Capacitive Sensor for Relative Angle Measurement

Paul L. Fulmek, Florian Wandling, Wolfgang Zdiarsky, Georg Brasseur, *Senior Member, IEEE*, and Stefan P. Cermak

***Abstract*—Based on a capacitive angle and angular rate sensor, a sensor measuring the relative angle between two rotating shafts has been developed. Two rotatable electrodes are placed between two sensor plates. The relative angle between the two rotors and the absolute position of the rotor blades are calculated from measurements of the capacitive coupling between different transmitting stator segments and a single receiving electrode. A prototype of this sensor has been developed with a range of the relative angle of $\pm 7.5^\circ$ with a resolution of 0.1°.**

***Index Terms*—Capacitive sensor, contact-less, low-cost, robust sensors, torque sensor.**

I. Introduction

The capacitive angle/angular speed sensor described in [1], [2], and [3] has been modified by mounting two asymmetric rotors on two concentric shafts between the sensor stators. Both grounded rotors realize a single effective rotor with a variable geometry, depending on the relative angle between the rotating shafts. The absolute angle and angular velocity of both rotors are measured as described in [1] and [2] with a modified geometry and algorithm. These modifications additionally allow measuring the relative angle between the two rotors within a range of $\pm 7.5^\circ$. Applying the relative rotation angle of a torsion bar to the two rotors using two concentric shafts as shown in Fig. 1, allows measuring the torque transmitted by the rotating shaft using Hooke's Law.

II. Capacitive Sensors

Capacitive sensors can generally be categorized in

- micromachined capacitive sensors;
- macroscopic capacitive sensors.

Micromachined sensors are directly built on a silicon wafer, based on different technologies. They are usually integrated with an ASIC. Today, micromachined sensors are widely used, as their reliability is high and series production is quite cheap. Macroscopic capacitive sensors are usually manufactured on a PCB. Both types of sensors evaluate the capacitance between a static and a moving electrode.

A. Micromachined Capacitive Sensors

Micromachined capacitive sensors can evaluate very small geometrical changes. They are usually used for indirect measurements of pressure, acceleration, and yaw-rate.

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The design of a capacitive pressure sensor is shown in ([4], pp. 109). The sensor evaluates the variation of the capacitance of a silicon diaphragm dependent on the applied pressure. Acceleration and yaw-rate sensors (see [5]) are another typical field of application for micromachined capacitive sensors. A micromachined spring-mass-dampener system is built on the silicon wafer; the mass is part of a capacitor. Yaw rate sensors are designed to utilize the coriolis acceleration: the mass is set to a rotational oscillation by applying electrostatic forces. The externally applied accelerations are evaluated using capacitive measurement technologies [6]. Acceleration and yaw-rate sensors are very important in the fields of automotive electronics. The operation of airbags, ABS-systems, and electronic stability programs rely on the signals from these sensors.

B. Macroscopic Capacitive Sensors

Macroscopic capacitance sensors are often realized by using the copper layer of PCBs as electrodes. The typical measurement range is 10^{-3}–10^{0} m. Several different sensor applications are presented in [7]. In the field of macrosopic distance measurements capacitive sensors have to compete with several other sensor principles, such as optical, inductive or resistive (potentiometer) solutions. Potentiometers have to rely on a galvanic contact, which limits their lifetime. Inductive sensors need a magnetic flux, which has to be produced by permanent magnets. Optical sensors need a clean and transparent environment.

Macroscopic capacitive position sensors are applied to linear or rotational measurement, or as proximity switch. Digital vernier calipers use a multiple-electrode structure as described in [8]. A similar structure has been reported in [9] for angular position/velocity measurement. Another application for capacitive sensors is the touch switch. Here, the capacitance of a sensing area is modified by a human finger. A proximity detector does not need any movable parts, and so it can be used in rough environments. A very similar application, used in most Notebooks today, is the touchpad, which works as a replacement of the mouse. A touchpad is built as a two-dimensional array of touch switches, and an analyzing ASIC. Touchpads have no moving parts (like formerly used trackballs), so they are very robust.

III. Relative Angle and Torque Measurement

The torque transmitted by a shaft can be measured by strain gauges or by evaluating the relative angle caused by the torsion of a torsionbar [10]. For rotating shafts the problem occurs how to transmit the sensor output. For operation in harsh environments only the use of noncontact signal transmission is reasonable. Many torque sensor principles, therefore, are based on measuring the relative angle between the two ends of a torsion bar, as shown in Fig. 1.

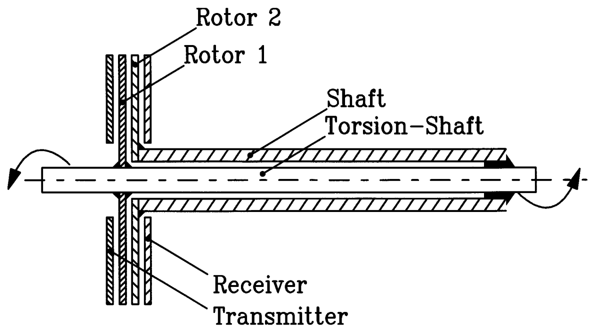

Fig. 1. Mechanical construction for applying the torsion to the rotors of the relative angle sensor.

Different optical and magnetic systems for noncontact rotational angle measurement have been reported. Optical position sensors are often incremental sensors. An example for an optical relative and absolute angle sensor-module is the "Torque and Angle Sensor Module TAS" produced by BOSCH [11]. Here two angular sensors are combined to evaluate the correct absolute and relative angle.

The following sections will describe a nonconductive capacitive sensor, for combined absolute and relative angular measurement. Another capacitive sensor for relative angular measurement (without the possibility of measuring the absolute position) is described in [12].

IV. Principle of Operation

Fig. 2 shows the electrode structure of the capacitive sensor. One stator plate is used as transmitter with 16 transmitter segments with center angles of 22.5°; the other stator contains the receiving ring electrode. The shaft electrically connects the conductive rotors to ground potential. These two rotors with asymmetrically arranged blades and a center angle of 60° (Fig. 2) are mounted mirror symmetrically on two concentric shafts. If one rotor is placed on top of the other, as shown in Fig. 2, a structure, very similar to the rotor structure for the angular speed sensor discussed in [2], results. The rotor for the absolute angle and angular speed sensor consists of two rotor blades with a clearance of 90°. The relative angle rotor-pair forms two blades whose recess clearance can vary between 60° and 120°, depending on the relative angle between the two rotors, while the sum of both blade angles always stays at 180°. In order to measure torque direction, it is necessary to distinguish between the two rotor blades. So the recess clearance of one rotor blade has to be between 60° and 0°, the other between 90° and 120°. In order to allow relative movements in both directions, the zero position of the relative angle is defined for blades with center angles of 75° and 105°, respectively. As long as the absolute value of the relative angle is below 15°, the two blades can be distinguished by verifying their size.

Depending on the relative angle the electrically effective size of the rotor blades is changed. These changes influence the capacitive coupling between transmitter segments and the receiving electrode. In one measurement cycle a pulse sequence is applied to each transmitting segment. Depending on the rotor position and the effective size of the rotor the received signals change for each segment. By applying a ratiometric algorithm to the received signals, the signed relative angle between the rotors and the absolute angle of both rotors within 360° are calculated.

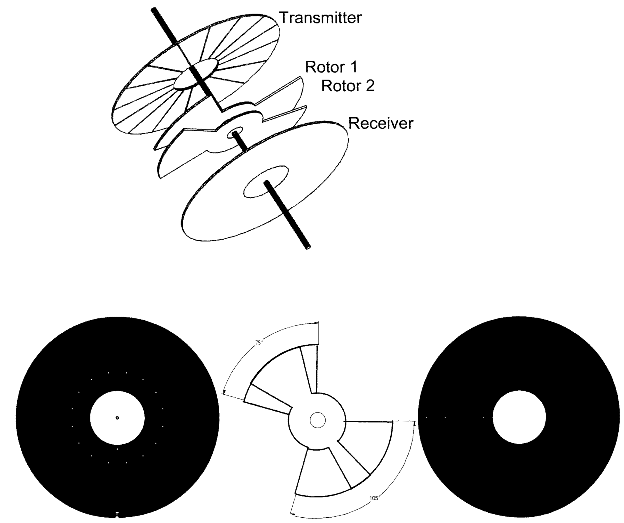

Fig. 2. Sensor topology of a capacitive relative angle sensor, transmitter plate with 16 segments, two mirror-symmetrical rotors, and receiving electrode.

V. Electrical Circuit and Signal Conditioning

Fig. 3 shows the microcontroller using segment drivers to switch the carrier signal to the transmitter segments. The receiving electrode reads the carrier frequency as a displacement current resulting from an excited transmitter segment. The receiving electrode is connected to the receiver electronic, comprising a resonant circuit as an input stage. The resonant circuit is tuned to the carrier frequency and acts as a low-noise, narrow-band voltage amplifier. The following stages consist of an amplifier, a narrow-band filter, a rectifier circuit, and a low-pass filter. Finally, the signal is fed into an ADC input of the controller. The microcontroller samples 16 segment values (SV), each corresponding to an excited segment. Further details on the signal conditioning circuits are given in [13].

VI. Algorithm for the Relative Angle Measurement

Fig. 4 depicts a linear representation of the circular sensor topology with 16 transmitter segments and a symmetric rotor configuration. The grounded rotor blades partly shield the electric field and produce an "electrical shadow image" on the receiving electrode. If the rotor blades move relatively, as shown in Fig. 4, the rotor shadow RS1 will be enlarged, and the rotor shadow RS2 reduced. This also means that the sum of the segment values SV_1 to SV_8 decreases, and the sum of SV_9 to SV_{16} increases proportional to the relative angle. The segment values of the completely shadowed and completely free segments are not influenced by the angular rotor position, which is a mandatary condition to apply the ratiometric algorithm. The relative angle between the rotors is calculated by evaluating the expression

$$\mathrm{SV}_{\max} = 2(\mathrm{SV}_1 + \mathrm{SV}_8 + \mathrm{SV}_9 + \mathrm{SV}_{16})$$
$$\mathrm{SV}_{\min} = 2(\mathrm{SV}_4 + \mathrm{SV}_5 + \mathrm{SV}_{12} + \mathrm{SV}_{13})$$
$$\mathrm{relative\_angle} = \frac{-\sum_{i=1}^{8} \mathrm{SV}_i + \sum_{l=9}^{16} \mathrm{SV}_l}{\mathrm{SV}_{\max} - \mathrm{SV}_{\min}} 90°. \qquad (1)$$

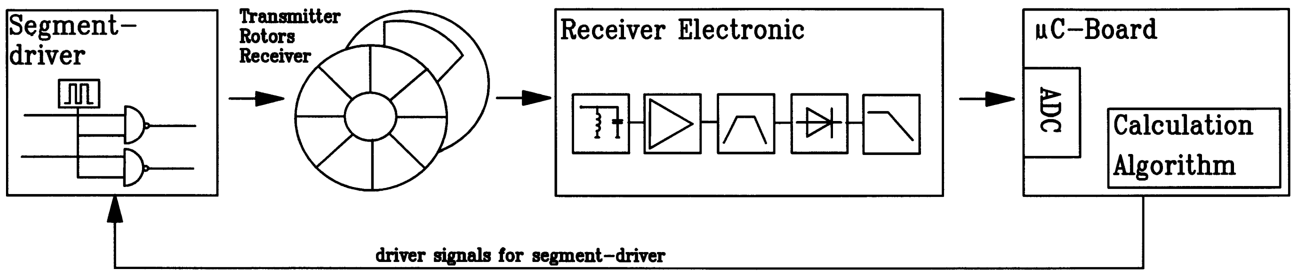

Fig. 3. Block diagram of the relative angle sensor electronic.

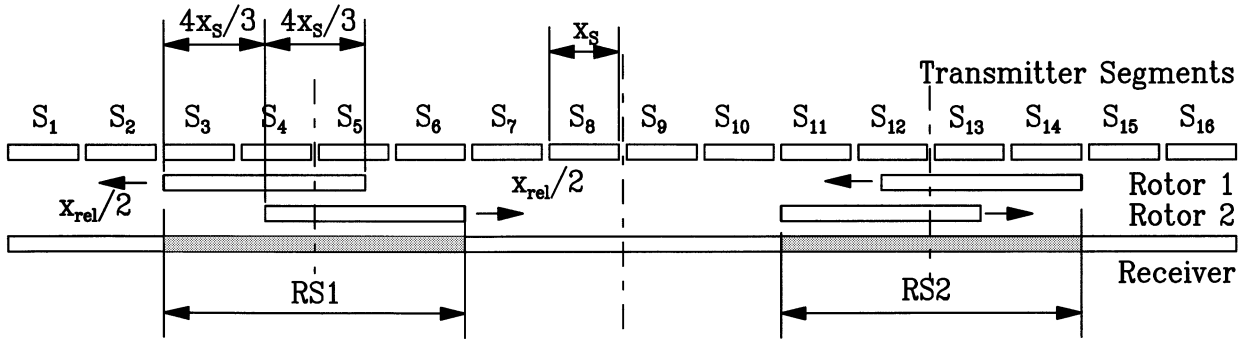

Fig. 4. Schematic geometry of the sensor.

In practice, the reference value, i.e., the difference between the maximum segment value $\mathrm{SV}_{\max}$ and the minimum segment value $\mathrm{SV}_{\min}$ in the denominator, is not constant and a calibration is necessary. It takes one turn to initialize the calibration table, and to reach the final accuracy.

To determine the direction of the relative movement, an asymmetry in the rotor geometry is introduced, as shown in Fig. 2. While a symmetric approach would define two 90° wide "rotor shadows" as zero position for the relative angular movement, this structure uses 75° and 115° wide rotor shadows as zero position. This asymmetry does not change the evaluation principle, because it is just an offset to the relative movement. To calculate the relative angle from (1), it is necessary to know the absolute position of the resulting rotor. For this reason, a second algorithm is used to evaluate the coarse rotor position with a resolution of one segment width (22.5° for a 16-segment transmitter). This coarse positioning algorithm calculates the cross-correlation of the measured segment values with a set of values defined for the zero-position. The maximum of the result gives the offset angle of the actual rotor position to the defined zero-position quantized with $22.5°$. Equation (2) evaluates the precise angular rotor position around the obtained coarse position and is valid for the first $\pm 11.25°$.

$$\begin{aligned}\mathrm{SV}_{\max} &= 2(\mathrm{SV}_1 + \mathrm{SV}_8 + \mathrm{SV}_9 + \mathrm{SV}_{16})\\ \mathrm{SV}_{\min} &= 2(\mathrm{SV}_4 + \mathrm{SV}_5 + \mathrm{SV}_{12} + \mathrm{SV}_{13})\\ \mathrm{absolute\_angle} &= \frac{\sum_{i=5}^{8}\mathrm{SV}_i - \sum_{l=9}^{12}\mathrm{SV}_l}{\mathrm{SV}_{\max} - \mathrm{SV}_{\min}} 90°. \end{aligned} \tag{2}$$

15 more expressions like (2) are needed to cover the total measurement range of 360°. Each new expression increments all indices within (2) by one and wraps the indices modulo 16. Additionally, each time an angular offset of 22.5° is added.

VII. Experimental Results

Our test bench consists of an optical reference sensor with a resolution of 20″. This sensor and a stepper motor are connected to a shaft. The stepper-motor is actuated in microstep-mode. The inner shaft (see Fig. 1) is connected to the outer shaft by a manually operated angular positioning unit with a resolution of 1′. This unit produces a relative angle between both rotors to simulate the torque transmitted by a torsionbar. A personal computer controls the stepper-motor, and reads out the reference sensor and the prototype sensor. An overview of the test bench is given in Fig. 5.

The first measurement was based on the sensor topology shown in Fig. 2. The measurement results show a high sensitivity of the presented rotor structure to a radial displacement. Therefore, two further structures (Fig. 6) have been developed with a 180°-symmetry, resulting in a reduced measurement range of 180° for the absolute angle and a range of 7.5° for the relative angle. The new structures use 32 transmitter segments with center angles of 11.25° and rotors with four blades and center angles of 30°. Each segment is electrically connected to its mirror segment, producing again 16 segment values for each measurement cycle. As described in [14] this structure is insensitive to radial displacement.

The third structure [Fig. 6(b)] measured was the so-called "inverse topology". This structure is the mechanical inversion of the topology explained before: the size of the blades is constant, while the free angles between the blades vary with the relative angle. Both inverse and normal structures use an effective rotor-shape with four rotor blades. The inverse structure, however, uses single rotors with two blades only. So, the rotors of the inverse topology can be manufactured more easily.

Figs. 7 and 8 show the measurement results obtained with the inverse topology. As mentioned before, the accuracy of

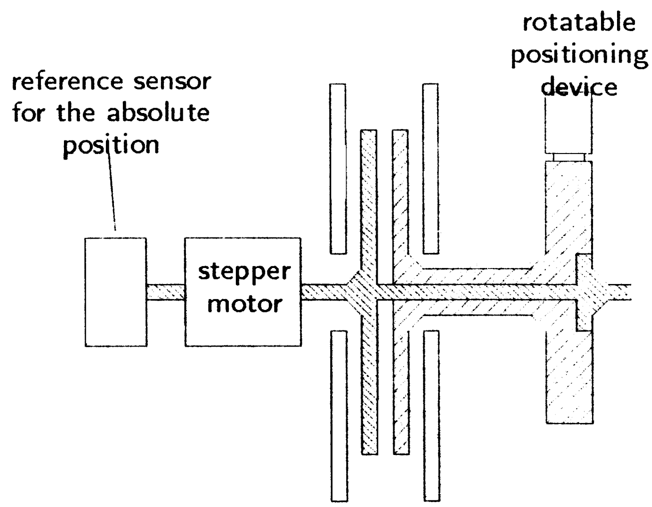

Fig. 5. Overview of the test bench used. The absolute position is set by a stepper motor, combined with a reference sensor. The relative angular position is set manually by the use of an angular positioning device.

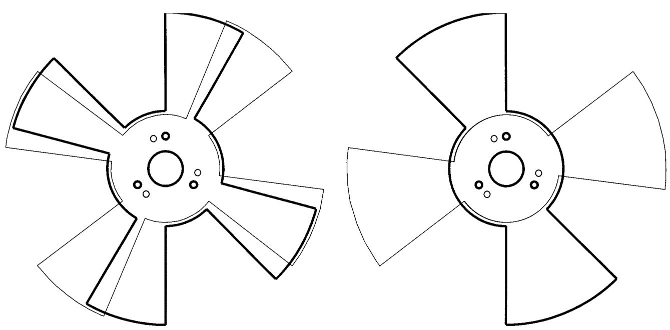

Fig. 6. The advanced rotor stuctures: (a) 180-degree periodic version of the original rotor and (b) The inverse topology, this version is the mechanical negation of the rotor a.

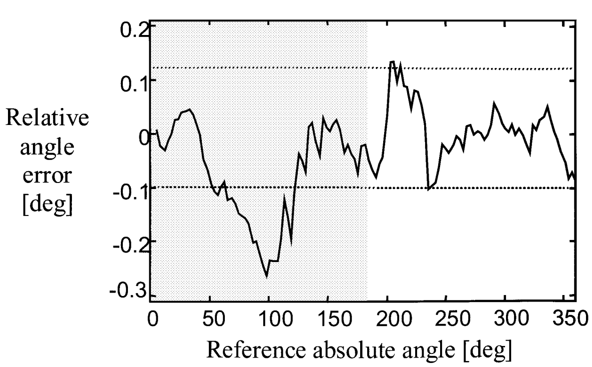

Fig. 7. Relative angle error versus absolute position.

the sensor can be increased by auto-calibration [15]. The gray shaded area in Fig. 7 gives the results of the uncalibrated sensor. After self-calibration the error is within 0.1°. Fig. 8 shows the relative angle error versus the relative angle. This error is below 0.08°.

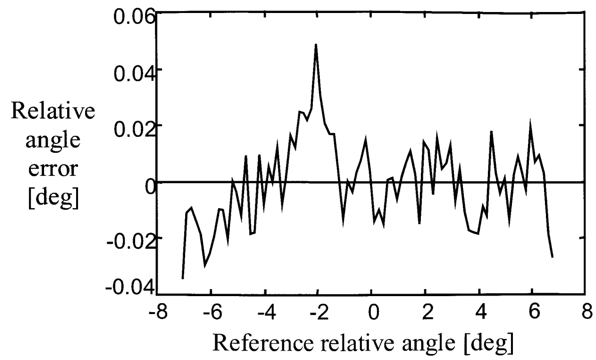

Fig. 8. Relative angle error versus relative angle range.

VIII. Conclusion

Based upon the described sensor prototype, it is possible to realize contact-less torque sensors for rotating shafts, measuring the torque in mechanical systems in harsh environments. Future developments will concentrate on increasing the resolution of the relative angle measurement. The dynamic performance of the sensor will be evaluated.

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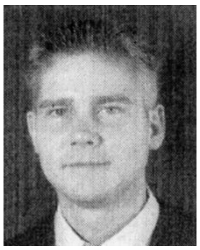

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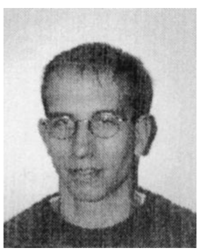

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