

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

Abhishek Ranjan, Bobby George

Department of Electrical Engineering (Indian Institute of Technology Madras, India, Email: boby@iitm.ac.in)

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 to 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

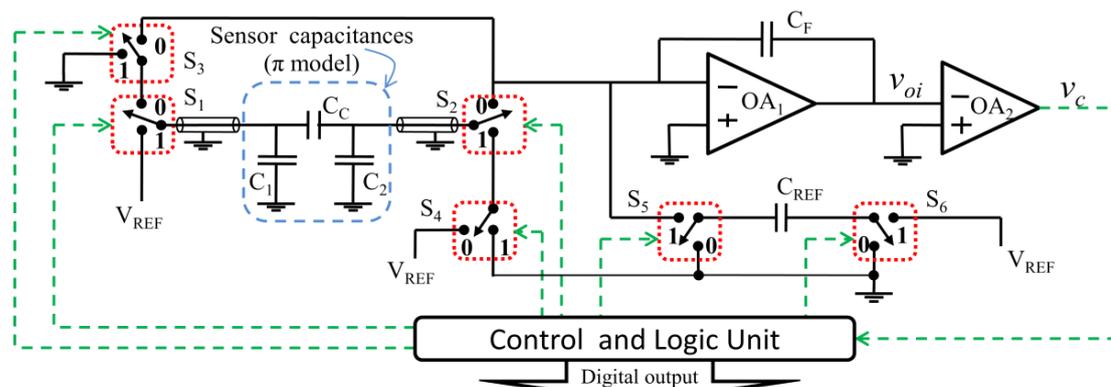


Figure 1. CDC Circuit showing sensor capacitors C_1 , C_2 , C_C in a π -model of a two electrode proximity sensor.

the proposed scheme. The sensing capacitances in the π -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_{oi} of the op-amp OA_1 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 π -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_2 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 OA_1 . This forces the charge in C_1 to be transferred to feedback capacitor C_F incrementing its output voltage v_{oi} 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 $v_{oi} = -N \times C_1 \times V_{REF} / C_F$. 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 $CLK = 1$; $S_5 = 0$ and $S_6 = 1$ charging C_{REF} to V_{REF} . When $CLK = 0$; $S_5 = 1$ 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_{oi} by $\Delta v = C_{REF} \times V_{REF} / C_F$. This operation is continued, for coming clock cycles, until a zero crossing of v_{oi} is sensed by the comparator OA_2 . The number of clock cycles N_{01} 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).

$$(N_{01} \times C_{REF} \times V_{REF}) / C_F = (N \times C_1 \times V_{REF}) / C_F \quad (1)$$

$$\text{i.e, } C_1 = (N_{01} C_{REF}) / N$$

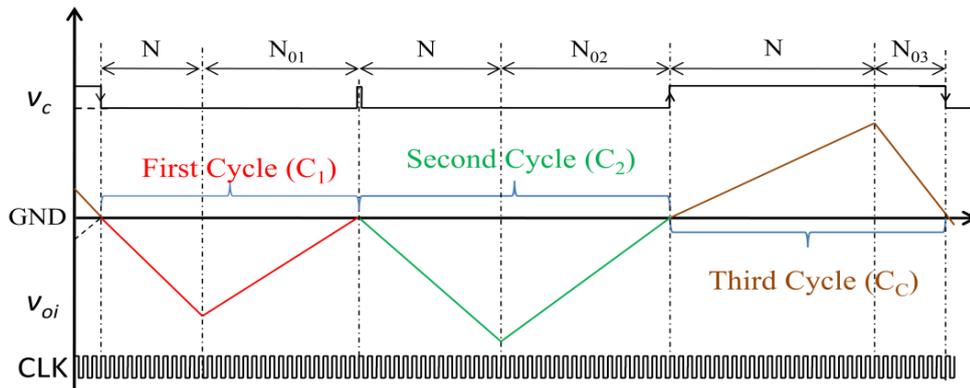


Figure 2. Diagram showing initial auto-zero phase, the integrator voltage v_{oi} , comparator output v_c and clock CLK for three cycles of operation.

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 $CLK = 1$; $S_1 = S_4 = 0$ and $S_2 = S_3 = 1$. 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 shorts the terminals of capacitor C_C

thereby discharging it. While charge in C_2 flows to C_F since one end of C_2 is at ground and other end is at virtual ground. The charging and discharging of C_2 is repeated for N clock cycles bringing $v_{oi} = -N \times C_2 \times V_{REF} / C_F$. Since the output of OA_1 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 C_1). The number of clock cycles, N_{02} , passed by before zero crossing of v_{oi} is recorded by the CLU with the help of comparator voltage v_c . N_{02} is indirectly a measure of capacitance C_2 , following the charge balancing principle. As in the case of C_1 , C_2 can be expressed as in equation (2).

$$C_2 = (N_{02} C_{REF}) / N \quad (2)$$

C. Conversion Cycle for C_C

The third cycle to measure capacitance C_C is initiated at the end of the second conversion cycle. In this case, during integration period, when $CLK = 1$; $S_1 = S_2 = S_3 = S_4 = 1$. This charges C_1 and C_C to V_{REF} while both the terminals of C_2 remain at ground potential. When $CLK = 0$; $S_1 = S_2 = 0$ and $S_3 = S_4 = 1$. In this condition, since, C_1 is grounded at each end, it will simply get discharged. On the other hand, charge in C_C is transferred to C_F . After repeating the same for N clock cycles, integrator voltage $v_{oi} = N \times C_C \times V_{REF} / C_F$. C_{REF} will not contribute any charge to C_F , as $S_5 = S_6 = 0$ throughout integration. The output voltage v_{oi} 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, $S_1 = 0$ and $S_2 = S_3 = S_4 = 1$ is maintained as in previous de-integration periods. When $CLK = 1$; $S_5 = S_6 = 0$ which connects both terminals of C_{REF} to ground. When $CLK = 0$; $S_5 = S_6 = 1$. This connects one terminal of C_{REF} to V_{REF} and other to inverting terminal of op-amp OA_1 , which is at virtual ground. In this condition, C_{REF} will charge to V_{REF} and the current flowing through C_{REF} goes through C_F changing the potential v_{oi} by $\Delta v = -C_{REF} \times V_{REF} / C_F$. This operation is continued until a zero crossing of v_{oi} is detected by the CLU. The number of clock cycles elapsed during de-integration is recorded by the CLU as N_{03} . Thus, C_C , as in the case of C_1 and C_2 can be expressed as in (3).

$$C_C = (N_{03} C_{REF}) / N \quad (3)$$

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 C_1 , C_2 and C_C respectively. The sensitivity of the measurement can be deduced in terms of N and C_{REF} .

Table-1. Switching Sequence employed by the CDC

Conversion Cycle	Clock State (CLK)	Integration period						De-Integration period					
		S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆
First Cycle (for C_1)	1	1	1	0	1	0	0	0	1	1	1	0	1
	0	0	0	0	1	0	0	0	1	1	1	1	0
Second Cycle (for C_2)	1	0	1	1	0	0	0	0	1	1	1	0	1
	0	0	0	0	0	0	0	0	1	1	1	1	0
Third Cycle (for C_C)	1	1	1	1	1	0	0	0	1	1	1	0	0
	0	0	0	1	1	0	0	0	1	1	1	1	1

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 C_1 , C_2 and C_C . For SPDT switches IC CD4053B was used. A low bias current op-amp (OA_1), for integrator, was implemented using LF347 from Texas Instruments, while comparator was realized using IC LM311. A dc reference voltage V_{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, C_F and C_{REF} were chosen as 100nF and 120pF respectively. The fixed number of clock cycles, N during integration was kept 8000 to restrict integrator output v_{oi} well below saturation limits. With known values of C_1 , C_2 and C_C 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.

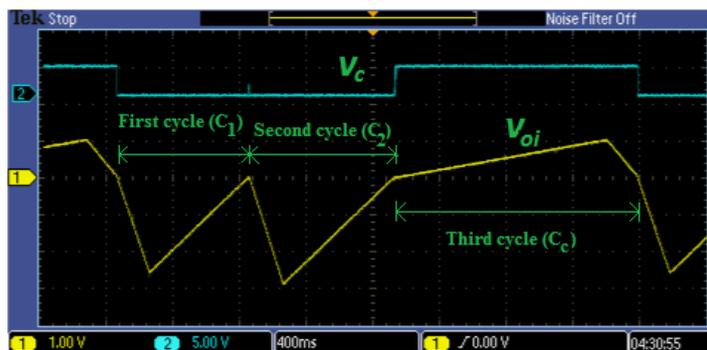


Figure 3. Screenshot of oscilloscope showing integrator output v_{oi} , comparator output v_c and the three conversion cycles corresponding to the three capacitances (C_1 , C_2 and C_c) measurements.

A capacitive proximity application that detects presence of a human near the sensor 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 3cm 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 (C_1 and C_2). Due to this, the integration clock counts in case of C_1 and C_2 was kept lower than that for C_c to avoid reaching saturation limits of op-amp OA₁.

In case of C_1 and C_2 measurements, $N = 4000$ counts whereas in C_c measurement $N = 12500$ counts. A higher integration clock counts in the third conversion cycle increases its (output corresponding to C_c) sensitivity. Values of C_F and C_{REF} 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.

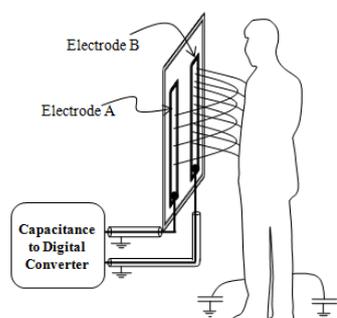


Figure 4. Pictorial representation of sensor electrodes and human, shielding part of the electric field.

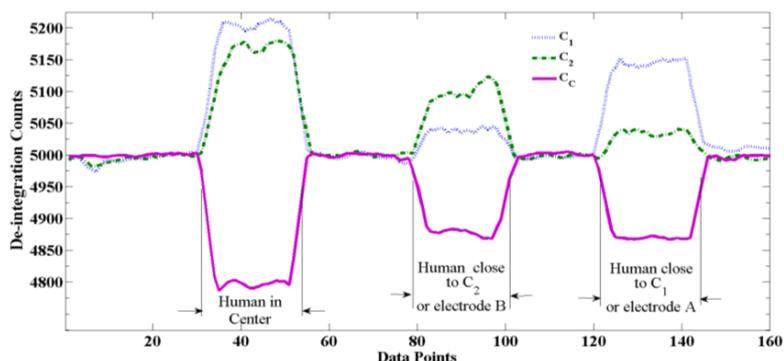


Figure 5. Plot showing changes in capacitance C_1 , C_2 and C_c . Position of the human with respect to the sensor electrodes is given in the plot with offset.

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

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