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Simulation and Verification of a Capacitive Proximity Sensor

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Abstract: This paper analysis and verifies capacitive sensing technology for a specific proximity measurement system. Capacitive sensing has proven to be an interesting alternative for proximity measurements compared to state of the art sensors such as optical or tactile sensors. Although these sensor systems are widely used (e.g. clamping protection) they reveal several drawbacks. Most optical sensors need a line of sight whereas tactile sensors cannot be used to determine a distance to an approaching object. Capacitive sensing on the other hand works contactless, with a variety of materials and allows monitoring of complex structures utilizing a volumetric measurement principle. With the help of simulation results an experimental setup is built to demonstrate the measurement principle. In a second step, simulation results are used to verify the obtained measurement results.

Keywords: capacitive measurement, optimization, proximity measurement, clamping protection.

1. Introduction

Identifying humans or other objects in dangerous environments is an important measurement task for many applications. Those applications have to reliably detect the objects of interest in a well-defined region and under different environmental conditions. Often, the region of interest (ROI) also comprises complex structures and offers little space for mounting a sensor device. In such cases capacitive measurement technology can be an interesting alternative to existing systems.

A capacitive sensor basically consists of two conductive elements (called electrodes, compare Figure 1). These electrodes can be made of metal plates, strip lines, simple electric wires, etc. This permits the use of the sensor even on complex structures. Additionally the sensor system works contactless and no line of sight is necessary [1].

If an object approaches the electrodes, the capacitance between the electrodes changes [2]. At least two capacitances have to be obtained for unambiguous proximity determination, due to the occurring coupling and shielding effect for approaching objects [3].

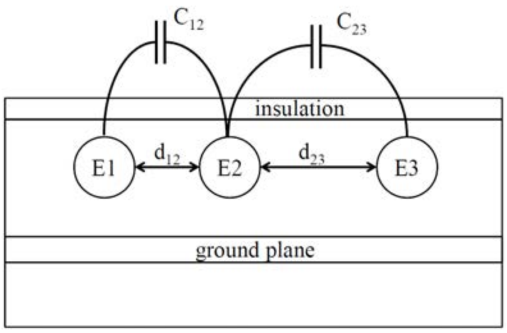

Figure 1. Sketch of the cross-section of the electrode layout with distances d_{12} and d_{23} between the electrodes E1 and E2 and the resulting capacitances C_{12} and C_{23}.

This paper focuses on two simulation problems which are solved with the help of COMSOL Multiphysics. The first problem deals with finding an electrode structure that can be used to determine a human hand in a certain ROI. The results are used to build an experimental measurement setup. The second problem deals with validating the obtained measurement results. A 3D simulation of the experimental setup is presented and the results are compared to the obtained measurements.

2. Use of COMSOL Multiphysics

In this paper COMSOL is used to solve an electro static problem. Hence, solving the Maxwell equations leading to a Laplace's equation of the form:

$$\mathrm{div}\,(-\varepsilon\ \mathrm{grad}(V)) = \rho = 0, \qquad (1)$$

where $\varepsilon = \varepsilon_0.\varepsilon_r$ (ε_0 is the permittivity of air and ε_r is the dimensionless relative permittivity), the charge density ρ (which is set to 0) and the electric scalar potential V. Dirichlet boundary conditions occur at the electrodes and the far boundary.
This so called forward problem is solved with COMSOL, whereas the optimization and post

processing is done with MATLAB®. Therefore the LiveLink™ for MATLAB is used.

3. Measurement Constraints

The final experimental setup should consist of simple electric wires which are positioned on a complex structure. Figure 1 shows a sketch of the cross-section of the layout. The ground plane below the electrodes is used to make the sensor sensitive in only one direction.
Among other things the measurement range and sensitivity of the sensor setup are influenced by the distance between the electrodes and the diameter of the electrodes (thickness of wires). Since the diameter is given by the used electric wires (d=1.4 mm), the distances have to be optimized according to measurement constraints (Table 1) for the given measurement task. The first two constraints in Table 1 derive from the used measurement hardware. Constraints three and four are given by the measurement task.

Table 1: Measurement constraints for the given experimental setup.

constraint	value
capacitive range	< 4 pF
capacitance offset	< 128 pF
distance to measure	1 - 50 mm
size of approaching object	150 x 100 x 10 mm

3. Simulation (2D) of a Capacitive Proximity Sensor

To determine the best distance for the experimental setup a defined approaching object and a certain measurement range a 2D simulation (shown in Figure 2 (a), (b) and (c)) is used.

The approaching object is divided into 65 slices. To avoid remeshing, only the relative permittivity (ε_r) of the slices was changed to simulate an approaching object with high permittivity (e.g. a human hand is simulated with an $\varepsilon_r = 80$). Figure 2 (a) and (b) show the effects of an approaching object, where the most left and second from left electrode are used to build a capacitor. All other electrodes are floating. Figure 2 (c) shows the difference when another pair of electrodes (first and sixth from left) is used.

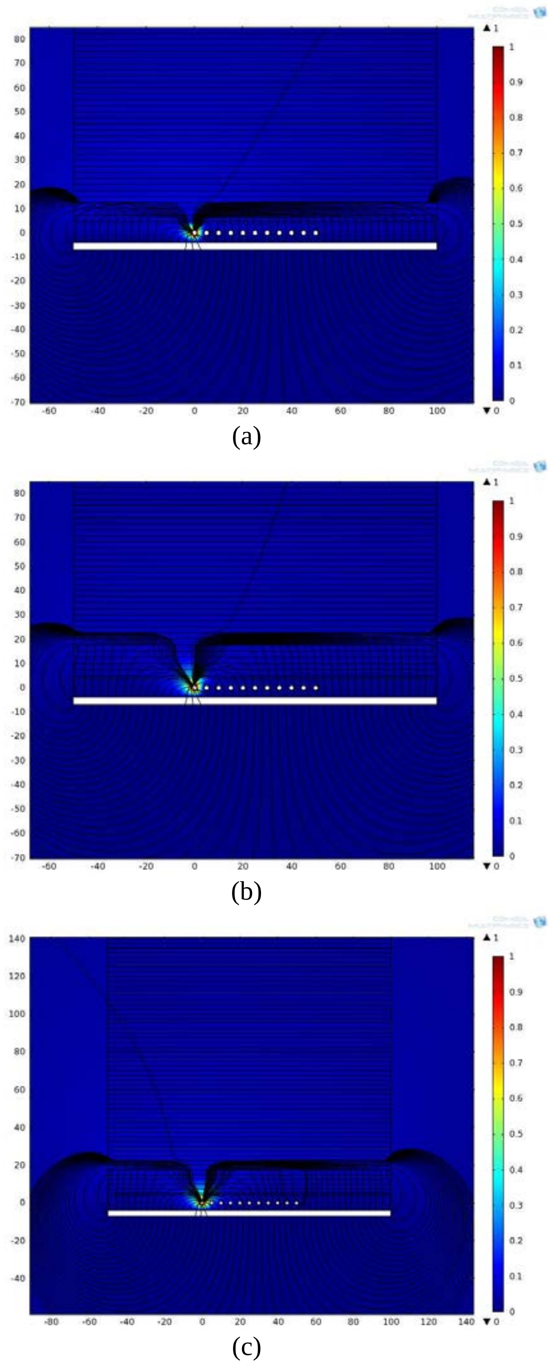

Figure 2. 2D simulation of the experimental setup for parallel electrodes (surface: electric potential, streamline: electric field). (a) + (b) First and second electrode from the left are used for capacitive measurement and two distances for the approaching object are simulated. (c) The most left and most right electrodes are used to simulate a capacitor.

As can be seen from Figure 2 the capacitance change is very small and thus the electrode design is an important part when dealing with capacitive proximity sensors.

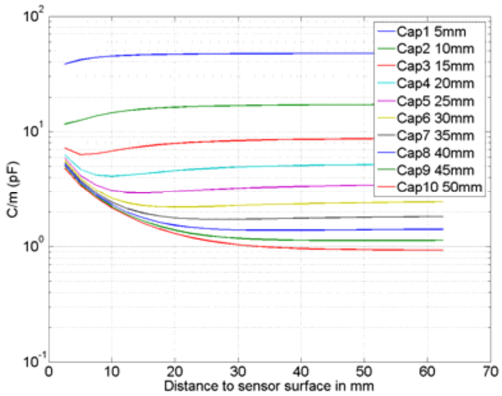

Figure 3. Simulated capacitance values for an approaching object for different pairs of electrodes.

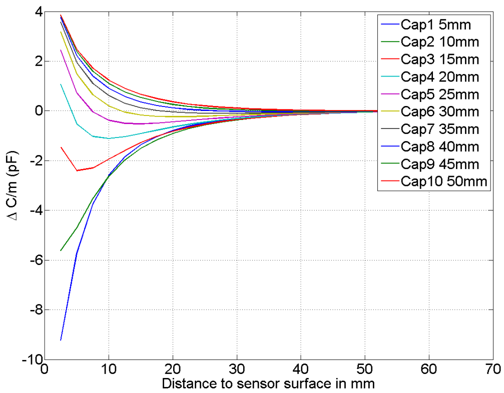

Figure 4. Simulated capacitance changes for an approaching object for different pairs of electrodes.

A simple grid search was used to find the electrode structure which best fits the measurement constraints.

As can be seen from Figure 3 and Figure 4 the measurement hardware cannot be used for the two closest pairs of electrodes since the capacitance changes exceeds the input range (compare with Table 1).

Figure 4 shows the change in capacitance for different distances between the electrodes. As can be seen, at least three electrodes (two capacitance values) are necessary, due to the ambiguous measurement. The capacitance for pairs of electrodes which are farther separated (compare with C_3 to C_6 in Figure 3) first decreases with an approaching object (shielding) and at a certain distance to the approaching object the capacitances increases very fast (coupling). No coupling effect occurs for pairs of electrodes which are very close together (compare with C_1 and C_2 in Figure 3). On the other hand no shielding effect occurs for capacitances which are far away from each other (compare with C_7 and C_{10} in Figure 3).

5. Measurement Results

According to the simulation results and the measurement constraints an experimental setup was built (shown in Figure 4). The setup uses three electrodes to measure two capacitances. The distances between the electrodes are 15 mm and 30 mm. The electrodes are placed under a sheet of black synthetic fiber and two layers of polyethylene of higher density (PE-HD). They are realized by 1 m long and 0.51 mm^2 thick simple electric wires. The frame itself if built up with polystyrene (styrofoam).

In order to determine a capacitance between a pair of electrodes a capacitance to digital converter integrated in the Analog Devices IC AD7746 [4] is used.

The light barrier, which is also installed on the setup, does need a line of sight orientation whereas the electrodes for the capacitive sensor can be flexibly installed. Thus the capacitive sensor is able to cover the whole ROI with no line of sight [5].

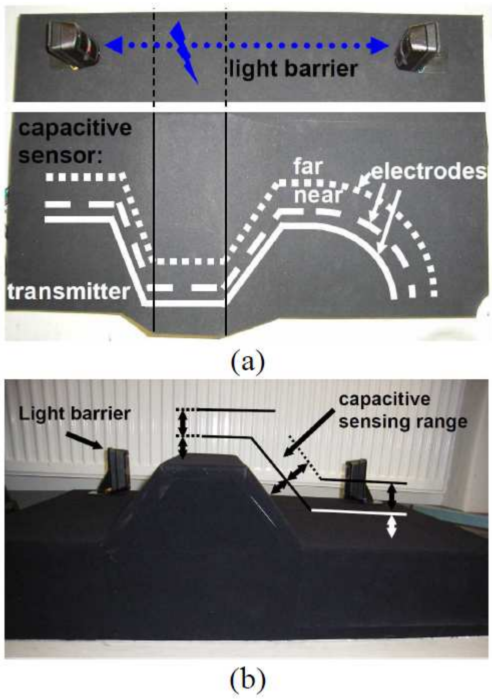

Figure 4. Experimental setup for measurement investigations. (a) Capacitive sensor and a light barrier. (b) Different warning stages can be realized by using more than two electrodes.

Figure 5 shows the measurement results for an approaching human hand. As can be seen, with both measured capacitances, unambiguous proximity estimation can be achieved.

6. Verification (3D) of the Experimental Setup

To validate the measurement results obtained from the experimental setup, a 3D simulation is used. Figure 6 shows the COMSOL model and Figure 7 shows the simulation results.

The 3D model for the simulation only uses a ground plane beneath the electrodes. The spacer (made of styrofoam) was not modeled, as it has no influence on the simulation results ($\varepsilon_r \approx 1$).

Similar to the 2D simulation, the approaching object is divided into 65 cuboids. To avoid remeshing, only the relative permittivity (ε_r) of the cuboids was changed to simulate an approach.

As can be seen in Figure 6 the simulated change in capacitance matches the measurements from the experimental setup. Hence the experimental setup works as assumed and can be used for proximity detection of a human hand.

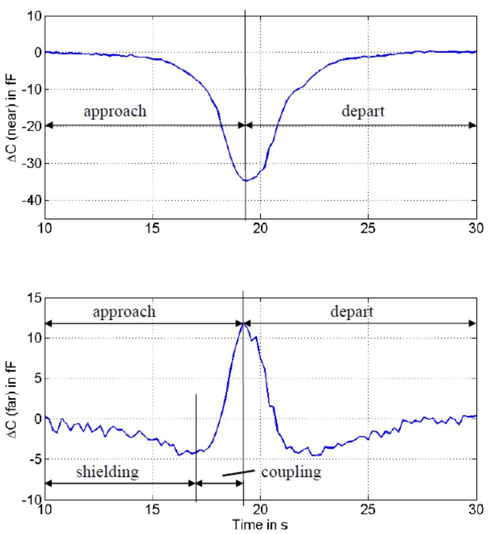

Figure 5. Measurement results for two pairs of electrodes for an approaching and departing human hand.

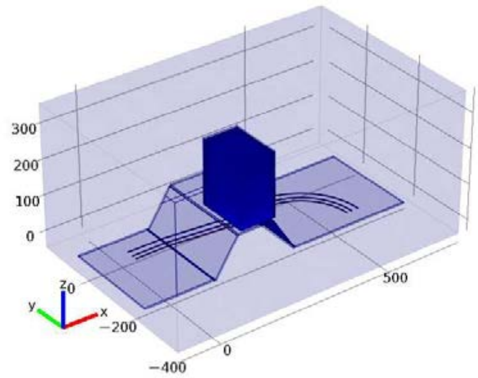

Figure 6. 3D simulation of the experimental setup.

7. Conclusions

With the help of COMSOL a capacitive proximity measurement system was simulated and built. It was shown how to get an optimal electrode structure for a certain measurement task out of simulations. The built measurement system can be used on curved and non-planar surfaces for proximity detection of objects with high relative permittivity. Furthermore, 3D simulations with COMSOL validate the obtained measurement results.

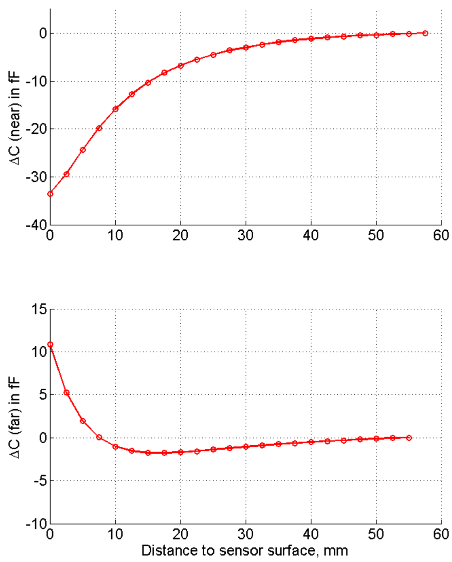

Figure 7. Simulation results for 3D simulation of the experimental setup.

8. References

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9. Acknowledgements

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