A CAPACITANCE SENSOR SUITE EVALUATION

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Abstract

An experiment was set up to evaluate a sensor suite containing an affordable commercially available capacitance to digital converter and a simple custom-built capacitance sensor. A set of surface mount capacitors was thoughtfully assembled for evaluation purposes. The results show good short-term stability, allowing the effective use of the sensor suite in an object classification application.

Introduction

Recent technology advancements delivered a high-resolution (24-bit) \(\Sigma-\Delta\) capacitance to digital converter (CDC) with capacitance input range of \(\pm 4.096\) pF \([1**]\). Potential applications of the CDC are numerous. The project that motivated our research involved placing the capacitance sensor on a robotic arm in order to classify the objects to be manipulated by the arm \([2]\). The initial set of objects included plastic, wood, metal, and a container filled with water. A simple capacitive sensor was developed to measure the variations in dielectric constant as a classification criterion for the limited object set \([3]\). The critical design criteria for this sensor suite were its physical size, and the sensitivity and reliability of measurements.

Capacitance to digital converter

The CDC is a surface mount circuit and the mounting board is designed to have digital connections to the microcontroller (I\(_2\)C protocol). We enclosed the board in a grounded shielded box leaving a small gap in the shielding at the base of the box where the CDC pins can be reached on the mounting board. A Teflon isolated coaxial cable directly connects to the measuring input pins. To improve the temperature stability, the housing was enclosed in Styrofoam (See Fig. 1).

Figure 1. Capacitance to digital converter housing.

Coaxial cables from the measuring point on the CDC to the capacitors measured were used to ensure stability and reliable testing. In the application phase, the sensor could be directly connected to the CDC.

A set of four capacitors was developed to test the CDC (See Fig. 2). Surface mounted capacitors with nominal values of 1 pF were used in various series combinations. In particular, we used series of five, four, two and one 1 pF capacitors giving nominal values of \([0.2, 0.25, 0.5,\) and \(1]\) pF. The evaluation set was measured using a commercial capacitance bridge (see Table 1).

The measurements have four-hour stability of 0.000005 pF suggesting good performance of the evaluation set. This set provides more than 40 different series and parallel combination values of capacitance in the range of 0.2 to 2 pF. Figure 3 shows the possible set of capacitance values using the developed evaluation set.

Figure 2. Evaluation set of capacitors.

Figure 3. Series and parallel capacitance combinations using the developed evaluation set. \(x\) represents all possibilities. Star represents measured values.

Measurement software developed for the CDC collects 10 sets of 100 readings. The readings are collected as a fraction of the full scale (\(\pm 4.096\) pF). The measurement frequency is 16 kHz and the applied voltage is 1.5 V. The sampling rate is approximately 10 Hz. For each set, the mean value was calculated and those mean values were averaged to produce a capacitance measurement value. The standard deviation of 10 mean values is on the order of 0.000065 pF.

The base capacitance value, measured with no capacitors connected to the CDC, has one-hour stability of 0.00003 pF. Figure 4 shows the testing at several temperatures and humidity levels. The humidity coefficient is measured to be 0.00001 pF per percent change in humidity.

The temperature coefficient specified by the surface mount capacitor manufacturer, is 30 parts in \(10^6\) per °C. Since the capacitance measurement circuit has an on-chip temperature sensor, the temperature coefficient has been measured to be on the order of 0.0001 pF per °C.

Based on measurements of the selected set of evaluation capacitators, it was observed that the 0.2 pF (nominal value) capacitor has the best stability (0.0001 pF) over 3 days. This measurement did not include corrections due to humidity and temperature changes. The higher-valued capacitors are more susceptible to environmental changes (measured stability up to 0.001 pF). The four evaluation capacitors were measured separately and in parallel combinations. The stability of the combinations was comparable to the stability of the solo values. But the numerical values of the combinations, compared to the solo values, had the offset of 0.002 pF.

**Identification of commercial products does not imply endorsement by the U.S. Government, nor does it imply that such products are necessarily the best available.**
Manufacturer specified accuracy of the CDC is 0.004 pF. A commercial capacitance bridge measures 1 pF capacitors at 16 kHz and 1.5 V with resolution of 16 parts in $10^6$ and accuracy of 104 parts in $10^6$. Table 1 compares CDC measurements with capacitance bridge measurements.

Table 1. Capacitance from CDC vs. capacitance bridge. Values are given in pF.

<table>
<thead>
<tr>
<th>Capacitance Nominal Value</th>
<th>0.2</th>
<th>0.25</th>
<th>0.5</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance Bridge</td>
<td>0.1878</td>
<td>0.2499</td>
<td>0.5569</td>
<td>1.1059</td>
</tr>
<tr>
<td>CDC</td>
<td>0.192</td>
<td>0.2549</td>
<td>0.5657</td>
<td>1.1205</td>
</tr>
<tr>
<td>Difference</td>
<td>0.0042</td>
<td>0.005</td>
<td>0.0088</td>
<td>0.0146</td>
</tr>
</tbody>
</table>

Considering the initial testing of CDC performance using the evaluation set of capacitors, it is clear that the CDC performs well within the 0.0001 pF resolution, but requires calibration if accurate measurement of the capacitance is needed. For some applications relative measurements are sufficient. Ongoing work in evaluating the CDC performance will include correction factors due to the environmental changes. The CDC contains a temperature sensor that has 0.1 ºC resolution and comparable accuracy. A humidity sensor will be implemented in order to improve the stability performance to 0.00001 pF or better. Both sensors should be calibrated periodically. Software will correct for environmental conditions in real-time for applications requiring higher sensitivity and reliability.

Object classification sensor suite

Figure 5 shows the custom-built sensor measuring the capacitance of wood samples. The sensor was constructed using 6.5 cm of inner conductor of a coaxial cable. Teflon insulation proved to be effective when measuring metal samples. The optimum length of the conductors was found experimentally. In Figure 5, as two conductors are tied by black insulators in this simple experiments, the gap between sensor and target material will not be enough repeatable, and the measured capacitance will be affected sensitively due to the gap size. To avoid this weakness, the sensor with shape of a flexible-PCB (printed circuit board) can be fabricated and replaced.

Figure 6. shows the results when measuring wood, plastic, and metal samples and a water filled container. Each test ran for one hour or more and the temperature was recorded. The humidity of the air was also observed and in some cases (wood) changed from 50% to 30%, but the measurement plateaus were distinguishable, allowing classification. Additional tests were carried out to estimate the distance between the sensor and sample for reliable detection. Presence of metal compared to non-metal sample was detected at the distance of 6 cm.

Conclusions

An affordable commercially available capacitance to digital converter was evaluated and a capacitance sensor was designed for an object classification application. The performance of the described capacitance sensor suite was demonstrated to be effective in the given application. Preliminary results show good measurement stability on the order of 0.0001 pF, and suggest areas for improvement (environmental change corrections) that could advance the performance and lead to a wider range of applications.

Acknowledgment

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References

[1] Analog Devices, Manufacturer Specifications: AD7746 24-bit Capacitance to Digital Converter **.

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