A New Capacitance-to-Digital Converter Suitable for Human Proximity Sensing

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Abstract - This paper presents a new, simple and efficient dual-slope Capacitance-to-Digital Converter (CDC) that gives digital values of capacitances in a π-model of a capacitive proximity sensor. This CDC is suitable for a capacitive proximity sensor with two electrodes. When a human approaches the electrodes, it forms three capacitances, i.e., between human body and first electrode, between body and second electrode and between body and ground. It can be represented in a T-model or in an equivalent π-model. Conventional signal conditioning methods can provide only a single output from this network. It will be very useful, in a proximity sensing point of view, if the signal conditioning circuit can capture changes in those three individual capacitances and provide corresponding outputs. Further it will also be useful, to store and process easily, if these outputs are obtained in digital form, directly. A novel dual-slope CDC that measures all the three values of the capacitances in a π-model and provides those three digital outputs has been developed and details are presented in this paper. Measuring all the three capacitance is advantageous because it can detect proximity as well as provides location of body in relation to sensor electrodes. A prototype CDC has been developed and tested. Results are promising.

I. Introduction

Sensing of human presence is a critical factor to avoid mishaps in hazardous environment by invoking necessary actions. Capacitive sensors are widely used to detect human proximity as they have many advantages compared to optical, inductive or mechanical methods. In order to detect human proximity, a simple two plate capacitive sensor can be used [1]. In such a sensor, one of the electrodes will be excited from a source and other electrode will be at virtual ground (e.g., inverting terminal of an I-to-V converter). This set-up can give an output when a human body is present but it cannot give location of the body with respect the individual electrodes. Location information is very useful in some applications; say to track direction of movement of a human hand near a touch display. This information can also improve the overall detection accuracy. Equivalent circuit of the sensor with two electrodes and a human body (in the sensor vicinity) will have three capacitances (other than the capacitance that exists between the electrodes, when no human is present) and can be represented in a T-model. This can also be represented in a π-model as in Figure 1. A new simple CDC that measures these capacitances is presented below.

II. Proposed Dual Slope Capacitance-to-Digital Converter

The proposed CDC works based on the principle of dual-slope ADC [2]-[4]. Figure 1 shows a block diagram of...
the proposed scheme. The sensing capacitances in the $\pi$-model are named as $C_1$, $C_2$ and $C_C$ as indicated in Figure 1. The CDC has three conversion cycles. The CDC performs an auto-zero phase before starting the conversion cycles. In auto-zero, the integrator output $v_{io}$ of the op-amp OA1 is brought to zero. The capacitances to be measured are charged and then discharged in a particular manner by the SPDT switches $S_1$, $S_2$, $S_3$ and $S_4$ from a dc reference voltage source ($V_{REF}$). This charge is then transferred to a feedback capacitor $C_F$ by suitably operating the switches using a Control and Logic Unit (CLU), indicated in Figure 1. This operation is repeated for a fixed number of clocks and named as integration period. This is followed by a de-integration period during which the $C_F$ will be discharged using a known capacitor $C_{REF}$. The detailed switching sequence and operation during each cycle (one for each capacitance in the $\pi$-model) are discussed in following sections.

A. Conversion Cycle for $C_1$

As soon the CDC is powered ‘ON’ it goes through an auto zero phase. This ensures that the feedback capacitor $C_F$ is not holding any charge before the measurement starts. The CDC then begins measurement of capacitor $C_1$ followed by $C_2$ and $C_C$ as shown in Figure 2. During the integration period of the cycle (for $C_1$) when clock CLK = 1 the switches are positioned at $S_1 = S_2 = S_4 = 1$ while $S_3 = 0$. In this condition, the capacitors $C_1$ and $C_C$ will charge to $V_{REF}$ while $C_F$ being grounded on both ends does not charge. When CLK = 0; $S_1 = S_2 = S_3 = 0$ and $S_4 = 1$. In this condition $C_C$ is short circuited and $C_1$ is virtually grounded due to configuration of op-amp OA1. This forces the charge in $C_1$ to be transferred to feedback capacitor $C_F$ incrementing its output voltage $v_{io}$ by $\Delta v = -C_1 \times V_{REF} / C_F$. This whole process is repeated for $N$ clock cycles. At the end of the integration process $v_{io} = N \times C_1 \times V_{REF} / C_F$. Switch $S_5$ and $S_6$ are kept at grounded, i.e. $S_5 = S_6 = 0$ irrespective of the CLK to exclude $C_{REF}$ throughout the integration period for $C_1$.

In the de-integration period, the charge acquired by $C_F$ during integration is neutralized to zero in a step by step manner as explained in this paragraph. Switch $S_1$ to $S_4$ are set to fixed state where $S_1 = 0$ and $S_2 = S_3 = S_4 = 1$ to confirm $C_1$, $C_2$ and $C_C$ are grounded and does not contribute any charge to $C_F$ during de-integration. When the CLK = 1; $S_1 = 0$ and $S_6 = 1$ charging $C_{REF}$ to $V_{REF}$. When CLK = 0; $S_1 = 1$ and $S_6 = 0$. In this case, due to the virtual ground, charge in $C_{REF}$ is moved to $C_F$ bringing a voltage change in $v_{io}$ by $\Delta v = C_{REF} × V_{REF} / C_F$. This operation is continued, for coming clock cycles, until a zero crossing of $v_{io}$ is sensed by the comparator OA2. The number of clock cycles $N_0$ elapsed for the same is stored in the CLU. The charge acquired by the $C_F$ during the integration and de-integration period is equal but opposite. Considering charge balancing and zero potential at the end of the conversion cycle we get equation (1).

$$\frac{N_0 \times C_{REF} \times V_{REF}}{C_F} = \frac{N \times C_1 \times V_{REF}}{C_F}$$

i.e. $C_1 = \frac{(N_0 C_{REF})}{N}$

Figure 2. Diagram showing initial auto-zero phase, the integrator voltage $v_{io}$, comparator output $v_c$ and clock CLK for three cycles of operation.

B. Conversion Cycle for $C_2$

As soon as the zero crossing (positive edge) is detected for first conversion cycle, the cycle for $C_2$ starts. During the integration process for $C_2$ switch $S_1$ to $S_4$ operates while $S_5 = S_6 = 0$. When CLK = 1; $S_1 = S_3 = 0$ and $S_2 = S_4 = 1$. In this condition, capacitors $C_2$ and $C_C$ will get charged to $V_{REF}$. Capacitor $C_1$ being grounded from both ends does not charge. When CLK = 0; $S_1 = S_2 = S_3 = S_4 = 0$. This short the terminals of capacitor $C_C$
thereby discharging it. While charge in C₂ flows to Cᵢ since one end of C₂ is at ground and other end is at virtual ground. The charging and discharging of C₂ is repeated for N clock cycles bringing \( V_{\text{ref}} = -N \times C₂ \times V_{\text{REF}} / C₁ \). Since the output of OA₁ is negative (at the end of integration period) in this case too, the de-integration operation is followed in the same way as in case of first conversion cycle (for C₁). The number of clock cycles, \( N_{02} \), passed by before zero crossing of \( V_{\text{ref}} \) is recorded by the CLU with the help of comparator voltage \( Vᵢ \). \( N_{02} \) is indirectly a measure of capacitance C₂, following the charge balancing principle. As in the case of C₁, C₂ can be expressed as in equation (2).

\[
C₂ = \frac{N_{02} \cdot C_{\text{REF}}}{N} \quad (2)
\]

C. Conversion Cycle for C₃

The third cycle to measure capacitance C₃ is initiated at the end of the second conversion cycle. In this case, during integration period, when CLK = 1; S₁ = S₂ = S₃ = S₄ = 1. This charges C₁ and C₃ to V₉ while both the terminals of C₂ remain at ground potential. When CLK = 0; S₁ = S₂ = 0 and S₃ = S₄ = 1. In this condition, since, C₁ is grounded at each end, it will simply get discharged. On the other hand, charge in C₃ is transferred to Cᵢ. After repeating the same for N clock cycles, integrator voltage \( V_{\text{ref}} = N \times C₃ \times V_{\text{REF}} / Cᵢ \). Cᵢ will not contribute any charge to Cᵢ, as S₁ = S₄ = 0 throughout integration. The output voltage \( V_{\text{ref}} \) at the end of this integration process is a positive value, so, in order to bring it down back to zero, during de-integration, a new switching sequence is required. In this duration, S₁ = 0 and S₂ = S₃ = S₄ = 1 is maintained as in previous de-integration periods. When CLK = 1; S₁ = S₄ = 0 which connects both terminals of Cᵢ to ground. When CLK = 0; S₃ = S₄ = 1. This connects one terminal of Cᵢ to Vᵢ and other to inverting terminal of op-amp OA₁, which is at virtual ground. In this condition, Cᵢ will charge to Vᵢ and the current flowing through Cᵢ goes through Cᵢ changing the potential \( V_{\text{ref}} \) by \( \Delta V = -Cᵢ \times V_{\text{REF}} / Cᵢ \). This operation is continued until a zero crossing of \( V_{\text{ref}} \) is detected by the CLU. The number of clock cycles elapsed during de-integration is recorded by the CLU as \( N_{03} \). Thus, C₃, as in the case of C₁ and C₂ can be expressed as in (3).

\[
C₃ = \frac{N_{03} \cdot C_{\text{REF}}}{N} \quad (3)
\]

The three conversion cycles described above, is repeated in a continuous manner in the same order as presented above. The switching sequence for the complete operation (three cycles) is also shown in Table-1. Equation (1) to (3) shows that changes in the count \( N_{01}, N_{02} \) and \( N_{03} \) are directly proportional to change in the sensor capacitances C₁, C₂ and C₃ respectively. The sensitivity of the measurement can be deduced in terms of N and Cᵢ.

Table-1. Switching Sequence employed by the CDC

<table>
<thead>
<tr>
<th>Conversion Cycle</th>
<th>Clock State (CLK)</th>
<th>Integration period</th>
<th>De-Integration period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S₁ S₂ S₃ S₄ S₅ S₆</td>
<td>S₁ S₂ S₃ S₄ S₅ S₆</td>
</tr>
<tr>
<td>First Cycle</td>
<td>1 1 1 0 1 0 0</td>
<td>0 1 1 1 0 1 0</td>
<td></td>
</tr>
<tr>
<td>(for C₁)</td>
<td>0 0 0 0 1 0 0</td>
<td>0 1 1 1 1 0 0</td>
<td></td>
</tr>
<tr>
<td>Second Cycle</td>
<td>1 0 1 1 0 0 0</td>
<td>0 1 1 1 0 1 0</td>
<td></td>
</tr>
<tr>
<td>(for C₂)</td>
<td>0 0 0 0 0 0 0</td>
<td>0 1 1 1 1 0 0</td>
<td></td>
</tr>
<tr>
<td>Third Cycle</td>
<td>1 1 1 1 1 0 0</td>
<td>0 1 1 1 0 0 0</td>
<td></td>
</tr>
<tr>
<td>(for C₃)</td>
<td>0 0 0 1 1 0 0</td>
<td>0 1 1 1 1 1 1</td>
<td></td>
</tr>
</tbody>
</table>

II. Experimental Setup and Results

A prototype of the proposed CDC was developed. A suitable program was developed and burned into a 16 bit microcontroller MSP430G2553 from Texas Instruments to realize the CLU that performs switching operations and determines digital values of C₁, C₂ and C₃. For SPDT switches IC CD4053B was used. A low bias current op-amp (OA₁), for integrator, was implemented using LF347 from Texas Instruments, while comparator was realized using IC LM311. A dc reference voltage \( V_{\text{REF}} \) of 1.2V is obtained using IC LM285-1.2. A 20 kHz clock frequency is used for CLK. It was generated by the controller. For testing the prototype developed, Cᵢ and Cᵢ were chosen as 100nF and 120pF respectively. The fixed number of clock cycles, N during integration was kept 8000 to restrict integrator output \( V_{\text{ref}} \) well below saturation limits. With known values of C₁, C₂ and C₃ the reading were observed and found to be accurate. The output obtained by varying each capacitor individually, keeping others constants also showed negligible cross sensitivity between \( N_{01}, N_{02} \) and \( N_{03} \). Waveforms observed from prototype CDC developed are shown in Figure 3.
A capacitive proximity application that detects presence of a human near the sensor has been developed. The sensor electrodes comprised of two thin Aluminium sheets placed vertically along its length as shown in Fig. 4. The placement and dimensions of the electrode plates was fixed to cover substantial portion of the torso of a human body standing near it. The length and width of electrode was taken as 45 cm and 3 cm respectively. The electrodes were separated by a distance of 20 cm. The whole sensor arrangement was kept at a height of about 80 cm above the floor level. The electrodes were connected to the prototype CDC using a coaxial shielded cable keeping its outer shield at ground potential. Depending on the length of the shielded cable used, an offset capacitance gets added up to the sensor capacitances (C₁ and C₂). Due to this, the integration clock counts in case of C₁ and C₂ was kept lower than that for C₃ to avoid reaching saturation limits of op-amp OA₁.

In case of C₁ and C₂ measurements, N= 4000 counts whereas in C₃ measurement N=12500 counts. A higher integration clock counts in the third conversion cycle increases its (output corresponding to C₃) sensitivity. Values of C₁ and C₃ used for this setup were 100nF and 33pF respectively. The data obtained was averaged using simple moving average method taking window size of 16 sample points. Figure 5 shows a distinct pattern of change in the digital outputs of the CDC observed depending on position (in relation to sensor electrodes) of human in proximity. This is achieved with the special capability of the new CDC to provide values of each capacitance in the π-model of human proximity described in Figure 1.

III. Conclusions

With the existing Capacitance to Digital Converters (CDCs) it is not possible to obtain each of the three capacitances in a π-model of a capacitive proximity sensor directly. In this paper we have presented a novel CDC to measure all three capacitances which has its advantage to detect human presence as well as provide information about its location with respect to electrodes. This will be useful for various safety applications where along with detection, the information of human’s relative position is also important.

References

