A Microcontroller-Based Self-Calibration Technique for a Smart Capacitive Angular-Position Sensor

Xiujun Li, Gerard C. M. Meijer, *Member, IEEE,* and Gerben W. de Jong

***Abstract*— A self-calibration technique for capacitive position sensors, based on the use of a microcontroller is presented. This technique offers a good trade-off between the memory size of the microcontroller and the algorithmic complexity. The application of this technique for self-calibration of the inaccuracy caused by the geometrical errors and pattern errors in a smart capacitive angular-position sensor is discussed. This self-calibration technique doesn't need any accurate reference. Experimental results show that the self-calibration is relatively effective in reducing the influences of the geometrical errors and pattern errors of the sensor. The reduction of the inaccuracy of the smart capacitive angular-position sensor amounts to more than a factor of two.**

***Index Terms*— Calibration, capacitive sensor, multiple electrode, position measurement, self-calibration.**

I. Introduction

The rapid decrease in unit cost and the increase of on-chip capabilities have enabled the widespread use of the single-chip microcontroller in instrumentation and measurement technology. This development enabled the use of new compensation, calibration and linearization techniques [1]–[3], and application of microcontrollers in system control, and data acquisition and processing in the sensors [4]–[7]. This paper presents a calibration technique for capacitive position sensors, which takes full advantage of the microcontroller facilities.

Often, the conventional sensors are manually adjusted using, for instance, trim potentiometer adjustments to remove the offset errors and gain variations [8], [9], while temperature compensation is accomplished with dedicated temperature-sensitive networks. This method is appropriate for integrated sensors with a few adjustable parameters, but for a sensor array or a complex sensor with multiple sensing elements, such as capacitive sensors with multi-electrodes [6], [11], [12], it is not suitable. An alternative way of calibration and compensation has become available in smart microcontroller-based sensors. By determining the relationship between the values indicated by the sensor under controlled conditions, and a reference value, a correction array for each sensor is obtained. This correction array is loaded in the EPROM of the microcontroller for later use to compensate for offset and gain errors in real-time, by a combination of the software/hardware corrections during signal acquisition and processing.

With respect to the present calibration techniques, two methods are commonly used: When the acquisition speed is critical, the fastest approach is the use of a look-up table requiring little or no calculation overhead to produce the correction voltage, but at the expense of the need for a large EPROM capacity [1], [3]. The second and slower technique is to apply a higher-order polynomial fit to the data obtained from the measurement [2]. This approach requires much less EPROM capacity, but at the expense of longer data-processing time.

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X. Li and G. C. M. Meijer are with the Department of Electrical Engineering, Delft University of Technology, Delft 2628 CD, The Netherlands.

G. W. de Jong is with Philips Research Laboratories, Eindhoven 5656 AA, The Netherlands.

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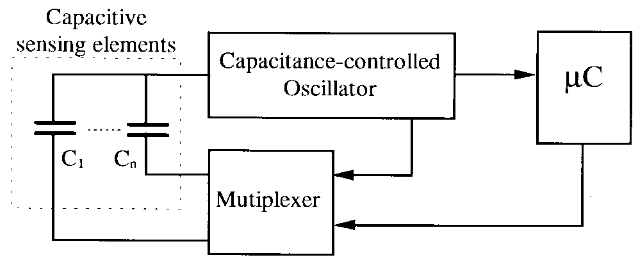


Fig. 1. The block diagram of a smart capacitive sensor system with multiple sensing elements.

In this paper, the calibration technique for a smart capacitive sensor consists of a combination of the two calibration techniques mentioned before [10]. The advantages of this technique are:

1) the use of a relatively simple piecewise-linear fit formula enables fast data processing;
2) only a few correction data are stored in the EPROM.

It is shown that the application of this technique in a smart capacitive angular-position sensor results in better performance. The calibration technique is used to calibrate the system for the systematical geometrical errors and pattern errors. An important and remarkable property is that no accurate reference is required for this calibration technique.

II. Basic Concepts of Calibration Technique

Fig. 1 shows the block diagram of a smart capacitive sensor system with multiple sensing elements, which can be used in a large variety of applications to measure, for instance position, speed, liquid levels, force, pressure, etc. Especially, for a large displacement measurement, the smart capacitive sensor with multiple sensing elements is more attractive [6], [11], [12].

In order to determine the measurand, the values of the capacitors C_i $(i = 1, 2, \cdots, n)$ are measured. Firstly, the capacitor's values are converted into period-modulated signals by the capacitance-controlled oscillator which generates a square-wave output signal with periods T_i $(i = 1, 2, \cdots, n)$. The multiplexer, which is controlled by the microcontroller, selects the capacitor to be measured. Secondly, length of these periods is measured by the microcontroller. By applying an

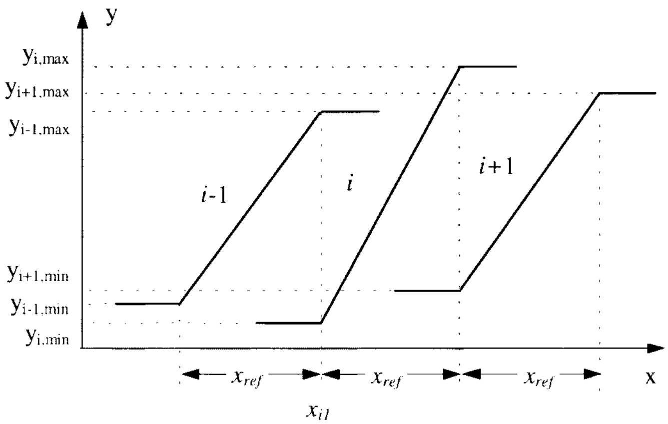


Fig. 2. The transfer function of the sensing elements in a sensor system with multiple sensing elements.

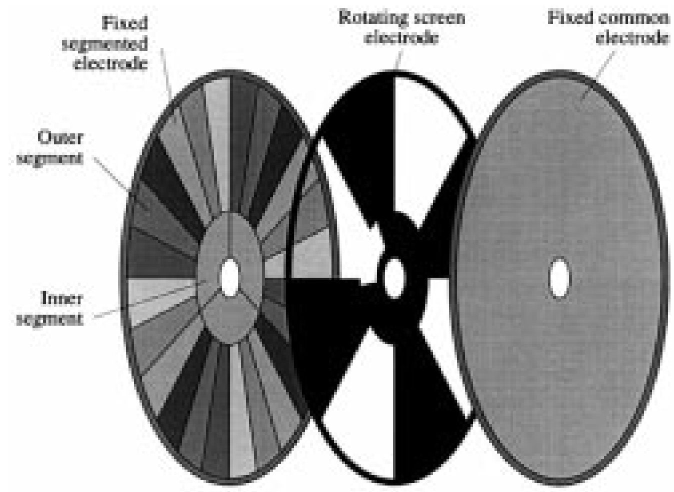


Fig. 3. A simplified structure of the capacitive angular-position sensor.

appropriate algorithm, the measurand can be calculated from the measured periods. The algorithm is performed by the microcontroller.

In the capacitive sensors presented in [6], even when using a good algorithm some nonidealities still remain, due to the geometrical errors and the pattern errors of the electrodes. Calibration is required to obtain a higher degree of accuracy. The calibration technique presented in this paper is very suited for this purpose.

Under certain conditions, the described calibration technique can be performed without using an accurate reference. This will be shown for the special case of a smart sensor with multiple sensing elements.

In a smart sensor with multiple sensing elements, the correction data can be obtained by performing some additional measurements for some sensing elements under certain condition. Sometimes, an accurate reference is not needed for such a calibration. Even, temperature compensation can be accomplished simultaneously if the correction data can be obtained in real-time.

As a general example, Fig. 2 shows the transfer functions from the measurand (x) to the outputs (y) of the sensing elements in a sensor system with multiple sensing elements for a large measurement range.

Where the transfer function in the x_{ref} zones of the curves validly represents the measurand. If the transfer function within the x_{ref} region is linear, we have

$$y_i = \frac{y_{i,\max} - y_{i,\min}}{x_{ref}}(x - x_{i1}). \qquad (1)$$

The parameter x_{i1} is the start point of the x_{ref} zone of a particular sensing element. Because the mismatching of the sensing elements, the ranges of the maximum values and minimum values ($y_{i,\max} - y_{i,\min}$), and the slopes of the transfer functions for the various elements are not equal. This will result in a systematical error on the sensor system.

Because these maximum values and minimum values are insensitive to the measurand in a certain range, it is possible to measure them with a relatively high degree of accuracy without using a reference sensor. An interesting application of this technique is described in the following section.

III. Application in a Capacitive Angular-Position Sensor

A. Sensing Element of the Capacitive Angular-Position Sensor

The described calibration technique has been implemented and tested for a smart capacitive angular-position sensor with multi-electrodes which has been presented in [6]. Fig. 3 shows a simplified drawing of the structure of the capacitive angular-position sensing element, which consists of three parallel discs. The common electrode is a single conductor. The segmented electrode is composed of 24 outer segments with the same width (15°) and area, and three inner segments also with the same width (120°) and area. The grounded rotating screen electrode is a screen with four outer windows and one inner window, of which the angular position is to be measured. The inner window is connected to one of the outer ones, thus forming a more complex opening.

The 24 outer segments on the segmented electrode are divided into six groups with four segments each. The four segments in each group, showing the same gray level in Fig. 3, are positioned in a cross-quad configuration. These four segments are connected together, resulting in six group capacitors between the common electrode and the outer segments on the segmented electrode. These six capacitances are used for a very accurate fine measurement and a first coarse measurement. For the accurate fine measurement which is valid over one segment angular width x_s (15°), the relation between the measured angular position x_m in degree and the sensing elements (capacitances) is represented as shown in (2), at the bottom of the page, where C_i is, respectively,

$$\left(\frac{x_m}{x_s}\right)_i = \frac{(C_{i+1} + C_{i+2}) - (C_{i-2} + C_{i-1})}{2(C_i - C_{i-3}) + \alpha(C_{i-2} + C_i + C_{i+2} - C_{i-3} - C_{i-1} - C_{i+1})}, \qquad -\frac{1}{2} \le \frac{x_m}{x_s} \le \frac{1}{2} \qquad (2)$$

the capacitance between the common electrode and six outer segments on the fixed segmented electrode. The parameter α is called the fine-tuning factor ($0 \leq \alpha \ll 1$). Choosing of appropriate fine-tuning factor will minimize the influence of the electric-field bending effect [12].

As presented in [6], [11], the effects of many stochastic and systematic mechanical nonidealities, such as the eccentricities, the nonflatness, and the obliqueness of the electrodes, etc., are significantly reduced by using the symmetrical structure and cross-quad connection of the outer segmented electrodes.

However, the measurement range is limited to only 90°. Three inner segments on the segmented electrode and one inner window on the rotating electrode have been equipped for the secondary coarse measurement over the full measurement range of 360°. For this purpose, the three corresponding capacitances have to be measured. Finally, after measuring the nine capacitances, the absolute angular-position over the full measurement range of 360° can be calculated.

B. Systematical Errors and the Calibration

Although some effects of the mechanical errors and the geometrical errors are strongly reduced by using a symmetrical and redundant configuration for the electrodes of the sensing element, some geometrical errors and the pattern errors of the segmented electrode, will still affect the equality of the segment-capacitance values between the outer segments and the common electrode. This results in a systematic inaccuracy with a period of six segment widths (90°) on the measured angular position because the outer window on the rotating electrode repeats itself after six segment widths.

In order to discuss this influence, we suppose that the electrode distance and the segment angular width x_s are the same for each segment, the different capacitance values between the segments and common electrode are reflected by the radial sizes of the segments only and the electric-field bending effect is ignored. Thus, after some calculations using (2), for the inaccuracy ε_i ($= x_m - x_p$) caused by the pattern error of the segmented electrodes, it is found that as shown in (3), at the bottom of the page, for the measurement range of one segment width. Where $C_{i,\max}$ ($i = 1, 2, \cdots, 6$) represents the capacitance between the outer segments on the segmented electrode and the common electrode when there is no screening by the rotating electrode. The parameter x_p is the angular position to be measured. For the sensor structure shown in Fig. 3, because of the cross-quad connection of the segments

$$C_{i\pm 6,\max} = C_{i,\max}. \tag{4}$$

The differences between the values of the capacitances $C_{i,\max}$ ($i = 1, 2, \cdots, 6$) mainly originate from the geometrical and pattern errors of the electrodes. By subtracting the inaccuracy described by (3) from the calculated position described in (2), the final result is obtained as shown in (5), at the bottom of the page, for the measurement range of one segment width. Where $x_m(C_i)/x_s$ represents the relationship described by the (2). Equation (5) shows that the multiplicative and offset errors are removed simultaneously. This is used as linear piecewise fit formula for the calibration. Thus, the values of six capacitors ($C_{i,\max}$, $i = 1, 2, \cdots, 6$) should be measured beforehand for applying the calibration.

Although (5) is obtained under some limitation conditions, it also contributes to compensate the effects of the electrode distance errors and the segment width x_s errors. This calibration is called a self-calibration because there is no need for any reference.

C. Calibration Procedures

In practical measurements of the angular position, firstly, the capacitances of the sensing element are converted to output periods of the oscillator, then these periods are measured by the microcontroller. The measured angular position is calculated from these measured periods. From (5) and supposing a linear transfer of the capacitance/period converter ($T_i = kC_i + T_{off}$), the relation between the measured position and the measured periods is found to be as shown in (6), at the bottom of the next page, for the measurement range of one segment width. Where T_{off} is the period of the output signal of the oscillator when no measurand (capacitance) is connected, and $x_m(T_i)/x_s$ represents the relationship described by (2) in which C_i is replaced by T_i.

An important property of (6) is that many undesired nonidealities, such as, multiplicative errors and offsets, of both the sensing elements and the processing circuit are eliminated or significantly reduced.

$$\varepsilon_i \cong \begin{cases} \dfrac{C_{i+1,\max} - C_{i-1,\max}}{2C_{i,\max}} x_s + \dfrac{C_{i+2,\max} + C_{i-1,\max} - 2C_{i,\max}}{2C_{i,\max}} x_p, & \dfrac{x_s}{2} \geq x_m > 0 \\ \dfrac{C_{i+1,\max} - C_{i-1,\max}}{2C_{i,\max}} x_s + \dfrac{C_{i+1,\max} + C_{i-2,\max} - 2C_{i,\max}}{2C_{i,\max}} x_p, & -\dfrac{x_s}{2} < x_m \leq 0 \end{cases} \tag{3}$$

$$\frac{x_m}{x_s} = \begin{cases} \left[1 - \dfrac{C_{i+2,\max} + C_{i-1,\max} - 2C_{i,\max}}{2C_{i,\max}}\right] \dfrac{x_m(C_i)}{x_s} - \dfrac{C_{i+1,\max} - C_{i-1,\max}}{2C_{i,\max}}, & \dfrac{x_s}{2} \geq x_m > 0 \\ \left[1 - \dfrac{C_{i+1,\max} + C_{i-2\,\max} - 2C_{i,\max}}{2C_{i,\max}}\right] \dfrac{x_m(C_i)}{x_s} - \dfrac{C_{i+1,\max} - C_{i-1,\max}}{2C_{i,\max}}, & -\dfrac{x_s}{2} < x_m \leq 0 \end{cases} \tag{5}$$

In order to apply the self-calibration technique in the measurement of the position, seven periods $[T_{i,\max}, (i = 1, 2, \cdots, 6)$, and $T_{off}]$ have to be measured. The measured values are stored in the microcontroller.

In a practical sensor structure, the widths of the window and the shield on the rotating electrode are relatively large as compared to the electrode distance. So that, when the rotating screen electrode is in the certain position where (2) yields zero, the influence of the electric-field bending effect on the capacitances C_i and C_{i-3} can be ignored. Then, it is found that the maximum value $T_{i,\max}$ is

$$T_{i,\max} \cong T_i \tag{7}$$

and the offset period of the oscillator T_{off} can be obtained by

$$T_{off} \cong T_{i-3}. \tag{8}$$

That means no additional signal processing circuit is required for the measurement of these seven correction data.

To obtain these seven correction data $[T_{i,\max}, (i = 1, 2, \cdots, 6)$, and $T_{off}]$, the screen electrode should be rotated at least 90°. Under stable conditions, for instance, when the changes of temperature and humidity are within a certain limited range, these correction data are valid and can be used for the calibration of the systematical errors according to (6). When environment temperature is significantly changed, these correction data should upgraded. It is possible to measure the seven correction data for various temperatures and to store them in the memory. This would require a large memory. Moreover, long-term drift of the correction data can offer a problem. Therefore, it would be a considerable advantage to upgraded these correction data in real-time. For the method presented in this paper, this is possible when both of the following conditions are met.

1) The change of temperature is small during the time that the seven data are collected, while the screen electrode is rotated over 90°.
2) The rotating speed of the screen electrode is not too high, so the correction data can accurately be measured.

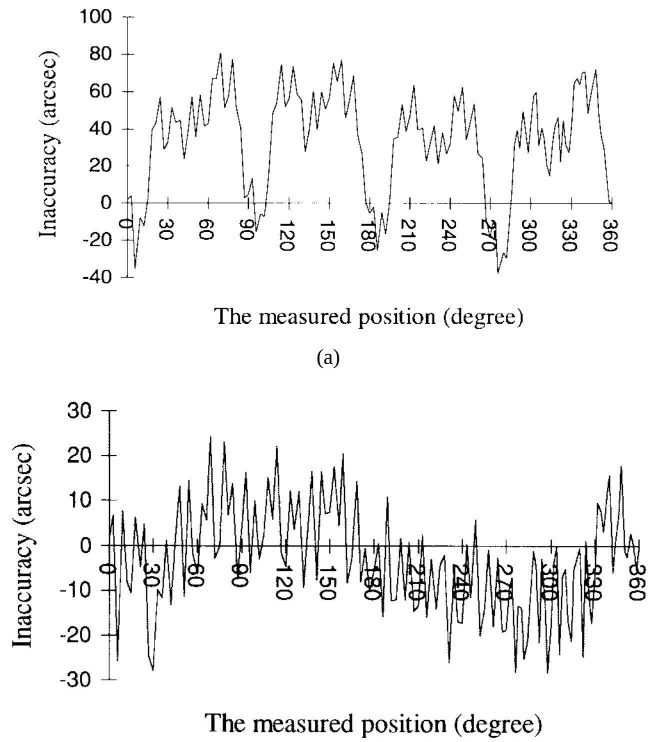
The recalibration procedure can be fully automated and, for instance, repeated when a significant temperature change is observed or after a certain period of time.

An attractive feature of this self-calibration technique is its simplicity: only a few correction data are required and an accurate reference is not needed. For applying this technique, seven periods are required to be measured beforehand. The correction is performed according to the algorithm of (6).

IV. Experimental Results

A capacitive angular-position sensor with the structure shown in Fig. 3 has been built and tested. Appropriate guarding electrodes surrounding the segmented electrode and the common electrode were used to reduce the influence of the electric-field bending in radial directions and of electromagnetic interference. With a window width of 48° of the screen electrode and a distance of 2.5 mm between the common electrode and segmented electrode with a diameter of 50 mm, a fine-tuning factor α of 0.0328, was found as the optimum value to minimize the effect of electric-field bending and mechanical errors. It has been shown that for an optimum structure of the sensing element the measured angular position has only a small sensitivity to changes of the geometrical parameters, such as the distance between two fixed electrodes, thickness and vertical position of the screen electrode, and the radial size of the electrode [12]. The common electrode and segmented electrode were made using simple printed-circuit-board technology. The capacitance between each of the nonshielded segments and the common electrode amounts to about 0.15 pF.

The performance of the sensor was tested using a smart signal-processing circuit which has a resolution of 2.0″, an angular table which has a resolution of 5.0″ and a microcontroller. The applied 8 b microcontroller is of the type 87C51FC



(a)

(b)

Fig. 4. The measured inaccuracies of the sensor system: (a) without self-calibration and (b) with self-calibration.

$$\frac{x_m}{x_s} = \begin{cases} \left[1 - \dfrac{T_{i+2,\max} + T_{i-1,\max} - 2T_{i,\max}}{2(T_{i,\max} - T_{off})}\right] \dfrac{x_m(T_i)}{x_s} - \dfrac{T_{i+1,\max} - T_{i-1,\max}}{2(T_{i,\max} - T_{off})}, & \dfrac{x_s}{2} \geq x_m > 0 \\ \left[1 - \dfrac{T_{i+1,\max} + T_{i-2,\max} - 2T_{i,\max}}{2(T_{i,\max} - T_{off})}\right] \dfrac{x_m(T_i)}{x_s} - \dfrac{T_{i+1,\max} - T_{i-1,\max}}{2(T_{i,\max} - T_{off})}, & -\dfrac{x_s}{2} < x_m \leq 0 \end{cases} \tag{6}$$

with 32 kB on-chip EPROM. The microcontroller runs at a clock frequency of 12 MHz. The fastest internal counter has a frequency of a quarter of the clock frequency: 3 MHz. The measured systematical inaccuracy of the sensor over a range of 360° without and with self-calibration amounts to $\pm 57.7''$ and $\pm 26.2''$, respectively, for a measurement time of 140 ms (see Fig. 4).

It is obvious that the self-calibration is rather effective in reducing the geometrical errors and pattern errors. The improvement in the inaccuracy of the sensor by applying the self-calibration amounts to a factor of 2.2. The remaining inaccuracy mainly originates from the noise of the processing circuit, the simple noise of the microcontroller, and the unsymmetry of the rotating electrode due to the inner window, which results in an inaccuracy with a period of 360°.

V. Conclusion

A calibration technique based on the use of a microcontroller has been presented. The application of this technique in a smart capacitive angular-position sensor results in a self-calibration which doesn't need any accurate reference. For the multiplicative and offset calibrations of the inaccuracy caused by the geometrical errors and pattern errors of the electrodes, only two simple linear fit formulas and seven correction data are required. Experimental results show that the self-calibration is relatively effective in reducing the inaccuracy caused by the geometrical errors and pattern errors of the sensor. A smart capacitive angular-position sensor with a high accuracy of $\pm 26.2''$ (15.7 b) has been obtained for a measurement time of 140 ms.

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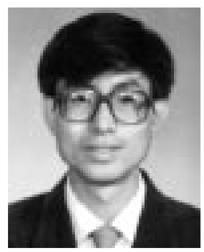

Xiujun Li was born in Tianjin, China, on February 19, 1963. He received the B.S. degree in physics and the M.S. degree in electrical engineering from Nankai University, Tianjin, China, in 1983 and 1986 and the Ph.D. degree from the Department of Electrical Engineering, Delft University of Technology, The Netherlands, in 1996.

He joined the Department of Electronic Science, Nankai University, China, in 1986. He is presently employed by the Department of Electrical Engineering, Delft University of Technology. His research interests are in the area of the smart capacitive sensor and signal processing.

Gerard C. M. Meijer (M'94) for a photograph and biography, see this issue, p. 763.

Gerben W. de Jong was born in The Hague, The Netherlands, on December 25, 1965. He received the ingenieurs (M.S.) and Ph.D. degrees, both in electrical engineering, from the Delft University of Technology, Delft, The Netherlands, in 1989 and 1994, respectively.

After his Ph.D. work, he developed IC's for smart capacitive sensors at the DUT, Department of Electrical Engineering. Since October 1995, he has worked at the Philips Research Laboratory in Eindhoven, The Netherlands.