A High-Stability Capacitance Sensor System and its Evaluation

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Abstract— A new capacitance sensor system was developed with a microcontroller, commercial humidity and temperature sensors, capacitance-to-digital-converter and a custom-built capacitance sensor. The performance of the system was evaluated by simulation and by testing of the prototype. 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 experimental results obtained in non-controlled environment using a standard capacitor 1 pF, the 24-hour 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 in sensing various materials under different scenarios.

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

I. INTRODUCTION

RECENT technology advancements made available a high-resolution (24-bit) Σ-Δ capacitance-to-digital-converter (CDC) with a capacitance input range on the order of couple of pF [1]. Potential applications of CDCs are numerous. The project that motivated our research involves a capacitance sensor incorporated on a robotic arm for classifying 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 dielectric constant as a classification criterion for a limited object set [3]. Initial results were published in [4]. This paper focuses on (a) evaluation of the CDC using a nitrogen filled standard 1 pF capacitor, (b) development of a correction model for the humidity and temperature influences on measurements, and (c) building useful sensors for detecting presence of selected materials under deferent scenarios related to airport security applications.

II. CAPACITANCE SENSOR SYSTEM DESIGN

A block diagram of the developed capacitance sensor

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system is shown in Fig. 1. It is based on a microcomputer that controls the CDC, 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 data and develop microcontroller software.

The microcontroller development kit used in this application is developed at the United States 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 I^2C communication capability necessary to use 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 the paper and more detailed information on microprocessor and the development kit could be found in product manuals [5] and [6].

The CDC in our application uses single ended input (see Fig. 2) in the range of ±4 pF with internal excitation signal at 16 kHz. The CDC supports 16 kHz and 32 kHz sources. Signal of 16 kHz was chosen in order to compare the CDC readings with commercially available capacitance bridge that operates up to 20 kHz. The CDC is designed for floating capacitance sensors and 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 offset in measured capacitance of up to 17 pF using an on-chip programmable capacitance digital to analog converter. Manufacturer statements on linearity (±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. The 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 the paper.

The CDC is a surface mount circuit and the mounting board is designed to have digital connections to the microcontroller (I^2C protocol). A Teflon insulated coaxial cable directly connects the measuring input pins on the CDC, to BNC 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 extent by temperature variations, humidity and temperature

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14. ABSTRACT
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sensors are used to measure ambient conditions. The data from humidity and temperature sensors is used for estimation of capacitance corrections due to ambient variations and cross-checking the CDC on-chip temperature readings, contributing to an improved measurement process reliability. The humidity sensor measures relative humidity, but for the ease of presentation throughout the paper humidity sensor readings are referred as simply humidity. The capacitance sensor system prototype is shown in Fig. 3.

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

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 ± 1ºC). 24-hour stability of the standard capacitor measured using a high accuracy commercial capacitance bridge is ± 2 parts in 10^6. Ambient humidity and temperature readings were used in developing a model for correcting the capacitance system dependence on the environmental conditions changes.

Observation of humidity effect on the capacitance sensor system showed that there was a time lag between the humidity change and the change in CDC readings. The humidity time constant, τ, is defined as the time elapsed between the onset of the ambient humidity change, and the start of the capacitance readings 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 minutes.

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

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

The following equation gives the humidity corrections:

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

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

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

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

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

IV. Application and Test Results

Capacitive sensors are widely used in various applications [7-10] and an overview of design techniques is published by Baxter [11]. Lee and *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]. Very high level of accuracy was achieved using 3-terminal capacitance in measuring inclination [14].

In this paper we describe the design of capacitance probes for possible use to sense different target materials at a distance. The probes design evolved from modifications on cross capacitance principle. High level of stability in measuring the capacitance changes was achieved. Fig. 5 shows the prototype of the sensor successfully used in sensing water and wood samples at 10 cm with 1 cm resolution. The copper electrodes (area 2.54 x 1.905 cm^2) are fixed on Teflon support and separated 0.47 cm. The bottom of the sensor is grounded and coaxial cabling is provided for measuring the capacitance. The prototype sensor is rigid as built, but similar sensors could be constructed using flexible PBC making it suitable for other applications.

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

A 6% of difference in accuracy between the simulation capacitance values and 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. 6a). Practically the electrodes are connected to the source directly through the Teflon insulation, and the simulation used two dimensional 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 dielectric constant of 81.

Note that both 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. 7a). In the parallel plate capacitor geometry it is expected that capacitance 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. The Fig. 7b 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 especially with the higher values of dielectric constant. The capacitor prototype has open plates (see Fig. 6a and 6b) and the curved electric field lines contribute to decreasing capacitance values with 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 over 5 hours with humidity changing less than 3% and temperature changing less than 1.5 ºC. Recorded system stability was 8 parts in 10^6 without corrections applied since ambient conditions did not significantly change. The stability was calculated as standard deviation of 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. Measured stability over 7 hours was 8 parts in 10^6 relative to the full scale. The test where the system measured a wood sample at 3 cm distance lasted 20 hours. During the test the temperature changed 1ºC and the relative humidity changed 15%. The standard deviations of the capacitance readings was 125 parts in 10^6 and corrected capacitance had 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 the residual pattern after corrections still follows relative humidity. This effect could be attributed to the dielectric constant of the wood sample changing due to water absorption in a high level of humidity (going form 27% to 43% humidity).

Figure 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 minutes.

While the shown tests demonstrate the potential of the capacitance sensor system they also point to further steps in exploring useful capacitance sensor system applications. The most significant is the research of system's dynamic capabilities and its calibration. Since this paper was focused on stability analysis very long tests were performed and the stability results revealed very good performance. In on-site applications a balance needs to be reached between the data rate and the system reliability. The CDC could be configured to have two capacitance inputs. This feature has to be explored in a periodic on-site calibration option in order to improve on measurement accuracy.

V. CONCLUSIONS

This paper describes development of a simple yet effective field-deployable capacitance sensor system for discrimination of materials at distances up to 10 cm from the target. The prototype consists of a microcomputer based measurement system including capacitance-to-digital-converter, 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 stability 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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