An Accurate Low-Cost Capacitive Absolute Angular-Position Sensor with a Full-Circle Range

Xiujun Li, Gerard C. M. Meijer, Gerben W. de Jong, and Jo W. Spronck

***Abstract*—A novel high-performance smart capacitive angular-position sensor with a full-circle measurement range is presented. The sensor is mainly composed of three parts: the capacitive sensing element, a signal processor and a microcontroller. Using an appropriate algorithm, the effects of the main undesired influences are eliminated or strongly reduced. The measurement range covers the full-circle range (360°). The structure of the sensing element is optimized to reduce the influence of the electric-field-bending effect and the mechanical errors. The signal processor has a multicapacitance input and a single period-modulated output, and includes a nearly linear capacitance/period converter. The microcontroller acquires output data from the processor, calculates the positions and optionally communicates with the outside digital world. The resolution of the smart capacitive angular-position sensor is 1.5 arcsec, and the nonlinearity is less than ± 58 arcsec over the 0–360° range for a measurement time of 140 ms.**

I. Introduction

Capacitors are increasingly being used as sensing elements in position-sensor systems, because of their low energy consumption and simple structure. In previous papers [1]–[5], it has been shown that with capacitive sensing elements rather high accuracy can be obtained. The remaining inaccuracy is mainly caused by the electric-field-bending effect and mechanical errors. The use of guarding electrodes is very important to reduce the influence of the electric-field bending and also of the external disturbing signals [1]–[5]. However, the guarding electrode cannot completely eliminate the influence of the electric-field bending. Even when using well-designed guarding electrodes, the electric-field-bending effect is still one of the major reasons for the nonlinearity of capacitive position sensors. The symmetrical and redundant structure of the sensing element can drastically reduce the mechanical errors, such as the nonflatness, obliqueness and eccentricity of the electrodes [5], [6]. However, the structure described in [5] has a limited measurement range of only 90°.

This paper presents the high-performance smart capacitive angular-position sensor with a full-circle measurement range. This new design uses a modified sensing element, a new algorithm and a high-performance signal processor.

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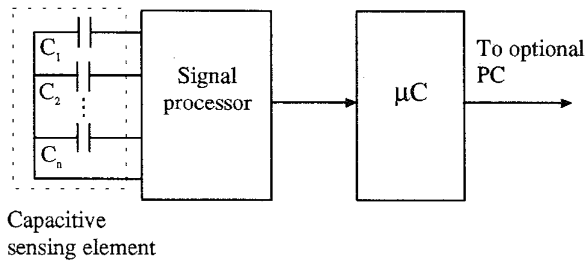

Fig. 1. An overview of the smart capacitive position sensor.

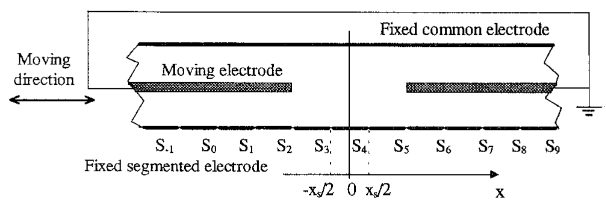

Fig. 2. A schematic drawing of the capacitive sensing element with a multisegment electrode structure.

II. Basic Principle

Fig. 1 shows an overview of the smart capacitive position sensor. It is mainly composed of three parts, the capacitive sensing element, a signal processor and a microcontroller.

The capacitive sensing element is a multielectrode structure of which the capacitor's values are sensitive to the position. The signal processor has a multicapacitance input and a single period-modulated output, and includes a nearly linear capacitance/period converter. It can linearly convert the capacitor's values of the sensing element to period-modulated signals. The microcontroller performs the measurement of the periods of the output signal of the capacitance/period converter and position calculation. It also enables the communication with the outside digital world.

Fig. 2 shows a schematic drawing of the capacitive sensing element with a multisegment electrode structure. It mainly consists of three electrodes: a fixed common electrode with a single conductor, a fixed segmented electrode with multiple segments which have the same width (x_s), and a grounded moving electrode. The capacitors are formed between the common electrode and the segmented electrode. The grounded moving electrode shields certain electrode segments from the common electrode and so decreases the capacitance between these electrodes significantly. The change of these capacitances is a measurement for the position (x_p) of the grounded moving electrode. Grounding of the moving electrode can be achieved by using a sliding contact.

To explain the measurement procedure, we suppose that the moving electrode is in the position shown in Fig. 2. The relation between the measured position x_m, the capacitances and the measurand x_p is represented by the equation

$$\frac{x_m}{x_s} = \frac{(C_{s5}+C_{s6})-(C_{s2}+C_{s3})}{2(C_{s4}-C_{s1})} \cong \frac{x_p}{x_s} \quad \left(-\frac{1}{2} \le \frac{x_m}{x_s} \le \frac{1}{2}\right) \tag{1}$$

where x_s is the width of one segment, and $C_{s1} \cdots C_{s6}$ are, respectively, the capacitances between the common electrode and six adjacent electrode segments ($S_1 \cdots S_6$). The measurement described by (1) is called an accurate fine measurement. In this relationship, because of the use of the ratio of two linear combinations of the capacitances, the first-order term of the electric-field-bending effect is completely eliminated, and its second-order term is also partly eliminated. If the nonidealities of the sensing element and the electric-field-bending effect are neglected, then $x_m = x_p$. The validity of (1) is limited to the measurement range of one segment width (x_s). Outside this range, other appropriate capacitors are selected. With these capacitors the position is calculated in a similar way. The procedure for selecting the appropriate capacitors is called the first coarse measurement.

III. The Sensing Element and Its Nonidealities

A. Structure of the Sensing Element

A simplified structure of the capacitive angular sensing element, which consists of three parallel discs, is shown in Fig. 3. The common electrode is a single conductor. The segmented electrode is composed of 24 outer segments with the same width (15°) and area, and 3 inner segments with the same width (120°) and area. The 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, forming the specially shaped opening shown in Fig. 3. The four outer windows are equidistant in angle and have the same area. The four outer windows on the screen electrode, which correspond to the 24 outer segments on the segmented electrode, are used for a very accurate fine measurement, and a first coarse measurement. The inner window, which corresponds to the 3 inner segments on the segmented electrode, is used for a second coarse measurement.

The 24 outer segments on the segmented electrode are divided into six groups with four segments each. The four segments in each group, which in Fig. 3 have the same gray level, have a mutual pitch of a quarter of a circle. These four segments are connected together, resulting in six group capacitors between the common electrode and the segmented electrode, corresponding to the capacitances ($C_{s1} \cdots C_{s6}$) in (1). The use of these cross-quad group capacitors significantly reduces the influence of both the stochastic mechanical errors and the systematic errors, such as the eccentricities, the nonflatness and the obliqueness of the electrodes. This technique has been described earlier in [5], [6]. However, the measurement range was limited to only 90°. Therefore, in the new sensor, three inner segments on the segmented electrode and one inner window on the rotating electrode are applied for a second coarse measurement to determine in which quadrant the inner window is positioned and which completes the measurement range to the full circle (360°). As a consequence, three other capacitances (C_{c1}, C_{c2}, and C_{c3}) have to be measured. Therefore, in total, nine capacitances are measured in order to obtain an absolute angular position over the full measurement range of 360°.

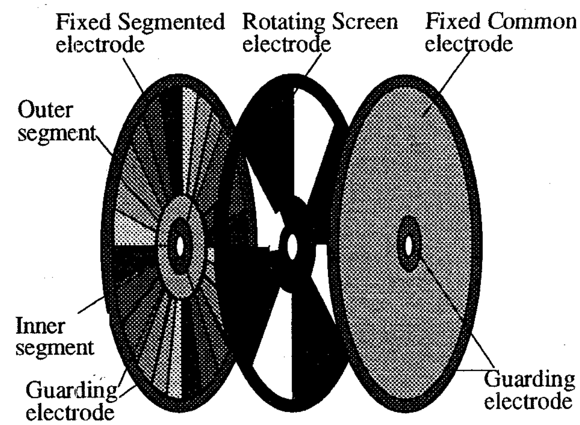

Fig. 3. A simplified structure of the sensor.

B. Nonidealities of Sensing Element

Due to the electric-field-bending effect, the capacitances between the completely shielded segments and the common electrode are not zero, and the capacitances between the nonshielded segments and the common electrode are less than in the case of a homogeneous field. This effect can be partly compensated by modifying (1) into

$$\frac{x_m}{x_s} = \frac{(C_{s5}+C_{s6})-(C_{s2}+C_{s3})}{2(C_{s4}-C_{s1})+\alpha(C_{s2}+C_{s4}+C_{s6}-C_{s1}-C_{s3}-C_{s5})} \quad \left(-\frac{1}{2} \le \frac{x_m}{x_s} \le \frac{1}{2}\right) \tag{2}$$

where α is called the fine-tuning factor ($0 \le \alpha \ll 1$) [5], [6]. Here, the appropriate fine-tuning factor will minimize the influence of the electric-field-bending effect. In our application, this optimal value for α amounts to 0.0328, which is found by a semiempirical trial-and-error method.

Other causes of the nonlinearity are mechanical errors. The nonflatness of the surface of the electrodes in the sensing element is the most important one. However, the sensitivities of the nonlinearity due to the electric-field-bending effect for certain geometrical parameters of the sensor, such as electrode distance, position of the rotating electrode in the vertical direction and radial sizes of electrodes, are opposite to those due to the mechanical errors. Thus, it is possible to optimize the geometry for the effect of electric-field bending

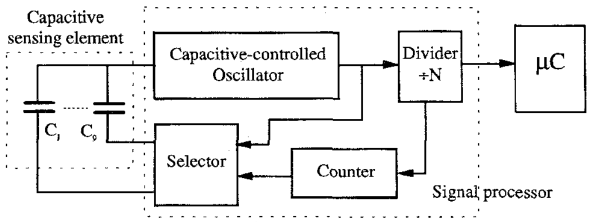

Fig. 4. The electronic circuitry for the smart capacitive position sensor.

and mechanical errors to minimize the total nonlinearity of the sensor.

IV. Signal Processing

Fig. 4 shows the electronic circuitry for the smart capacitive position-sensor system. The signal processor is composed of a capacitive-controlled oscillator [3], a frequency divider, a counter and a selector. It has a multicapacitance input. Only one signal wire is required between the signal processor and the microcontroller.

In order to determine the position x_m, nine capacitances C_i $(i = 1, 2, \cdots, 9)$ have to be measured. The nine capacitor values are converted into period-modulated signals by the oscillator which generates square-wave output signals with periods T_i which are related to the capacitor values by the linear equation

$$T_i = aC_i + b \quad (i = 1, 2, \cdots, 9). \tag{3}$$

These periods are measured by the microcontroller. The counter and the selector select the capacitance to be measured. The selector also acts as a buffer for the oscillator signal which is used to excite the capacitors to be measured.

By substituting (3) into (2), for the measured position x_m it is found, that

$$\frac{x_m}{x_s} = \frac{(T_{s5} + T_{s6}) - (T_{s2} + T_{s3})}{2(T_{s4} - T_{s1}) + \alpha(T_{s2} + T_{s4} + T_{s6} - T_{s1} - T_{s3} - T_{s5})} \tag{4}$$

for $-1/2 \leq (x_m/x_s) \leq 1/2$. Note that in this equation, the parameters a and b are eliminated. Therefore, the influences of the unknown offset and the unknown gain of the signal processor and other linear systematic errors are eliminated.

V. Algorithm for Measurement

The microcontroller is used to measure the periods of the output signal of the processor, to calculate the position and to communicate with the outside digital world. The calculation of the absolute angular position from the measured nine periods is performed in three steps: an accurate fine measurement over a range of 15°, and a first and a second coarse measurement over ranges of respectively, 90° and 360°. The accurate fine measurement is performed using (4).

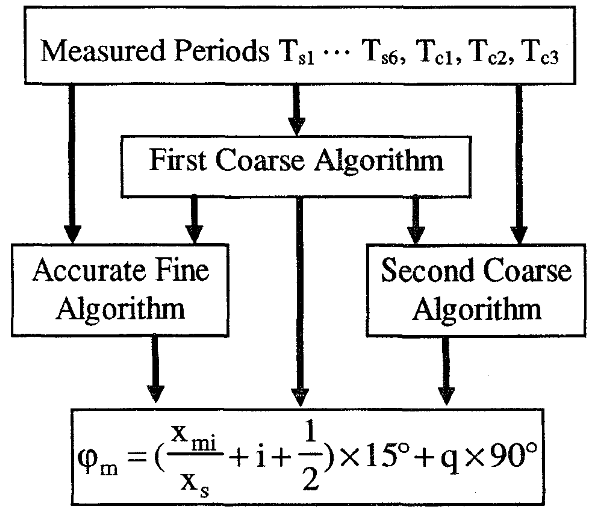

Fig. 5. The procedure to perform the measurement algorithm.

With the first coarse measurement it is found in which circle segment $i(i = 0, 1, \cdots, 5)$ the angular position is situated. This is done by comparing the six measured values of the periods $(T_{s1} \cdots T_{s6})$. After the first coarse measurement, the position is accurately known over a range of 90°. The second coarse measurement determines in which quadrant $q(q = 0, 1, \cdots, 3)$ the angular position is situated. The measured absolute angular position φ_m is found using the equation

$$\varphi_m = \left(\frac{x_{mi}}{x_s} + i + \frac{1}{2}\right) \times 15° + q \times 90° \tag{5}$$

where x_{mi}/x_s is the result of the accurate fine measurement within one segment width. Fig. 5 shows the procedure of this measurement algorithm.

VI. Experimental Results

An angular-position sensor based on the structure described in Fig. 3 has been built and tested. A distance of 2.5 mm between the common electrode and segmented electrode with a diameter of 50 mm was found to be an optimum to minimize the effect of electric-field bending and mechanical errors. 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. Guarding electrodes, surrounding the segmented electrode and common electrode, were used to reduce the influence of the electric-field bending and of electromagnetic interference. The rotating electrode with a thickness of 0.2 mm was made out of stainless steel by spark erosion technology and is grounded by using a sliding contact. All the electrodes were mounted in a metal housing, with a diameter of 57 mm, which is connected to ground and shields against external interference.

The signal processor was implemented with discrete components, and powered by a single 5 V supply voltage. The

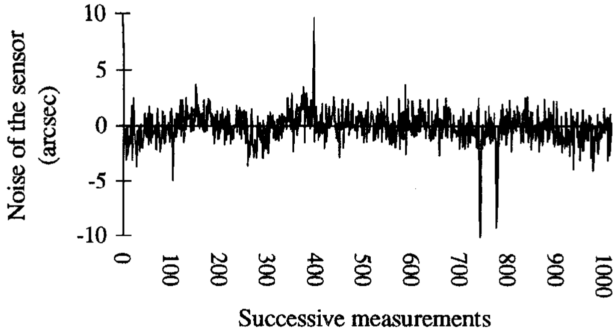

Fig. 6. The noise of the smart sensor.

frequency of the oscillator is about 8.0 kHz, and the applied range of the oscillator frequency is about 4 kHz–8 kHz. The nine periods were measured in a total measurement time of about 140 ms. The microcontroller directly gives a digital output signal representing the measured position.

Fig. 6 shows the noise of the smart sensor system, which includes the sampling noise of the microcontroller. The resolution of the smart sensor is limited by noise and amounts to 1.5 arcsec (19.7 b). The measured systematic nonlinearities of the smart sensor over the measurement range of 360°, with and without fine-tuning, are less than ±58 arcsec (14.4 b) and ±123 arcsec (13.3 b), respectively, (see Fig. 7).

The nonlinearity shown in Fig. 7(a) mainly consists of two periodic parts: one with a period of one segment width (15°) and the other with a period of six segment widths (90°). The effect of the electric-field bending mainly causes a nonlinear component with a period of one segment width (15°), because of the repeatability of one segment width for the accurate fine measurement. The mechanical errors, such as the nonflatness, the obliqueness, and the eccentricity, and the pattern errors of the electrodes mainly cause a nonlinear component with a period of six segment widths (90°), because the measurement with the outer electrodes repeats itself after six segment widths. From Fig. 7(b) it is concluded that the effect of the fine-tuning is very effective in reducing the influence of the electric-field-bending effect. The remaining nonlinearity after fine-tuning mainly originates from the mechanical errors and the pattern errors of the electrodes, and can be further reduced by applying appropriate calibration.

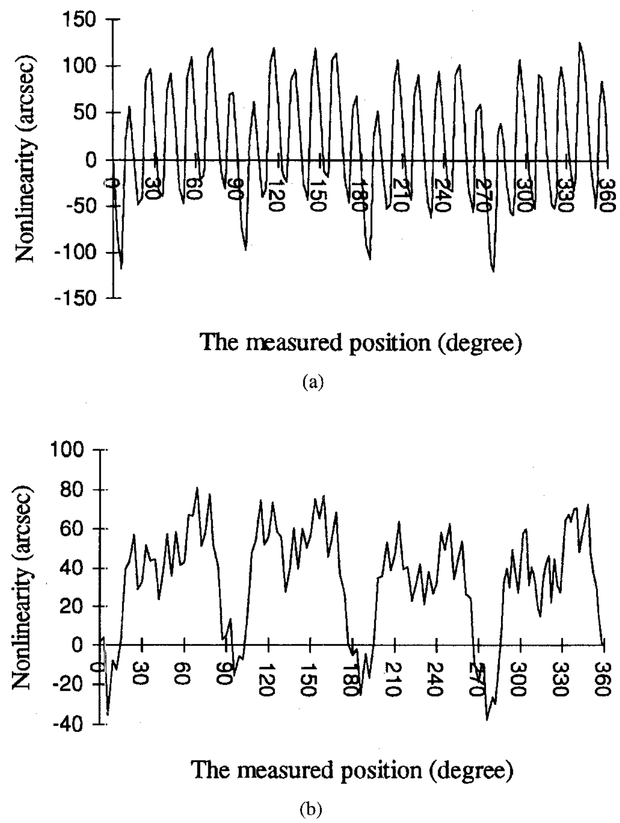

Fig. 7. The measured nonlinearity (a) without fine-tuning ($\alpha = 0$), (b) with fine-tuning ($\alpha = 0.0328$).

This nonlinearity is mainly due to the mechanical errors, the pattern errors of the electrodes and the remaining effect of the electric-field bending.

VII. Conclusion

A high-performance smart capacitive angular-position sensor with a full-circle measurement range and a digital output has been presented. The applied algorithm eliminates or strongly reduces the influences of many systematic nonidealities of the sensing element and the signal processor in a very effective way. The smart sensor system includes a simple signal processor which linearly converts the multiple capacitor values to a period-modulated signal. Only a single signal wire is required to communicate with the microcontroller. A prototype of the sensor has been built using low-cost material. The nonlinearity of this smart capacitive angular-position sensor is less than ±58 arcsec over the measurement range of 360° for a measurement time of about 140 ms.

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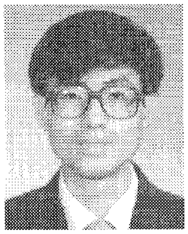

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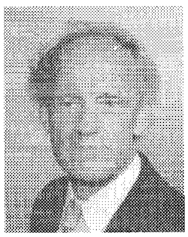

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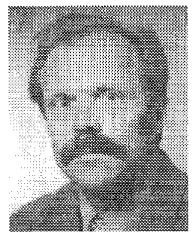

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