Autonomous Self-Aligning and Self-Calibrating Capacitive Sensor System

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Abstract. An autonomous capacitive sensor system for high accuracy and stability position measurement, such as required in high-precision industrial equipment, is presented. The system incorporates a self-alignment function based on a thermal stepping motor and a built-in capacitive reference, to guarantee that the relative position between the sensor electrodes is set to 10±0.1 µm. This is needed to achieve the performance specifications with the capacitive readout. In addition, an electronic zoom-in method is used to reach the 10 pm resolution with minimum power dissipation. Finally, periodic self-calibration of the electronic capacitance readout is realized using a very accurate and stable built-in resistive reference. The performance is evaluated experimentally and with simulations.

Keywords: Capacitive Sensor System, Position Measurement, Self Alignment, Self Calibration, Thermal Actuator

1 Introduction

For the chosen target application a measurement accuracy better than 100 pm with a signal bandwidth of 1 kHz is required, while the measurement stability has to be within 10 pm per minute. Such a measurement can be performed in a contact-less way, using a proximity type capacitive sensor. The distance between the parallel sensor electrode and the target electrode is determined based on the electrical capacitance's between them. With dedicated electronics the ratio of the total capacitance and the measurable capacitance difference is limited to an order of magnitude of 10^6. For high accuracy and stability measurement, the capacitor electrodes should be close and parallel, within 10±0.1 µm. Due to limited access to the sensor, this cannot be achieved by conventional manual alignment or by using precision alignment instruments. Also, re-alignment is often required after transportation. The measurement system should therefore be able to autonomously reposition and realign itself, without compromising the *mechanical stability* when the system is *at rest*, which is not offered by available, simple systems [2]. Also the readout electronics will need to autonomously (re-)calibrate periodically to guarantee the measurement precision. Chapter 2 describes the proposed measurement system and the subsystems thereof. In Chapter 3 the performance of these sub-systems is evaluated experimentally.

2 Proposed System

The capacitive displacement measurement system can be split in two main subsystems: (i) the mechanical suspension of the sensor electrode with a motion mechanism and (ii) the electronic system, which measures the capacitance and converts it into a displacement value. Accuracy and stability will be the main design requirements.

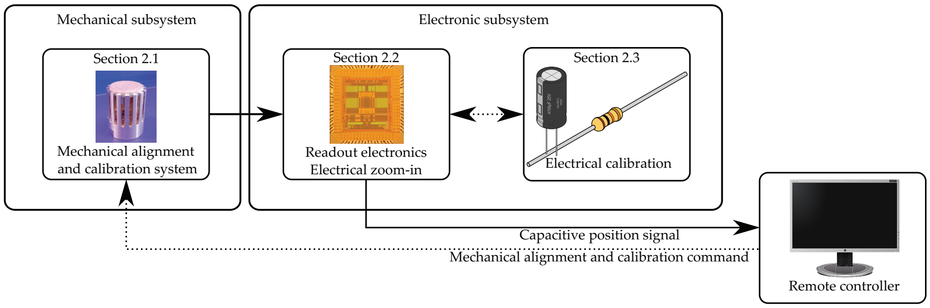


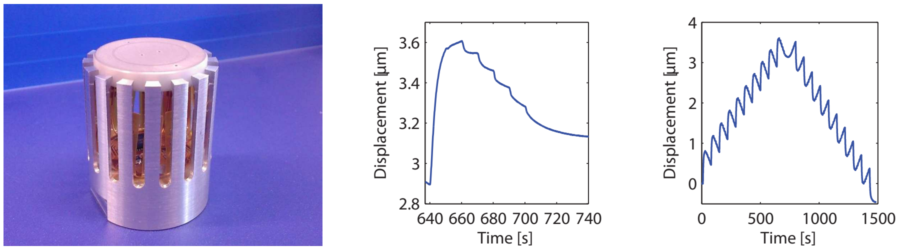
Fig. 1: Schematic overview of the measurement system architecture. The solid arrows represent permanent communication, and the dashed arrows represent occasional communication. Only position data and calibration and alignment commands are communicated with the remote controller.

The system accuracy is reached by positioning the measurement electrode (Section 2.1) and using a dedicated capacitance readout (Section 2.2). The output stability is a combination of the mechanical and the electronic stability. The electronic stability is reached by regularly calibrating the readout with a stable reference (Section 2.3). Heat production will also limit the measurement stability and should thus be minimized in the design of the system parts. A final step to improve the stability and accuracy is mechanical calibration of the entire measurement process, from displacement to the reconstructed position, with an accurately known displacement of the motion mechanism.

Implementation of the measurement system will be as follows. First the sensor is mounted with rough position and alignment tolerances. Then the remote controller drawn in Fig. 1 sends an alignment command and the measurement electrode moves towards and aligns with the measurement target. Meanwhile the sensor capacitance is read and sent back to provide feedback for this process. The mechanical calibration will influence the measured position and is thus performed only before or between measurements. Electrical calibration is performed periodically every few minutes during normal operation.

2.1 Mechanical Auto-alignment and Calibration Mechanism

The main function of the mechanical subsystem is to generate a motion in three directions (up-down, pitch and roll) to align the electrode, while the position stability at rest is better than 10 pm per minute. The total motion magnitude must be at least 100 µm while the final positioning and alignment accuracy is such that the electrode distance is within 10±0.1 µm. For the mechanical calibration, an accurately reproducible motion is needed. Conventional solutions often cannot meet the stability requirements [2], and therefore the thermal stepper mechanism reported in [3] is used.



(a) ⌀25 mm thermal stepper with integrated switches for the heaters.

(b) Displacement during a single step.

(c) Displacement during a sequence of steps.

Fig. 2: Picture of a thermal stepper design and the measured displacement response.

The thermal stepper consists of a ring of metallic fingers, a so-called spring nest. (See Fig. 2a.) The fingers clamp the sensor electrode and friction holds it in place. In order to create an overall motion of the measurement electrode, a single finger must be able to slide over the electrode surface. This is accomplished by changing the temperature of one finger while the temperature of the others remains constant, which is done with an electrical heating resistor on each finger. The friction force in this one finger is much larger than the friction force in each of the other fingers, causing only the single finger to start moving. To efficiently actuate the motion directions needed to actively align the electrode, a large number of fingers are used. Using a dedicated heating sequence, an overall net movement can be generated, as is shown in Fig. 3.

To generate this movement, it is essential that the displacement of a single finger, and thus the finger temperature, can be controlled independently. Therefore, the thermal resistance between fingers must be large and the fingers must be thermally connected to a large heat-sink. The preload force of the fingers must be just sufficient for the expected load, because larger contact forces decrease the motion efficiency.

The limited speed due to the thermal time constant (in the seconds range) causes no problems, since the motion is only required during installation. During measurement the actuation will be turned off entirely, reducing its thermal influence to zero.

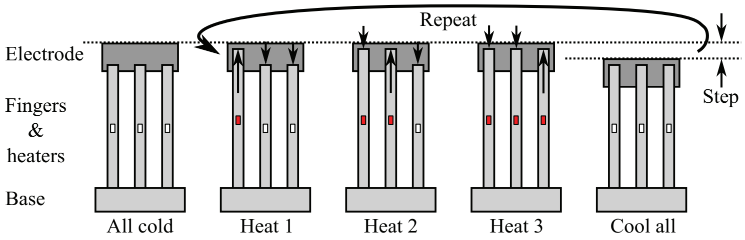


Fig. 3: Thermal cycle for a single-dimensional downwards movement. The contact shear forces during motion are indicated. The dark resistors are heating their finger.

To align the electrode surfaces, an upward motion cycle pushes the electrodes towards each other, automatically aligning them when they touch each other. Cooling down all fingers simultaneously from an equal, elevated temperature results in the required electrode distance while maintaining the electrode alignment [3]. When the suspension of the target electrode is too compliant to act as a physical alignment reference, pitch and roll can be actively controlled by the thermal stepper, using a segmented electrode for pitch and roll information. The mechanical calibration uses the calibrated thermal step response of all fingers simultaneously, so that there will be no slip. The measured capacity change is compared to the known displacement to deduce the real sensor gain at the current location [3].

2.2 Pico-meter Resolution Capacitive Sensor Interface Circuit

Since the resolution of the capacitance measurement is high, an interface circuit based on the charge balancing principle is a very good candidate for this application. As shown in Fig. 4, this circuit is basically an incremental $\Sigma\Delta$ converter, and can be used to obtain the ratio between the sensor capacitor C_{X} and the reference capacitor C_{REF} with very high resolution. However, there is one drawback if it is directly applied to the sensor. The measurement range of the circuit is from $-C_{\mathrm{REF}}$ to C_{REF}, which corresponds to a much larger displacement range than the required ±1 µm. This causes a waste of system resources.

The solution to this problem is to use electrical zoom-in, as illustrated in Fig. 5. A zoom-in capacitor C_{Z} is introduced which is driven with an excitation signal opposite to the sensor capacitor (C_{X}) excitation, so that the effective input of the interface becomes C_{X}-C_{Z}. When the value of C_{Z} is very close the nominal value of C_{X}, the reference capacitor C_{REF} can be largely reduced. In this way the conversion speed of the circuit can be increased.

The realized circuit employs a 3rd order loop filter for sufficient noise shaping with a clock frequency of 5 MHz. It also has a fully differential structure to suppress charge-injection error. The prototype circuit was fabricated in a standard 0.35 µm CMOS technology and consumes 15 mW from a 3.3 V power supply.

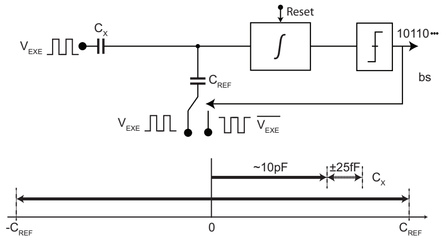


Fig. 4: Capacitive sensor interface based on the charge balancing principle.

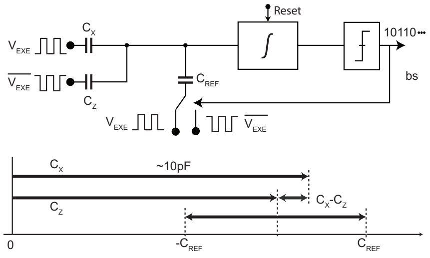


Fig. 5: Zoom-in capacitor used to reduce the measurement range of the interface, in order to decrease the conversion time.

2.3 Electronic Self-calibration with External Stable Reference

As mentioned above, the high resolution capacitive sensor interface uses two extra reference capacitors during operation. One is a zoom-in capacitor C_{Z} (~10 pF) while the other is a reference capacitor C_{REF} (~100 fF). The performances of the interface, e.g. accuracy and stability, are determined by the quality of these two capacitors.

Unfortunately, capacitive components are not accurate and stable enough for the given application. The best available off the shelf capacitive component is accurate up to 1 % while the thermal stability is in the order of tens of ppm/°C [4]. Therefore, to achieve the required performance, these two reference capacitors have to be calibrated periodically by more stable and accurate references and dedicated electronics.

There are different stable and accurate references available, for instance time-frequency reference, voltage reference and resistor reference. After some investigation and comparison, stable and accurate resistors with 0.005 % accuracy and 0.5 ppm/°C temperature stability [5], were selected as the built-in reference for the capacitance measurement.

The comparison between the capacitor and resistor is based on the charge balancing principle, the charge generated by the capacitor (unknown charge) is balanced by the charge generated by the resistor (reference charge). To improve the energy efficiency and measurement speed, a charge-balancing based $\sum\Delta$ resistance-capacitance comparator is proposed, see Fig. 6.

The circuit works as follows: a reference current source I_{ref} that is generated by a reference voltage V_{ref} and resistor R_{ref} is continuously connected to the input of an integrator. The generated charge is then stored in the integrator, thus making the integrator output non-zero. A comparator monitors the output of the integrator to switch the compensation charge on and off. Only when the

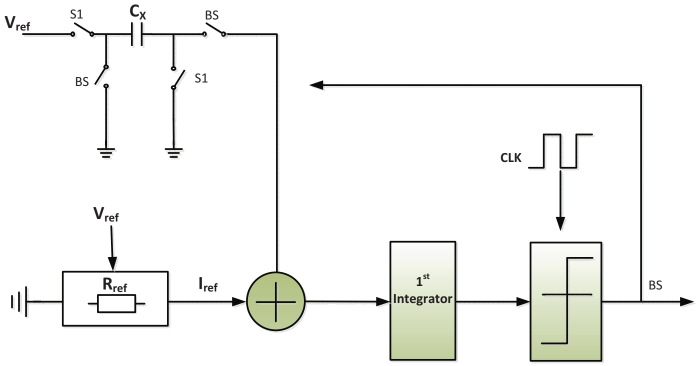


Fig. 6: Simplified block diagram of the proposed RC (resistance-capacitance) comparator. The capacitance is charged at every clock by enabling s1 switches. Only when the comparator output (BS) is ‘1’ the charge is applied to the integrator by enabling the BS switches.

output of the integrator is positive, the comparator output is ‘1’, which controls the feedback path to supply a compensation charge. The compensation charge is generated by the unknown capacitor C_X and a reference voltage V_ref.

Assume the circuit operates for N cycles. The total charge that is supplied by the current source can be calculated as: $Q_\mathrm{ref} = N\frac{V_\mathrm{ref}}{R_\mathrm{ref}}\Delta t$, where Δt is the time interval between two decision-making actions of the comparator.

Whenever the output of the comparator is ‘1’, a compensation charge is generated by the capacitor. Therefore, the total compensation charge is: $Q_\mathrm{X} = N_1 V_\mathrm{ref} C_\mathrm{X}$, where N_1 is the number of ‘1’s in the comparator output during one measurement cycle.

Finally, with sufficient operating cycles (N), the loop will bring the integrator output to zero, meaning that the reference charge balances the unknown charge. Thus the capacitance can be calculated as: $C_\mathrm{X} = {}^{N}\!/_{N_1}{}^{\Delta t}\!/_{R_\mathrm{ref}}$. As can be seen from the equation, the effect of the reference voltage is canceled out, thus the final result is a function of a reference resistor and a reference time.

To improve the resolution and speed of the RC comparator, a 3rd order $\sum\Delta$ modulator is implemented. The higher order loop provides better noise shaping, which enhances the resolution with fewer operating cycles required [1]. In addition, the modulator is implemented as a fully differential structure to achieve good immunity to common-mode interferences.

3 Experimental Results

3.1 Motion Mechanism

Fig. 2a shows a realized motion system. In Fig. 2b the measured sensor displacement of a single upwards step sequence that results in a 0.5 µm net displacement is shown. The series of sequences, in Fig. 2c shows a motion in both directions in the micrometer range with an average speed of approximately 0.5 $^{\mu m}/_{min}$.

3.2 Capacitive Sensor Interface Electronics

Fig. 7 shows the measurement setup for evaluating the performance of the interface with an off-chip capacitive sensor. The sensor is connected to the interface via shielded coaxial cables, which adds 10 pF parasitic capacitance to load of the interface. The sensor itself is mechanically actuated by a shaker which is shaking at 100 Hz, creating a small capacitance variation on the sensor. The measured response of the sensor is shown in Fig. 8. It can be seen that the measurement noise floor is 65 $\mathrm{aF}_{\mathrm{rms}}$, which means that the equivalent displacement resolution is 65 $\mathrm{pm}_{\mathrm{rms}}$ if this interface is connected to the designed displacement sensor. The measurement time for this interface is as low as 20 µs.

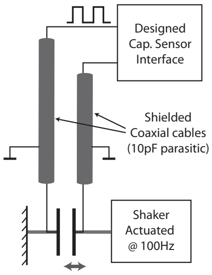


Fig. 7: Measurement setup with a mechanically actuated capacitive sensor.

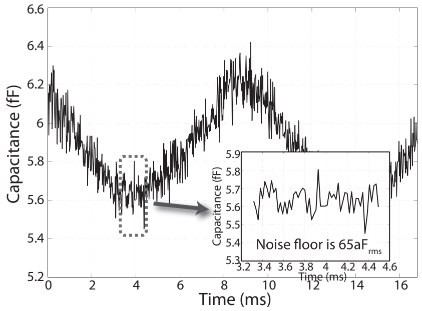


Fig. 8: Measurement result, the measured noise floor is 65 $\mathrm{aF}_{\mathrm{rms}}$.

3.3 Electronic Self-calibration

The RC comparator principle was first implemented and simulated in Matlab. Fig. 9 shows the simulation result of the comparator with 1500 operating cycles. In theory, only 500 cycles is sufficient to achieve 20-bit resolution with a 3^{rd} order $\sum\Delta$ converter. However, this calculation is based on the assumption that only the quantization noise of the comparator contributes to the error. In reality, the thermal noise of the system is the limiting factor of the overall performance, thus more operating cycles are required to suppress the thermal noise. In this design, the number of operating cycles is selected to be 1500. The result shows that the conversion error is only a few atto-Farad (aF), while the input capacitance is in the range of pico-Farad (pF). Therefore more than 20-bit resolution is achieved. The operating time for each cycle in this design is around 6 µs, which makes the total measurement time 10ms. The spectrum of the result is shown in Fig. 10, which clearly shows a 3^{rd} order noise-shaping profile.

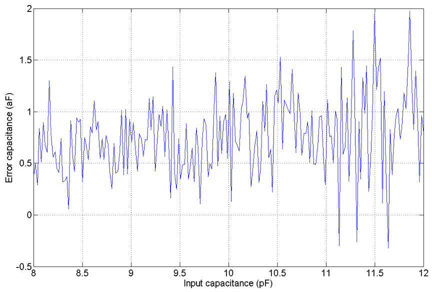


Fig. 9: Simulated error versus input capacitance with 1500 operating cycles.

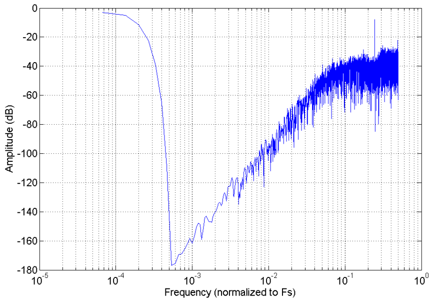


Fig. 10: Simulated output spectrum of the proposed RC comparator.

4 Conclusions and Future Work

The developed solution for a stable and high accuracy position measurement is the combination of a mechanical positioning and alignment system and efficient, high resolution readout electronics.

The intelligent operating algorithm of the system first uses the thermal actuator to position the measurement electrode. Secondly, the electronic part is used to zoom in electrically and perform the measurement with high accuracy. Finally a calibrated motion is performed as a mechanical reference and a resistor is used as a stable electrical reference to guarantee the measurement stability over time.

The subsystems that implement these tasks have been designed and their performance is verified with measurements and simulations. The next step consists of further developing these subsystems into an autonomous self-aligning and self-calibrating capacitive sensor element.

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