Investigations on the Leakage Effect in Capacitive Sensing

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Abstract— In the measurement of mutual capacitance between electrodes both the coupling and the leakage effect contribute to the measurement result whereas the leakage mode is dominant in the self capacitance mode. While the coupling effect is mainly defined by the geometry and material distribution close to the electrodes, the root cause or modulation of the leakage effect may be far away from the electrode. It is shown that utilizing both effects may lead to an improvement of an ECT-like scenario reconstruction performance in open environments (e.g. pretouch applications).

Keywords—leakage effect; capacitive sensing; open environment; ECT; reconstruction

I. INTRODUCTION

Since more than 20 years capacitive sensing has been used in a broad field of applications. Most applications using capacitive sensing can be divided in two types:

- Capacitive sensing within a known environment.
- Capacitive sensing with predefined objects of interest.

An example for the first case is electrical capacitance tomography (ECT). Because of the enclosed structure of an ECT system, the region of interest is well known and the sensor is barely influenced by external disturbers (e.g. by moisture or electrostatic discharge). Additionally some other simplifications can be made. For example no interaction between the electric and the magnetic field is observed, no free charges inside the pipe, and the length of sensing electrodes compared to the length of the objects of interest can be neglected. These properties paired with dedicated signal processing algorithms permit a reconstruction of the spatial permittivity distribution within the pipe (i.e. generating a 2D cross-sectional image of the inside) [1], [2], and [3].

An example for the second type is proximity estimation in various fields of applications. If the nature of approaching object types is known, experimental investigations have shown the ability to estimate the distance of the approaching object to the sensor surface [4]. Due to the prior knowledge of approaching object types, the environment in which the sensor is used may vary in certain limits. It is shown in [4] and [5] that with different object types approaching, an object type classification has to be made prior to the actual distance estimation. In [6] a Bayes risk decision in combination with a maximum likelihood detector was used for object classification and distance estimation. It was shown that distance estimation and even object classification are possible with capacitive sensing under certain circumstances. The presented approach can only be successful if:

- A limited number of different object types are approaching.
- Object types do not change properties. This would lead to different capacitance measurements for one and the same object type (for example small and big objects from the same type would lead to different measurements and wrong classification).
- External environmental influences are limited (for example moisture on the sensor surface would lead to a virtually increased sensor surface as shown in [4]).

When using a capacitance measurement system for a broad field of applications in the open environment, neither can the environment be defined nor can potential approaching objects be assumed. Thus, certain issues have to be taken into account before using capacitive sensing in an uncertain environment. This paper investigates the so called leakage effect which has a big impact on the capacitance measurement results when measuring in the open environment (i.e. no defined environment nor any restriction to approaching objects).

Capacitance measurement principles can be divided in two modes of operation:

- Mutual capacitance mode (i.e. determination of the mutual capacitance between two electrodes).
- Self capacitance mode (i.e. determination of the capacitance between a single electrode and the distant ground).

Both modes have different properties. In [7] and [8] the benefits and drawbacks of each mode are described. When measuring in mutual capacitance mode, the leakage displacement current $i_d$ can be defined as the current originating from the transmitter electrode but not entering the receiver electrode. Instead, it returns through other grounded surfaces or the distance ground. The sketch in Figure 1 illustrates this effect.

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As can be seen, the leakage current effect develops due to the 3D arrangement of objects. The shielding effect presented in [9] can be seen as a part of this leakage in 2D. However, leakage (as defined in this paper) includes displacement currents originating from the transmitter electrodes and entering the distant 3D ground (also without any object in the vicinity of the sensor surface). As can be seen from Figure 1, the displacement current \( i_L \) entering the distant ground through the object cannot be simulated in a 2D simulation. One can imagine that also an accurate simulation in 3D for an undefined environment will be difficult as the displacement current will change with a changing environment. Figure 2 shows a sketch of a sensor front end with two electrodes. Several parasitic effects can be observed. The leakage effect is modeled by the object’s connection to ground through the parallel equivalent circuitry consisting of RGND, LGND and CGND.

II. INFLUENCES ON THE MEASUREMENTS

It was stated above that the leakage effect has an impact on the capacitance measurement results. A transmitted displacement current, which does not enter the receiving electrode but the distant ground, results in a lower measurement signal. This was already presented to scientific community for example in [1], [4], or [9] and literature referenced in there. An example with raw measurement data obtained with two commercial measurement systems is shown in Figure 3. The arrow in Figure 3(a) indicates minimum distance between the approaching object and the sensor surface.

As can be seen from Figure 3 the leakage effect does have a big impact on capacitance measurements. Therefore, when not considered by signal processing algorithms, the leakage effect can lead to wrong results. In [6] for example it was tried to reconstruct the region of interest of a two finger robotic hand by means of capacitance measurements. State of the art algorithms typically applied in ECT applications [10] were used to reconstruct the spatial relative permittivity distribution. Figure 4 shows a reconstruction result for a measurement with two objects (a PVC rod and an iron rod) in the measurement volume \( \Omega \). The PVC rod can be reconstructed, as the coupling effect outweighs the comparatively small leakage effect. In contrast, for the iron rod the leakage effect is prevailing. Since this effect is typically not considered in classical ECT algorithms, the position of the iron rod cannot be reconstructed.
III. COUNTERMEASURES

The two approaches leading to the necessary measurements for a reconstruction of the leakage current are described below. In the first approach it is tried to reconstruct the leakage effect by suppressing it. The second approach tries to directly measure the leakage current.

A. Suppression of the Leakage Effect

The suppression and admission of leakage displacement currents is supposed to be one way to get a leakage tomographic picture. Several methods were used, which are also depicted in Figure 5:

- Switches.
- Current compensated coils (wide frequency range).
- Band-stop filter (frequency selective).

In order to suppress leakage currents, any shunting path between the transmitting electrode and the circuitry ground has to be eliminated. Typically this is hard to achieve in an actual applications, where ground planes for shielding are used (e.g. the sensor front end has to be sensitive in only one direction or has to be shielded from disturbers at the back). Thus, most setups are built up similarly to the one shown in Figure 5 where the leakage current \( i_{L1} \) enters the circuitry ground as shown in Figure 5.

In general they consist of:

- Measurement electrodes (at the top).
- Some kind of spacer to separate top and bottom plane (in the middle).
- Backside shield, which is connected to circuitry ground in mutual capacitance mode (at the bottom).

Usually the grounded shield completely covers the backside of the sensor surface. Thus, it provides an additional return path for the leakage current, which should be suppressed (as shown in Figure 5).

A realization of the proposed concept is shown in Figure 6. The setup uses the approach (a) in Figure 5 (i.e., switches are used to separate the circuitry ground from the distance ground). If the device is in “leakage suppression mode”, data transfer is done over a RF link and power is supplied by batteries.

If the switch is closed and measurement is done including leakage currents, the data and power are transferred over an USB connection.

Different objects are used to validate this leakage suppression approach:

- Human hand.
- Iron rod (connected and not connected to world ground).
- PVC bar

As can be seen in the measurement results in Figure 7, a much higher signal variation in the coupling mode can be observed for the approaching human hand if leakage suppression is used. However, the leakage effect is still present for larger distances. Leakage current \( i_L \) flows from the transmitting electrode to the backside shield and back to the circuitry ground as shown in Figure 5. A reduced difference in the measurement results is observed if the approaching object is smaller and thus, the capacitance to world ground is smaller (i.e. leading to less leakage effect) compared, to a human hand.
Figure 7. Experimental measurement results for leakage suppression. Three objects (a) to (c) (human hand, iron rod and PVC bar) are used to evaluate the leakage suppression of the measurement setup shown in Figure 6. (d) A human hand provokes the highest capacitance change since it is the biggest object with the highest permittivity. Part of the leakage current can be suppressed resulting in a lower decrease and higher increase of the measured capacitance. (e) and (f): An approaching iron rod not connected and connected to the distant ground, respectively, is shown. Leakage current is still present. However, small effects of the leakage suppression can be observed. (g) The PVC bar does have a minor connection to the distant ground (minor leakage current flows) and thus, the measurements obtained are similar.

Figure 7 (e) and (f) show the results of using an approaching iron rod (not connected and connected to the distance ground, respectively). In both cases, the leakage effect is still present (decreasing capacitance in the beginning of the approach). With the third approaching object (a PVC bar) no leakage effect can be measured with the setup. The capacitance to the distant ground is very small for the comparatively small object size and its low relative permittivity (εr ≈ 3). Thus, similar measurements are obtained with and without leakage suppression.

B. Measuring simultaneously in mutual- and self capacitance mode

The second approach aims to reconstruct the leakage effect by additionally measuring the transmitting discharge current (called self capacitance mode). If a capacitance measurement system is able to work in both modes simultaneously, all displacement currents (i_D and i_L in Figure 1) are measured. In contrast to the first approach, the leakage current i_L is not suppressed when measuring in the mutual capacitance mode. The coupling current i_D cannot be measured on its own. Thus, the leakage current still affects the measurements and the reconstruction results.

Figure 8 shows a sketch of a system using mutual- and self capacitance modes. The shield on the backside of the electrodes has to be able to work in two modes. If the mutual capacitance mode is used (compare Figure 8 (b)), the shield has to be set to ground.

When measuring in the self capacitance mode, the shield has to act as an active guard (set to the excitation signal as shown in Figure 8(a)). The reason for switching the potential on the backside shield, is to minimize the offset capacitance C_{Off} between the transmitter electrode and the backside shield (in the self capacitance mode) or the receiving electrode and the backside shield (in the mutual capacitance mode). C_{Off} is indicated with dashed lines in Figure 8. If the backside shield is not used as active guard in the self capacitance mode (for example, is set to ground potential) or used as active guard in the mutual capacitance mode, C_{Off} would be very high (several magnitudes higher than the capacitances of interest). Thus, a reliable measurement would be difficult. As the switching of the backside shield is essential, simultaneous measurements in both modes are not possible. Thus, the measurement hardware used in this work attempts to switch between both measurement modes fast enough so that only minor changes to the measurands and the environment can occur.

IV. CONCLUSION

This work presents investigations on the leakage effect in capacitive sensing. It is shown, that this effect can have a significant impact on the measurement results and the signal processing afterwards, in particular when capacitive sensing is used in open environments. Two hardware approaches to deal with the leakage effect are. While the first approach aims to suppress (i.e. leakage suppression), the second approach (i.e. simultaneous measurement in self capacitance mode and mutual capacitance mode) may provide additional information and was successfully applied in an example.
REFERENCES


