



SIMULATION OF 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. In this paper we demonstrate that the leakage mode concept allows for simulation of 3D problems in 2D. This is useful in applications such as Electrical Capacitance Tomography or object classification as it allows simplifying the computational complexity while providing additional information compared to the classical 2D approach.

Index terms: leakage effect; capacitive sensing; open environment; ECT; reconstruction

I. INTRODUCTION

For many years, capacitive sensing has been used in a broad field of applications. Most applications using capacitive sensing can be classified in one of the following two categories:

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

An example for the first case is electrical capacitance tomography (ECT) in process industry. Because of the enclosing 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) (refer to Figure 1). Additionally, other simplifications can be made. For example, the materials that may appear are usually well known, the interaction between the electric and the magnetic field can be neglected, no free charges inside the pipe are relevant (due to AC excitation), 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].

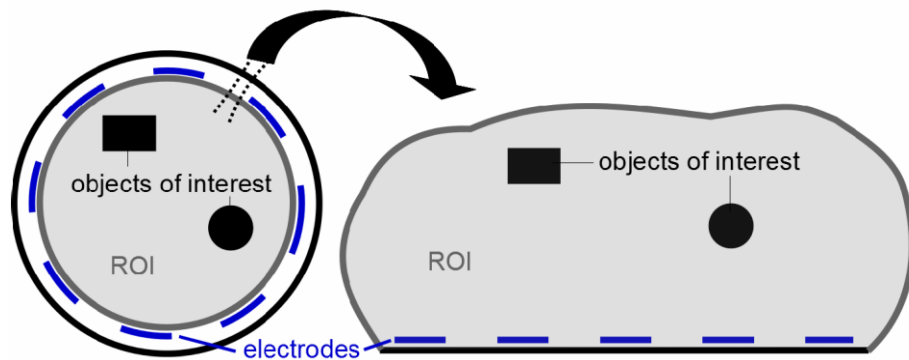


Figure 1: Two examples of capacitive sensing applications [11]. ECT (left geometry) aims at reconstructing the spatial permittivity distribution within the interior of a pipe by solving an inverse problem based on the inter electrode capacitances. By opening the enclosed structure, the ECT approach is extended to an open environment reconstruction problem (right side).

An example for the second type is proximity estimation in various fields of applications. Experimental investigations have proven that if the nature of the approaching object is known it is possible to estimate the distance of the approaching object with respect to the sensor surface [4]. In [4] and [5] it is demonstrated that 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 is used for object classification and distance estimation. It is shown that

distance estimation and even object classification are possible with capacitive sensing under certain circumstances. The presented approach can only be successful if:

1. A limited number of different objects is allowed.
2. Object properties do not change significantly.
3. External environmental influences and changes are limited (for example moisture on the sensor surface can lead to a virtual increase of the 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 potentially approaching objects be restricted to certain types of objects. Thus, certain issues have to be taken into account before using capacitive sensing in an uncertain environment. This paper investigates what we call the leakage effect, which has a huge impact on the capacitance measurement results when measuring in the open environment (i.e. no defined environment nor any restrictions to approaching objects).

The paper is structured as follows. Section II describes the origins of the leakage effect in capacitive sensors and demonstrates its impact on measurement and reconstruction results. Section III proposes an efficient modeling approach for simulation. Section IV discusses measurement concepts and circuitry implementations to determine the leakage current for different modes of operation of a capacitive sensor and the findings are summarized in Section V.

II. THE LEAKAGE CURRENT EFFECT IN CAPACITIVE SENSING

Capacitance measurement principles can be categorized into two modes of operation:

1. Mutual capacitance mode (i.e. determination of the mutual capacitance between two electrodes).
2. 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_L 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 2 illustrates this effect.

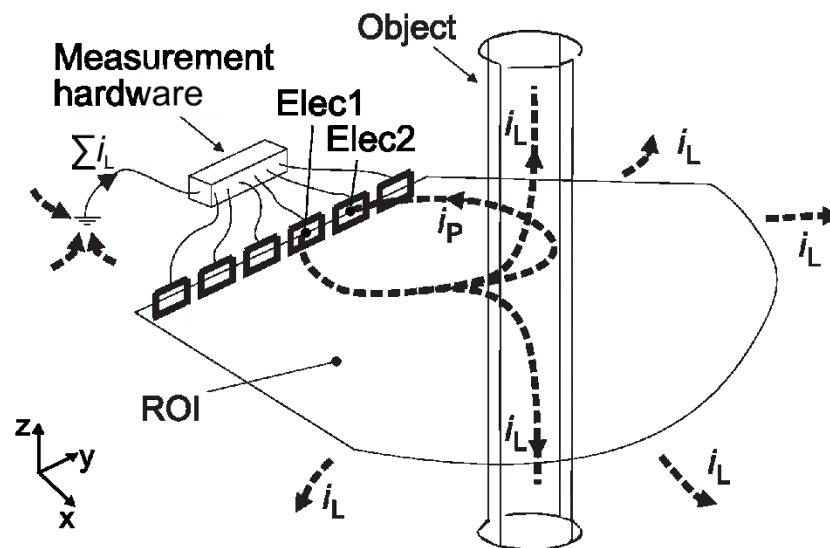


Figure 2: A pictorial description of the leakage effect adopted from [9]. In contrast to the coupling displacement current i_p the leakage displacement current i_L does not return to the receiving electrode (Elec2) but returns through other grounded surfaces. The leakage current has a higher influence than the coupling current on certain objects and situations. Thus, it is reasonable to exploit leakage current information for object localization and classification

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 2, 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 3 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 R_{GND} , L_{GND} and C_{GND} .

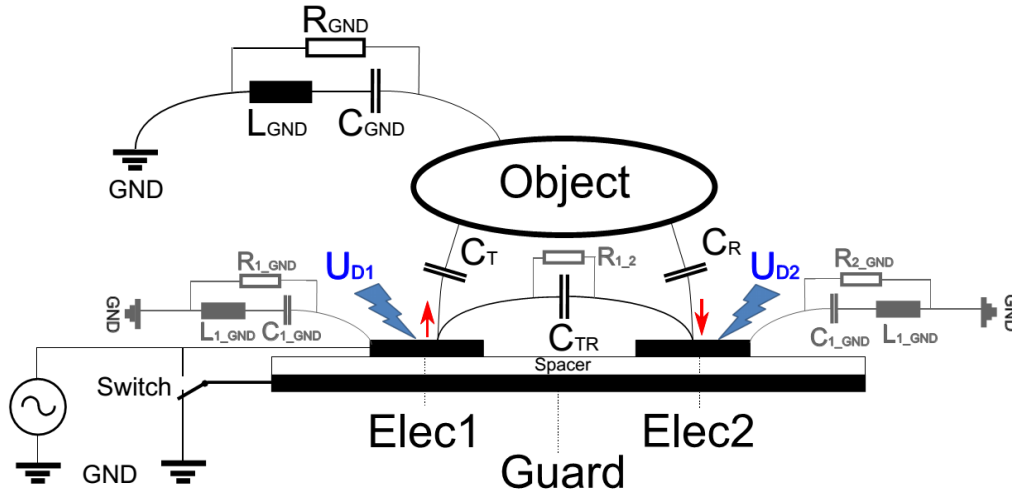


Figure 3: Sketch of a two-electrode capacitance sensor front end including several parasitic effects. Red arrows indicate the displacement current originating from electrode 1 (Elec1) and entering electrode 2 (Elec2) [12]. U_{D1} and U_{D2} denote capacitive crosstalk from disturbers in the vicinity to Elec1 and Elec2. The main parasitic effects to ground are presented by the equivalent parallel circuits connected to the electrodes and the object. Depending on the measurement circuitry different measurement modes are available. The guard electrode can be set to ground or the excitation signal (active guarding).

II-A. IMPACT OF THE LEAKAGE CURRENT EFFECT

It was stated above that the leakage effect has an impact on the capacitance measurement results. In differential mode, a transmitted displacement current that does not close the loop through the receiving electrode but through the distant ground, results in a lower measurement signal. This was presented e.g. in [1], [4], or [9] and literature referenced in there. Figure 4 shows an example with raw measurement data obtained with two commercial measurement systems. The arrow in Figure 4(a) indicates the minimum distance between the approaching object and the sensor surface. As can be seen from Figure 4 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] it is aimed to reconstruct the region of interest of a two finger robotic hand by means of capacitance measurements. State of the art algorithms as typically applied in ECT applications [10] are used to reconstruct the spatial relative permittivity distribution. Figure 5 shows a reconstruction result for a measurement with two objects (a PVC rod and an iron rod) present in the measurement volume Ω_{ROI} . 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 classical ECT algorithms typically do not consider this effect even the presence of the iron rod may not be reconstructed correctly.

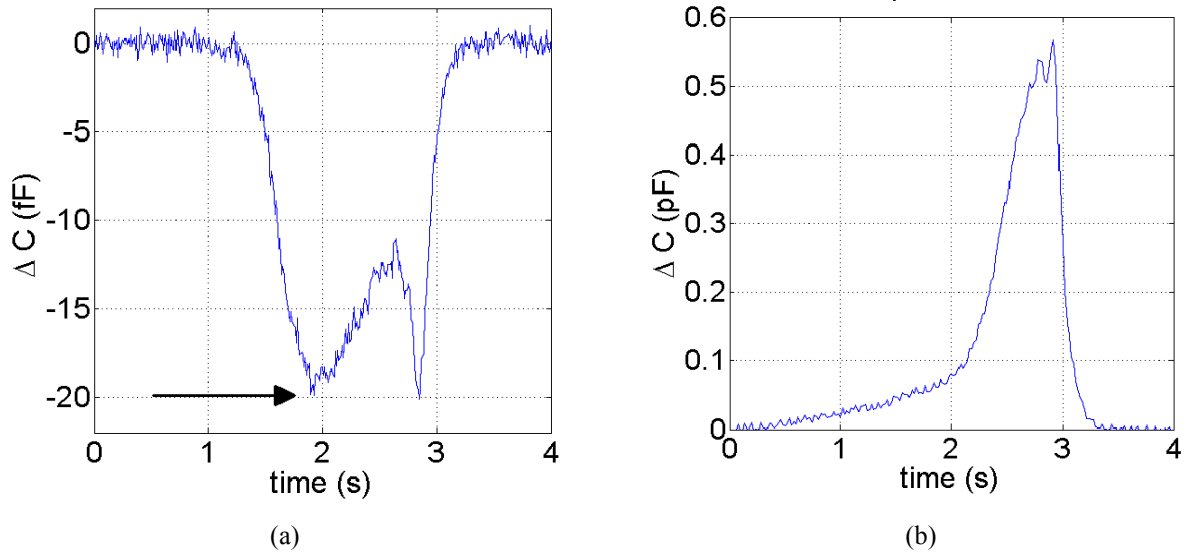


Figure 4: Measurement results of a human hand obtained with two commercial available capacitance measurement systems. A human hand is approaching and leaving the sensor surface. The black arrow indicates the transition from approaching and leaving the sensor surface. (a) Capacitance obtained from the coupling current i_P in mutual capacitance mode. (b) Capacitance obtained from the displacement current i_L (originating a sensing electrode and returning through the distant ground, i.e. self-capacitance mode).

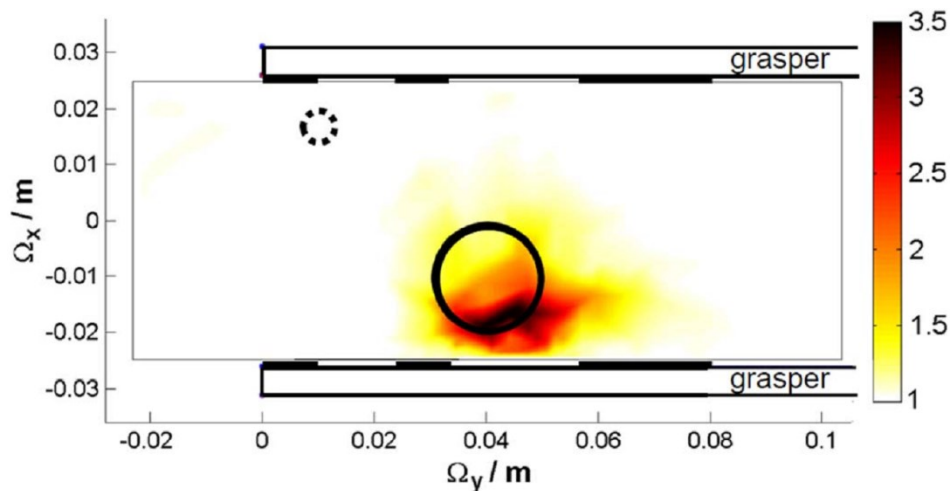


Figure 5: Reconstruction result of a 2D simulation of the inner volume of a two finger robotic hand comprising two different objects from [6]. A PVC rod (black circle) can be reconstructed with a reasonable match. A ferromagnetic rod (smaller dashed black circle) is not reconstructed by the algorithm, mainly due to the leakage effect.

III. AN EFFICIENT METHOD TO SIMULATE THE LEAKAGE EFFECT

We present a method that allows simulating the 3D leakage effect to be simulated within a 2D simulation setup. For example, this is useful for fast ECT reconstruction techniques. The different results for a 3D simulation (i.e. a real world setup) and a simplified 2D simulation is exemplarily shown in Figure 6. It shows the profile of both simulations (i.e. 3D and 2D). A 2D simulation reduces the 3D problem to 2D space by assuming that the 3D geometry does not change in one axis (e.g., no change in z-axis: geometry indefinitely long). A setup as shown in Figure 2 has different lengths in z-direction for objects and electrodes. Since the frequency is low, we can use an electrostatic simulation. Thus, equivalently we replace the leakage current density by a space charge placed into Ω_{ROI} of the electrostatic 2D simulation. A cutout of Figure 6(b) (indicated by the dashed green line) is shown in Figure 6(c). Gauss' law states that the total flow of charge due to the displacement current through a surface is found by integrating \mathbf{D} over that surface:

$$\Psi_{\Omega} = \int_{\Omega} \mathbf{D} d\Omega \quad \text{in } C$$

with Ω as an elementary area, \mathbf{D} the electric displacement field normal to $d\Omega$ and Ψ_{Ω} the enclosed charge [13]. In other words, the total electric flux through any closed surface is proportional to the charge enclosed by this surface. For a slice as shown in Figure 6(c) (cutout of Figure 6(b)), one can imagine the charge per volume as

$$\frac{\int D d\Omega_A + \int D d\Omega_B}{V} = \rho \quad \text{in } C/m^3$$

as the height h is reduced to zero for the 2D. Thus, it is proposed that putting a negative space charge into Ω_{ROI} in the 2D simulation can be used to compensate for the 3D leakage effect (i.e. displacement \mathbf{D} in 3D simulation shown in Figure 6(b)) [14].

To validate this method, a measurement setup is simulated in both 3D and 2D (with and without the “leakage method”) and the results are compared. The test setup comprises two electrodes separated from a ground plane by a spacer with a relative permittivity $\epsilon_r = 2$ (compare Figure 7). In the simulation, an approaching object ($\epsilon_r = 80$) is simulated at different positions above the same sensor surface. To avoid errors in the simulation results stemming from changing meshes, the approaching object is placed at each simulated position and only the relative permittivity value is changed from one simulation to another. Thus, although 13 objects are shown in Figure 7, only one object is assigned a relative permittivity of $\epsilon_r = 80$ at a given simulation step. The

capacitance between the two electrodes is evaluated for different distances between the object and the sensor surface. This is done in a 2D and in a 3D simulation [14].

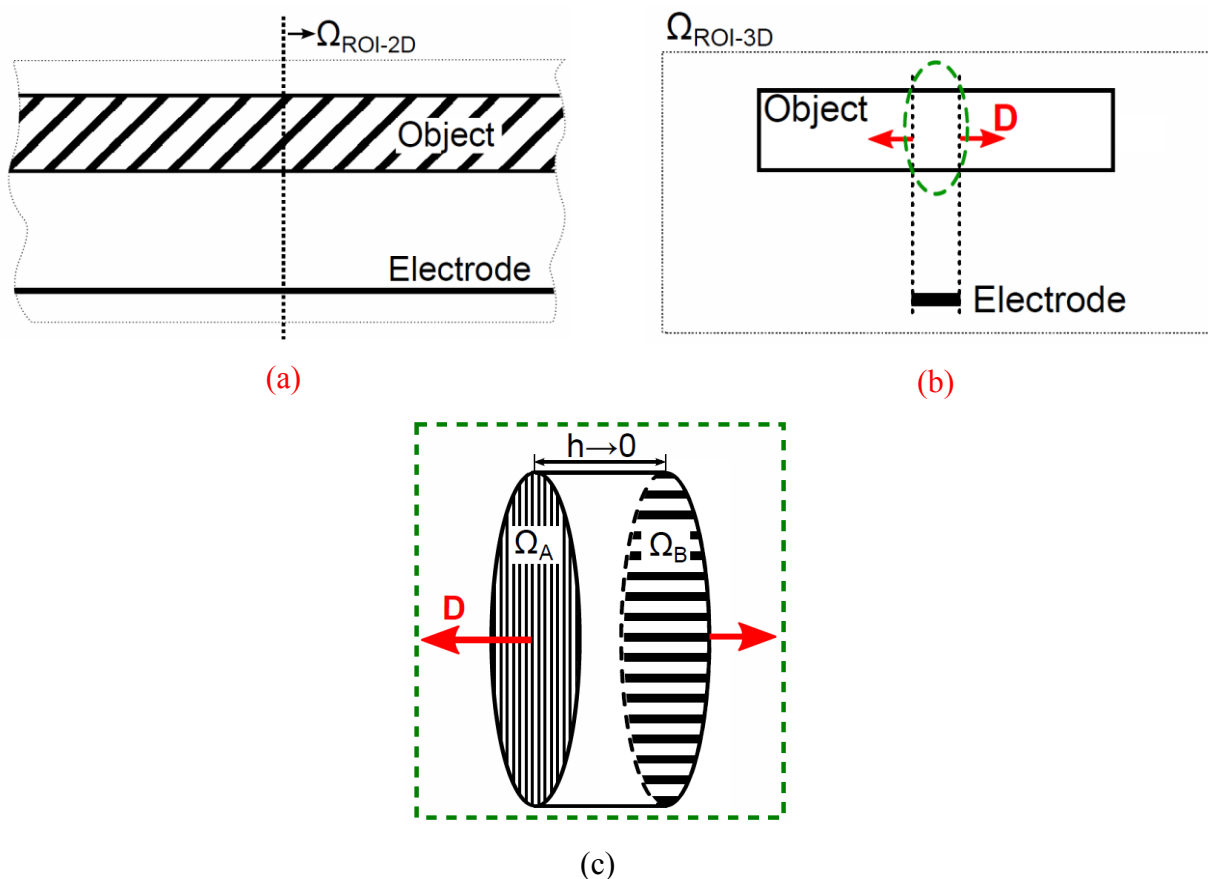


Figure 6: Profiles of a 2D and 3D simulation setup and cutout to explain leakage displacement. (a) Profile of a 2D simulation where an unchanging z-axis is assumed (i.e. indefinitely long electrode and object). (b) Profile of a similar 3D simulation with different length of electrode and object. Due to its different length an electric flux density D exists in 3D which cannot be simulated in the 2D simulation. (c) Cutout of the profile shown in (b) [14].

As can be seen from Figure 8, although the same setup is used, there is a significant difference in the evaluated capacitances, which increases as the objects gets closer to the sensor surface. The simulated capacitance is always higher in 2D compared to the result in 3D. This error in 2D is caused by the objects' "different" connection to ground. If, for example, a negative charge is placed at the approaching object in the 2D simulation, this charge has the same effect as a capacitive ground connection into the third dimension. The negative charge has to increase as the object approaches the sensor surface and the electric potential increases. The effect of such a negative charge placed on the approaching object is shown in Figure 8. The remaining difference

between the trends of the 3D simulation and the proposed simulation method is sufficiently low [14].

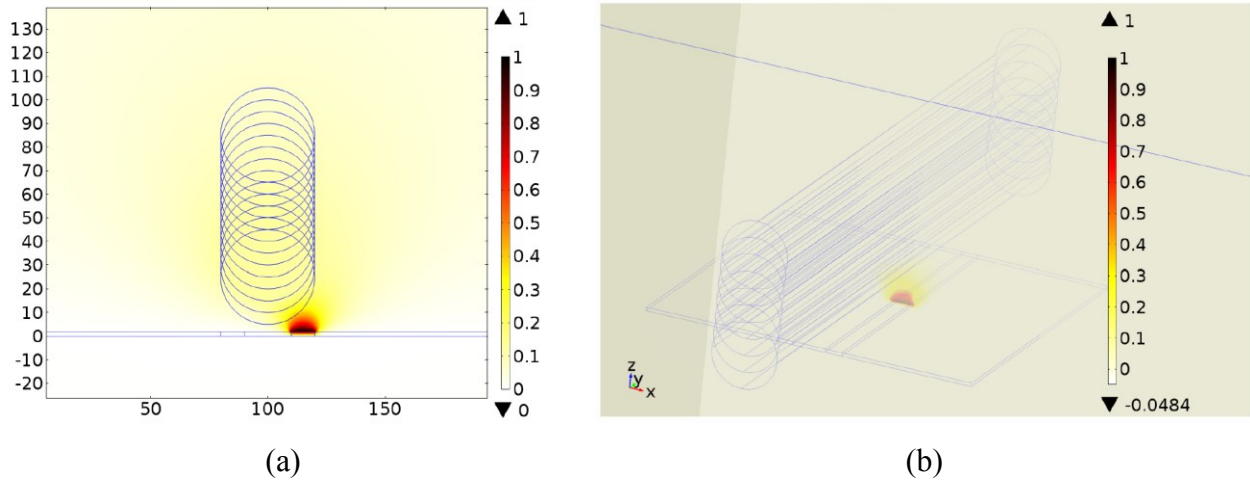


Figure 7: Simulation setup to validate the leakage effect with an approaching object. Both simulations (2D and 3D) use the same scenario and dimensions. (a) The 2D simulation is easier to set up and faster to solve. However, as shown in Figure 8, the results differ from the 3D simulation. (b) A 3D simulation delivers a more accurate result but is also more difficult to set up and requires more time for solving the forward problem [14].

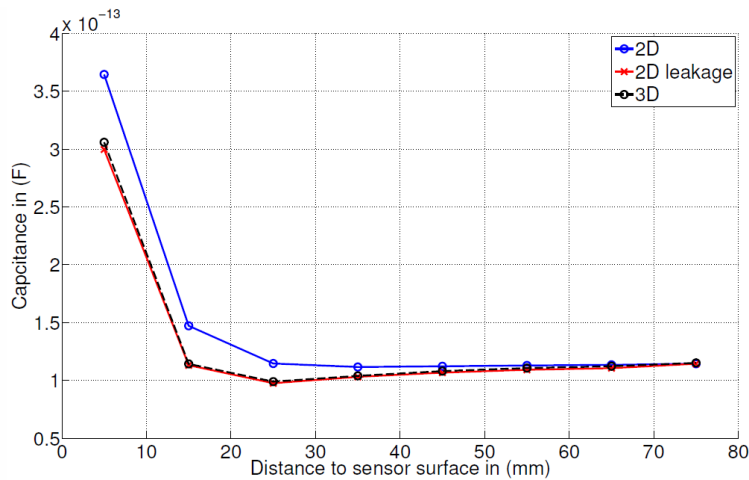


Figure 8: Simulation results presenting the difference between a 2D and a 3D (setups are shown in Figure 7). As can be seen here, the capacitance between the two electrodes for an approaching object differs between the 2D and 3D simulation (traces “2D” and “3D”). Using a changing negative charge (placed at the approaching object) in the 2D simulation, this difference can be eliminated (simulation trace “2D leakage”) [14].

IV. LEAKAGE CURRENT MEASUREMENT

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 determine the leakage effect by suppressing it. The second approach tries to directly measure the leakage current.

IV-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 can be used, which are also depicted in Figure 9:

1. Switches.
2. Current compensated coils (wide frequency range).
3. 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 9 where the leakage current i_L enters the circuitry ground.

In general the sensor front end consists of:

1. Measurement electrodes (at the top).
2. Some kind of spacer to separate top and bottom plane (in the middle).
3. 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 9).

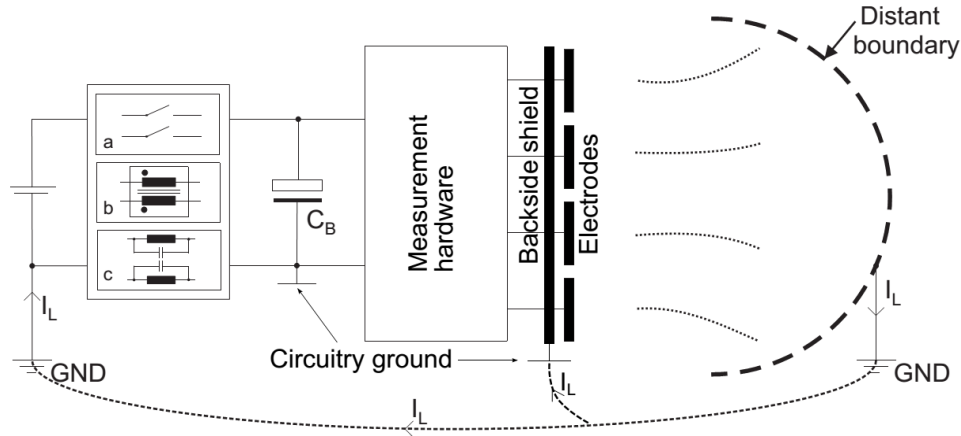


Figure 9: Sketch of possible leakage suppressing methods adopted from [9]. The main goal is to be able to measure with and without leakage currents. This can be achieved in several ways: (a) Switches can be used to separate the circuitry ground from the distance ground. Additional energy buffering (C_B) has to be considered. (b) Current compensated coils can be used to suppress the leakage current for a wide frequency range. Additional switches must be measured with the leakage currents included. (c) A band-stop filter can be used for frequency selective leakage suppression.

A realization of the proposed concept is shown in Figure 10. The setup uses the approach (a) in Figure 9 (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 an RF - link and batteries supply the circuitry with power. If the switch is closed and measurement is done including leakage currents, the data and power are transferred over an USB connection.

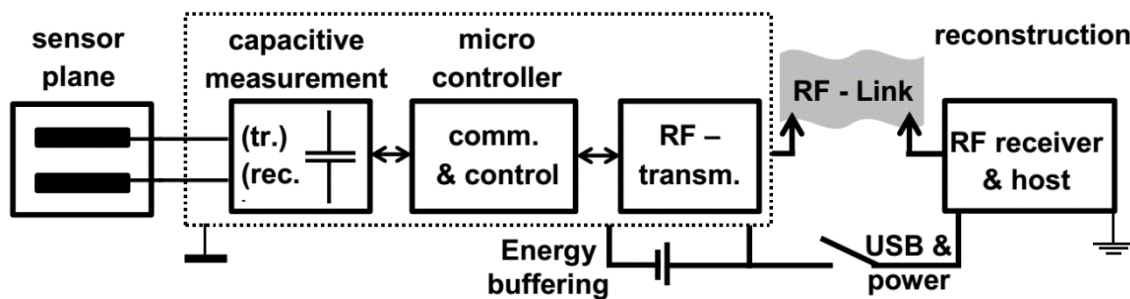


Figure 10: Block diagram of a measurement hardware for leakage suppression [12]. A switch can be used to separate the distant ground from the circuitry ground to suppress leakage currents. If the switch is opened, data transfer is done over a RF link and power is supplied by batteries.

Different objects are used to validate this leakage suppression approach:

1. Human hand.
2. Iron rod (connected and not connected to world ground).
3. PVC bar

As can be seen in the measurement results in Figure 11, 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 9. 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 11 (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 ($\epsilon_r \approx 3$). Thus, similar measurements are obtained with and without leakage suppression.

IV-B. MEASURING SIMULTANEOUSLY IN MUTUAL- AND SELF-CAPACITANCE MODE

The second approach aims to reconstruct the leakage effect by additionally measuring the transmitting displace current (called self-capacitance mode). If a capacitance measurement system is able to work in both modes simultaneously, all displacement currents (i_p and i_L in Figure 2) 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_p cannot be measured on its own. Thus, the leakage current still affects the measurements and the reconstruction results.

Figure 12 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 12 (b)), the shield has to be set to ground.

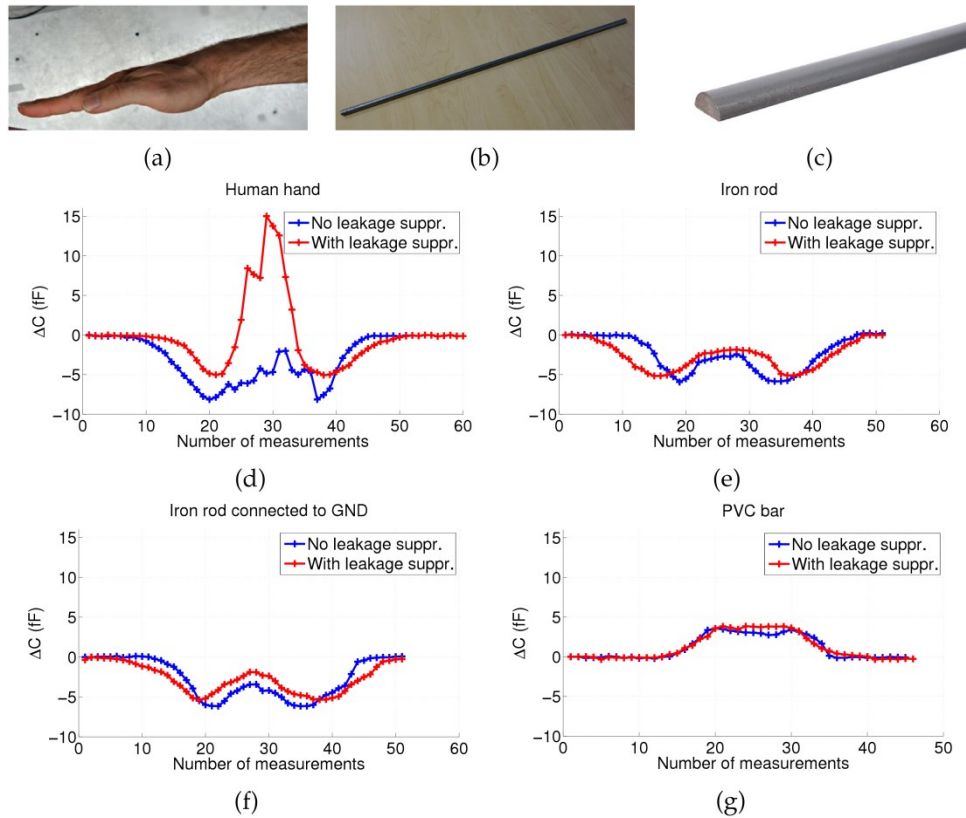


Figure 11: Experimental measurement results for leakage suppression [14]. Three objects (a) to (c) (human hand, iron rod and PVC bar) are used to evaluate the leakage suppression of the measurement setup shown in Figure 6. (d) A human hand provokes the highest capacitance change since it is the biggest 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.

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 12(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 12. If the backside shield is not used as active guard in the self-capacitance mode (for example, it 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.

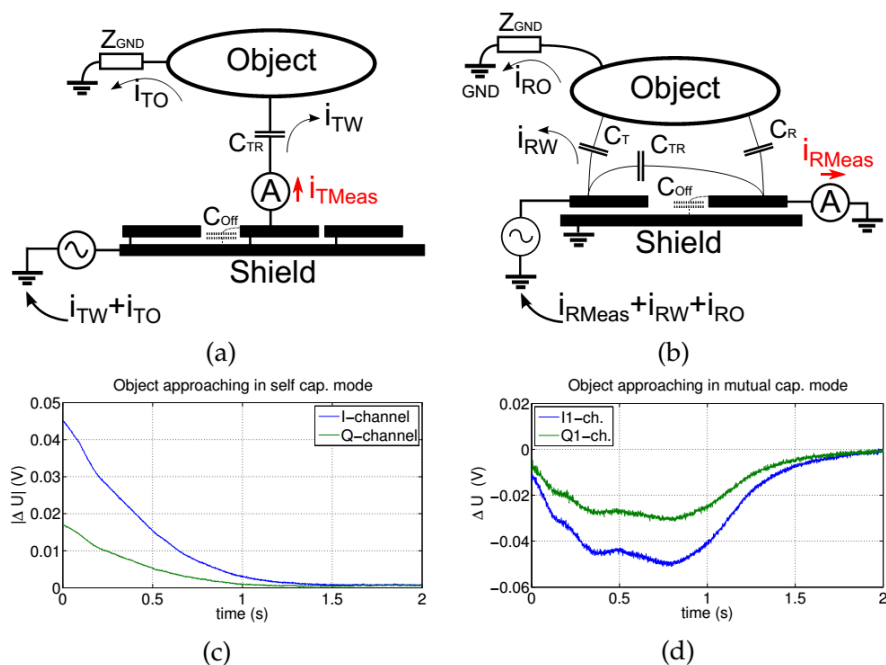


Figure 12: Sketch and measurement results of the self- and mutual capacitance measurement mode to reconstruct the leakage effect [14]. (a) In the self-capacitance mode, the current originating on one electrode is measured. The backside shield has to work as an active guard. Otherwise the main part of i_{TMeas} would flow from the electrode to the shield. (b) In the mutual capacitance mode the received displacement current on one electrode is measured. In this mode, the backside shield has to be set to circuitry ground. Otherwise the main part of i_{RMeas} would come from the shield. (c) Measurements for the self-capacitance mode. For an approaching object with a relative permittivity higher than 1, i_{TMeas} is increasing. (d) Due to parasitic effects an approaching object first decreases the received displacement current in the mutual capacitance mode. At a certain distance the received current increases very quickly.

V. CONCLUSIONS

This work presents investigations on the simulation of 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 discussed and a simulation approach to incorporate the leakage effect in the forward problem is presented.

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