Elimination of Shunting Conductance Effects in a Low-Cost Capacitive-Sensor Interface

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***Abstract*—A low-cost and reliable interface for capacitive sensors, based on the use of a relaxation oscillator and a microcontroller, is presented. The novel interface system is designed to measure small capacitances in a reliable and accurate way even when the sensor capacitors are shunted by parasitic conductances. The problem of shunting conductances is solved by performing a series of eight measurements and using a new auto-calibration technique. Moreover, all multiplicative and additive errors of the interface are also eliminated by using this new auto-calibration technique. In the microcontroller, the final result is calculated based on the new measurement algorithm. A prototype has been built and tested. Experimental results show that the interface is able to measure a capacitance of 0–1.2 pF with a shunting conductance of up to 0.42 μS, with a resolution and a relative accuracy of 0.03% and $\pm$0.15%, respectively. The measurement time is about 400 ms.**

***Index Terms*—Auto-calibration, capacitive sensor, conductance effect, sensor interface.**

I. INTRODUCTION

CAPACITIVE sensors can be found in many applications, such as those that measure the position, speed, and acceleration of moving objects, force, pressure, liquid levels, dielectric properties, and flow materials. A main drawback of the capacitive sensor is its sensitivity to pollution and condensation, which can cause serious reliability problems. In fact, this limits the use of capacitive sensors to those applications where a "clean" environment can be guaranteed. The measurement systems for capacitive sensors based on a modified Martin oscillator [1]–[3] offer a relatively high resolution. Moreover, a very low baseline drift has been obtained by means of the auto-calibration technique called the three-signal method [4]. However, these capacitive measurement systems cannot accurately measure the capacitance with the shunting conductance.

In [5], a capacitive interface based on the charge/discharge method was presented. It has been shown that the shunting conductance effects can be reduced when semiconductor switches with low ON resistance and fast communication time are used to control the charge and discharge of the capacitive sensing element. However, a high-frequency interface is required for this method.

This paper presents a low-cost and reliable interface for capacitive sensors, based on the use of a relaxation oscillator, a microcontroller and a new auto-calibration technique. The use of the new auto-calibration technique eliminates the effect of shunting conductance of the capacitive sensor as well as the effect of all multiplicative and additive errors of the interface.

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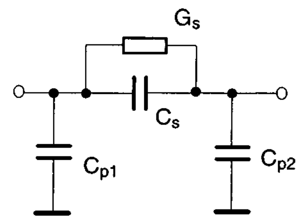

Fig. 1. Simple electrical model of the capacitive sensing element.

II. MEASUREMENT CONCEPT

A. A Practical Electrical Model of a Capacitive Sensing Element

Generally, a practical capacitive sensor and its connecting wires require shielding and guarding to reduce the effects of EMI and the electric-field bending [6], [7]. However, these techniques introduce rather large parasitic capacitances, C_{p1} and C_{p2}, between the two terminals of the sensing capacitor and the ground (see Fig. 1).

For all capacitive sensors, especially for the planar ones, pollution, condensation, and nonperfect assembly material can cause a shunting conductance G_s in parallel with the sensing capacitor. Fig. 1 shows a simple electrical model of a capacitive sensor. The capacitor C_s is the sensing capacitor. In most applications, the values of these parasitics are application dependent and not very stable. Therefore, the influence of these parasitics should be eliminated or strongly reduced. One can reduce the effect of the two parasitic capacitances C_{p1} and C_{p2} by applying a two-port measurement technique [6]–[8]. In the next section, a new measurement algorithm will be described to eliminate the effect of the shunting conductance.

B. Low-Cost Capacitive Interface

Fig. 2 shows a simplified schematic diagram of the interface for capacitive sensors. The interface consists mainly of a relaxation oscillator (the modified Martin oscillator), a multiplexer and a microcontroller. In this circuit, C_s and G_s denote the sensor capacitance and its shunting conductance, respectively. The capacitor C_{ref} is a known reference capacitor with a negligible shunting conductance.

The modified Martin oscillator linearly converts the capacitor values to period-modulated signals. The switch S_s is used to relay the sensing element with the modified Martin oscillator. The multiplexer, which is controlled by a microcontroller,

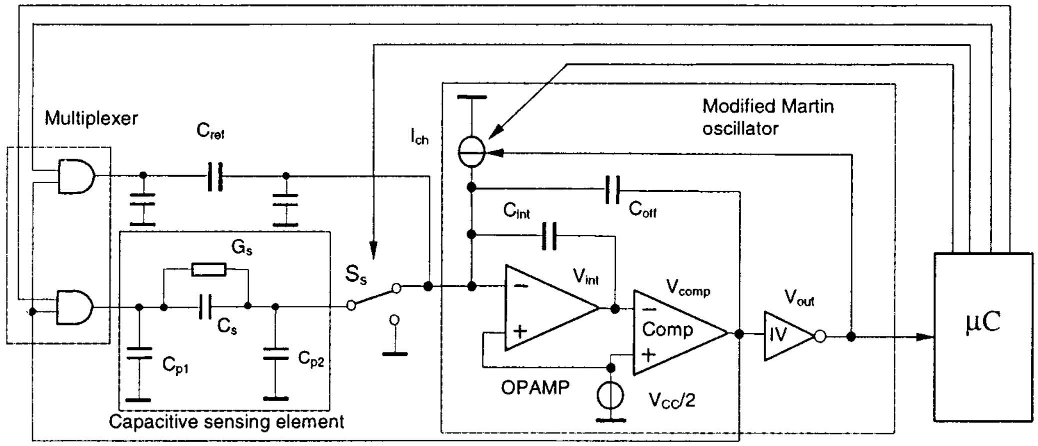

Fig. 2. Schematic diagram of the interface.

selects the capacitance to be measured. Meanwhile, the multiplexer should have low output impedance to drive the measured capacitance. The microcontroller performs the measurement of the period lengths, and the calculation based on the measurement algorithm. It also enables the communication with the outside digital world.

C. New Measurement Algorithm

As presented in [1], [3], and [4], the three-signal auto-calibration technique is applied to ensure the accuracy and reliability of the interface by eliminating the multiplicative and offset parameters of the interface. To eliminate the effect of the shunting conductance G_s in the capacitive measurement, we developed an extension of this auto-calibration technique, as will be described below.

In the ideal case, when there is no parasitic shunting conductance $(G_s \rightarrow 0)$, the period of the output signal from the modified Martin oscillator is related to the capacitance by a linear equation

$$T_{out} = 2\frac{V_{cc}}{I_{ch}}\,(C_i + C_{off}) + 4\tau_d \tag{1}$$

where

- V_{CC} power supply voltage;
- I_{ch} amplitude of the square-wave charge/discharge current;
- C_i capacitance to be measured;
- τ_d delay time in the oscillator loop, which is mainly determined by the delay time of the comparator.

An initial offset capacitor C_{off}, which includes some parasitic capacitance effect, enables the oscillator to be self-oscillated.

According to the operating principle of the modified Martin oscillator, the shunting conductance of the measured capacitor will cause an additional charge/discharge current. When the reference voltage is connected to a voltage $V_{CC}/2$ (half of the power supply voltage), the amplitude of this current amounts to $V_{CC}G_s/2$. However, its polarity is opposite to that of the current I_{ch}. With respect to the effect of the shunting conductance, for the measurement of C_s (1) can be rewritten as

$$T = \frac{2V_{cc}}{I_{ch} - V_{cc}G_s/2}C_s + \left[\frac{2V_{cc}C_{off}}{I_{ch} - V_{cc}G_s/2} + 4\tau_d\right]. \tag{2}$$

It is shown that the shunting conductance G_s not only affects the multiplicative factor but also the additive factor in the relation of the output signal period from the oscillator and the capacitance C_s.

The three-signal auto-calibration as proposed in [4] will eliminate the effect of those multiplicative and additive errors and parameters, which are constant during the three measurements. However, in this case, the shunting conductance G_s is connected to a certain measured capacitance C_s and its effect only appears when the capacitor C_s is measured. This means that due to the shunting conductance G_s the multiplicative and the additive factors for the measurement of capacitances C_{ref} and C_s are different. Therefore, to eliminate the effect of the shunting conductance G_s, more measurements are required.

Using two different charge/discharge currents $(I_{ch1} \neq I_{ch2})$, the effect of the shunting conductance G_s on the measurement of capacitance C_s can be eliminated. This requires at least four-signal measurements, resulting in the following output periods:

$$\begin{aligned}
T_{x1} &= \frac{2V_{cc}(C_s + C_{off})}{I_{ch1} - V_{cc}G_s/2} + 4\tau_d \\
T_{xr1} &= \frac{2V_{cc}(C_s + C_{ref} + C_{off})}{I_{ch1} - V_{cc}G_s/2} + 4\tau_d \\
T_{x2} &= \frac{2V_{cc}(C_s + C_{off})}{I_{ch2} - V_{cc}G_s/2} + 4\tau_d \\
T_{xr2} &= \frac{2V_{cc}(C_s + C_{ref} + C_{off})}{I_{ch2} - V_{cc}G_s/2} + 4\tau_d.
\end{aligned} \tag{3}$$

Using these four measurements, it is found that

$$\frac{(T_{x1} - T_{x2})}{(T_{xr1} - T_{x1}) - (T_{xr2} - T_{x2})} = \frac{C_s + C_{off}}{C_{ref}}. \tag{4}$$

It is shown that by using (4) not only the effect of the shunting conductance G_s is eliminated but also that of the unknown parameters, V_{CC}, I_{ch1}, I_{ch2}, and τ. However, it is also found that the effect of the unknown parameter C_{off} still exists. To eliminate this effect, the whole series of measurements is required with $C_s = 0$, resulting in four additional equations

$$\begin{aligned} T_{off\,1} &= \frac{2V_{cc}C_{off}}{I_{ch1}} + 4\tau_d \\ T_{ref\,1} &= \frac{2V_{cc}(C_{ref} + C_{off})}{I_{ch1}} + 4\tau_d \\ T_{off\,2} &= \frac{2V_{cc}C_{off}}{I_{ch2}} + 4\tau_d \\ T_{ref\,2} &= \frac{2V_{cc}(C_{ref} + C_{off})}{I_{ch2}} + 4\tau_d. \end{aligned} \tag{5}$$

With these four measurements, it is found that

$$\frac{(T_{off\,1} - T_{off\,2})}{(T_{ref\,1} - T_{off\,1}) - (T_{ref\,2} - T_{off\,2})} = \frac{C_{off}}{C_{ref}}. \tag{6}$$

Subtracting (6) from (4), the measurand C_s is found from

$$\frac{(T_{x1} - T_{x2})}{(T_{xr1} - T_{x1}) - (T_{xr2} - T_{x2})} - \frac{T_{off\,1} - T_{off\,2}}{(T_{ref\,1} - T_{off\,1}) - (T_{ref\,2} - T_{off\,2})} = \frac{C_s}{C_{ref}}. \tag{7}$$

It is shown that the effect of the shunting conductance of the sensing capacitor is eliminated by using this measurement procedure. Meanwhile, the effect of many unknown parameters of the interface, such as the offset, the charge/discharge current, or the time delay, is eliminated as well. Moreover, in [3], [4] it is shown that the interface is immune to most of the nonidealities of the OPAMP and the comparator, such as slewing, limitations of bandwidth and gain, offset voltages and input bias currents. These nonidealities only cause additive or multiplicative errors, which are eliminated by the measurement algorithm.

To ensure the oscillator functioning, according to (3) it is required that: $G_s < 2I_{ch,\min}/V_{CC}$, where $I_{ch,\min}$ is the minimum one of I_{ch1} and I_{ch2}.

The new measurement method requires the measurement of eight signals. Therefore, as compared to the three-signal technique, this method requires a longer measurement time. Often the occurrence of the conductance G_s is due to some nonidealities, such as pollution and condensation. Often these nonidealities do not appear over a long period of time. In this case there is no need for a permanent use of the eight-signal measurement. To optimize the measurement speed and get ready to eliminate the effect of a shunting conductance, the result of the eight-signal measurement can be compared with that of a three-signal measurement. A comparison made by the microcontroller can justify the use of the extended algorithm. As soon as it appears that there is no significant shunting conductance, the faster three-signal technique is applied. From time to time, this check has to be performed.

From (3) and (5), for the shunting conductance G_s it is found that

$$G_s = \left(1 - \frac{T_{ref\,1} - T_{off\,1}}{T_{xr1} - T_{x1}}\right) \cdot \frac{2I_{ch1}}{V_{CC}}. \tag{8}$$

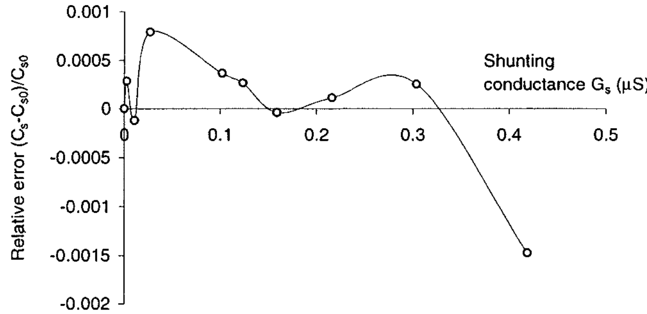

Fig. 3. Measured relative error of the interface.

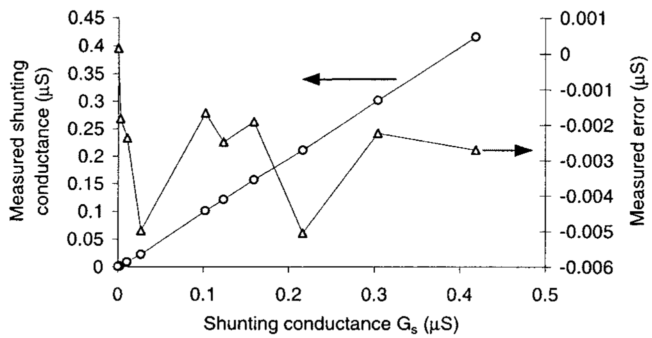

Fig. 4. Measured shunting conductance and its error.

III. Measurement Results

A prototype based on the circuit shown in Fig. 2 has been built. The multiplexer is implemented with simple NAND gates. The switch S_s is implemented with a simple quad bilateral switch (CD4066). The oscillator is fabricated as an ASIC, which has been presented in [3]. The frequency of the oscillator is between 12 kHz and 110 kHz, depending on the sensor signals. A microcontroller of the type INTEL D87C51FA, which has a counting frequency of 3 MHz, is employed to control the situations of the multiplexer and the switch S_s, to measure the output period of the interface, to implement the new measurement algorithm and to communicate with the outside digital world. The system is powered with a single 5 V supply voltage.

To reduce the relative effect of the noise, we must make I_{ch1} and I_{ch2} significantly different. On the other hand, a very large difference between these two currents will cause an increased nonlinearity error. As a compromise, we have chosen that $I_{ch2} = 1.6 I_{ch1}$. The selection of these two currents is controlled by the microcontroller.

The resolution and the relative accuracy of the interface have been measured for the case that $C_s = C_{ref} = 1.2$ pF and $G_s = 0.0006$ μS $\sim$ 0.42 μS with a measurement time of about 400 ms. The measured resolution amounts to 0.03%. Fig. 3 shows the relative error of the interface as a function of the shunting conductance.

The error is less than $\pm$0.15% for a shunting conductance up to 0.42 μS.

Fig. 4 shows the measured shunting conductance with (8) and its measured error.

IV. Conclusions

In this paper, a new auto-calibration technique, which eliminates the effect of the shunting conductance of the sensor capacitances, has been presented. This new auto-calibration technique includes the normal auto-calibration procedure, so that all multiplicative and additive errors of the interface are eliminated as well. The required hardware configuration is based on the use of a microcontroller and a relaxation oscillator. A high-performance interface has been realized with low-cost components. Experimental results show that the new auto-calibration technique is very effective in reducing the effect of the shunting conductance. A resolution of 0.03% and a relative accuracy of $\pm$0.15% have been achieved for the measurement of a capacitance of about 1.2 pF with a shunting conductance up to 0.42 μS in a measurement time of about 400 ms.

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