Sensor Interface for Multimodal Evaluation of Capacitive Sensors

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Abstract. Capacitive proximity sensing can be done in different modes. The single ended mode usually offers a higher signal to noise ratio (SNR) and - in conjunction with active guarding - high robustness. However, it can be blind for objects with low permittivity close to the sensor surface. The differential mode usually has a worse SNR but has the capability to detect objects in situations where the single ended mode is blind. Thus, we propose a measurement circuitry to combine both modes. It is compared to state of the art sensors and the benefits of this approach are demonstrated by means of experimental investigations.

1. Introduction - Differential and Single Ended Capacitive Sensing
Capacitive proximity sensing is usually done in one of two measurements modes [1]. They can e.g. be denoted as
- Differential mode (also called mutual capacitance mode) and
- Single ended mode (also called self capacitance mode).

With the differential mode, the capacitance between two conductive areas (called electrodes) is determined. By applying a voltage to a first electrode (called transmitter) and measuring the displacement current induced on the second electrode (called receiver) this capacitance can be measured.

The single ended mode measures the displacement current originating from an electrode (called transmitter). This current corresponds to the capacitance between the transmitter and the distance ground (if measuring to the open environment) as shown in Figure 1(a). A difficulty associated with the single ended mode is the fact that the sensitivity is quite high at the edges of the electrode in particular when conductive objects resides in the vicinity, e.g. as the carrier of the electrode. In this case moisture and contamination may significantly affect the measurement and no reliable proximity determination is possible. A commonly used method to cope with this problem is active guarding where a guard is placed between the actual electrode and a metallic carrier. Thus, the sensitivity moves away from the edges of the electrodes. However, this also leads to a reduced sensitivity with respect to small objects in the vicinity of the electrodes.

Electrical Capacitance Tomography (ECT) represents a technology that is usually based on mutual capacitance. It is a noninvasive imaging system aiming on the determination of the spatial material distribution in some region from capacitive measurements (in differential mode) taken from the outside [2]. This is done by solving a so called inverse problem with heavy signal processing. In process tomography, the region of interest is typically the interior of a pipe. Typical measurement tasks are the determination of the gas content in oil exploration. Recently in [3] we showed that the
ECT approach can be transferred to the open environment. With a differential mode capacitive measurement system we demonstrated the basic functionality, but we also found limitations. For example, it may not be possible to detect small conductive objects. This is due to two competing effects referred to as coupling and shielding effect [4]. Signal cancelation may occur at transitions between these effects. As the shielding effect is the main effect in the single ended mode, this can be used to identify the presence of both effects. Thus, we propose to combine single ended and differential mode to avoid the blind spots.

![Figure 1](image.png)

**Figure 1** Conductive areas (electrodes) are used as sensing elements. (a) Sketch of the sensor front end with two electrodes. Electrode 1 is used as a transmitter and electrode 2 is used as a receiver. The red arrows indicate the two displacement currents originating from electrode 1 and entering electrode 2, which are measured when using the single ended mode and the differential mode, respectively. The guard electrode can be set to ground or to the excitation signal (i.e., active guarding). An object’s parasitic connection to ground is indicated by the equivalent circuit of $R_{\text{GND}}$, $C_{\text{GND}}$, and $L_{\text{GND}}$. (b) Picture of the used sensing elements. Thin (approx. 100 mm) and flexible copper strips are used as electrodes. A 2 mm thick PVC material is used as spacer between the electrodes and the guard at the backside.

2. Measurement System

The proposed measurement system (shown in Figure 3(a)) is able to work in the differential mode and the single ended mode. It provides a high measurement rate (> 1 kHz). The measurement frequency can be changed between 10 kHz and 1 MHz to any frequency value. Thus, it is possible to obtain additional information about parasitic effects, due to their frequency dependency as shown in Figure 1(a). Furthermore, a change in the measurement frequency can be used to deal with electromagnetic compatibility (EMC) problems as shown in [5].

Figure 2 gives an overview of the presented measurement system. A sinusoidal signal, generated by a direct digital synthesizer (DDS), is applied to one or more electrodes through a switch circuitry. The displacement current originating the electrodes used as transmitters is measured by a transmitter circuitry (single ended mode). Each electrode is also connected to a receiver circuitry. If an electrode is not used as a transmitter, the receiver circuitry measures the displacement current entering this electrode (differential mode). Since each electrode can be used as a transmitter or a receiver a total of $N_{\text{elec}}(N_{\text{elec}}-1)/2$ independent measurements, where $N_{\text{elec}}$ is the number of electrodes, can be obtained with the differential mode. With the additional single ended mode a total of $N_{\text{elec}}(N_{\text{elec}}-1)/2 + N_{\text{elec}}$ independent measurements can be obtained. The backside of the sensor can be connected to ground (differential mode) or to the excitation signal (i.e., active guarding in single ended mode).

A low noise amplifier (LNA) is used to amplify and connect the output of the receiver and transmitter circuits to the I/Q demodulator (where I and Q represent the in-phase and the quadrature component, respectively). With the I/Q demodulator it is possible to get amplitude and phase information of the measured signals with respect to the excitation signal. These DC signals are digitized and stored in a microcontroller. The microcontroller also controls the signal generation, the
switch circuitry and the I/Q demodulation (not shown in Figure 2). The processed measurement data can be sent to a host computer to store or post process the data (e.g. signal processing for imaging applications [6]).

![Diagram of the measurement system](image)

**Figure 2** Overview of the presented measurement system. A DDS is used to generate a sinusoidal signal between 10 kHz and 1 MHz. Switches are used to connect the electrodes to the signal generation, receiver and transmitter measurement circuitries. An I/Q demodulator is used to get amplitude and phase information of the measured signal. The post processing consists of an analog digital converter (ADC), a microcontroller (µC) board and a host computer (PC).

Table 1 gives an overview of the proposed measurement system (shown in Figure 3(a)) and the two commercial available systems, which were used in this work.

![Picture of the sensor and the approaching objects](image)

**Figure 3** Picture of the sensor and the approaching objects. (a) The measurement system consists of three stacked printed circuit boards (PCB): A commercial available µC board at the top, the digital part comprising the DDS, ADC and clock generation positioned in the middle and a PCB at the bottom comprising all amplifier circuits, the switches and the I/Q demodulator. (b) A human hand and two approaching objects were used to evaluate the sensor. The metallic rod has a diameter of 5 mm and the plastic case has a size of 200 x 300 mm.

### 3. Measurement Results and Discussion

Several experiments (Figures 4 to 6) are carried out with the proposed measurement system and compared to a commercial available singled ended sensor and a differential sensor (Analog Devices AD7148 and AD7746 [7]).

In the first experiments shown in Figure 4 a human hand approaches the sensor surface and leaves again. The human hand can be detected in single ended mode as well as in differential mode with both measurement systems (proposed sensor and commercial available ones). Although, due to shielding and coupling effects (described in Section 1) at a certain distance to the sensor surface the measured capacitance increases (marked with arrows in Figure 4). This effect (decreasing and increasing capacitances) yields to ambiguities in proximity determination.
Table 1  Properties of the Proposed Measurement System compared to state of the art sensors

|                          | Proposed sensor | AD7746       | AD7148       |
|--------------------------|-----------------|--------------|--------------|
| Excitation signal        | Sinusoidal signal | Square wave | Square wave |
| Frequency                | Tunable from 10 kHz to 1 MHz | 32 kHz | 250 kHz |
| Measurement rate         | 1.25 kHz (max. 6.25 kHz @ 1 MHz) | 10 Hz to 90 Hz | 40 Hz |
| Measurement method       | Single ended and Differential mode | Differential Mode | Single ended Mode |
| Shielding                | Active guarding and Grounded shielding | Grounded shielding | Active guarding |
| Number of electrodes     | $N_{elec} = 7$ | $N_{elec} = 3$ | $N_{elec} = 8$ |
| Number of independent measurements | 28 (for each frequency) | 2 | 8 |

As can be seen in Figure 5 a metallic rod (compare Figure 3(b)) can also be detected with a good SNR. Again, the two competing effects shielding and coupling can be observed for the sensors working in the differential mode (marked with arrows).

Figure 4  Human hand approaching and leaving the sensor surface. (a), (c) Measurement (I- and Q-channel in the case of the proposed sensor) for the differential mode sensors. The arrows indicate the transitions between the shielding and coupling effects. (b), (d) Measurements with the single ended mode.

Figure 5  Metallic rod approaching and leaving the sensor surface. (a), (c) Measurement for the differential mode sensors. The arrows indicate the transitions between the shielding and coupling effects. (b), (d) Measurements with the single ended mode.
Figure 6 Plastic case approaching and leaving the sensor surface. (a), (c) Differential mode results. Although the approaching object has a small influence on the electric field, it can reliably be detected by the proposed sensor. (b), (d) In the single ended mode it is very difficult to detect this kind of objects.

In Figure 6 an empty plastic case (compare Figure 3(b)) approaches the sensor surface. Due to the small volume and the low permittivity ($\varepsilon_r$ close to 1) this object has a small influence on the electric field. Thus, the capacitance change is very small. As can be seen, the plastic case cannot be detected by the commercial sensor working in the single ended mode. In this case the differential mode outperforms the single ended mode. The plastic case can reliably be detected with the proposed sensor working in the differential mode as shown in Figure 6(a).

4. Conclusion
In this paper a versatile and fast multichannel capacitive measurement system has been presented. The measurement system is able to work in the differential as well as the single ended mode. The ability of the measurement system has been demonstrated by means of experimental investigations. The new developed multichannel system features the design and application of new capacitive measurement techniques as it provides a flexible measurement platform for arbitrary sensor arrangements. Thus, the research and development can focus on the frontend, i.e., the electrode topology, and the reconstruction, i.e., imaging methods.

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