrated using an end-point method, and the measured points between the calibration points presented a maximum end-point non-linearity error of $|E_{nl}| = 0.64\,^{\circ}\mathrm{C}$.**

***Keywords*—Multi-sensors, grain storage, capacitive sensors, temperature sensors, PCB sensors, low-power circuits.**

I. Introduction

ESTIMATION of the moisture content (MC) in grains and nuts plays an important role in harvesting, storage and processing of agricultural products such as corn, wheat, and peanuts [1]. Successful storage of dry grain for long periods of time depends on the kernel moisture content. It is estimated [2] that, at $T = 15.5°$C, corn kernels with 19% moisture content can last about 35 days, while at the same temperature, but with a reduced moisture content (17%), the allowable storage time is more than doubled, reaching up to 75 days. After a few days in the silo, if there is no air circulation, the air surrounding the grain will reach an equilibrium in temperature and in what concerns temperature and humidity, providing an excellent environment for the development and proliferation of mold and insects [3].

A commercial device (CTR-800) for measurement of MC in rice, wheat, and barley was presented in 1986 by Shizuoka Seiki, , Fukuroi, Japan. This type of MC tester was modified by [4] to be used with corn. It works by measuring the electrical conductivity of single-kernel as they pass between crushing rollers. An updated version of the CTR-800 (the CD-6E model), which can measure sixteen types of grains, was developed by Shizuoka Seiki, and it is currently available in the market. It is a portable instrument that can measure a sample with a few grains (instead of a single-grain) but, as in the previous version, it is a destructive method.

Capacitive sensors are used in many applications such as: intravenous fluid monitoring in hospitals [5], nondestructive *in situ* detection of the kernel moisture content in corn ears in the field [6], water pollution [7] and dairy products [8]. Since there is a high correlation between the MC of the grain and its dielectric constant, methods that measure capacitance, dissipation factor and phase angle of parallel plate capacitors have been successfully demonstrated to measure MC in grains [9], [10], [11]. However, these presented methods can measure only a single grain kernel.

An improvement over the capacitive single-grain methods, a hand-held instrument adequate to measure small portions of kernel samples, was presented by Kandala et al [1]. It used a parallel-plate capacitor, with 50 mm of diameter, so that samples with seven kernels could be measured. The prototype was tested with samples of peanut kernels (which must be inserted between the plates) and an electronic circuit measured the complex impedance of the parallel-plate capacitor. A commercial device (MT-16, from Agratronix, Streetsboro, Ohio, USA) uses the capacitive method to measure the MC of 16 different grains, seeds and beans. The sample had to be inserted manually into a measuring cylinder and a high frequency capacitive measurement circuit used a calibration curve to correlate the measured capacitance with the MC of the sample. It is important to observe that, due to their structures, none of these sensors could be installed inside silos. Other

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technologies (photoluminescence [12] and electromagnegtic imaging [13]) could measure the MC of grains inside a silo, but are very expensive. Some authors measure the relative humidity (RH) of the air inside grain trailers [14] or in silos [15], and correlate the measured value of RH with the grain MC.

Sensors fabricated based on PCB technology are easy to fabricate, low-cost and robust.The PCB capacitive interdigitated fringing field sensor has been used in many applications: detection of ice events [16], water pollution [17], detection of water [18], [19] and irrigation management [20]. From a dual heat pulse probe soil moisture sensor [21] to a capacitive interdigitated fringing field sensor to measure water content in paper pulp [22].

Recently, in [23] it was demonstrated that PCB capacitive fringing field capacitive sensors can be used to measure MC in corn kernels. The PCB sensor technology is an excellent choice to be used inside a silo: it is robust, and allows for a large sensing area. Another important feature of this technology is that it is low-cost, and tens of sensors can be used to provide an accurate profile of the MC along the whole silo.

The temperature also plays an extremely important role in the maximum storage time of the kernels, since corn with 17% moisture content stored at $T = 26.5$°C can be stored for only 20 days. But if the temperature is reduced to $T = 4.5$°C, the storage time increases to approximately 280 days.

Therefore, to slow mold growth and inhibit insect activity, both the MC and the temperature of the grain must be controlled, and a technique called grain aeration provides a powerful tool for stored grain management. The aeration process has typically four regions of operation, designated as: aeration maintenance, aeration cooling, aeration drying, and aeration hot air drying. To implement the grain aeration techniques it is necessary to measure both MC and temperature with uniformly distributed sensors along the silo, providing the required information to implement aeration systems with heaters and fans that create air-paths inside the silo that, at the same time, cool and dry the grain, delivering a storage environment that can maintain the grain quality for a long period.

In this paper, we present a smart multi-sensor based on PCB technology, that can measure both the moisture content and the temperature of the grain inside a silo. The proposed system presents many advantages that are not found in the aforementioned works:

1) The sensor is very robust for use inside a silo, since it consists of a conventional FR-4 PCB board;
2) it is very reliable, since the sensing elements are the copper tracks of the PCB, which are used to measure both MC (capacitance) and temperature;
3) it has a large sensing area, allowing for averaging the MC of a large number of kernels;
4) since it is a smart-sensor, with all electronics implemented on the same PCB of the sensor (including a microcontroller), a two-wire communication protocol can be easily implemented, reducing the complexity of the cabling inside the silo. A silo with 30 m in height, with one sensor at every 1 m, would require 30 pairs of MC and temperature sensors at every measuring point. If we assume that all pairs of sensors receive the same wires for the power supply (V_{bat} and GND), each pair requires two additional wires: one wire for transmitting the value of the MC sensor and one wire for transmitting the value of the temperature sensor. Thus, one would need more that 60 wires running along the silo.
5) The microcontroller allows for the transmission of digital signals, which can easily be sent over long wires. For example, if a RS-485 transceiver is incorporated in the smart-sensor, the signals can be transmitted over distances up to 1200 m;
6) due to its low-cost, tens of sensors can be installed in a silo, providing an accurate MC and temperature profile of the silo, allowing for the implementation of precise aeration techniques;
7) a simple novel bridge configuration allows for the temperature measurement of a copper RTD with very small sensitivity ($dR_T/dT = 21.07$x$10^{-3}\,\Omega/$°C);
8) The reconfiguration of the sensor (capacitance x temperature) is made on-the-fly, with a simple dual pole double throw (DPDT) relay;

This article firstly describes how capacitive fringing field capacitive sensors can be used to measure MC in corn kernels, presenting the advantages of such sensors when used inside large silos. Next, it proposes a modification in the conventional structure of the interdigitated fringing field capacitive PCB sensor, demonstrating that with the modified structure we have, using the same PCB tracks, can be both a capacitance and a temperature (RTD) sensor. Section III presents the developed measuring circuits, with a novel resistive bridge structure used to measure temperature, and a simple time interval technique, which uses two oscillators and a single frequency-to-voltage converter to measure capacitance values. In the same section it is also shown how the reconfiguration of the sensor can be done, using only one dual pole double throw (DPDT) relay. In the Experimental Results section, we present the characterization measurement of the PCB RTD and the measured results with the novel bridge structures, for RTD values between 0 and 47.5°C.

II. Principle of Operation of the Proposed Capacitive and Temperature Sensors

A. Principle of Operation of Fringing Field Capacitive Sensors

A conventional PCB fringing field capacitive sensor is composed of interdigitated coplanar electrodes (usually called fingers), made with the copper tracks of a PCB, as shown in Fig. 1. The capacitance of a structure with fingers of length l, distance between two fingers d, thickness of the copper h, and n fingers, is given by:

$$C \approx \epsilon_0 \epsilon_r \frac{nlh}{d} \tag{1}$$

where ϵ_0 and ϵ_r are, respectively, the permittivity of free space and the relative permittivity of the dielectric material between two fingers. A correction factor in (1) may be necessary if the condition $lh >> d^2$ is not met, but with usual values used in these sensors this is not necessary.

When the material which is in contact with the PCB changes its ϵ_r (for example, the corn grains in contact with the PCB losing moisture), the sensor's capacitance changes and these variations can be related to the moisture content in the grains [23].

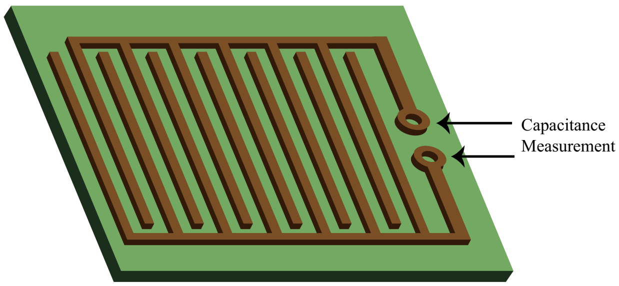

Fig. 1: Conventional PCB fringing field capacitance sensor.

B. Principle of Operation of Resistance Temperature Detectors

Resistance temperature detectors (RTDs) consists of a metal wire (or a thin film), typically platinum or copper, used to measure temperature. These metals have a very well-known resistivity and a positive resistance temperature coefficient. If the resistance R_0 of the wire at a given temperature is known, then by measuring the change in resistance due to a temperature change, it is possible to calculate the temperature.

The most common way of measuring an RTD is by passing a constant current through the resistance and measuring the voltage drop across it, usually using an instrumentation amplifier.

III. Proposed Reconfigurable Smart-Sensor for Measuring Temperature and Moisture Content

We designed a modified capacitive sensor and, instead of using an interdigitated structure, we used two long copper tracks that run side by side through the whole surface of the PCB [24], as shown in Fig. 2.

The modified structure of the tracks in the PCB fringing field capacitor has a very important feature: since the new structure has very long and thin copper tracks, we can use the resistance of these tracks as an RTD, to measure temperature.

The sensor was built using a double sided 96 mm x 92 mm standard FR-4 PCB, with a thickness of 1.6 mm and copper thickness of $35.6\,\mu$m. The 100 fingers of the parallel tracks have a length $l = 90\,\mathrm{mm}$, width $w = 0.5\,\mathrm{mm}$, and are separated by a distance $d = 0.5\,\mathrm{mm}$.

A photograph of the fabricated sensor is presented in Fig. 3. Both sides of the four layer PCB (the fringing field capacitor in the bottom and the signal processing circuits in the top) were protected with a conventional polymeric solder mask.

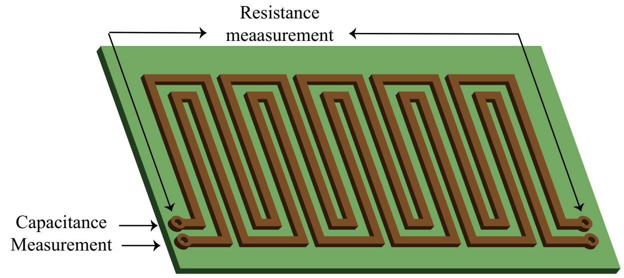

Fig. 2: Modified structure of a capacitive and RTD reconfigurable sensor.

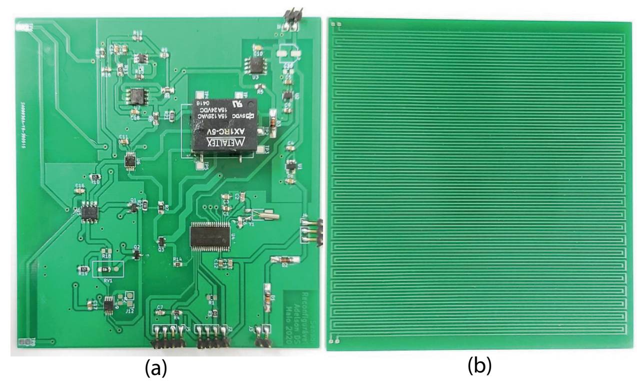

Fig. 3: Photograph of the PCB sensor with the signal processing circuits: (a) top side, with the components soldered; (b) bottom side, with the fringing field capacitor.

IV. Signal Processing Circuits

A. Temperature measuring circuit

If a material with a resistance R_i at a temperature T_i has a linear thermal resistance coefficient given by

$$\alpha = \frac{1}{R_i}\frac{dR}{dT}, \tag{2}$$

we can write the resistance of the material as a function of the temperature as

$$R(T) = R_i\left[1 + \alpha\left(T - T_i\right)\right]. \tag{3}$$

If the temperature in (3) is in °C, and for $T = 0\,°\mathrm{C}$, the value of $R(T)$ is R_0, the equation is simplified to:

$$R(T) = R_0\left[1 + \alpha T\right]. \tag{4}$$

Since the external temperature and solar radiation influences greatly the grain temperature, to slow mold growth and inhibit insect activity, aeration techniques must be employed to control the temperature variation inside the silo. Typically, the temperature must be kept in the $10\,°\mathrm{C} \leq T \leq 25\,°\mathrm{C}$ range. However, we measured our sensor using RT values equivalent to a larger temperature range (from $T = 0\,°\text{C}$ to $T = 40\,°\text{C}$), to obtain more information about the sensor.

RTDs produce small percentage changes in resistance in response to a change in temperature, and bridge circuits are an attractive alternative to accurately measure the small resistance changes [25]. Bridge circuits may be driven by constant voltage or constant current, as shown in Fig. 4(a) and Fig. 4(b).

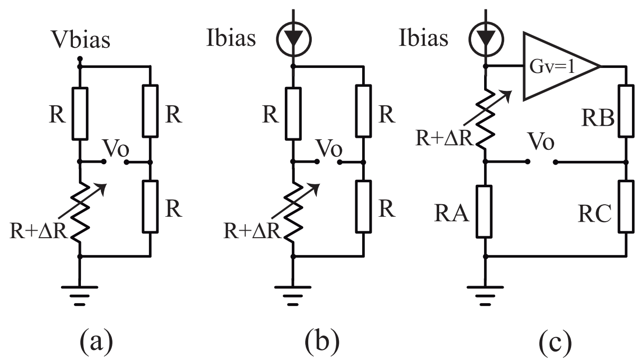

Fig. 4: Modified bridge circuit.

Both configurations present some non-linearity in the differential output voltage V_O when a single-element varying resistor is used, respectively given by:

$$V_O = \frac{R\,V_{bias}}{4}\left[\frac{\Delta R}{R + \Delta R/2}\right], \tag{5}$$

$$V_O = \frac{R\,I_{bias}}{4}\left[\frac{\Delta R}{R + \Delta R/4}\right]. \tag{6}$$

In this work we propose a modified bridge circuit, where a constant current is applied to one arm, and the voltage on this branch is transferred to the other bridge arm. This configuration is shown in Fig. 4(c).

The simplified schematic of the implemented circuit is shown in Fig. 5. The op-amp A1 (OPA2192, from Texas Instruments, USA) drives (through a bipolar transistor Q_1 used as a current buffer) the left branch of the bridge, with the RTD resistance R_T in series with a low temperature coefficient (TC) resistor R_{REF}. A bandgap voltage reference V_{REF} with initial voltage accuracy $V_{REF} = 2.5\,\text{V}\pm\,0.05\%$, 3 ppm/°C maximum temperature drift and very-low noise, $3\,\mu$Vpp/V, (REF5025, from Texas Instruments, USA) is applied to the positive input of the op-amp. A negative feedback forces the voltage on the center of the bridge left branch V_1 (that is the voltage on R_{REF}) to be equal to V_{REF}. The OPA2192 has low input offset voltage (typically $V_{os} = \pm 5\,\mu$V) and a very low drift $dV_{os}/dT = \pm 0.1\,\mu V/°\text{C}$.

The current that flows in R_{REF} is given by

$$I_0 = \frac{V_{REF}}{R_{REF}}. \tag{7}$$

If the input current in the instrumentation amplifier and in the op-amps $A1$ and $A2$ is neglected, the current I_O also flows through the RTD resistance. Since, typically, the input current in the op-amps and in the instrumentation amplifier are, respectively, $I_{bias} \approx 4$ pA and $I_{bias} \approx 70$ pA, these currents can be neglected when compared to the value of I_0 that will be used, $I_0 = 20$ mA.

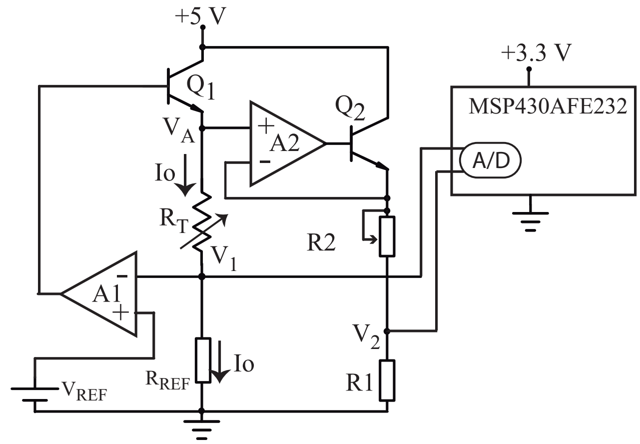

Fig. 5: Simplified implemented bridge circuit.

The voltage in the emitter of Q_1 (top left branch of the bridge) is given by:

$$V_A = V_{REF} + V_{R_T}. \tag{8}$$

This voltage V_A is composed of a constant term (V_{REF}) and a term that varies with temperature ($V_{R_T} = I_0\,R_T$). This value of V_A is sent to op-amp $A2$ (connected as a follower with Q_2 as a current buffer), and Q_2 drives the top right branch of the bridge, that is a simple voltage divider, composed of R_2, R_1. For $T = 0\,°\text{C}$ ($R_T = R_0$), the bridge must be perfectly balanced, and if we use $R_1 = R_{REF}$, this forces $R_2 = R_0$.

Thus, at the voltage divider output (V_2), we have a voltage that follows the voltage variation on the RTD (V_{R_T}), given by

$$V_2 = V_A \frac{R_1}{R_1 + R_2} = V_A \frac{R_1}{R_1 + R_0}. \tag{9}$$

The characteristic of R_T as a function of the temperature is an intrinsic property of the PCB copper tracks, and must be measured. After we measure this characteristic of $R_T(T)$, we obtain R_0 and dV_{R_T}/dT.

Since $V_1 = V_{REF}$, using (9) we can write the output of the bridge ($V_d = V_2 - V_1$) as:

$$V_d = V_2 - V_1 = \left(V_A \frac{R_1}{R_1 + R_0}\right) - V_{REF}. \tag{10}$$

This voltage $V_d = V_2 - V_1$ is sent to one of the internal differential input A/D converters of the microcontroller MSP430AFE232. The differential A/D converter was used in the 15 bits resolution bipolar mode, with 600 mV full-scale voltage. The converted values are multiplied in the microcontroller with a gain G_v, to provide a signal with the desired output scale. The output voltage calculated by the microcontroller is:

$$V_{out} = G_V V_d. \tag{11}$$

B. Capacitance Measuring Circuit

A simple and efficient method to measure a capacitive fringing field PCB sensor is the use of a time-interval technique [26]. In this paper, we use a circuit that operates based on a time-interval technique, where the frequency of a relaxation oscillator (made with the capacitance of the sensor) was sent to a LM231 frequency-to-voltage converter (FxV), filtered and read by the internal A/D converter of the MSP430AFE232 microcontroller. The simple relaxation oscillator is shown in Fig. 6.

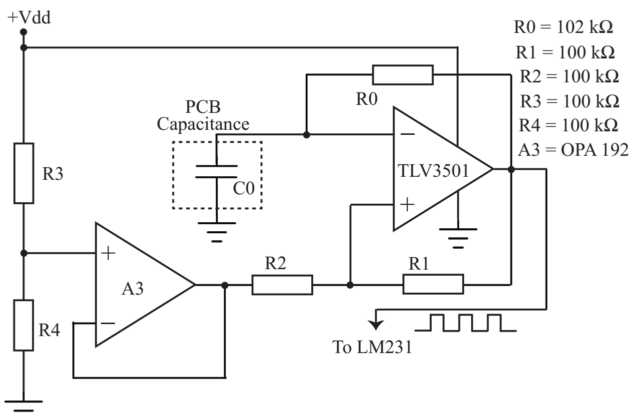

Fig. 6: Relaxation oscillator using the TLV3501 comparator.

A 40 ns propagation delay time rail-to-rail comparator (TLV3501 from Texas Instruments, USA) was used to implement a relaxation oscillator, as shown in Fig. 6. The circuit had a positive feedback through a voltage divider ($R_1$and R_2) connected to a voltage equal to $V_{dd}/2$, set by the voltage divider $R_3 - R_4$ and op-amp A3 (with $R_3 = R_4$).

Assuming that the rail-to-rail comparator could reach V_{dd} and zero, a hysteresis of $V_{dd}/4$ wass added to the comparator. This defines the comparator trip points at $V_{TH} = 3V_{dd}/4$ and $V_{TL} = V_{dd}/4$. The time required to charge (or discharge) a capacitor C_{sensor} through a resistor R_0 between $V_{TL} = V_{dd}/4$ and $V_{TH} = 3V_{dd}/4$ is given by:

$$t = \left[R_0 ln(3)\right] C_{sensor}. \tag{12}$$

The square wave at the output of the comparator (with 5 V amplitude) has a frequency given by:

$$f_{sensor} = \frac{1}{2\left[R_0 ln(3)\right] C_{sensor}}. \tag{13}$$

If we have an identical circuit, but with a known capacitor C_{REF} in lieu of the sensor capacitance C_{sensor}, the frequency of this oscillator will be:

$$f_{ref} = \frac{1}{2\left[R_0 ln(3)\right] C_{REF}}. \tag{14}$$

Thus, using (13) and (14) we can write

$$C_{sensor} = C_{ref} \frac{f_{ref}}{f_{sensor}} \tag{15}$$

A single LM231 received alternately (through an analog switch SW1) the output voltages of the oscillators, generating output voltages given, respectively, by:

$$V_{out(sensor)} = k f_{sensor} \tag{16}$$

and

$$V_{out(ref)} = k f_{ref}. \tag{17}$$

Replacing (16) and (17) into (15) we can write:

$$C_{sensor} = \left(\frac{V_{out(ref)}}{V_{out(sensor)}}\right) C_{REF}. \tag{18}$$

The complete capacitive measuring circuit is shown in Fig. 7. Due to the large time constant of the LM231 output filter, the microcontroller waited 30 s before making the A/D conversion in each oscillator.

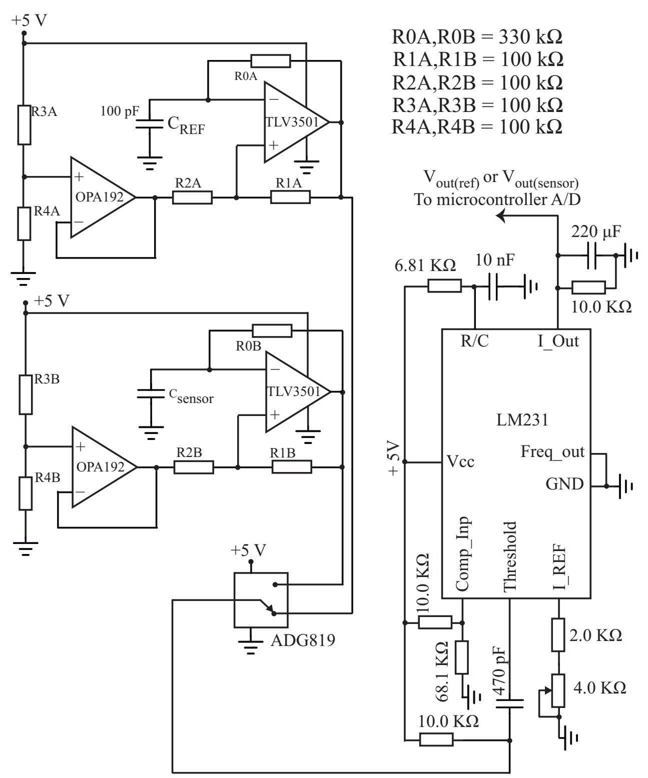

Fig. 7: Complete capacitive measurement circuit.

C. Sensors Reconfiguration On-the-fly

The copper tracks of the PCB must be connected to different circuits, depending on what is being measured: capacitance or temperature. The simplified circuit diagram presented in Fig. 8 shows how the sensor was reconfigured, on-the-fly, to make the two distinct measurements.

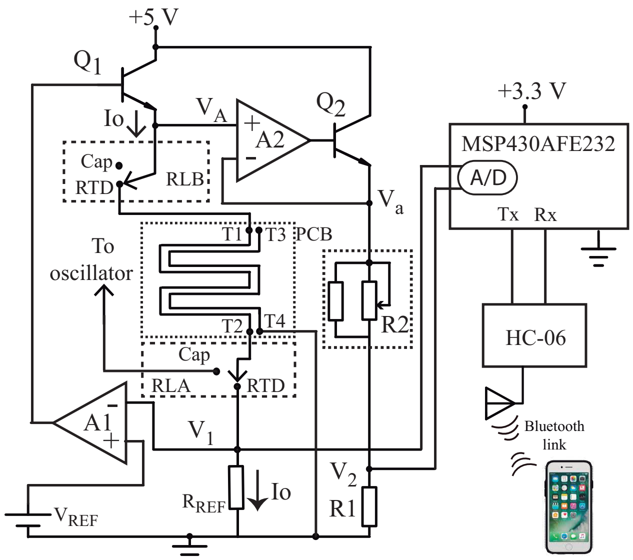

Fig. 8: Sensor reconfiguration is made with a double pole double throw miniature relay (RLA and RLB).

A double pole double throw (DPDT) PCB relay (ML2BC1, from Metaltex, Brazil) was used to reconfigure the sensor. Firstly the relay was used to connect the contacts T1 and T2 of one of the continuous copper tracks to the contacts *RTD* with RLB and RLA, respectively. This connection allowed for the temperature measurement. At the same time, another relay (not shown in the simplified diagram of Fig. 8), turned on the 5 V power supply of the analog part of the circuit and shutdown the power of the oscillator circuit.

Next, after the temperature measurement was finished, the 5 V analog circuit power supply was shutdown and the 5 V oscillator circuit was turned on. The contact T1 of the copper track was left floating (using RLB) and contact T2 was connected (with RLA) to the oscillator circuit. This configuration allowed for a capacitance measurement. Copper track contacts T3 and T4 are permanently floating and connected to ground, respectively.

The measured data stored in the microcontroller (capacitance and temperature) were transmitted to an external device (smartphone or a PC) using a Bluetooth link, with a HC-06 módule (Guangzhou HC Information Technology Co., China). The data were read in a smartphone, using the Serial Bluetooth Terminal app, available at the Google Play. The microcontroller waits for a command from the smartphone, and after it receives it, the values stored in the A/D converter are transmitted to the smartphone. The baud rate of the link was set at 115200 bps.

V. Experimental Results

A. Temperature Measurements

A temperature test was performed with the sensor inserted in a thermal chamber. The temperature was varied in the 10 to 50 °C range, and a LM185 temperature sensor (Texas Instruments, USA) was used to measure the temperature in the chamber. A plot of the measured temperature with the sensor and the LM185 temperature sensor is shown in Fig. 9. Although the copper used to fabricate the PCB tracks was not optimized for use as an RTD (we used an ordinary FR-4 PCB), the results in this small temperature range showed a very high linearity.

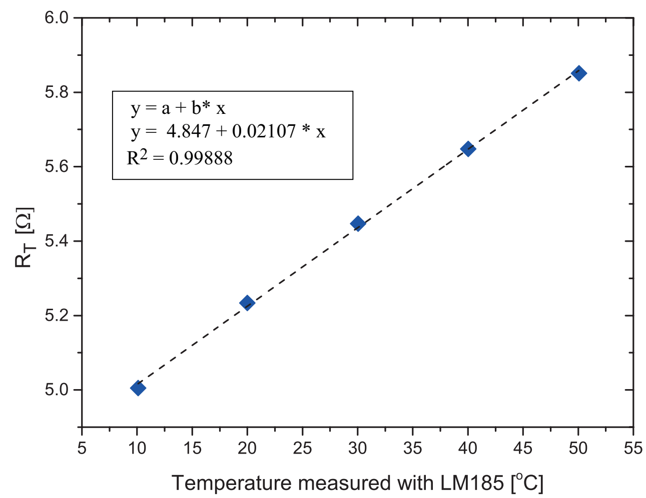

Fig. 9: Comparison of the temperature measured with the developed sensor and a LM185.

From the plot of Fig. 9 we obtain $dR_T/dT = 21.07\text{x}10^{-3}\,\Omega/°\text{C}$, and then we can write:

$$R_T(T) = 4.847 + 21.07\text{x}10^{-3}\text{T}. \tag{19}$$

This equation was used to calculate the values of R_T during the bridge characterization.

To avoid self-heating of the RTD, the power dissipated on it must be very low (a typical value for a platinum RTD-100 is 100 mW) and if the current in the copper track is $I_0 = 20$ mA, this will dissipate approximately 1.8 mW, avoiding any influential self-heating as in a conventional RTD-100.

The temperature measurement circuit included an offset adjustment, using a digital potentiometer (X9C102, from Xicor, Inc. - USA). The calibration of the bridge circuit, similar to any circuit with RTDs, was accomplished in simple steps:

i) Zero adjustment

1) Firstly, the circuit was turned-on and an internal routine in the microcontroller zeroed the offset of the A/D converter;
2) Next, a trimmed resistor was adjusted until its value was equal to the resistance of the PCB track at 0°C (R_0) and connected to the contacts of the RTD in the circuit.

With this resistor connected, the microcontroller A/D converter performed a conversion, reading the value of V_d.

3) If V_d was not zero (when perfectly balanced, V_d must be equal to zero), the microcontroller adjusted the digital potentiometer $P2$, a new A/D conversion was performed and V_d was again compared to zero. These last two steps were repeated until the measured value of V_d was zero. It is worth noting that, at $T = 0\,°$C, the digital potentiometer allowed for the zero adjustment in steps of approximately $5\,\mu$V. Since we can measure V_d with a resolution of $36.6\,\mu$V, we can consider that a perfect zero adjustment was always obtained.

ii) Gain adjustment

1) We chose $dV_d/dT = 10$ mV/°C. The resistor used in the place of the sensor was adjusted until its value was equal to the resistance of the PCB track at a higher temperature (we used $47.5\,°$C, since seed damage occurs at this high temperature), the value of V_d was measured and a line equation was calculated using this point and the zero. The slope of this line was used to calculate, inside the microcontroller, the gain G_v to obtain the correct value of $V_{out} = 475$ mV.

It is worth noting that, at $T = 0\,°$C, the digital potentiometer allowed for the zero adjustment in steps of approximately $5\,\mu$V. Since we can measure V_d with a resolution of $36.6\,\mu$V, we can consider that a perfect zero adjustment was always obtained.

The results from the measurements are plotted in Fig. 10. Since we calibrated the circuit using the zero and the full-scale point, the best method to evaluate the errors in the measured points is end-points non-linearity, The measured intermediate points presented a maximum end-points non-linearity of $|E_{nl}| = 0.64\,°$C, at $16.5\,°$C.

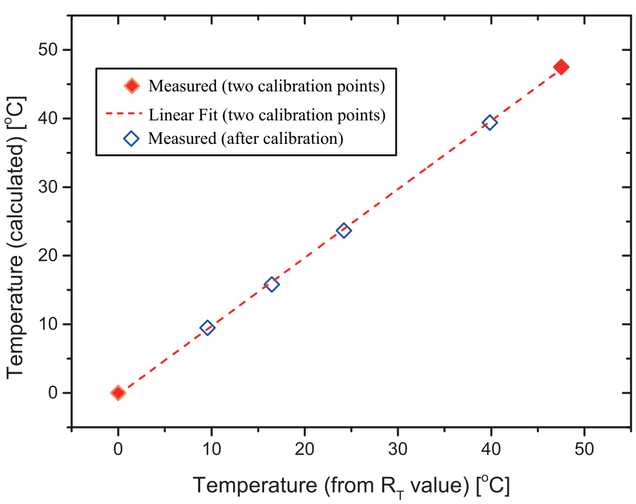

Fig. 10: Measured V_{out} as a function of the temperature (calculated with R_T values).

Since it is a novel structure, it is important to analyze how the tolerance of the components affects the performance of the circuit. As it is a relatively simple circuit, we decided to make corner analyses, considering the thermal variations of V_{REF}, R_{REF}, R_1, and R_2. In the analyses we considered that the automatic zero adjustment was made at $T = 25\,°$C and we calculated the errors at the bridge output V_D at $T = 0\,°$C and $T = 50\,°$C. It is important to observe that unmatched values of R_{REF} and R_1 do not affect the circuit performance during the zero adjustment phase, since R_2 (with its digital potentiometer) will always guarantee $V_D = 0$ when a resistor with $R_T = R_0$ is included in the sensor's position.

Therefore, the corner analyses were made considering the extreme values of $V_{REF} \pm \Delta V_{REF}$, $R_{REF} \pm \Delta R_{REF}$, $R_1 \pm \Delta R_1$, and $R_2 \pm \Delta R_2$. We considered that resistors R_{REF} and R_1 have a thermal coefficient $TC = \pm 5$ ppm/°C; R_2 is composed of a resistor R_x ($TC = \pm 5$ ppm/°C) in parallel with the digital potentiometer X9C102, which has a very high $TC = \pm 600$ ppm/°C. Since X9102 is three orders of magnitude higher that R_x, its thermal variations do not impact largely the value of R_2, that shows a variation of only a few mΩ when X9C102 changes between its extreme values.

The corner analyses showed that the circuit is quite robust, since the worst case errors found were $E_{V_d} = 53$ ppm and $E_{V_d} = 43$ ppm, respectively, for $T = 0\,°$C and $T = 50\,°$C.

B. *Capacitance Measurements*

The signal conditioning circuit was characterized and calibrated using commercial ceramic capacitors, in order to check its accuracy. The ceramic capacitors used to calibrate the signal conditioning circuit were initially measured using a GenRad 1659 RLC Digibridge. The plot of the measured capacitance using the proposed circuit and the capacitor value measured with the GenRad Digibridge is shown in Fig. 11.

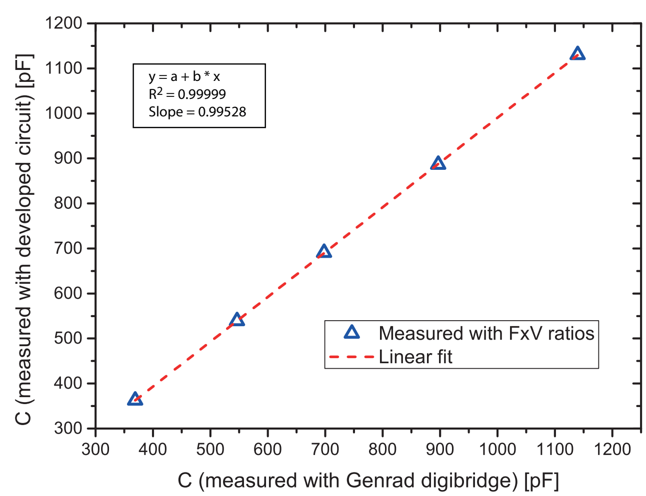

Fig. 11: Plot of measured capacitance with the proposed circuit as a funtion of their values measured with a GenRad 1659 RLC Digibridge.

As we can observe in Fig. 11, the measured circuit presented an excellent performance, as the linear fitted equation has $R^2 = 0.9999$ and a slope practically equal to 1 (S = 0.99528).

In [23] it was shown that, in the 9% to 27% moisture content range, for several corn kernel samples measured with a commercial grain moisture tester (AgraTronix MT-16, USA), the average kernel moisture content is proportional to the weight of the kernel sample. Since the corn is harvested with a moisture content of approximately 22% to 25% and must be stored in silos with a humidity in the range of 13% to 15%, we can use the kernel weight to estimate its moisture content. We measured the sensor capacitance with corn kernels in the 5.2% to 22.2% range.

A sample of hand picked corn ears shelled by hand was used to measure the capacitance of the sensor as a function of the corn kernel weight. Initially the corn sample was weighed (at approximately 21 °C). Next, the sample was dried in an oven (for different periods of time), weighed and several capacitance measurements were performed, so that different moisture content levels were achieved in each measurement. For each moisture content level, we measured the capacitance five times (with a five minutes interval between measurements), to check the repeatability of the sensor.

After all capacitance measurements were taken, the sample was left in the oven for 24 hr, in order to guarantee that all the water evaporated from the kernels, so that, based on this dry sample, the amount of water in all measurements could be precisely determined by the sample weight.

In Fig. 12 the plotted results of the measured capacitance as a function of the percent volumetric moisture content are presented. Recently, it has been shown that, due to the non-espheric characteristic of the corn kernel, placing the sensor horizontally leads to different results from a sensor placed vertically [27], so it is important to observe that our measurements were taken with the corn sample poured over the PCB in a horizontal position.

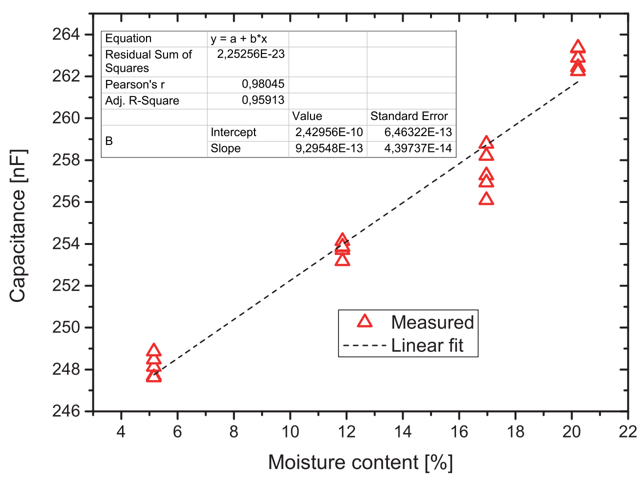

Fig. 12: Plot of measured sensor capacitance versus moisture content.

Table 1 shows the results of the repeatability test for capacitance measurement. The highest value of the standard deviation was found to be 1.06 pF, two orders of magnitude smaller than the mean value 257.5 pF, measured at MC = 16.9%.

TABLE I: Repeatability Test

MC	Mean Value [pF]	σ [pF]
5.2%	248.1	0.52
11.9%	253.7	0.35
16.9%	257.5	1.06
20.2%	262.8	0.51

C. *Second-order Effects in Capacitance Measurement*

There are three effects that must be taken into account when measuring kernel moisture content with PCB capacitive fringing field sensors. Firstly, it has been shown that these sensors present a temperature sensitivity (approximately 0.114% per °C in air) [18]. A second problem is that the water dielectric constant also changes with temperature (decreases at approximately 0.43% per °C for $T > 0\,°\mathrm{C}$). So a compensation equation (dependent on the temperature) could be used to correct for the capacitance measurements. A third effect, that is difficult to compensate for, is that the dielectric constant of the kernel, a living organism, depends on its chemical composition and on what grain is being measured [9].

Therefore, it is recommended that a calibration procedure, at different temperatures and with the specific kernel that will be monitored in the silo, be performed with different moisture contents. Since the proposed sensor can measure the temperature, it is easy to obtain a calibration curve of kernel moisture content as a function of the measured capacitance and temperature.

VI. Conclusions

Many portable instruments with sensors that can measure the MC in grains are available. However, these instruments cannot be used inside silos and, due to their small area, are capable of measuring only very small samples of grains. In this work we presented a multi-sensor based on PCB technology that can measure moisture content and temperature in grains stored in silos, and that has a large sensing area, allowing for averaging the MC of a large number of kernels. The novel structure of the PCB tracks used to form the fringing field capacitor allows for a simple reconfiguration of the sensor using a DPDT relay. After the reconfiguration, it is possible to use the copper tracks as an RTD and measure the temperature of the grain in a silo.

The developed sensor is very robust, reliable (the sensing elements are the copper tracks of the PCB) and, since it is a smart-sensor, with all electronics implemented on the same PCB of the sensor, a two-wire communication protocol can be easily implemented, reducing the complexity of the cabling when many sensors are distributed inside the silo. The embedded microcontroller allows for the transmission of digital signals, and if a RS-485 transceiver is incorporated in the smart-sensor, the signals can be transmitted over distances up to 1200 m. Since it is low-cost, tens of sensors can be installed in a silo, providing an accurate MC and temperature profile of the silo, allowing for the implementation of precise aeration techniques.

The capacitive sensor demonstrated an average capacitance variation of $\Delta C = 14.6$ pF when the moisture content in the kernel changed from 5.2% to 20.22%, resulting in a sensitivity of 0.98 pF/%. Although the worst value of the standard deviation in our experiment (1 part in 257) was smaller than the value found in [23] (1 part in 90), this is explained by the different approaches used in the measurements: we present a repeatability test (several measurements made with a 5 minutes interval between measurements), without removing the sensor from its position inside the corn kernels sample; Dean et al [23] presented a reproducibility test, with the sensor being inserted and removed from the corn sample for each measurement. In a silo, the sensor is not removed, so that a standard deviation similar to the result presented in this paper should be expected. A time-interval technique that uses two relaxation oscillators (one with a reference capacitor and another with the capacitive sensor), allowed for a ratiometric measurement. Although the frequency in each oscillator is inversely proportional to the value of the capacitors, the ratio of the frequencies is linearly proportional to the capacitor ratio.

The measured values of $R_T(T)$ as a function of the temperature, when compared to a LM185 temperature sensor (used as a reference), showed a linear behavior in the 10 to 50 °C temperature range ($R_T(T) = 4.847 + 21.07\text{x}10^{-3}$ T), with an R-squared value of $R^2 = 0.99888$.

A novel bridge configuration allows for the independent adjustment of the gain and the offset in the temperature signal processing circuit, making it easy to calibrate. The bridge circuit was calibrated using an end-point straight line method (using the points at $T = 0\,°\text{C}$ and $T = 47.5\,°\text{C}$), and the measured values of temperature between these two points presented an end-point non-linearity error of only $|E_{nl}| = 0.64\,°\text{C}$ (at $16.5\,°\text{C}$). Future efforts include the test of the multi-sensor with different kernels, like rice, peanuts, soybeans, and sunflower-oilseed.

References

[1] C. V. K. Kandala, C. L. Butts, and S. O. Nelson, "Capacitance sensor for nondestructive measurement of moisture content in nuts and grain," *IEEE Transactions on Instrumentation and Measurement*, vol. 56, no. 5, pp. 1809–1813, 2007.

[2] K. Hellevang. (1999) Consider pros, cons of alternative grain storage methods. [Online]. Available: https://www.ag.ndsu.edu/news/newsreleases/2018/sept-3-2018/consider-pros-cons-of-alternative-grain-storage-methods

[3] F. Fleurat-Lessard, "Integrated management of the risks of stored grain spoilage by seedborne fungi and contamination by storage mould mycotoxins - an update," *IEEE Transactions on Instrumentation and Measurement*, vol. 71, no. 2, pp. 22–40, 2017.

[4] S. O. Nelson and K. C. Lawrence, "Evaluation of a crushing roller conductance instrument for single-kernel corn moisture measuremnt," *ITrans. ASAE*, vol. 35, no. 2, pp. 625–629, 1989.

[5] U. Salmaz, M. A. H. Ahsan, and T. Islam, "High-precision capacitive sensors for intravenous fluid monitoring in hospitals," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1–9, 2021.

[6] L. Fan, Z. Chai, Y. Wang, Z. Wang, P. Zhao, J. Li, Q. Zhou, X. Qin, J. Yao, S. Yan, Z. Wang, and L. Huang, "A novel handheld device for intact corn ear moisture content measurement," *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 11, pp. 9157–9169, 2020.

[7] X. Wang, Y. Wang, H. Leung, S. C. Mukhopadhyay, M. Tian, and J. Zhou, "Mechanism and experiment of planar electrode sensors in water pollutant measurement," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 2, pp. 516–523, 2015.

[8] S. Mukhopadhyay, C. Gooneratne, G. Gupta, and S. Demidenko, "A low-cost sensing system for quality monitoring of dairy products," *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 4, pp. 1331–1338, 2006.

[9] S. Nelson, "Measurement and applications of dielectric properties of agricultural products," *IEEE Transactions on Instrumentation and Measurement*, vol. 41, no. 1, pp. 116–122, 1992.

[10] S. O. Nelson, C. V. K. Kandala, and K. C. Lawrence, "Moisture determination in single grain kernels and nuts by rf impedance measurements," *IEEE Transactions on Instrumentation and Measurement*, vol. 41, no. 6, pp. 1027–1031, 1992.

[11] C. V. K. Kandala, S. O. Nelson, R. G. Leffler, K. C. Lawrence, and R. C. Davis, "Instrument for single-kernel nondestructive moisture measurement," *ITrans. ASAE*, vol. 36, no. 3, pp. 849–854, 1993.

[12] M. V. Belyakov and M. G. Kulikova, "Control of bulk products' humidity and grinding size by the photoluminescent method photoluminescent quality control," *Journal of food processing and preservation*, vol. 44, no. 9, pp. 74–82, 2020.

[13] M. Asefi, I. Jeffrey, J. LoVetri, C. Gilmore, P. Card, and J. Paliwal, "Grain bin monitoring via electromagnetic imaging," *Computers and Electronics in Agriculture*, vol. 119, pp. 133–141, 2015.

[14] M.-G. C. Danao, R. S. Zandonadi, and R. S. Gates, "Development of a grain monitoring probe to measure temperature, relative humidity, carbon dioxide levels and logistical information during handling and transportation of soybeans," *Computers and Electronics in Agriculture*, vol. 119, pp. 74–82, 2015.

[15] N. Martyn, P. Khotemlyansky, V. Panchishin, V. Krasnoshekov, L. Valiullin, A. Kislov, and M. Konishchev, "Wireless system for remote monitoring of temperature and humidity in the grain storage and grain dryer," *IOP Conference Series: Earth and Environmental Science*, vol. 390, no. 1, p. 012034, 2019.

[16] R. Dean, "A pcb sensor for detecting icing events," *IEEE Sensors Letters*, vol. 5, no. 1, pp. 1–4, 2021.

[17] A. Azmietal, "Performance of coating materials on planar electromagnetic sensing array to detect water contamination," *IEEE Sens. J.*, vol. 17, no. 16, 2017.

[18] R. N. Dean, A. K. Rane, M. E. Baginski, J. Richard, Z. Hartzog, and D. J. Elton, "A capacitive fringing field sensor design for moisture measurement based on printed circuit board technology," *IEEE Trans. Inst. Meas.*, vol. 61, no. 4, 2012.

[19] R. N. Dean, A. Rane, M. Baginski, Z. Hartzog, and D. J. Elton, "Capacitive fringing field sensors in printed circuit board technology," in *2010 IEEE Instrumentation Measurement Technology Conference Proceedings*, 2010, pp. 970–974.

[20] N. Costa, E. F.and Oliveira, F. Morais, P. Carvalhaes-Dias, L. Duarte, A. Cabot, and J. A. Siqueira Dias, "A self-powered and autonomous fringing field capacitive sensor integrated into a micro sprinkler spinner to measure soil water content," *Sensors*, vol. 17, no. 4, 2012.

[21] M. França, F. Morais, P. Carvalhaes-Dias, L. Duarte, and J. Siqueira Dias, "A multiprobe heat pulse sensor for soil moisture measurement based on pcb technology," *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 2, pp. 606–613, 2019.

[22] F. Morais, P. Carvalhaes-Dias, L. Duarte, E. Costa, A. Ferreira, and J. Siqueira Dias, "Fringing field capacitive smart-sensor based on pcb technology for measuring water content in paper pulp," *Journal of Sensors*, vol. 2020, 2020.

[23] R. N. Dean, J. D. Craven II Jr., E. A. Guertal, and K. A. Varnavas, "A pcb sensor for status monitoring of stored food stocks," *IEEE Sensors Letters*, vol. 3, no. 4, 2019.

[24] A. Santos, J. Monsalve-Diaz, P. Carvalhaes-Dias, F. Morais, P. Dias-Lima, F. Flosi, and J. Siqueira Dias, "Reconfigurable sensor based on

PCB technology for moisture and temperature measurement," *Sensors & Transducers*, vol. 246, no. 7, 2020.

[25] K. Elangovan and A. C. Sreekantan, "An efficient universal digitizer with linear transfer characteristic for resistive sensor bridges," *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1–4, 2021.

[26] T. Islam, S. A. Khan, M. F. A. Khan, and S. C. Mukhopadhyay, "A relaxation oscillator-based transformer ratio arm bridge circuit for capacitive humidity sensor," *IEEE Transactions on Instrumentation and Measurement*, vol. 64, no. 12, pp. 3414–3422, 2015.

[27] R. Dean, M. Reed, and E. Guertal, "Optimizing fringing field sensor performance with non-spherical particles," in *IEEE Sensors Conference, Virtual Conference*. Sydney, Australia: IEEE, 2021.

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