Research Article

Fringing Field Capacitive Smart Sensor Based on PCB Technology for Measuring Water Content in Paper Pulp

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We present a capacitive smart sensor based on printed circuit board (PCB) technology to measure the amount of water content in a paper pulp at the wet end of a paper machine. The developed sensor incorporates in the same PCB the signal processing circuits. It is a handheld portable device, and its output is sent to the reading equipment using a Bluetooth wireless connection, providing to the sensor's operator ease of mobility around the wet end of a paper machine. The prototype was tested in a laboratory, using a wire mesh to emulate the end of a paper machine, and we were able to measure and easily detect when it reaches the water content in the range of 90% to 92%, as required in the paper fabrication process. Standard deviation of the capacitance measurements at various moisture levels is four orders of magnitude smaller than the mean. The smart sensor was tested in the 20°C to 40°C temperature range, in a paper pulp with a gravimetric water content of 91%. Since the variation of capacitance with temperature is practically linear, we propose a simple linear compensation equation to correct the observed sensitivity with the temperature. To keep the signal processing circuits small, low cost, simple, and robust, a novel direct interface sensor to microcontroller circuit technique was used to make the capacitive measurement, allowing for measuring small capacitance deviations without high-frequency oscillators. It was shown that it is possible to integrate the signal processing circuits in the top layer of the PCB interdigitated sensor without adding noise or degrading the performance of the capacitive sensor.

1. Introduction

In most paper making machines, the properties of the paper are measured only at the dry end of the machine, after the paper is ready. Thus, if the paper that is being produced does not have an acceptable quality, the paper is discarded (probably to be recycled into a paper with lower quality), and the machine's parameters are altered so that the produced paper meets the desired quality standard.

Therefore, being able to measure the water content of the paper pulp at the wet end of a paper machine is fundamental to control the quality of the paper, reduce waste, and minimize the effects in the environment, leading to environmentally friendly manufacturing processes. Many techniques

have been proposed to measure the water content in the paper pulp in the wet end of the paper machine, before it enters the fabrication process.

Some techniques are very simple and are capable of only giving a rough estimate of the water content, like the use of fans. In this technique, a conventional fan is rotated inside the paper pulp, and by measuring the motor's torque, it is possible to estimate the water content in the paper pulp [1]. This method is not precise because for very low pulp concentration (high water content in the pulp) the fan rotates freely.

Microwave closed cavity resonators can estimate the water content in the paper pulp with a very high resolution, and fibre concentrations as low as 0.6% have been measured with a 0.03% standard deviation [2]. However, the method
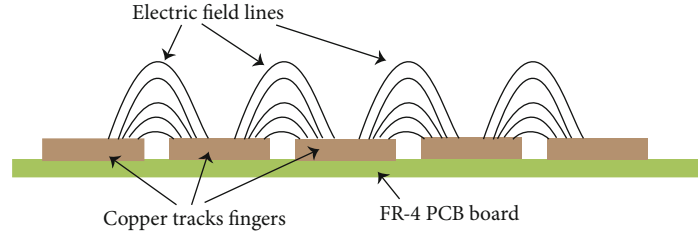
Figure 1: Electric flux in the vicinity of the sensor's fingers.

cannot be used in the monitoring of paper pulp in the wet end of the paper machine, since it is necessary to manually take a sample of paper pulp and insert it in the closed cavity resonator. Besides this limitation, it requires very complex instrumentation, since a spectrum analyser and a tracking generator are required.

Other techniques based on microwave attenuation of the material have been proposed [3], but these techniques are difficult to use, specially with low attenuation materials because the attenuation measurements are influenced by multiple reflections.

A microwave open cavity resonator measurement system that would allow usage in the production line has been proposed [4]. However, the resonance frequency of paper pulp is around 2.6 GHz. Most cellphone communication systems operate at 2.4 GHz, and to avoid interference from the cellphone signals, the microwave sensors must be shielded, so the open cavity sensor is impractical.

An electromagnetic field perturbation sensor was also proposed, to measure the conductivity of the paper pulp, and from these measurements, the water content in the pulp can be estimated [5–8]. However, this technique presents two weaknesses: (a) it is necessary to assume that all the water in the pulp is absorbed by paper fibres, so that the electrical conductivity is due only to the water molecules and (b) different additives can be used in the paper pulp, leading to different conductivities of the material for the same paper pulp with a given water content.

Typically, the paper pulp arrives with high volumetric percentage amount of water content ($\theta_w \approx 99\%$) at the wet end of the paper machine and it must be dried until it reaches the $\theta v = 90 - 92\%$ range before it goes to the next fabrication step. Sundara-Rajan et al. [9] investigated a metal grid fringing field capacitance sensor with an impedance spectroscopy instrumentation to measure moisture content in paper pulp and concluded that from the measured impedance data, the dependence of both admittance and phase on the moisture content is not important (or totally unreliable, as in the case of the measured phase). On the other hand, it was observed that the variation of capacitance for a water pulp content θ_w changing from 90% to 96%, resulted in a $\Delta C = 0.6$ pF.

Based on the promising results obtained in the study conducted in [9], in this work, we present a wireless capacitive fringing field smart sensor based on a interdigitated printed circuit board (PCB) sensor to measure water content in paper pulp.

2. The PCB Capacitive Sensor

2.1. Principle of Operation of Fringing Field Capacitive Sensors. Low-cost fringing fields capacitive sensors using conventional metal grids or PCB fabrication techniques have been successfully presented for many applications, like soils [10], cereal grains [11], air [12, 13], and human skin [14].

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 Figure 1. The capacitance of a structure with fingers 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 Equation (1) may be necessary if the condition $lh \gg d^2$, 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 paper pulp in contact with the PCB), the sensor's capacitance changes and these variations can be related to the moisture content in the paper pulp [9].

In [10], it has been shown that a small ionic content of the water over the PCB sensor did not alter its response: with the water over the sensor changing its conductivity from $\sigma = 32.2$ mS/m to $\sigma = 5.7$ mS/m, the observed change in the measured capacitance was only 0.02%.

However, depending on the type of paper being produced, a high content of several additives (such as titanium dioxide and alkalis) are added to the paper pulp, and it is recommended to perform a calibration of the sensor in each type of paper pulp. It is very important to notice that the absolute value of the measured capacitance is not important, since we are interested only in which values in the sensor's output indicate that the water content in the paper pulp is within the required range.

3. The Developed Smart Sensor

One important characteristic of the capacitive PCB sensors, which has not yet been explored, is the use of this technique to the fabricate smart sensors, since all the signal processing

circuits could, in principle, be fabricated on the top side of the PCB.

The sensor was designed with four layers 85 mm × 85 mm × 2.4 mm FR-4 substrate, with 35 μm copper thickness. There are 40 interdigitated fingers of copper tracks, with a length $L = 75$ mm, width $W = 2$ mm, and space between fingers $S = 2$ mm. The W/S relationship was chosen based on the conclusions presented in [15], who found that using $W = S$ maximizes the value of capacitance per unit area. To determine the length L, we used $L \gg S$, so that the fingers can be considered infinite [15, 16].

In the wet end of a paper machine, the sensor must be moved around so that different portions of the pulp can be measured, and wired systems, with sophisticated instruments connected to the sensor (like an impedance analyser), make this task very complicated. In this work, we present a precise handheld wireless capacitive smart sensor that can be easily moved around the wet end of the paper machine and can be read using a smartphone or tablet which has the following features:

(i) It is the first wireless handheld PCB smart sensor that can be moved around the wet end of a paper machine, without heavy and clumsy instruments and cables attached to the sensor

(ii) It is the first capacitive smart sensor based on PCB technology, with all signal processing circuits included in the sensor body

(iii) The novel time interval technique developed for the direct interface to microcontroller technique allows for a much higher resolution in capacitance measurement than the conventional technique proposed by Reverter et al. [17] without using high-frequency oscillators to implement it

(iv) It is extremely low cost, although the results measured with the sensor do not show an error of more than 0.43% when compared to sophisticated commercial capacitance meters

Since the sensitivity of this type of fringing field capacitive sensor depends on the distance between the copper fingers and the material being measured, we used a conventional solder mask (thickness = 200 μm) over the interdigitated capacitor. This protective layer is necessary to avoid short circuits between the fingers caused by the paper pulp and also to eliminate water adsorption by the FR-4.

The PCB internal copper layer close to the bottom side of PCB forms a guard plane that provides shielding from the interference of the high-speed digital signals and also from external electric fields. The internal copper layer close to the top side of the PCB is also used as a guard plane, but it is connected to V_{dd}, to minimize the errors that are induced by the power supply [18]. The top side of the PCB contains the SMD components of the direct interface sensor to microcontroller circuit and the Bluetooth module. Instead of using a solder mask on the top side of the PCB, we protected the components and the FR-4 board with a silicone layer, given

that the components will operate in an extremely wet environment. When used in an industrial environment, it is recommended to pot the top of the PCB with an epoxy.

It was observed that, for small capacitance measurements, the wiring between the sensor and the microcontroller is very sensitive to electromagnetic interference and also introduces parasitic capacitances. An important feature of the proposed sensor is that the length of the connection of the sensor with the processing circuit is extremely small, using a PCB via between the top side and the bottom interdigitated capacitor, measuring only approximately 2.4 mm (the thickness of the FR-4 board). The layout of the PCB interdigitated capacitor is presented in Figure 2.

4. Signal Processing Circuits

The signal processing circuits can be divided in two blocks: (a) the capacitance measurement circuit that uses a direct interface sensor to microcontroller and (b) the data transmission circuit, which uses a conventional Bluetooth module to transmit the measured data to an external device (a smartphone or tablet).

4.1. Direct Interface Sensor to Microcontroller. The direct interface sensor to microcontroller technique is an ingenious technique presented by Reverter et al. [17, 19], used to measure resistors and capacitors using only a microcontroller (which contains an internal comparator), without any additional analogue circuits. In this work, we present a novel simple and robust direct interface sensor to microcontroller technique, based on the technique developed by Reverter et al. to measure the sensor's capacitance that allows an increased capacitance measurement resolution without using high-frequency oscillators.

To measure capacitance using the direct interface sensor to microcontroller technique, a system based on an RC circuit is used. In this method, the microcontroller measures the time needed to charge and discharge a capacitor C_X between two fixed voltages, through a resistance R_X. The circuit can be used to measure both R_X or C_X, depending on which one is known. There is another method, which is also regarded as a direct interface sensor to microcontroller, where the microcontroller measures the number of given cycles required to transfer the charge from a reference capacitor to the capacitor under measurement [20–23]. However, this technique is more complex, since it requires an external switched capacitor circuit, and we will not use it in this work. Another interesting technique of charge transfer method to measure capacitance directly with a microcontroller is the QTouch Peripheral Touch Controller, developed by ATMEL [24], where a special processing circuit inside the microcontroller transfers the charge from the measured external capacitor to an internal capacitor in the microcontroller. However, this technique is not well suited for detecting small capacitance changes [25].

A schematic diagram of a simple direct interface sensor to microcontroller circuit used to measure capacitance is shown in Figure 3.
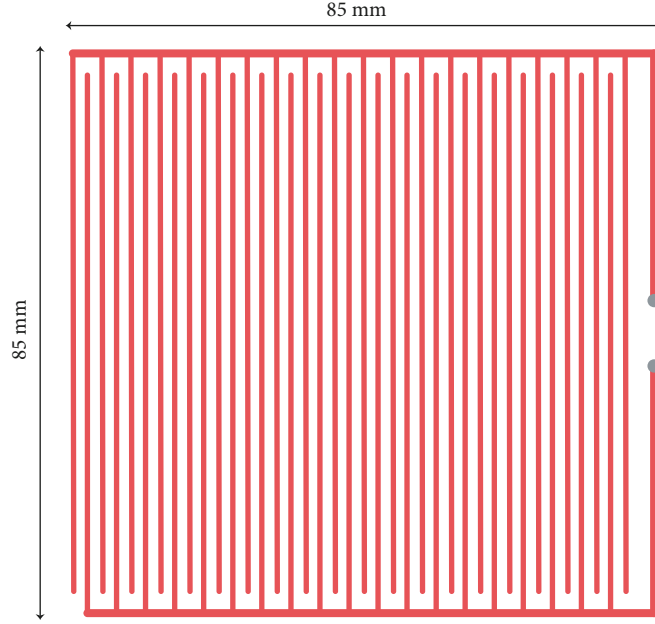
FIGURE 2: Layout of the PCB interdigitated capacitor with 40 fingers of copper tracks, each finger with a length $L = 75$ mm, width $W = 2$ mm, and space between fingers $S = 2$ mm.
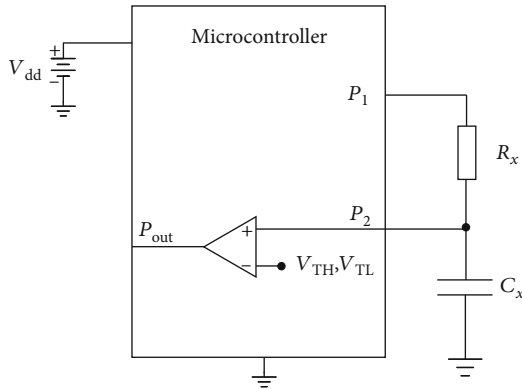

FIGURE 3: Schematic diagram of a direct interface sensor to microcontroller circuit used to measure capacitance. P_1, P_2 and P_{out} are microcontroller I/O pins.

The circuit operates based on a time-interval technique where during the period of time proportional to the device under measurement, pulses from a constant frequency oscillator are counted. The circuit of Figure 1 is intended to measure the capacitor C_X (or resistor R_X); the time interval is given by the phases of charge (or discharge) of the capacitor C_X through R_X. These phases are shown in Figure 4.

The number of pulses from the oscillator can be counted during the phases of charge ($t_0 - t_1$, with n_1 pulses) or discharge ($t_1 - t_2$, with n_2 pulses). The charge phase is initiated by setting the I/O microcontroller pin P_1 to logic level "1," putting a voltage equal to the circuit supply voltage V_{dd} in this pin and charging the capacitor through R_X.

The voltage at the capacitor (V_{CX}) is read by the I/O microcontroller pin P_2 that is connected to a microcontroller internal comparator with hysteresis, with trip points V_{TL} and

V_{TH}. The time required to charge a capacitor C_X from a voltage V_{TL} to a voltage V_{TH} is given by

$$t_c = C_X R_X \left[\ln \left(\frac{V_{dd} - V_{TL}}{V_{dd} - V_{TH}} \right) \right]. \qquad (2)$$

The time required to discharge C_X from V_{TH} to V_{TL} is written as

$$t_d = C_X R_X \left[\ln \left(\frac{V_{TH}}{V_{TL}} \right) \right]. \qquad (3)$$

The terms inside brackets in Equations (2) and (3) are constant, showing that both t_c and t_d are proportional to $C_X R_X$. Thus, counting the oscillator pulses during any of these periods of time t_d or t_c, one can easily calculate the value of C_X or R_X, if one of them is known. Due to the smaller noise in the V_{TL} voltage [18], the oscillator pulses are usually counted during the discharge time (t_d).

5. Limitations of the Conventional Measurement Technique

It is important to notice that, for small values of capacitance, the time intervals t_c and t_d can be very small. For example, if a capacitance $C_X = 10$ pF is being measured, with typical values of $R_X = 2.2$ MΩ, $V_{dd} = 3.6$ V, $V_{TH} = 1.8$ V, and $V_{TL} = 0.9$ V, we obtain $\Delta t_d = 15.3$ μs.

Thus, to be able to detect a 1% variation in C_X ($\Delta C_X = 0.1$ pF), we would have to be able to detect a variation $\Delta t_d \approx 153$ ns. In such a system, to detect this $\Delta C_X = 0.1$ pF with a difference of only ten counts in the oscillator frequency (what would seem extremely unreliable), we would need a high oscillator frequency of $f_{ck} > 50$ MHz. Since the
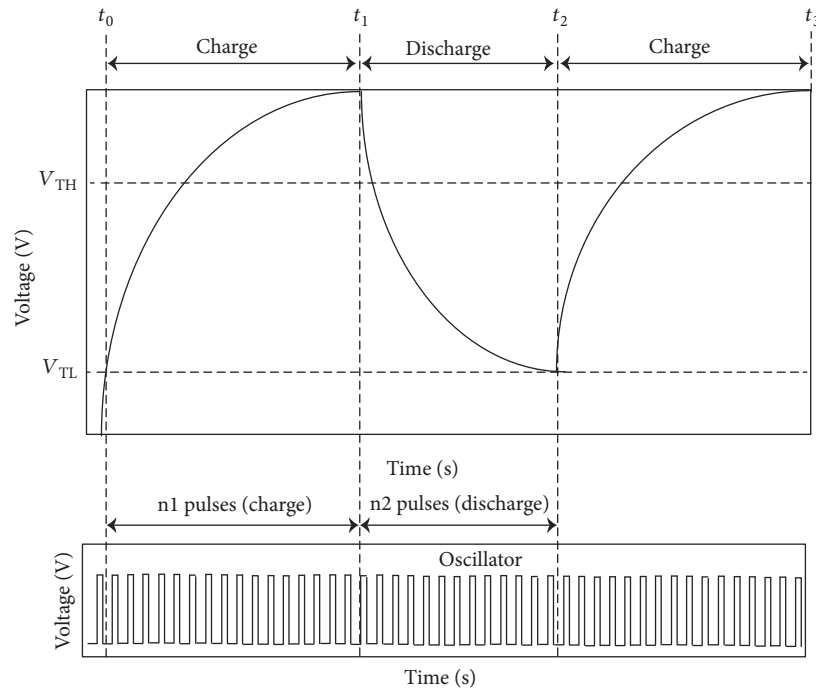
FIGURE 4: Conventional time-interval technique diagram, showing oscillator pulses and charge/discharge of a capacitor being measured.
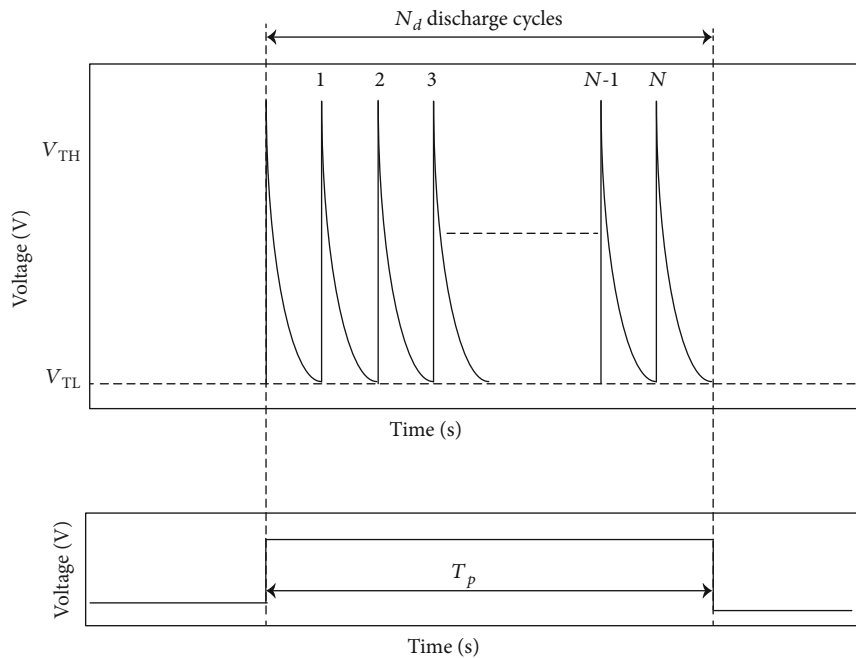

FIGURE 5: Time diagram of the proposed direct interface sensor to microcontroller circuit. P_0, P_1, P_2, and P_3 are microcontroller I/O pins.

value of resistor R_0 is near the highest practical limit, the conventional time interval technique is very difficult to be used using the microcontroller oscillator.

5.1. A Novel Direct Interface Sensor to Microcontroller Circuit Measurement Technique.
To allow for the measurement of very small capacitance variations, we developed a different method for reading the direct interface sensor to microcontroller circuit. Instead of counting pulses from the oscillator, the developed method charges the capacitor almost instantaneously (typically less than 1 ns), and then counts the number of discharge cycles, during a fixed time period T_p. A time diagram of the proposed scheme is presented in Figure 5. If the capacitance measurement does not have to be updated at a fast rate, this period of time T_p can be very long (hundreds of milliseconds or even seconds).
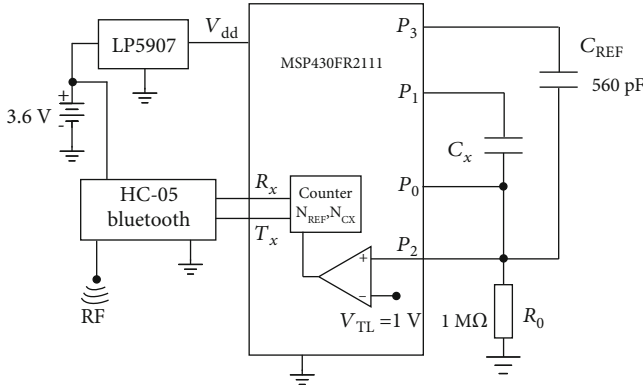
FIGURE 6: Block diagram of the smart sensor circuit.

Using this new scheme with $T_P = 1$ s, the number of discharge cycles for $C_X = 10$ pF is $N_{d0} = 65359$. If C_X presents a variation $\Delta C_x = 0.1$ pF, the discharge time will be $\Delta t_d = 15.3 \mu$s$+ 153$ ns, and the number of discharge cycles during $T_P = 1$ s will be $N_{d1} = 64712$, so the difference in the number of counts will be $\Delta N_d = N_{d0} - N_{d1} = 647$, making it easy to detect this small variation of capacitance. Furthermore, since we are taking the average of thousands of measurements, the noise present at the comparator's trip point is filtered.

6. Circuit Implementation

To make the sensor portable and taking into account that the current consumption of the signal processing circuit is very low (approximately 50μA, including one Bluetooth transmission every 2 s), we decided to power the circuit using a single 1.2 A/3.6 V lithium/thionyl chloride battery.

The signal processing circuit used in the smart sensor is presented in Figure 6. Since in this circuit the capacitors are charged to V_{dd}, it is necessary to provide a low-noise and temperature-stable voltage for V_{dd}. So, to provide a stable voltage for V_{dd}, we used the LP5907 from Texas Instruments, an ultralow noise ($<6.5 \mu$V$_{RMS}$) 3.3 V low drop-out (LDO) voltage regulator, with a typical temperature coefficient of 40 ppm/°C in the 25°C–50°C range.

The internal comparator of microcontroller (MSP430FR2111, from Texas Instruments) used for the smart sensor does not depend on V_{dd}. Instead of a voltage given by a fraction of V_{dd}, the comparator's trip point can be programmed (using and internal DAC) to a few fixed values, and in our design, we used the value of $V_{TL} = 1$ V.

We can use a very precise and low TC resistor R_0 (for example, a 0.001% and ±5 ppm/°C resistor) and eliminate the errors due to this component. However, there are some errors that cannot be cancelled for

(a) The temperature drift in V_{TL} (approximately 1μV/°C) defined by V_{ref}, the internal microcontroller's reference voltage

(b) The nonzero output impedance of the CMOS transistors introduce a small series resistance to R_0 during the discharge cycles

(c) Parasitic capacitances in the microcontroller pins influence the value of the capacitance being measured

To eliminate these errors, a self-calibrating circuit is used, where a dummy circuit, with the same configuration of the circuit used to measure the capacitance measures a well-known capacitor C_{REF} [26]. The measurement procedure starts with the dummy calibration circuit firstly activated, and the number of discharge cycles with C_{REF} is obtained. Next, the circuit with the capacitor under measurement C_X is activated, the measured number of discharge cycles is compared to the calibration capacitor.

Assuming that both capacitors (C_{REF} and C_X) are discharged, the measurement starts with the microcontroller's I/O pin P_3 at "0" logic, P_1 at high impedance (HZ), and P_0 set to "1." This forces a voltage equal to V_{dd} in node A between C_{REF} and R_0. Since P_3 is left in HZ, capacitor C_X is floating during this phase.

During the charge cycle, capacitor C_{REF} is connected directly to the microcontroller pin P_0 and is charged up to V_{dd} at a very fast dV/dT, limited only by the output current of the microcontroller pin. Since pin P_1, connected to C_X, is initially in high impedance (HZ), all current that leaves the microcontroller pin P_0 goes into C_{REF}. Thus, if the microcontroller's output current limit has a typical value of 8 mA, the time required to charge a 100 pF capacitor would be only 8 ns and can be neglected compared to the discharge times that are in the order of tens of μs.

After C_{REF} has been totally charged (in the next instruction of the microcontroller, which occurs at least 125 ns after P_0 is set to high), P_0 is set to high impedance, and the capacitor C_{REF} discharges through R_0. The comparator detects when the voltage in C_{REF} reaches V_{TL}, and this discharge time is given by

$$t_{dREF} = -R_0 C_{REF} \left[\ln \left(\frac{V_{TL}}{V_{dd}} \right) \right]. \tag{4}$$

Next, the same procedure is performed, but using the capacitor under measurement C_X, and its discharge time is

$$t_{dCX} = -R_0 C_x \left[\ln \left(\frac{V_{TL}}{V_{dd}} \right) \right]. \tag{5}$$

The ratio of the discharge time during the calibration phase (t_{dREF}) and during the measurement phase (t_{dCXs}) is

$$\frac{t_{dREF}}{t_{dCX}} = \frac{C_{REF}}{C_X}, \tag{6}$$

and the value of C_X can be easily calculated as

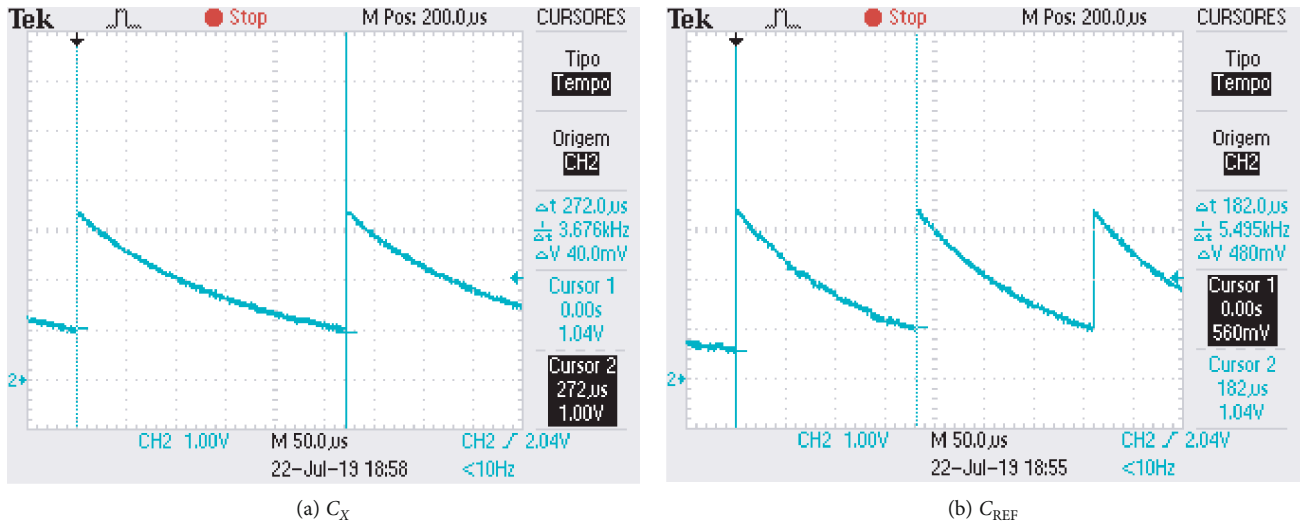$$C_X = C_{REF} \left(\frac{t_{dCX}}{t_{dREF}} \right). \tag{7}$$

FIGURE 7: Oscilloscope screens showing the cycles of charge/discharge of the (a) reference capacitor C_{REF} and (b) sensor's capacitance (in air) C_X.
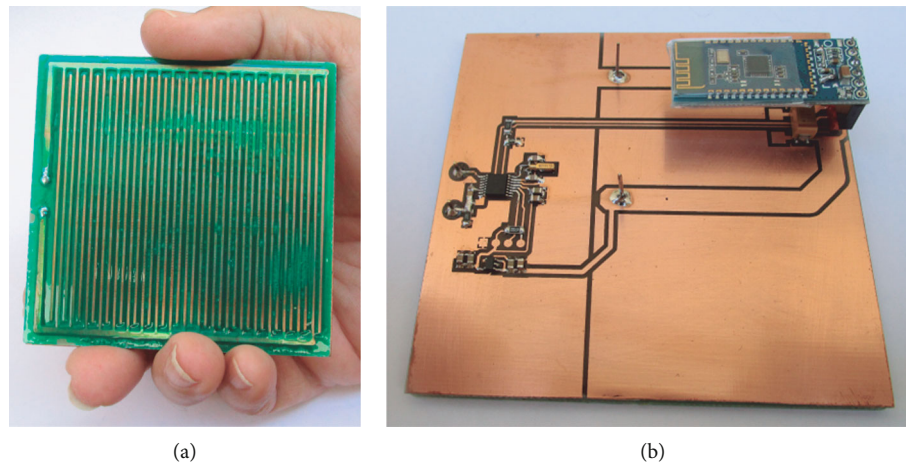

FIGURE 8: Photograph of the smart sensor's PCB: (a) bottom side and (b) top side.

The number of pulses counted in each measurement phase is given by

$$N(C_X) = \frac{T_P}{t_{dCX}}, \quad (8)$$

$$N(C_{REF}) = \frac{T_P}{t_{dCREF}}. \quad (9)$$

Therefore, combining Equations (7), (8), and (9), we conclude that

$$C_X = C_{REF}\left(\frac{N_{REF}}{N_{CX}}\right), \quad (10)$$

and we have a linear and easy to use relationship to calculate C_X from the values of N_{CX} and N_{REF}.

A print of the oscilloscope screens showing the instantaneous charge and the discharge time (which depends on the capacitor value) of both the reference capacitor C_{REF} and the sensor's capacitance (in air) C_X is shown if Figure 7.

To obtain a precise measurement periods T_p (we used $T_p = 1$ s), a real time clock crystal ($f = 32768$ Hz) was used. The timer which defines T_p starts with the transition of P_0 from HZ to high. After the measuring period T_p ends, the next transition of P_0 from HZ to high starts the timer T_p again, to measure the unknown capacitor C_x.

In this prototype, where we want to test if it is possible to fabricate high-speed digital and communication circuits in the top layer of the PCB sensor without interfering with the capacitive measurement, a commercial HC-05 Bluetooth module was soldered on the top of the smart sensor PCB. This module transmits the measured data to an external device (a smartphone or tablet). Of course, in a final product, a Bluetooth module like the DA14531-00000OG2 from Dialog Semiconductors should be used, which would make it easy to epoxy the PCB top side.

It is important to notice that the communication protocol between the microcontroller and the Bluetooth module is
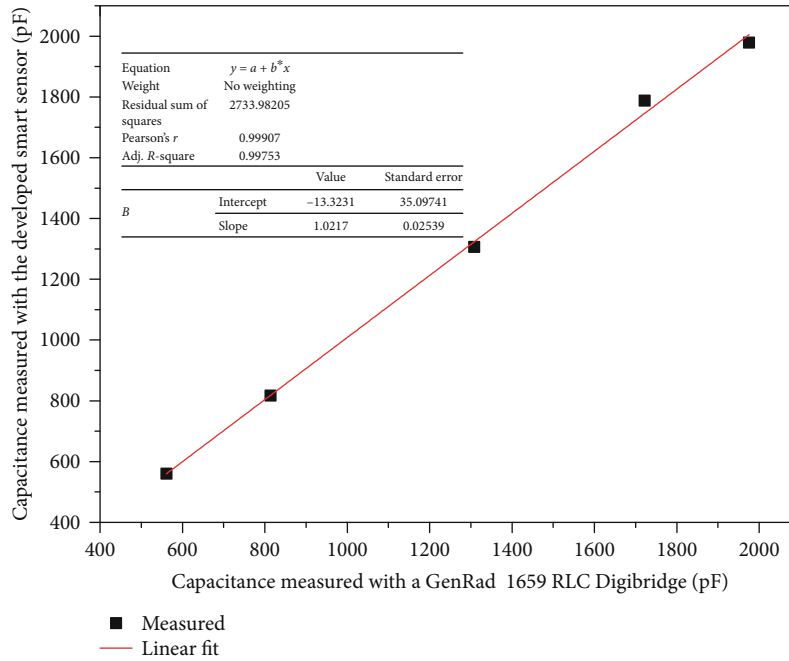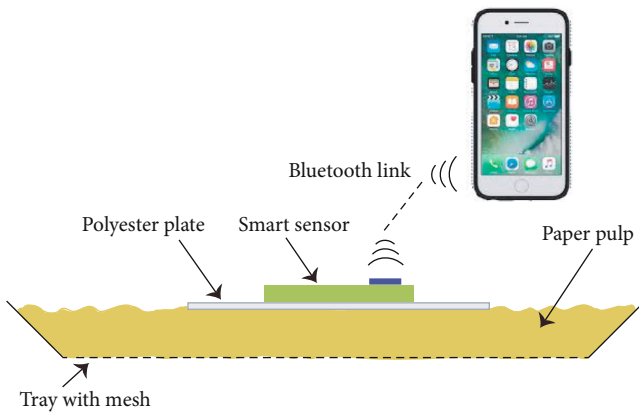
Equation	$y = a + b^*x$	
Weight	No weighting	
Residual sum of squares	2733.98205	
Pearson's r	0.99907	
Adj. R-square	0.99753	
	Value	Standard error
Intercept	−13.3231	35.09741
B Slope	1.0217	0.02539

■ Measured
— Linear fit

FIGURE 9: Sensor's calibration curve.

FIGURE 10: Schematic diagram of the measurement set-up.

FIGURE 11: Measured capacitance (average from five measurements), as a function of the gravimetric water content in a paper pulp.

exactly the same if we use an HC-05 or a low-cost Bluetooth module like the DA14531-00000OG2, so nothing would need to be changed. A photograph of the smart sensor's PCB, without the battery connected, is shown in Figure 8.

7. Experimental Results

7.1. Sensor's Calibration. A circuit of the proposed capacitance measurement circuit was reproduced and implemented on the top of a two-layer PCB, without the interdigitated capacitor on the bottom side. Commercial capacitors were firstly measured with a GenRad 1659 RLC Digibridge, and then measured using our direct to microcontroller interface circuit.

In Figure 9, we show a plot of the measured capacitance values with our sensor, as a function of the values obtained with the GenRad 1659 RLC Digibridge. The maximum calcu-
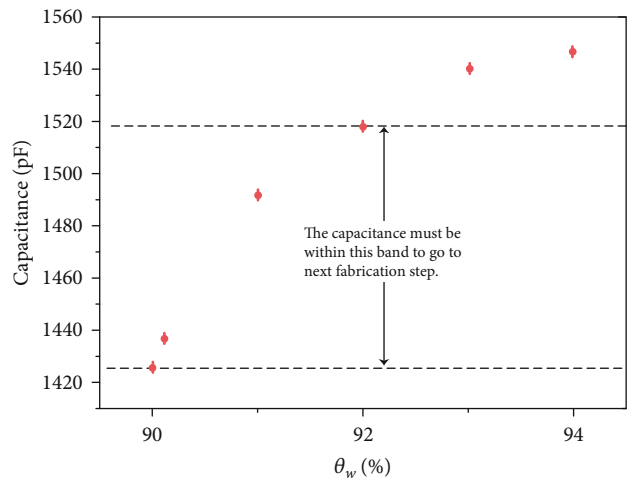
lated difference between the measurements was only 0.43%, for a very large capacitance range, from 560 pF to 1.98 nF.

7.2. Materials and Methods. The paper pulp at the end of a paper machine is basically a suspension composed of water and paper fibres. This suspension is spread over a mesh tray (known in the paper industry as the "wire"), and the moisture content of this paper pulp has to be measured, in order to allow it continues to the next fabrication step.

To prepare a set-up measurement for our sensor, we built a small mesh (a circular tray with a diameter of 30 cm) to emulate, in a laboratory, the conditions found in the wet end of an industrial single-side paper fabrication machine.
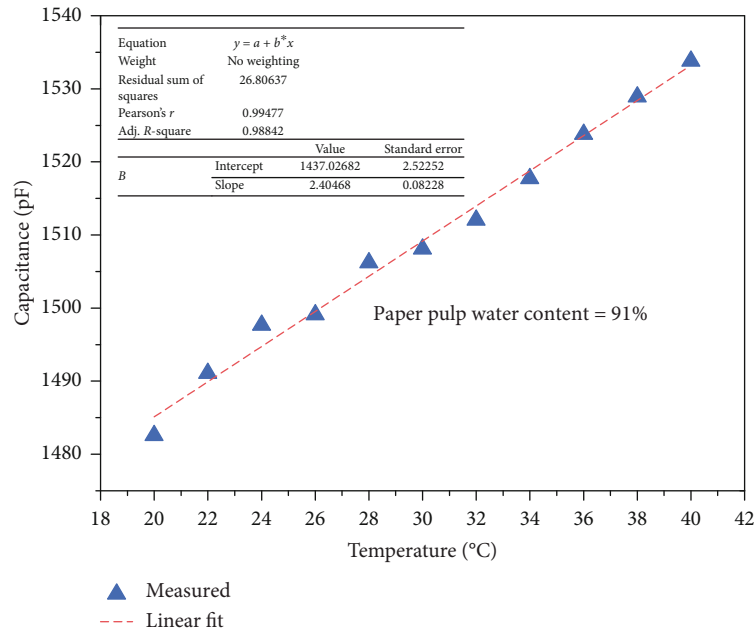
Equation	$y = a + b * x$	
Weight	No weighting	
Residual sum of squares	26.80637	
Pearson's r	0.99477	
Adj. R-square	0.98842	
	Value	Standard error
Intercept	1437.02682	2.52252
B Slope	2.40468	0.08228

Paper pulp water content = 91%

▲ Measured
--- Linear fit

FIGURE 12: Variation of capacitance as a function of the temperature.

$\theta_v = 90\%$

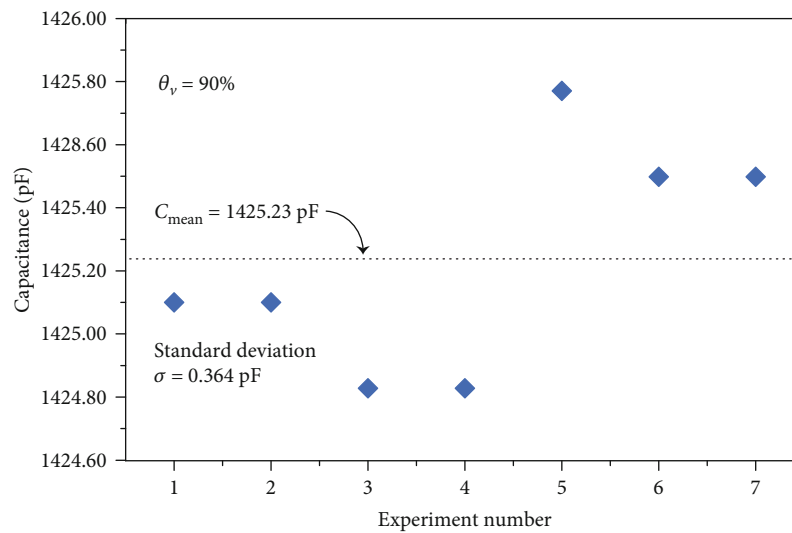$C_{\text{mean}} = 1425.23$ pF

Standard deviation
$\sigma = 0.364$ pF

FIGURE 13: Repeatability test for a paper pulp with $\theta_w = 90\%$.

The sensor was installed on a thin transparent polyester plate (with a thickness of 0.5 mm), so that the apparatus can be placed on the paper pulp, ensuring a large surface with good contact between the paper pulp and the polyester plate.

In our experiment, the paper pulp suspension was obtained by liquidizing (using a conventional kitchen's blender) controlled amounts of a tissue paper and water, weighted in a precision scale. In Figure 10, we show a schematic diagram of the measurement set-up.

Firstly, we prepared six suspensions of paper pulp with gravimetric water contents in the range $\theta_w = 90\%$ to $\theta_w = 94\%$, each sample with a volume of approximately one liter. The smart sensor was programmed to transmit continuously the values of N_{REF} and N_{CX}, so that every 2 s we can calculate the value of C_X, and the values of N_{REF} and N_{CX} were read in

a smartphone. For each value of paper pulp with different values of θ_w, we took several measurements, without moving the sensor on the paper pulp surface.

In Figure 11, we present a plot of the measured capacitance (the average from five measurements, taken every two seconds), as a function of the volumetric water content in the paper pulp, at $T = 25$ C. As it can be observed, the variation is nonlinear, as with other PCB-based sensors used to measure water content.

This is easily explained by the fact that a PCB capacitive sensor has a fixed value capacitor (defined by the dielectric composed of the solder mask film) in parallel with one varying capacitor, which is defined by the dielectric composed of the paper pulp. The resulting capacitance of this parallel association is nonlinear [10].
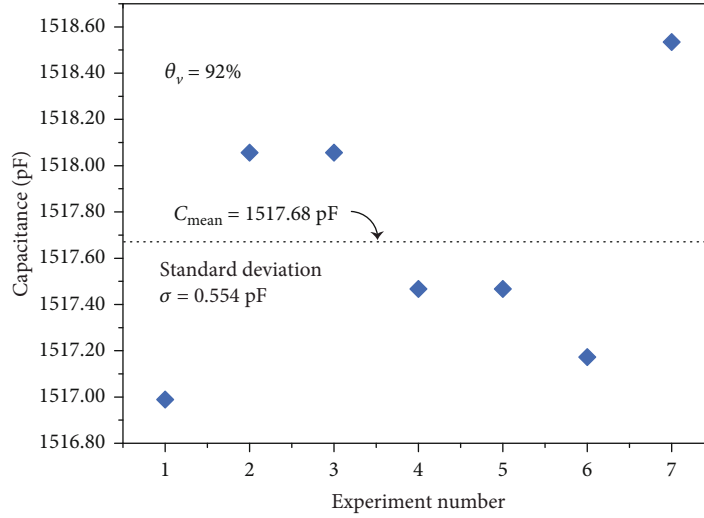
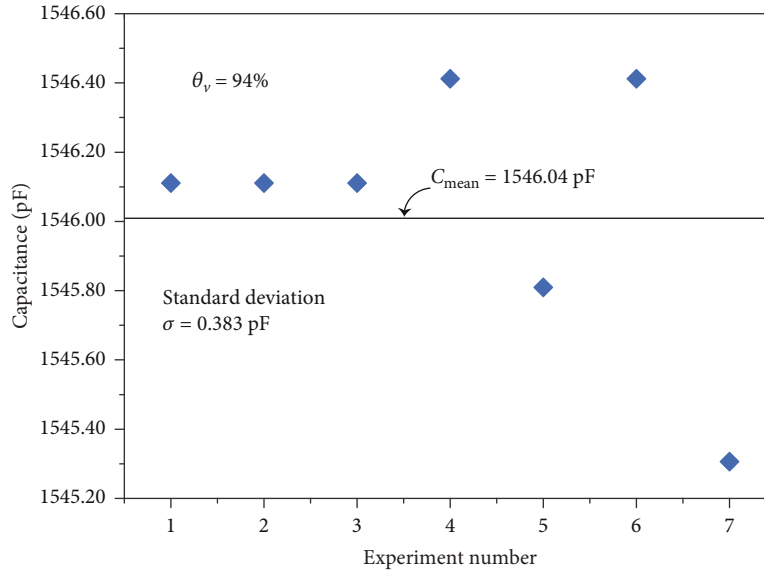FIGURE 14: Repeatability test for a paper pulp with $\theta_w = 92\%$.

FIGURE 15: Repeatability test for a paper pulp with $\theta_w = 94\%$.

7.3. Sensor's Variation with Temperature.

7.3. Sensor's Variation with Temperature. It has been shown in [27] that fringing field capacitive sensors are sensitive to temperature variations. Since the operator at the wet end of the paper machine can easily obtain the temperature of the paper pulp, it is important to provide a temperature correction to the capacitance measured in the paper pulp.

To obtain the correction equation, a simple experiment was conducted. A tray with paper pulp with 91% of water content was prepared, and the developed sensor was used to measure the paper pulp. The system was inserted into a thermal chamber and submitted to temperature variations in the range of 20°C to 40°C. It is assumed that the water content does not change during the measurement period, and the measured change in capacitance is only due to the sensor's temperature sensitivity. The measured results are plotted in Figure 12.

TABLE 1: Calculated values of the mean and the standard deviation in the repeatability tests.

θ_v	Mean	Standard deviation
90%	1425.24 pF	0.364 pF
92%	1517.68 pF	0.554 pF
94%	1546.04 pF	0.383 pF

As one can observe, the change in capacitance is practically linear with the temperature, so we can write

$$C(T) = C_0[1 + \alpha(T - T_0)], \tag{11}$$

where C_0 is the value of the capacitance measured at 25°C (as shown in Figure 11), $T_0 = 25$ C, T is the temperature
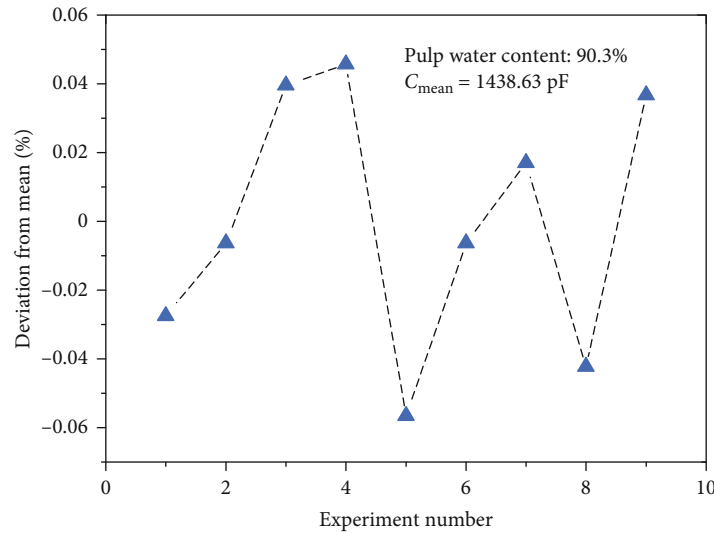
FIGURE 16: Measured capacitance and calculated deviation from the mean (in %) for the reproducibility test.

measured in the paper pulp, $C(T)$ is the measured value of the capacitance, and α is the value of dC/dT, calculated as $\alpha = 2.4\,\text{pF}/^{\circ}\text{C}$ from the slope of the linear equation presented in Figure 12.

Thus, after measuring $C(T)$ and T, the value of C_0 can be easily calculated using Equation (2). With C_0 calculated, we can determine if it is within the desired capacitance range of 1428 pF to 1519 pF, corresponding to the water content range (60% to 92%). This can be easily implemented in the smartphone software.

8. Repeatability and Reproducibility Test

During the paper fabrication process, the repeatability of the water content measurements in the paper pulp is important to obtain a constant paper quality. Thus, we ran a series of tests to evaluate the developed smart sensor in what concerns repeatability and reproducibility.

8.1. Repeatability Tests. We performed repeatability tests for paper pulp with a water content $\theta_w = 90\%$, $\theta_w = 92\%$, and $\theta_w = 94\%$. The emulsion was placed on the mesh and the sensor was installed. Next, without disturbing the paper pulp or the sensor, we took seven capacitance measurements, in intervals of 2 s. It is assumed that the paper pulp cannot change its moisture content during this small period of time [9]. In Figures 13–15, we present the results of these tests. The calculated values of the mean and the standard deviation are shown in Table 1. It is observed that the worst case occurred for $\theta_v = 92\%$, when the calculated standard deviation is $\sigma = 554\,\text{fF}$, four orders of magnitude lesser than the mean value $C_{\text{mean}} = 1517.68\,\text{pF}$.

8.2. Reproducibility Test. To emulate a fabrication environment, where the operator moves the sensor around the wire region to check the paper pulp moisture, we conducted a reproducibility test. The reproducibility test evaluates the ability of the sensor to be installed and removed several times, reading the same paper pulp with consistent values.

In our test, we prepared a paper pulp, installed the sensor, and made one measurement. Next, the sensor was removed, cleaned, and a new measurement was taken with the same paper pulp. This was repeated nine times, and the results are shown in Figure 16. The maximum deviation from the mean value was only 0.006%, showing that the sensor can be moved around the wet end of the machine and used to measure different portions of the paper pulp with consistent results. A sample of paper pulp with $\theta_w = 90.3\%$ was used in this reproducibility test.

9. Conclusions

A capacitive fringing field smart sensor designed to measure the water content in the paper pulp in the wet end of a paper machine was developed and tested in laboratory. The interdigitated capacitive sensor is based on standard PCB technology. The smart sensor was fabricated using a four-layer PCB, which allows for adding a ground shield plane and a V_{dd} plane in the inner layers of the PCB. The interdigitated capacitor is patterned in the bottom side of the PCB and the signal processing circuits are soldered on the PCB's top side.

This construction technique eliminates the need for wiring between the sensor and the signal processing circuits (the connection is extremely short, made with a PCB via between the top and bottom layers), eliminating the stray capacitances and the interference that could be coupled through the wiring. A novel signal processing technique was developed, which allowed for the system to measure very small deviations of capacitance using a low-frequency oscillator.

A circuit of the proposed capacitance measurement circuit was reproduced and implemented on the top of a two-layer PCB, without the interdigitated capacitor on the bottom side. Commercial capacitors were firstly measured with a GenRad 1659 RLC Digibridge, and then measured using

our direct to microcontroller interface circuit. The maximum calculated difference between the measurements was only 0.43%, for a large capacitance range, from 560 pF to 1.98 nF.

The sensor was tested in a laboratory using a set-up which emulated the wet end of a paper machine. Although the paper pulp enters the wet end of a paper machine with a high moisture content (typically 99%), it is necessary to wait until it reaches the range θ_w = 90% to 92% until it can go to the next fabrication step. In this θ_w range, a variation of ΔC = 92.1 pF was measured. Repeatability tests showed that the measured values presented a deviation from the mean that are four orders of magnitude lesser than the mean. Reproducibility tests, made with nine different measurements in the same paper pulp, showed that the maximum error observed was less than 0.006%.

The smart sensor was tested in the 20°C to 40°C temperature range, in a paper pulp with a gravimetric water content of 91%. Since the variation of capacitance with temperature is practically linear, we propose a simple linear compensation equation to correct for the observed sensitivity with the temperature.

The measured data is transmitted wireless (via Bluetooth), eliminating connections between the sensor and the paper machine controllers.

Data Availability

The measured data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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