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Topic: Design and Modeling of Sensors and Actuators

Light Weight Signal Processing for a Wireless Capacitive Sensing Platform for Mobile Applications

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Summary

In this paper we present a light weight signal processing for Electrical Capacitance Tomography (ECT) allowing for an implementation on a low power wireless capacitive sensing platform. The sensing platform is capable of both single-ended and differential measurement mode. The sensor front-end design is flexible and can be easily optimized according to the requirements of the application with little effort.

Introduction

The classical ECT is a well-studied imaging technique. It is based on the measurement of the capacitance between electrodes arranged around a region of interest (ROI). In classical ECT this ROI is the cross sectional area of a pipe and the system reconstructs the permittivity distribution from the capacitance measurements by solving a nonlinear and ill-posed inverse problem [1]. The number of unknowns, e.g., reconstructed image pixel, typically exceeds the number of independent measurements. Furthermore, due to the soft field (field lines are influenced by the object) character of ECT, the achievable resolution of the image is low compared to that of hard field tomography systems (field lines propagate straight through the object) such as x-ray or ultrasonic tomography. However, the advantage of ECT is that in particular the sensor front end are simple electrodes and thus the required space is quite low, making it applicable in many situations. Images from ECT may be further processed for tasks such as object detection in robotic and/or mobile applications. In comparison to other object detection methods this approach offers the capability to provide estimates of the position, size and other properties of the object.

With respect to the implementation of a battery powered, wireless ECT system several issues need to be considered. First, a low complexity reconstruction algorithm has to be chosen such that real time/online reconstruction constraints can be met by a low power and low performance microprocessor. Second, the quality of the reconstruction images has to be sufficient for the respective objective, e.g., object detection. Finally, a measurement platform is needed fulfilling the requirements with respect to measurement rate, computational power and power consumption in order to provide full flexibility to the user and to access a wide field of applications.

Sensing Principle

Two different sensing principles can be used in capacitive sensing. First, the single ended measurement mode, also called self capacitance mode, determines the capacitance of an electrode with respect to ground. Second, the differential measurement mode, also called mutual capacitance mode, determines the capacitance between electrodes. The modes are illustrated in Fig. 1. In the single ended measurement mode an excitation signal is applied onto an electrode and the resulting displacement current emerging from this electrode is measured. This corresponds to the capacitance between an electrode and the distant ground.

In differential measurement mode, the capacitance between a pair of electrodes is measured. Therefore, an excitation signal is applied to an electrode and the displacement current is measured at the receiver electrode. In the differential measurement mode the coupling of an object influences the measured displacement current i_d between the receiver and transmitter electrode. In case of a well-grounded object the measured displacement current i_d decreases due to the so called leakage displacement current i_l. The leakage

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displacement current i_l represents the current returning through grounded surfaces instead of passing through the receiver electrode. As shown in [2], the use of a sensing platform measuring in both measurement modes simultaneously is beneficial to obtain information about the object in the ROI.

Each measurement mode comes with certain properties, e.g., number of independent measurements, etc. In the single ended measurement mode the number of independent measurements N is equal to the number of electrodes $N = n$. In the differential measurement mode the number of independent measurements N can be calculated by

$$N = n(n-1)/2 \quad (1)$$

Further information about advantages and disadvantages of each measurement mode can be found in [3], [4].

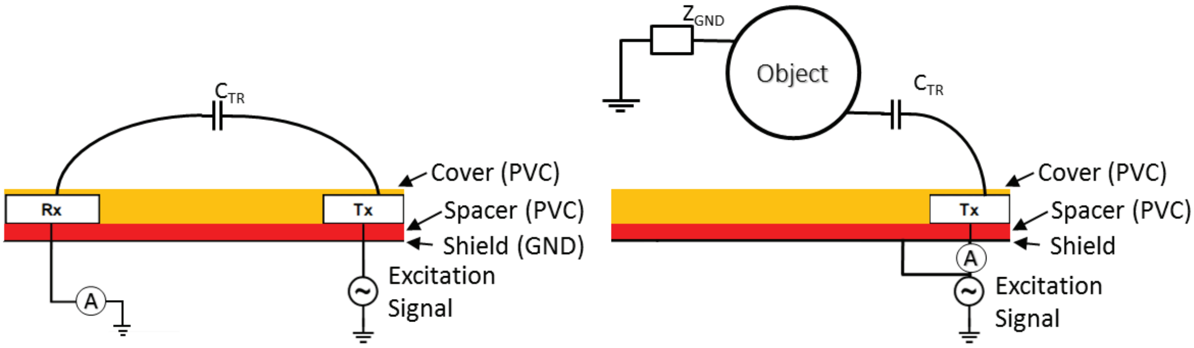

Fig. 1: Capacitive measurement principles. On the left side the differential measurement mode is shown and on the right side the single ended measurement mode (with active guarding) is depicted.

Reconstruction Algorithm

A great variety of reconstruction algorithms can be used in ECT, but only a few meet the constraints in the field of mobile applications. The most important constraints can be defined as:

- Real time capability
- Low computational complexity
- High quality of the reconstruction

According to these requirements, a tradeoff between speed and quality has to be made. Due to the first two constraints, iterative and non-linear reconstruction algorithms, e.g., Gauss-Newton method [5], cannot be used for mobile applications. High speed reconstruction algorithms are typically non-iterative with low complexity. Optimal Approximation (OA) techniques come with the same computational effort as Linear Backprojection (LBP) algorithm, but yield better image quality. One drawback of Optimal First Order Approximation (OFOA) is that it may generate artefacts in regions of low permittivity, which is a drawback in object detection. As shown in previous work [6], the quality of the reconstructed image can be improved by applying a nonlinear transformation, e.g., box cox [7], onto the permittivity values before we reconstruct the image. Therefore, a reasonable balance between quality and computational effort is achievable. Due to the low computational complexity this approach is suitable for a use on mobile platforms with limited computational and energy resources. A brief explanation including a classification of several reconstruction algorithm in ECT can be found in [8].

The OFOA is a type of the fast Bayesian reconstruction techniques and is based on minimizing the Mean Square Error (MSE). In particular, it is an extended implementation of the linear Minimum Mean Square Error (LMMSE) approach [6]. The image is obtained by a simple linear matrix multiplication of the measurement vector and correction of the bias as

$$\hat{\varepsilon}_{MMSE} = W\mathbf{y} + B \approx E\{\varepsilon\,|\mathbf{y}\} \tag{1}$$

$E\{\varepsilon\,|\mathbf{y}\}$ represents the expected value of the permittivity ε conditioned on the measurement ***y***. *W* and *B* are obtained from

$$W = C_{\varepsilon} C_{YY}^{-1} \tag{2}$$

$$B = \bar{\varepsilon} - W\bar{\mathbf{y}} \tag{3}$$

C_{ε} is the cross-covariance matrix of the measurements and permittivity. C_{yy} is the auto-covariance matrix of the measurements. $\bar{\mathbf{y}}$ is the expected value of the measurements and $\bar{\varepsilon}$ is the expected value of the permittivity, according to the prior probability distribution [5] of the permittivity ε.

Sensor Platform

We developed a sensor platform consisting of two parts: a battery powered mobile unit to be used in mobile applications, e.g., gripper arms, and a stationary unit. The stationary unit includes the receiver module and a host computer. The mobile unit consists of the transmitter module and the measurement acquisition circuit board stacked onto each other. A maximum of six electrodes is supported by this measurement platform. One main advantage of this sensor platform is the support of both measurement modes. In order to achieve this it is mandatory to switch the shield from ground to active guard as shown in Fig. 1. Thus, it is not possible to measure in both modes simultaneously and we need to use time division multiple access to the electrodes. This is implemented using a switch matrix directly controlled by the microcontroller. It connects the electrodes with the used Capacitance to Digital Converter (CDC) from analog devices AD7746 and AD7148 (see [9] and [10] for further information).

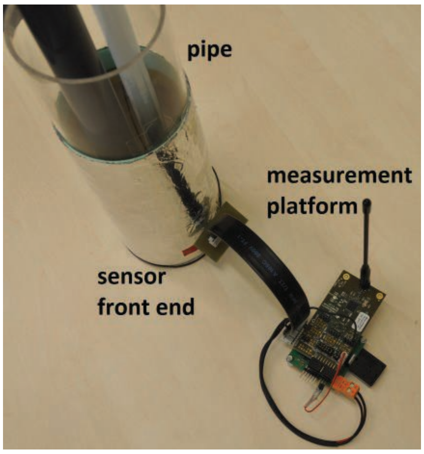

Fig. 2: Photo of a battery powered mobile ECT unit including the sensor front end and a wireless capacitive sensing platform.

The sensor front end can be easily adopted/exchanged according to the application. It can be attached to surfaces and has a thickness of only 70 µm. As it has no moveable parts it is also mechanically stable and durable. A front-end comprising six electrodes and a shield plane mounted on the circumference of a pipe to reconstruct a cross-sectional image of the permittivity distribution is shown in Fig. 2. The preprocessed measured sensor data is forwarded via a Radio Frequency (RF) link to the stationary unit. The mobile unit is capable of executing low computational reconstruction algorithms like OSOA as described in the previous section. This allows to transmit the entire reconstructed tomography image or relevant information only, e.g., a certain section of image or a classification result. Reducing the transmitted payload also leads to a shorter data transmission. Consequently, the power consumption of the mobile unit can be reduced significantly and the battery lifetime can be improved. As shown in [11] one key mechanism to increase the battery lifetime is to use low power/sleep mode of each sub module as often as possible. The system can not only be used in classical ECT scenarios but also in open environments such as described in [4] for a KUKA Lightweight Robot IV for a collision avoidance application.

The hardware platform also allows using reconstruction algorithm with high computational effort, e.g., nonlinear iterative methods. In this case, the raw measured data is transmitted to the stationary unit. As the transmitted payload is comparatively high and cannot be reduced the RF-Module must be active for a comparatively long time. The USB powered stationary unit receives the data and forwards it via an USB interface to the host computer. There the reconstructed image is either displayed or a reconstruction algorithm is run to obtain a tomography image with an improved image quality.

According to the requirements of a specific application a tradeoff between power consumption/mobility versus the image quality of the measurement system has to be made. Due to the design of the hardware this sensor platform provides the flexibility to the user to achieve a reasonable balance. The complete measurement setup is shown in Fig. 3.

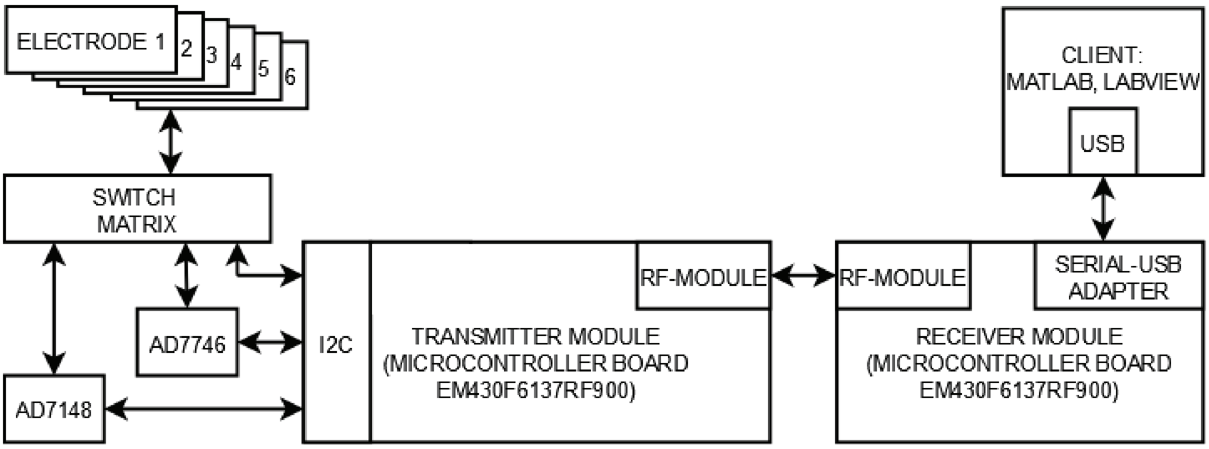

Fig. 3: Block diagram of the measurement setup including mobile and stationary unit [12].

Experimental Results

In Fig. 4 a reconstruction result for an object placed in ROI is presented. The ROI is the cross section of the pipe. In this setup six electrodes are arranged around ROI. The result shows that the region with the highest permittivity matches the true position of the object.

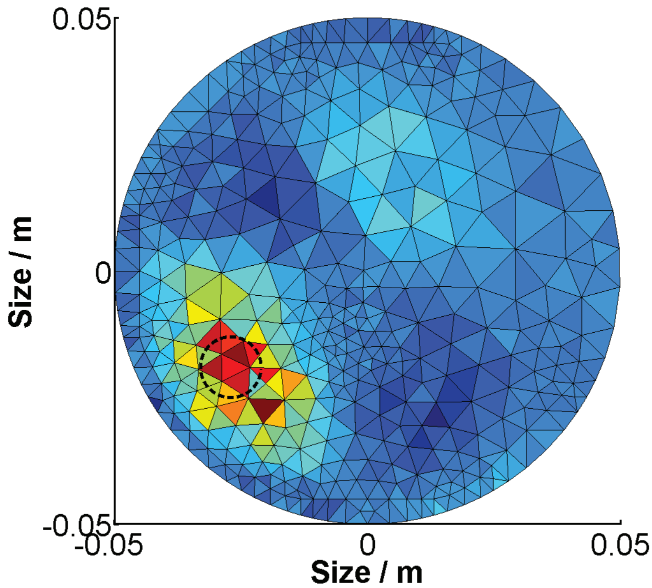

Fig. 4: Cross-sectional reconstruction image of a pipe. The dashed black circle depicts the true position of the inclusion in the ROI.

Conclusion

In this paper we present a wireless capacitive sensor platform, which supports both single ended and differential measurement mode. Furthermore, the platform is capable to run reconstruction algorithms with low computational effort, meeting the constraints to use ECT in the field of mobile applications. In addition, power saving strategies can be implemented on the mobile unit to increase the battery life time of the sensor platform according to the requirements of the application. In addition, this platform can be used as a classical ECT sensor forwarding the raw sensor data to a host where complex reconstruction with high computational effort may take place.

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