

A High-Stability Capacitance Sensor System and Its Evaluation

Svetlana Avramov-Zamurovic, *Member, IEEE*, and Rae Duk Lee

Abstract—A new capacitance sensor system was developed with a microcontroller, commercial humidity and temperature sensors, a capacitance-to-digital converter, and a custom-built capacitance sensor. The performance of the system was evaluated by simulation and testing of the prototype. The impact of variations of ambient conditions on the system performance was analyzed, and a model for correcting the humidity and temperature influence was developed. Based on the experimental results obtained in an uncontrolled environment using a standard capacitor of 1 pF, the 24-h stability of the system was estimated to be within 30 parts in 10^6 . The high stability and sensitivity of the system allow its effective use in object-detection applications. Several sensors were constructed and evaluated while sensing various materials under different scenarios.

Index Terms—Capacitance measurement, capacitance sensor, electric field simulation, humidity, temperature variations.

I. INTRODUCTION

RECENT technological advancements have made available a high-resolution (24-bit) Σ - Δ capacitance-to-digital converter (CDC) with a capacitance input range on the order of a couple of picofarads [1]. Potential applications of these CDCs are numerous. The project that motivated our research involves a capacitance sensor incorporated on a robotic arm to classify the objects to be manipulated by the arm [2]. The critical design requirements in this application were small physical size and high sensitivity and reliability (stability and repeatability) of measurements. A simple capacitive sensor was developed to measure the variations in the dielectric constant as a classification criterion for a limited object set [3]. The initial results were published in [4]. Avramov-Zamurovic and Lee focused on the following: 1) evaluating the CDC using a nitrogen-filled standard 1-pF capacitor; 2) developing a correction model for the humidity and temperature influences on measurements; and 3) building useful sensors for detecting the presence of selected materials under different scenarios related to airport security applications.

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S. Avramov-Zamurovic is with the U.S. Naval Academy, Annapolis, MD 21402-5000 USA, and also with the National Institute of Standards and Technology, Gaithersburg, MD 20899 USA (e-mail: avramov@usna.edu).

R. D. Lee is with the National Institute of Standards and Technology, Gaithersburg, MD 20899 USA (e-mail: rdlee@nist.gov).

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II. CAPACITANCE SENSOR SYSTEM DESIGN

A block diagram of the developed capacitance sensor system is shown in Fig. 1. It is based on a microcomputer that controls the CDC and ambient humidity and temperature sensors and collects measurement data. The CDC is connected to a custom-made capacitive sensor placed under a target object. A personal computer is used to display the data and develop the microcontroller software.

The microcontroller development kit used in this application was developed at the U.S. Naval Academy in the Weapons and Systems Department. The microcomputer used is an 8-bit processor operating at 30 MHz, with excellent math performance. This hardware was selected because it has I²C communication capability, which is necessary in the use of CDC and sensors, and is programmed in user-friendly Dynamic C. The features critical to the performance of the microcontroller in the capacitive sensor system application are presented in this paper, and more detailed information on the microprocessor and the development kit can be found in the product manuals in [5] and [6].

The CDC in our application uses a single-ended input (see Fig. 2) in the range of ± 4 pF with an internal excitation signal at 16 kHz. The CDC supports 16- and 32-kHz sources. The 16-kHz signal was chosen to compare the CDC readings with those of a commercially available capacitance bridge that operates up to 20 kHz. The CDC is designed for floating capacitance sensors, and the measured capacitance is isolated from the ground. It is tolerant of parasitic capacitance to ground of up to 60 pF. There is an option to eliminate the offset in measured capacitance of up to 17 pF using an on-chip programmable capacitance digital-to-analog converter. Manufacturer statements on linearity ($\pm 0.01\%$), effective resolution (21 bit), and accuracy (4 fF) have to be verified using standard capacitors, and the uncertainty levels need to be established. This is a focus of future research. Detailed explanation of all aspects of the CDC is given in the manufacturer manual [1], and the characteristics relevant to the capacitance sensor system are given in this paper.

The CDC is a surface-mounted circuit, and the mounting board is designed to have digital connections to the microcontroller (I²C Protocol). A Teflon-insulated coaxial cable directly connects the measuring input pins on the CDC to the Bayonet-Neill-Concelman connectors. The connectors are mounted on the grounded shielded box that encloses the CDC.

The CDC has an on-chip temperature sensor used in a self-calibration process. Since it was observed that the CDC is significantly impacted by humidity variations and, to a lesser

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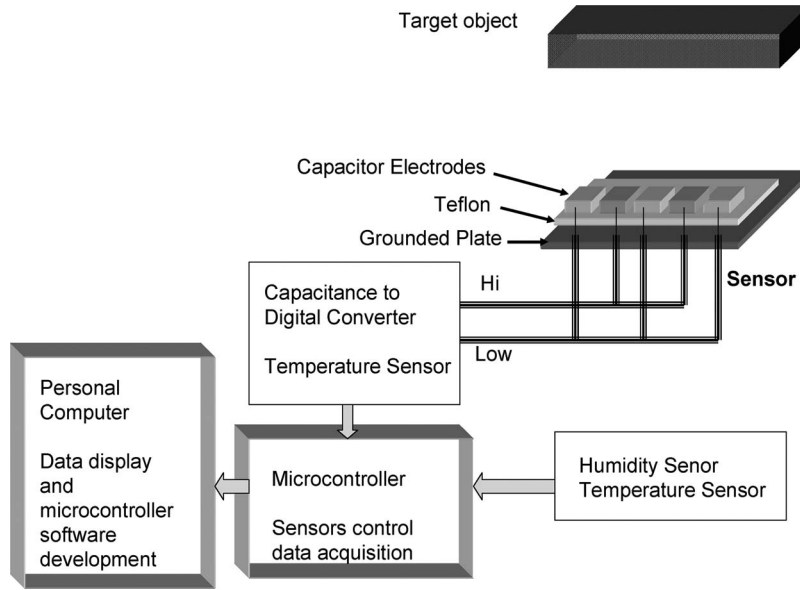


Fig. 1. Capacitance sensor system block diagram.

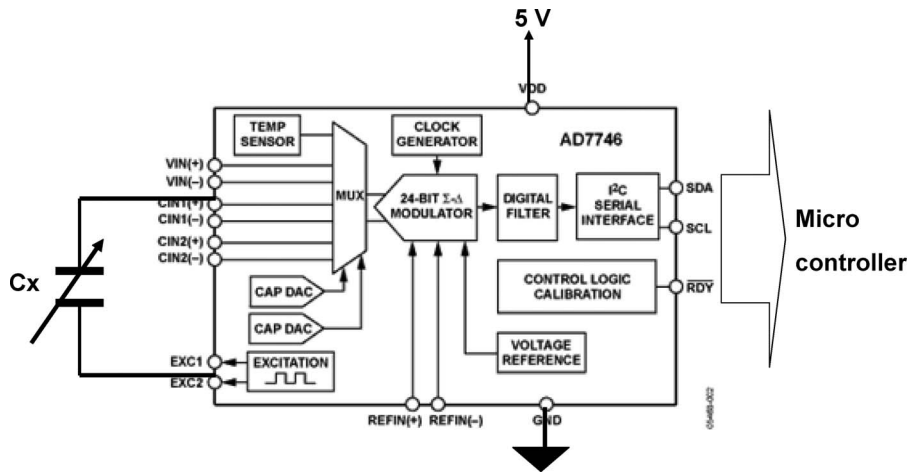


Fig. 2. Electrical schematic of the CDC used in the capacitance sensor system. The CDC circuit schematic used was taken from <http://www.analog.com/en/analog-to-digital-converters/capacitance-to-digital-converters/ad7746/products/product.html>.

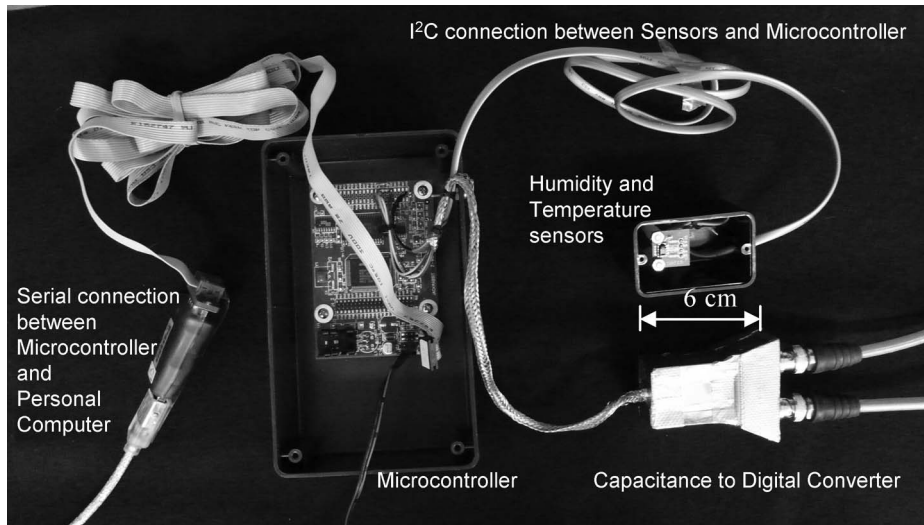


Fig. 3. Capacitance sensor system prototype.

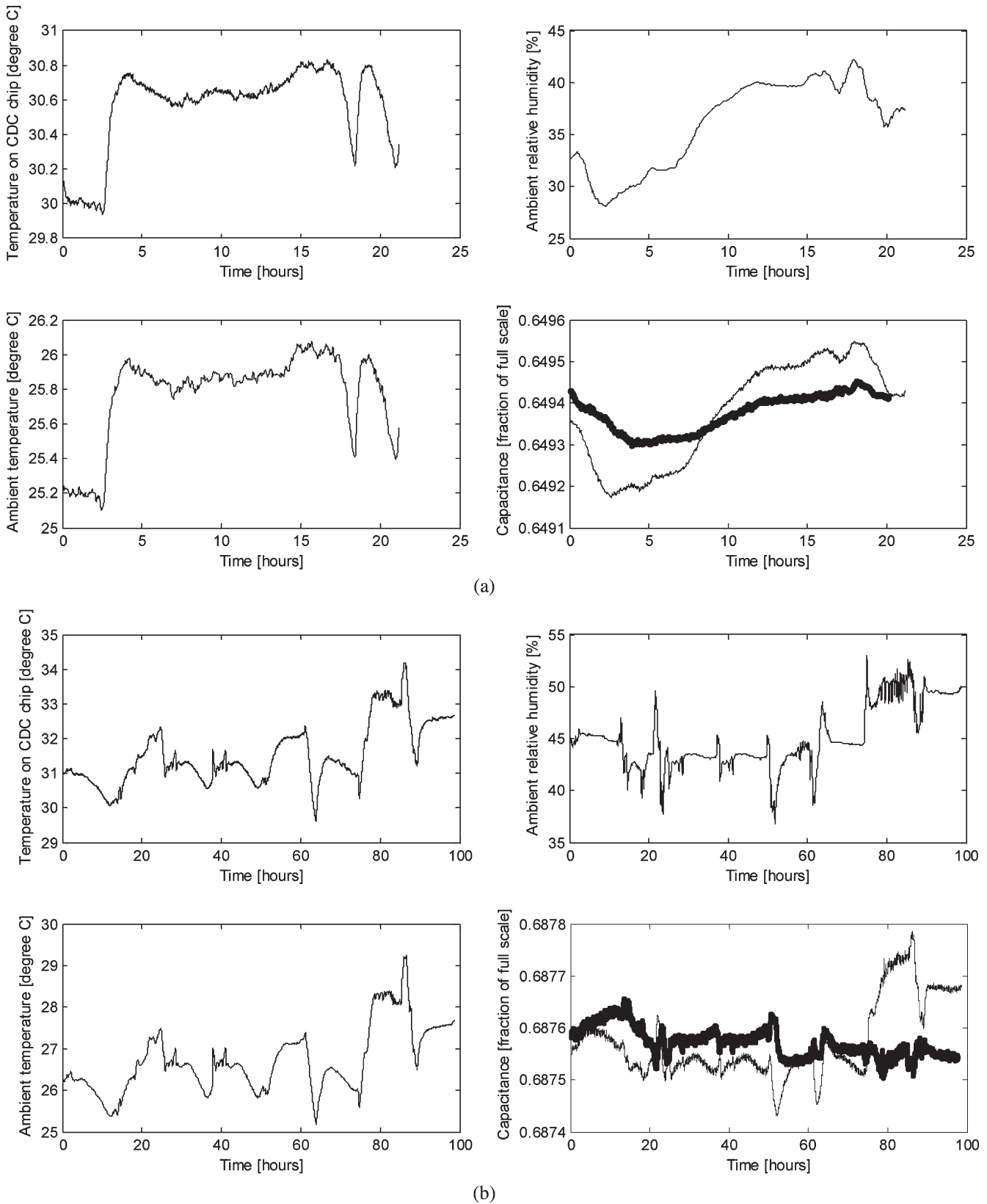


Fig. 4. Capacitance system data set as a function of time. (---) Measured and (—●—) corrected capacitance. (a) Test T4. (b) Test T2.

extent, by temperature variations, humidity and temperature sensors are used to measure ambient conditions. The data from humidity and temperature sensors are used to estimate capacitance corrections due to ambient variations and to cross

check the CDC on-chip temperature readings, contributing to an improved measurement process reliability. The humidity sensor measures relative humidity, but for ease of presentation throughout this paper, humidity sensor readings are simply

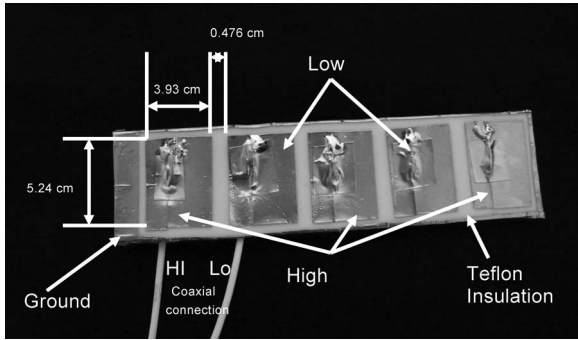


Fig. 5. Capacitance sensor prototype.

referred to as humidity. The capacitance sensor system prototype is shown in Fig. 3.

The CDC averages a preset number of capacitance readings. The measurements are recorded as a fraction of the full scale. The measured frequency of 16 kHz and an applied voltage of 2.5 V are specified. Internal noise filters are applied to each measurement, and the software periodically executes the CDC offset and gain self-calibration. The manufacturer-specified maximum capacitance data rate is 90 Hz, but with all of the filtering, temperature and humidity sensor readings, and self-calibration procedures implemented, the practical system data rate is 3 measurement/min.

III. EVALUATION OF THE CAPACITANCE SENSOR SYSTEM STABILITY AND CORRECTION MODEL

A nitrogen-filled standard 1-pF capacitor with no active thermal control was used to establish the stability of the capacitance sensor system in the laboratory environment ($26 \pm 1^\circ\text{C}$). The 24-h stability of the standard capacitor, which was measured using a high-accuracy commercial capacitance bridge, is ± 2 parts in 10^6 . The ambient humidity and temperature readings were used in developing a model for correcting the capacitance system dependence on environmental condition changes.

Observation of the effect of humidity on the capacitance sensor system showed that there was a time lag between the change in humidity and that in CDC readings. Humidity time constant τ is defined as the time elapsed between the onset of the ambient humidity change and the start of the capacitance reading drift. A sliding window was used to match the capacitance and humidity data. The time constant for the developed prototype was estimated to be 30 min.

To eliminate random noise, the data sets consisting of capacitance, humidity, and temperature readings were averaged over 3 min. Since the rapid (on the order of 10 min) burst-type deviations of humidity from the average value do not significantly influence the capacitance readings, a running average AH over 30 min was applied on the humidity data. The preprocessing (time constant, noise filtering, and running average) requires about 1 h of lead time before the capacitance corrections can be applied.

Humidity factor HF was calculated using the running average humidity value delayed for the time constant and the current capacitance. This factor should be constant for the given CDC chip and the enclosure. This assumption was tested by taking

the data over 1 h and calculating the least squares fit to a linear approximation. The process was repeated for very large data sets (on the order of 100 h), and the average value for the humidity factor was estimated to be 2×10^{-5} , as a fraction of the full-scale capacitance for a change in relative humidity of 1%. Once the system humidity factor is found, it may need to be periodically recalibrated. Since the focus in this analysis is on the stability of the capacitance sensor system, the mean humidity \bar{H} was subtracted.

The following expression gives the humidity corrections

$$C_c(k) = C(k) - HF(AH(k - \tau) - \bar{H}) \quad (1)$$

where $C(k)$ is the current value of capacitance, and $C_c(k)$ is the corrected capacitance value.

The temperature corrections were similarly developed. The temperature time constant was estimated to be 3 min, and the running average was calculated over 45 min. The temperature factor is found to be 2×10^{-5} , as a fraction of the full-scale capacitance per degree Celsius.

This model was applied to the data sets obtained using the standard 1-pF capacitor. Fig. 4 shows the data for tests T4 and T2, with and without ambient variation corrections applied. Based on the results from different tests, as summarized in Table I, the stability of the capacitance sensor system is estimated to be on the order of 30 parts in 10^6 .

The model corrections reduced the effects of ambient variations on the capacitance readings by at least a factor of two.

IV. APPLICATION AND TEST RESULT

Capacitive sensors are widely used in various applications [7]–[10]; an overview of design techniques has been published by Baxter [11]. Lee *et al.* introduced cross capacitance as a way to very precisely measure liquids [12] and implemented the technique on measuring the deterioration of engine oil [13]. A very high level of accuracy was achieved using three-terminal capacitance in measuring inclination [14].

In this paper, we describe the design of capacitance probes for possible use in sensing different target materials at a distance. The probe design evolved from modifications on the cross-capacitance principle. A high level of stability in measuring the capacitance changes was achieved. Fig. 5 shows the prototype of the sensor that was successfully used in sensing water and wood samples at 10 cm with 1-cm resolution. The copper electrodes (with an area measuring $2.54 \times 1.905 \text{ cm}^2$) are fixed on Teflon support and separated by 0.47 cm. The bottom of the sensor is grounded, and coaxial cabling is provided to measure the capacitance. The prototype sensor is rigidly built, but similar sensors could be constructed using flexible printed board circuit, making it suitable for other applications.

In the design phase, the sensor topology was analyzed using a MAXWELL 3-D v4.1 electric field simulation software based on mesh analysis, with the error specified at 0.5% [see Fig. 6(a) and (b)]. The design goal was finding a balanced sensor geometry with an adequate electric field depth to sense a change in the dielectric constant of the target sample at 10 cm and keeping the capacitance value on the order of a few picofarads due to the CDC range of 4 pF. Simulation results for the prototype sensor

TABLE I
CAPACITANCE SENSOR SYSTEM STABILITY WITH RESPECT TO A 1-pF STANDARD CAPACITOR. $\sigma(C)$ AND $\sigma(C_c)$ ARE THE STANDARD DEVIATIONS OF THE CAPACITANCE READING AND CORRECTED CAPACITANCE, RESPECTIVELY

Test N° and location	Test time [hours]	Humidity variation range [%]	Temperature variation range [°C]	Stability $\sigma(C)$ [parts in 10^6]	Stability with corrections $\sigma(C_c)$ [parts in 10^6]
T1 Lab	29	7	1.5	57	30
T2 On-site	100	20	4	73	30
T3 Lab	28	18	1.5	170	20
T4 Lab	25	10	0.5	57	12

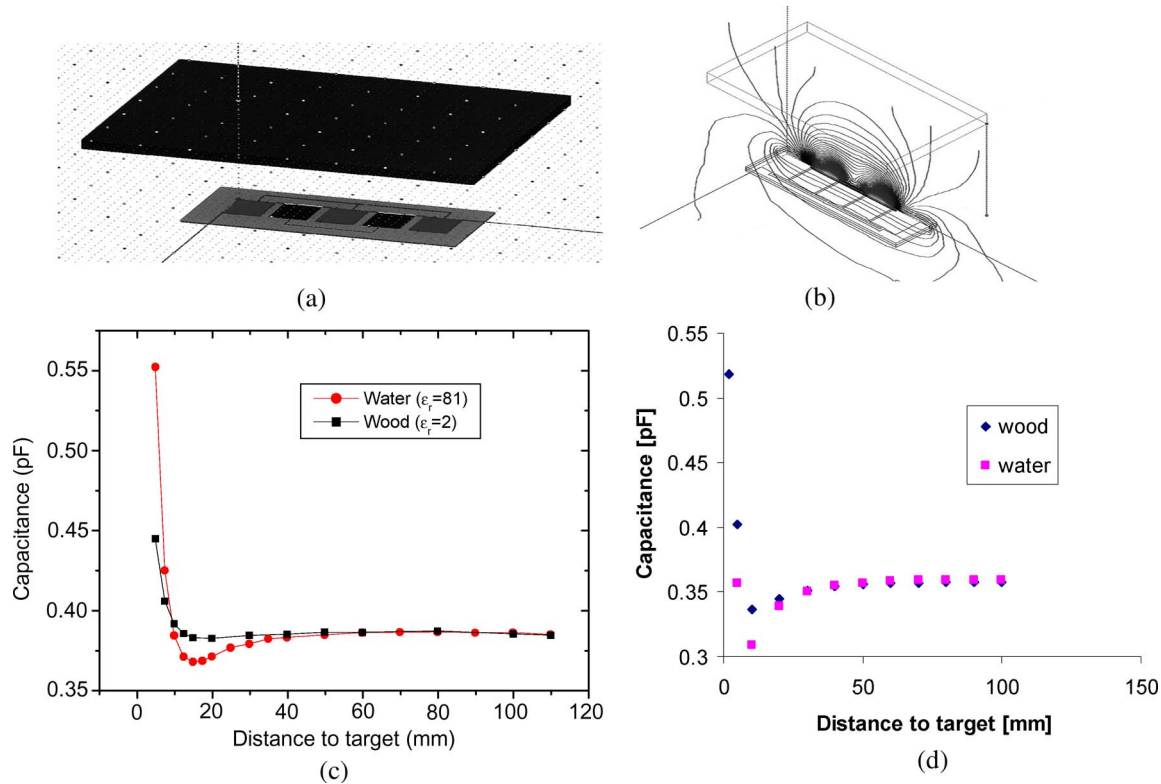


Fig. 6. Sensor 3-D simulation. (a) Sensor geometry and (b) equipotential electric field line distribution on the z -axis. Simulation versus measurements. Sensor capacitance as a function of the distance to the target for the wood and water samples. (c) Simulated and (d) measured results using a capacitance bridge.

and measurements using a commercial capacitance bridge are shown in Fig. 6(c) and (d).

The 6% difference in accuracy between the simulation capacitance values and the measurements is attributed to several discrepancies between the simulation and the prototype realization. Measurements were made on a large grounded plate to minimize the effect of the surroundings, where the simulation has a smaller grounded shield [see Fig. 6(a)]. Practically, the electrodes are directly connected to the source through the Teflon insulation, and the simulation used 2-D layouts and had the connection traces parallel to the electrodes. Tap water in a plastic bottle measured as a sample differed from the prism-shaped model in size and had a dielectric constant of 81.

Note that both the simulation and measurements show a zone when the target sample is very close (less than 1 cm) to the sensor where the capacitance trend changes direction.

To explain the sensor behavior at close proximity to the target, a simulation was performed [see Fig. 7(a)]. In the parallel-plate capacitor geometry, it is expected that the ca-

pacitance will increase if a dielectric sample is inserted. This assumption is based on the parallel electric field lines used in capacitance calculation. The capacitance trend is more complex to predict on the edges of the capacitor plates. Fig. 7(b) shows the capacitance changes as a function of the inserted dielectric sample location. It is clear that a dipping effect is noticeable around the plate edges, particularly with higher values of the dielectric constant. The capacitor prototype has open plates [see Fig. 6(a) and (b)], and the curved electric field lines contribute to decreasing capacitance values with an approaching dielectric sample. In the prototype, in the area close to the plates, the dielectric is in the region of approximately parallel electric field lines, and the capacitance value starts to rise.

The prototype sensor probe was first measured using the capacitance sensor system without any target sample. The tests lasted more than 5 h, with a humidity change of less than 3% and a temperature change of less than 1.5 °C. The recorded system stability was eight parts in 10^6 without the applied corrections since the ambient conditions did not significantly change.

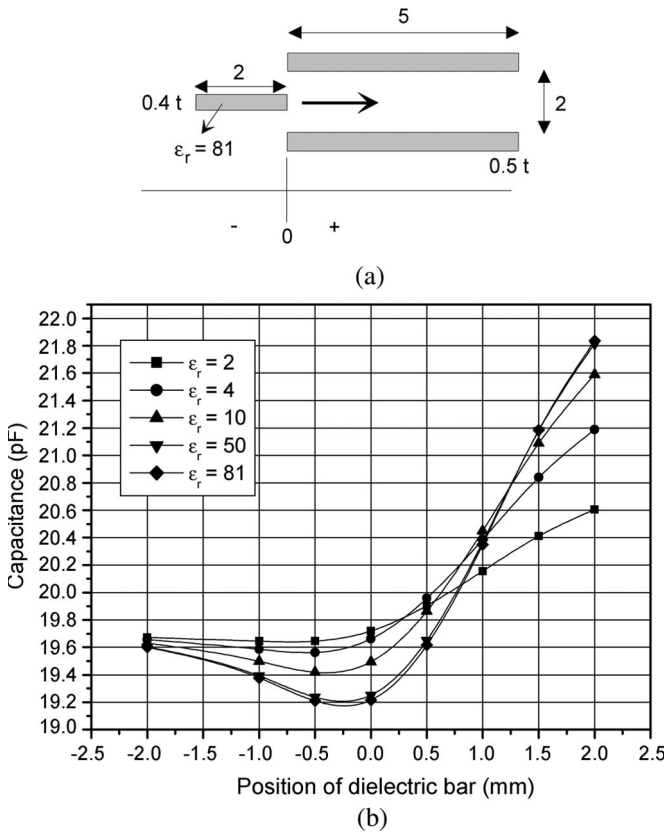


Fig. 7. Simulation of the insertion of a dielectric sample between parallel plates of a capacitor in the air. (a) Capacitance topology. All of the dimensions are expressed in units of millimeter. (b) Capacitance changes as a function of dielectric position.

The stability was calculated as the standard deviation of the readings relative to the full scale. The prototype sensor probe was then tested using a water sample at the distance of 7 cm in similar environmental conditions. The measured stability over 7 h was eight parts in 10^6 relative to the full scale. The test where the system measured a wood sample at 3-cm distance lasted 20 h. During the test, the temperature changed by 1°C , and the relative humidity changed by 15%. The standard deviations of the capacitance readings were 125 parts in 10^6 , and the corrected capacitance had a standard deviation of 43 parts in 10^6 relative to the full scale (see Fig. 8). The corrections were applied using humidity and temperature factors calculated from the stability tests using a 1-pF capacitor. Note that the residual pattern after corrections still follows the relative humidity. This effect could be attributed to the dielectric constant of the wood sample changing due to the water absorption in a high level of humidity (ranging from 27% to 43% humidity).

Fig. 9 shows the resolution of the capacitance sensor system in sensing a water sample at distances in steps of 1 cm. Each measurement lasted about 5 min.

While the shown tests demonstrate the potential of the capacitance sensor system, they also point to further steps that explore useful capacitance sensor system applications. The most significant is the research on the system's dynamic capabilities and its calibration. Since this paper was focused on stability analysis, very long tests were performed, and the

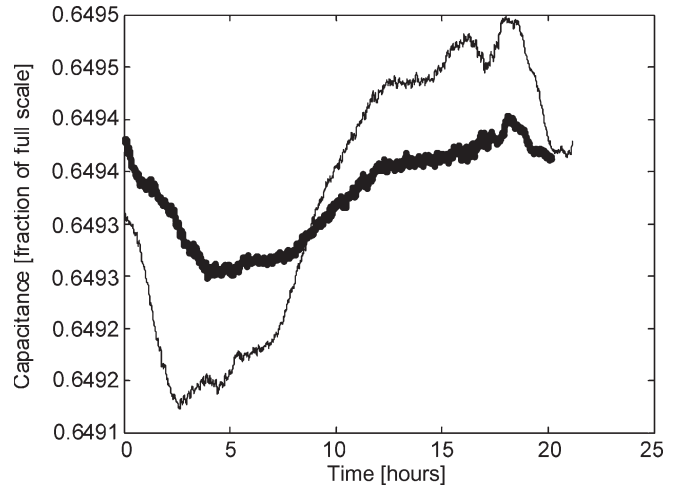


Fig. 8. (---) Measured and (—●—) corrected capacitance when a wood sample ($10 \times 10 \times 0.5$ cm) was measured using the capacitance sensor system at a distance of 3 cm.

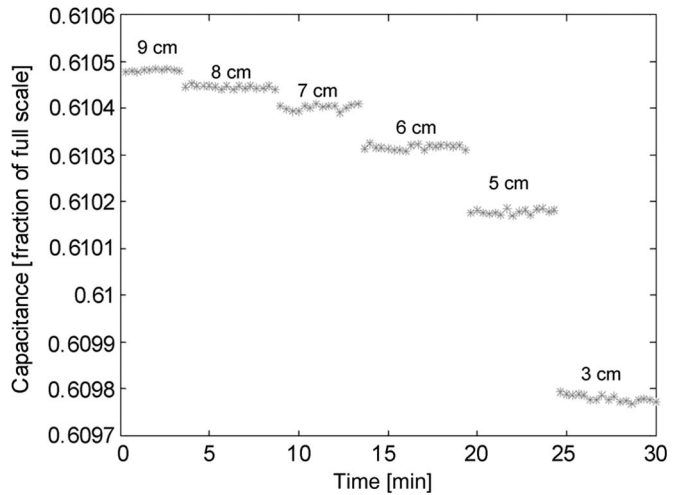


Fig. 9. Water sample sensed at various distances using the capacitance sensor system.

stability results revealed very good performance. In on-site applications, a balance between the data rate and the system reliability needs to be reached. The CDC could be configured to have two capacitance inputs. This feature has to be explored in a periodic on-site calibration option to improve on the measurement accuracy.

V. CONCLUSION

This paper has described the development of a simple yet effective field-deployable capacitance sensor system for the discrimination of materials at distances of up to 10 cm from the target. The prototype consists of a microcomputer-based measurement system, including a CDC, ambient sensors, and capacitance probes. A model was developed to reduce the sensitivity of the system to ambient temperature and humidity variations. The time constants for temperature and humidity variations were determined from measurement data. The system was tested under laboratory and field conditions and

calibrated against laboratory standards. It showed a stability that is better than 30 parts in 10^6 while measuring 1-pF capacitance and high sensitivity to variations in material dielectric constants.

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Svetlana Avramov-Zamurovic (M'97) received the B.S. and M.S. degrees in electrical engineering from the University of Novi Sad, Novi Sad, Yugoslavia, in 1986 and 1990, respectively, and the Ph.D. degree in electrical engineering from the University of Maryland, College Park, in 1994.

From 1990 to 1994, she was involved in the development of a voltage ratio bridge for the NASA Zeno experiment. Since 1990, she has been a Guest Researcher with the National Institute of Standards and Technology, Gaithersburg, MD. She is also currently a Professor with the U.S. Naval Academy, Annapolis, MD. Her research interests include the development of impedance-measuring techniques.



Rae Duk Lee was born in Korea in 1945. He received the B.S. and M.S. degrees from Soong-Jun University, Taejon, Korea, in 1968 and 1980, respectively, and the Ph.D. degree in physics from Han-Nam University, Taejon, in 1991.

He joined the Electricity Laboratory, Korea Research Institute of Standards and Science (KRISS), Daejeon, Korea, in 1978, from which he retired in 2006. He then became a Guest Researcher with both KRISS and the National Institute of Standards and Technology (NIST), Gaithersburg, MD. He has been

working on the development of impedance standards at low frequency. He is currently with NIST, working on the development of a calculable cross capacitor.