## Curvature Effects on Elongated Capacitive Proximity Sensors

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***Abstract* – This paper analyses impacts on capacitive proximity sensors due to bended and elongated electrodes. Capacitive sensors are well suited for distance measurements and can be installed on planar and non-planar surfaces. Although distance measurement is possible with a variety of electrode structures, the sensitivity of the sensor changes with different structures. Impacts are analysed and demonstrated by means of experimental investigations and numerical simulations.**

### 1. INTRODUCTION

Identifying the presence of a human in dangerous environments is an important measurement task for many applications. Employed sensor systems have to reliably detect the human proximity within a well defined region under various environmental conditions. This sensor information is typically processed by a master unit, which may trigger safety mechanisms in order to prevent damage to a human. Typical application scenarios comprise seat occupancy detection for safe airbag deployment, clamping protection for automatic doors, automatic power tools etc. Capacitive sensing technology has proven to be an interesting alternative for proximity sensing compared to state of the art systems based on optical methods (e.g. light barriers) or contact based methods (e.g. tactile sensors) [1]. Capacitive sensors work with a variety of materials and offer the advantages of a volumetric measurement principle. The sensor elements (i.e. the electrodes) are unparalleled simple while providing high versatility with respect to geometrical constraints. Hence, this technology also allows monitoring complex structures or machines, where traditional systems e.g. based on a line of sight principle fail. However, the individual shapes of the sensor electrodes dictate the coupling mechanisms between the electrodes to objects in the environment. These coupling mechanisms have been recently studied in [2] for planar sensor geometries. However, investigations towards complex electrode structures comprising non-planar electrode arrangements (i.e. the electrode planes are arbitrarily oriented) have not been reported. In this paper, we provide a detailed analysis of the 3D sensitivity distribution of an example sensor setup by means of numerical analysis and comparative studies with equivalent circuit models.

### 2. EXPERIMENTAL SETUP

Fig. 1 and Fig. 2 show the developed test setup. It uses three electrodes (one transmitter electrode and two receiver electrodes) to determine the distance to an approaching object. The sketch in Fig. 1 shows the different layers of the test setup. The electrodes are positioned under a sheet of black synthetic fibre 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, which permits the realization of a very flexible electrode structure. To make the sensor sensitive in only one direction (above the electrodes) a ground plane made of an aluminium foil is used (refer to [5]). The frame itself is built up with polystyrene (styrofoam). To determine the capacitance between a pair of electrodes, a capacitance to digital converter integrated in the Analog Devices IC AD7746 [6] is used. A wireless transmitter connects to a host controller for evaluating the measurement results and permitting a portable and flexible experimental setup.

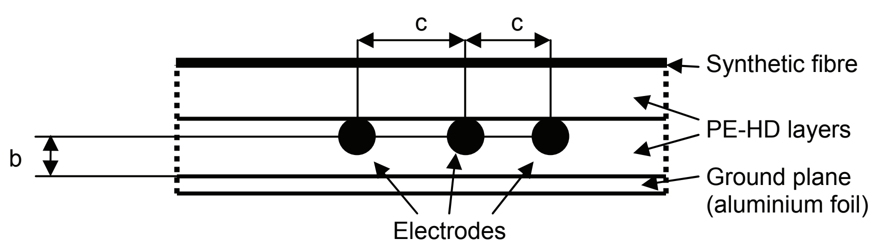
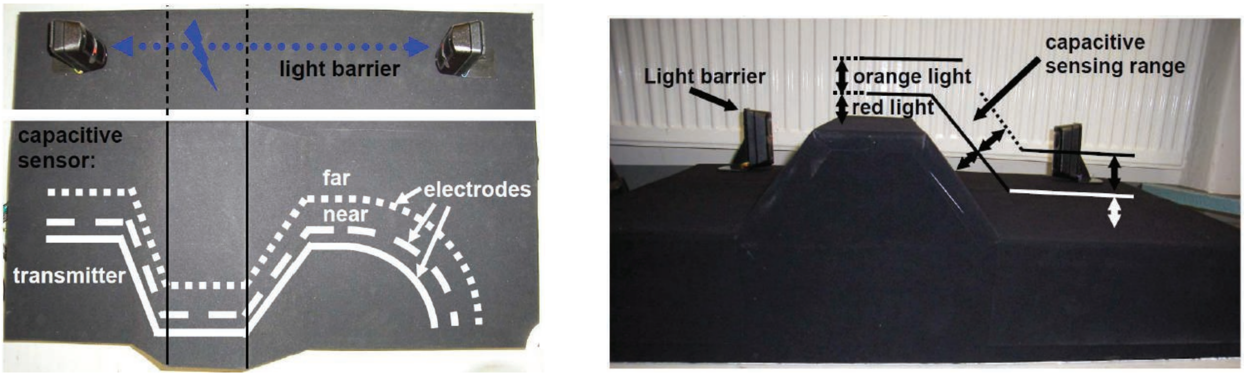



Fig. 1: Cross section of the experimental setup with the different layers (drawn not in scale).




(a) (b)

Fig. 2: Experimental setup for measurement investigations. (a) Capacitive sensor and a light barrier. The light barrier does need a line of sight orientation whereas the electrodes for the capacitive sensor can be flexibly installed. (b) Different warning stages can be realized using more than two electrodes (compare Fig. 3a).

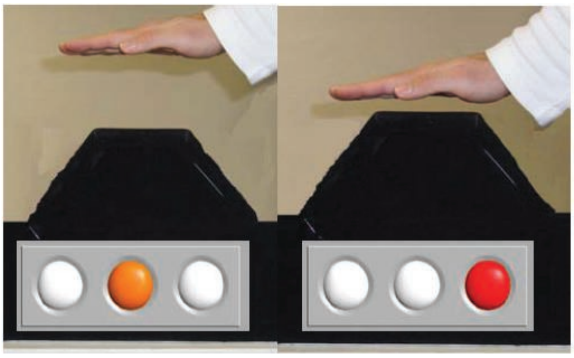
## 3. DISTANCE MEASUREMENT BASED ON CAPACITIVE SENSING

Common techniques for capacitive proximity measurements evaluate the capacitance between one electrode and ground (single ended input) or between two electrodes (differential input - used in this work) in different ways [3]. For unambiguous distance measurement results, at least three electrodes (e.g. one transmitter and two receivers) are necessary [4]. The capacitance between a pair of electrodes with length L and a ground plane in the vicinity can be approximated by [1]:

$$C \cong \frac{\pi \varepsilon_0 \varepsilon_r L \ln(1+\frac{2b}{c})}{(\ln(\frac{2b}{a}))^2} \tag{1}$$

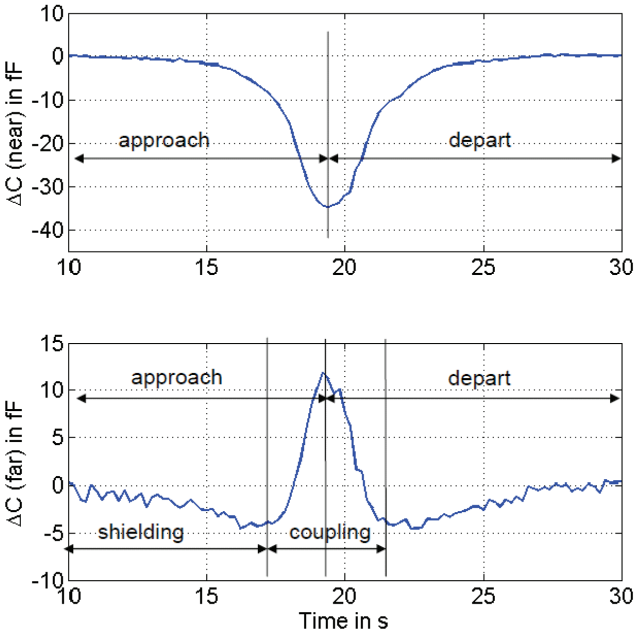
For a parallel electrode structure with the length of 1 m and a relative permeability $\varepsilon_r$ of 1, capacitances of 1276 fF and 361 fF for the near and the far electrode, respectively, can be calculated.

If an object comes in the vicinity of the sensor, the capacitance between the receiver and the transmitter electrodes changes (see Fig. 1b). Due to these changes, it is possible to determine the distance to an approaching object. This has been recently studied in [2] and [3] for planar and parallel electrode structures. However, if bending electrodes structures are used, unambiguous distance measurement is not guaranteed. The following measurements and numerical simulations are used to identify the possibilities and challenges for proximity sensing with these bended electrode structures.
As can be seen in Fig. 2a, the capacitive sensor covers an area with no line of sight and different changes in direction between the start point and the end point. Fig. 2b shows the measurement results for an approaching human hand in an area with a parallel electrode structure. This can easily be used for e.g. a human detection sensor as indicated in Fig. 3.



(a)

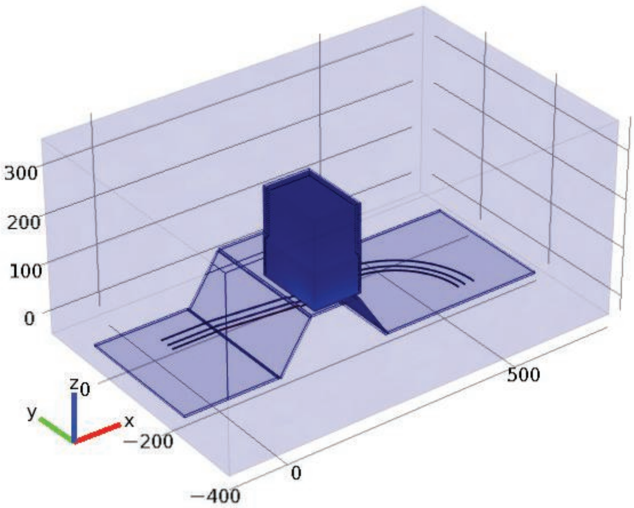
Fig. 3: Measurement results with the experimental setup. (a) Real time signalling (green, orange or red) of the proximity of a human hand. Two distances of a human hand above the capacitive sensor. The signalling indicates the distance to the hand.
(b) Measured capacitances for the nearer (above) and farer (below) receiver electrode.



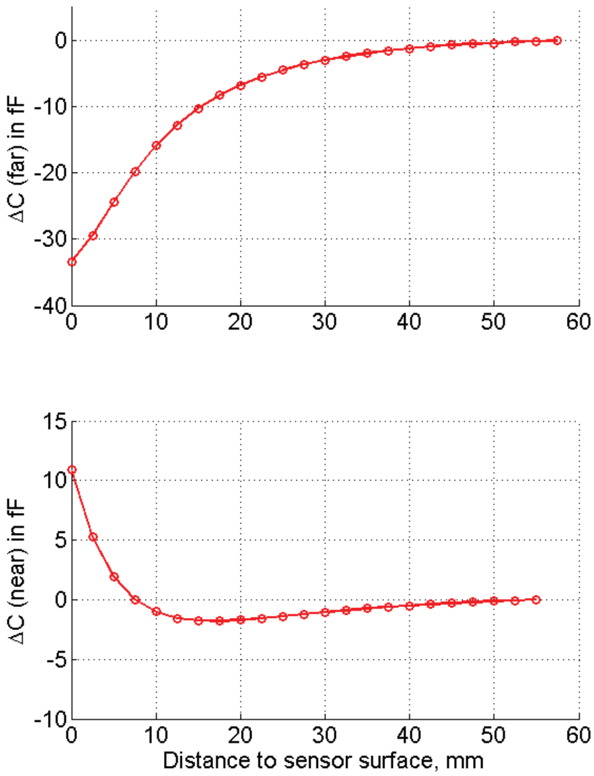

(b)

## 4. SENSITIVITY ANALYSIS OF THE ELECTRODE STRUCTURE

The investigation of impacts on the sensivity due to bending electrode structures are based on finite element simulations. Different sceneraios for an approaching object are chosen and compared with the ideal situation (parallel electrode structure, see Fig. 1 and 2). The simulation setup is shown Fig. 4a, corresponding results are shown in Fig. 4b.




(a)




(b)

Fig. 4: Simulation of an approaching object. (a) Plot of the simulated setup with colored electric potential.
(b) Simulation results for an approaching object.

The object was simulated as a whole block, with slices of different relative permittivity $\varepsilon_r$ to simulate an approach. Fig. 4a shows two receiving electrodes (connected to ground) and one transmitter electrode (connected to a voltage of $V_0$=1 V) mounted on the experimental setup structure. As can be seen, the simulation results match with the measurement results. Small differences originate from differences between the experimental setup and the simulated geometry (e.g. laying of electrodes).

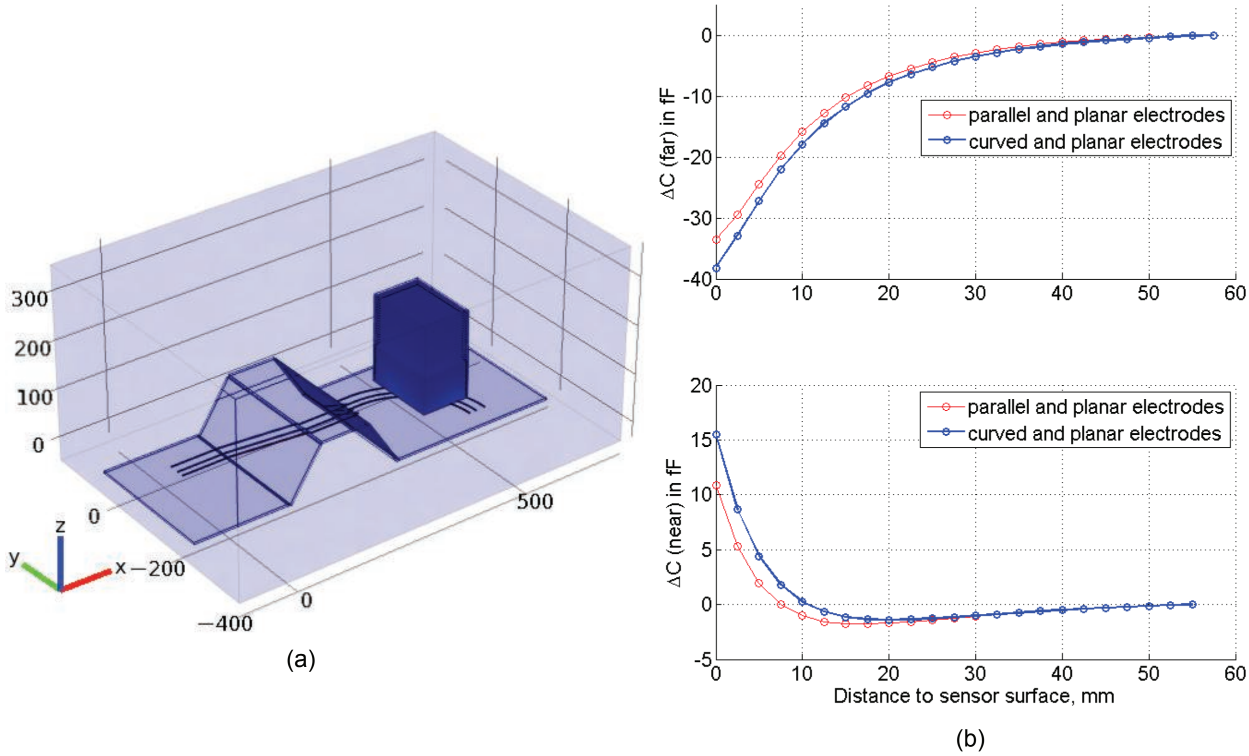



Fig. 5: Simulation of an object approaching over a curved electrode arragnment. (a) Plot of the simulated setup. (b) Simulation results for the approaching object compared with the ideal solution (compare Fig. 4).

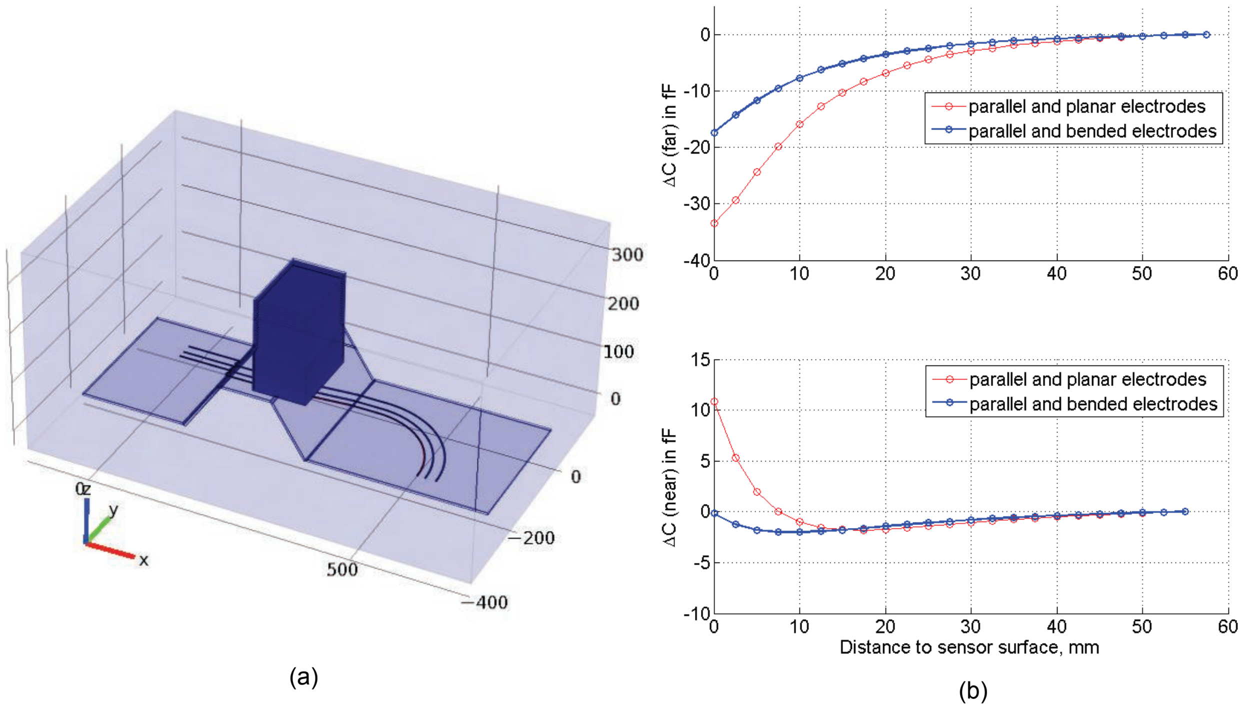



Fig. 6: Simulation of an object approaching over a bended electrode arrangement. (a) Plot of the simulated setup. (b) Simulation results for the approaching object compared with the ideal solution (compare Fig. 4).

## 5. RESULTS

Fig. 3b shows the measurement results (with occurring coupling and shielding effect [5]) for an approaching and departing object. As shown in Fig. 3a, signal lights indicate an approaching object farther away (orange) and very close (red). However, in curved areas the sensitivity of the sensor deviates from the sensitivity obtained by a planar sensor arrangement. As can be seen Fig. 5 the sensitivity increases for objects approaching above curved electrode structures (maximum difference of 14% and 42.7% for the near and the far electrode, respectively). Especially for short distances this effect would lead to a wrong distance measurement for the whole sensor arrangement. Due to the increased covered electrode area, a higher capacitance is measured. Thus, the approaching object appears closer. than it really is. If only the curved electrode structure is exposed to an approaching object, distance measurement is still possible because of the unambiguousness with the near and the far electrode.
In Fig. 6 a bended electrode structure leads to a smaller capacitance measurement (maximum difference of 48.1% and 98.4% for the near and the far electrode, respectively). If an object enters the vicinity of such a structure, the measured capacitance is smaller compared to the ideal case. Thus, a measurement system would provide a distance which is farther away than the object.
To overcome these difficulties of elongated and non-planar capacitive sensors, the sensitivity of the sensor has to be increased or decreased in these special areas. Possibilities would be a decrease or increase of:

- the distance between the sensor electrodes.
- the relative permittivity $\varepsilon_r$ (e.g. another spacer material).
- the electrode surface.

in the desired areas.

## 6. CONCLUSION

A capacitive sensor system with elongated and curved electrodes is presented. Experimental investigations and numerical simulations demonstrate the benefits of this approach. It permits detection of approaching objects on curved and non-planar surfaces. Furthermore, investigations on the sensitivity changes due to bended electrode structures are given and challenges with this approach are presented.

## REFERENCES


[1] L. Baxter, *Capacitive Sensors, Design and Applications*. IEEE Press, 1997.

[2] M. Neumayer, B. George, T. Bretterklieber, H. Zangl, and G. Brasseur, “Robust sensing of human proximity for safety applications,” in *Instrumentation and Measurement Technology Conference (I2MTC)*, vol. 1. IEEE, May 2010, pp. 458 – 463.

[3] W. Buller and B. Wilson, “Measurement and modeling mutual capacitance of electrical wiring and humans,” *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 5, pp. 1519–1522, Oct. 2006.

[4] Schlegl T., Bretterklieber T., Neumayer M., and Zangl H., *“A Novel Sensor Fusion Concept for Distance Measurement in Automotive Applications"*, In IEEE Sensors, Nov. 1-4, pp. 775-778, 2010.

[5] H. Zangl, “Design paradigms for robust capacitive sensors,” Ph.D. dissertation, Graz University of *Technology, Graz, Austria, May 2005.*

[6] A. Devices, “Ad7746,” Analog Devices, Datasheet, May 2010.