TomoSense: Towards Low Cost Multi-Device Aware Independent Planar Surface Sensing

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***Abstract*—We present a plane surface non-invasive sensing system for creating new cross-device interaction in the wild based on electrical capacitance tomography (ECT) measurement setup. The core element of the system is the plane capacitance sensor consisting of 32 electrodes built into an experimental tabletop assembly coupled with the spatial-awareness concept. The interaction is enabled taking the advantage of the principle of physical objects interfering with the electrostatic field in proximity of the surface, which is shown here for a set of mobile devices. The presented system is independent, i.e. does not require any external sensing methods to be coupled with in order to detect devices in the proximity. Additionally, no technical requirement concerning the type of interaction device is posed hence, we enable to embed devices world into the natural environment. Moreover, the system design and operational foundations in terms of both simplicity and measurement protocol make the equipment easily scalable. All these properties open way to elaborate new interaction techniques that are even more allusive. This paper offers a glimpse of technical details of the system as well as discussion on the further exploration of the TomoSense potential.**

Keywords- capacitance sensing; interactive surface; ECT; multi-device sensing, spatial-awareness.

I. INTRODUCTION

Spatial awareness concept is a key to development of multi device systems and especially interactions in these multi device environments, such as presented in [1, 3]. Recent work on sensemaking shows specific scenarios for multi device interactions emerging, while the range of possible areas where users already use multiple devices simultaneously grows [4]. However, the methods for determination of mutual position of devices are not perfect. Most of published research and applications involve techniques that require mounting external sensors/cameras and/or satisfaction of conditions, such as the line-of-sight for camera based systems or direct contact with special surface such as the specialized interactive tabletop displays in order to elaborate spatial-awareness for these systems. Consequently, most of them are either difficult to deploy in-the-wild conditions or spatial-awareness can be explored in the laboratory conditions only. Therefore, we propose TomoSense: an ECT-based prototype sensing system constituted of a plane capacitance sensor easy to be embedded within an ordinary table and a process tomography measurement equipment coupled with a dedicated measurement protocol. TomoSense enables to identify devices in the close proximity of the electrodes that are hidden below the plane (i.e. table) surface thus enabling ad hoc interactions in different locations, as proposed in [2]. This paper covers a short technical overview of the prototype concept as well as first results and discussion on the further studies.

However, while a number of interaction techniques have been proposed, the method of sensing the relative position of the devices still remains a challenge. Past experiments often used stationary and costly sensing, such as interactive tabletops [1] or motion tracking systems [2]. Alternatively, Rädle et al. [3] developed a Kinect-based system for spatial awareness that required placing a sensor above the surface on which the devices were placed. All of the past approaches have certain limitations, such as the need for line-of-sight for camera-based systems, or the need for direct contact with the surface for interactive tables. As a consequence of these constraints, studies of multi-device systems either do not use spatial awareness or focus solely on laboratory experiments [4], [5] . As more and more users carry multiple mobile devices simultaneously [6], a need emerges for a versatile sensing method that would enable in situ studies and create possibilities for a wide deployment.

This paper introduces TomoSense — an electrical capacitance tomography sensor embedded in an ordinary table that enables identifying devices on and above the table and acquiring positional information. TomoSense is a research prototype that enables more ubiquitous positional sensing for devices and approximates the concept of an interactive tablecloth (a concept first proposed by Müller-Tomfelde and Fjeld [7]) — the possibility to create ad-hoc interactive surfaces in any location. Here, we provide a description of TomoSense, details of the sensing method used, preliminary insights from its application to device sensing and plans for future studies as further development of a concept initially postulated here [8].

II. TOMOSENSE

TomoSense is a rectangular planar sensor dedicated to electrical process tomography measurement modality that consists of 32 electrodes arranged in 4 rows and 8 columns all embedded just below the surface of an ordinary table. Fig. 1 is a photo of the table with a sensor intentionally (showing

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the principle of operation, while to be easily hidden with an opaque layer during normal operation) visible underneath the transparent plastic layer (3mm thickness) of the upper table surface. It is worth to note that, while we use an ordinary utility table for our experiments, the system itself can be a part of virtually any other surface as well. The table presented as an example here has a size of $610mm$ x $450mm$, while each electrode is $95mm$ x $60mm$ with the gaps in between the electrodes of $10mm$. The bottom part of sensor ($10mm$ below the table surface) was electrically screened in order to improve the signal-to-noise ratio (SNR) and thus improving the sensing properties of the system in the space above the sensor. Electrical capacitance tomography is based on the principle of measuring the change of capacitance between all the consecutive pairs of sensing electrodes (irrespective of their position or orientation) quickly switching the excitation to successive electrodes, while grounding the rest. Experiments were conducted with sensor of 32 electrodes located as shown in Figure 1, using 32 channel quality equipment enabling real time on-the-fly monitoring of the measurement space; further details on ECT process tomography can be found here [6]. In order to better illustrate the working concept of the proposed system, we show here 2D reconstructed images (using basic LBP algorithm), while it is reasonable to store and process only the relative position of the devices omitting the imaging and visualization at all in further research work [6].

Electrical capacitance tomography is based on the principle of measuring the change of capacitance between consecutive pairs of sensing electrodes, irrespective of their position or orientation. In order to conduct the measurement, one of the electrodes is excited with a certain electrical potential (in the range of $5 - 15V$) while the rest of electrodes are grounded. This work was conducted using a custom-made 32 channel research-grade ECT device. The device is fully flexible as it allows to adjust the interchannel gains of separate measurement channels. All the electrodes in TomoSense are connected to the device and monitored in real time.

III. SENSING

A typical electrical capacitance tomography system consists of three major components (Figure 2); the ECT sensor with electrodes placed around the monitoring object, the data-acquisition ECT measurement unit, which excites the electrodes and measures the capacitance between each pair of electrodes, and the computer with complementary software installed, for image reconstruction, image analysis and sensitivity matrix of the used ECT sensor. Typically, used sensors consisting of N electrodes (e.g. $N = 8, 12, 16$) lead to M capacitance measurements $M = (N - 1) * N/2$, ($M = 28, 66, 120$) [9]. The number of the amounted electrodes in ECT sensor is related to image acquisition rate and the required resolutions. The use of 12 electrodes allows the acquisition of 100 frames per second. In the presented ECT sensor ($N = 32$) and with the applied ECT measurement unit, the acquisition rate was at 11 frames per second that gives $M = 496$ measurement records for one frame. The measured capacitance records are collected in a matrix where i, j represent the numbers of the electrodes in between the successive pairs of measurement electrodes [10]. The changes of capacitance between each pair of electrodes are dependent mainly on the permittivity value of the space between electrodes and the distance between electrodes. In order to prepare the image of permittivity distribution in space between each pair of electrodes, it is necessary to calculate the sensitivity matrix, which provides information about the influence of the level of permittivity changes in each part of the measurement space (in our case, above the table) on particular capacitance measurements [11]. Before starting the reconstruction process, the sensitivity matrix has to be calculated. The measurement procedure is conducted by connecting each electrode to an ECT system. The measurement of capacitance C was conducted between each pair of electrodes, C_{1-2}, C_{1-3}, ..., C_{1-32}, C_{2-3}, C_{2-4}, ... , C_{2-32}, ... , C_{31-32}. The measurement vector M_{1x496} consist of $N = 496$ measurements. The reference vector for empty measurement space M_{ref} is recorded in order to eliminate the influence of the distance between the distant electrodes on the results. The sensing area is divided into 23x30 pixels. The reference data is used to create the reconstructed image of the objects placed on or above the surface of TomoTable. In order to obtain the image, a sensitivity weight matrix $W_{496x690}$ is calculated. It provides information on how the changes in each pixel influence the measurements of capacitances between each pair of electrodes. The values of weight matrix are calculated based on distance of a pixel from a given electrode. For electrodes located farther away from each other, the influence on pixel changing is much smaller than for adjacent electrodes. The resulting image I is obtained by first subtracting M_{ref} from M to obtain the relative measurement vector M_e and then multiplying M_e by the weight matrix W.

Fig. 1. Photo of TomoSense - top view of the system with a single mobile device (iPhone 6) placed on the table. Note the size of the sensed surface relative to the smartdevice.

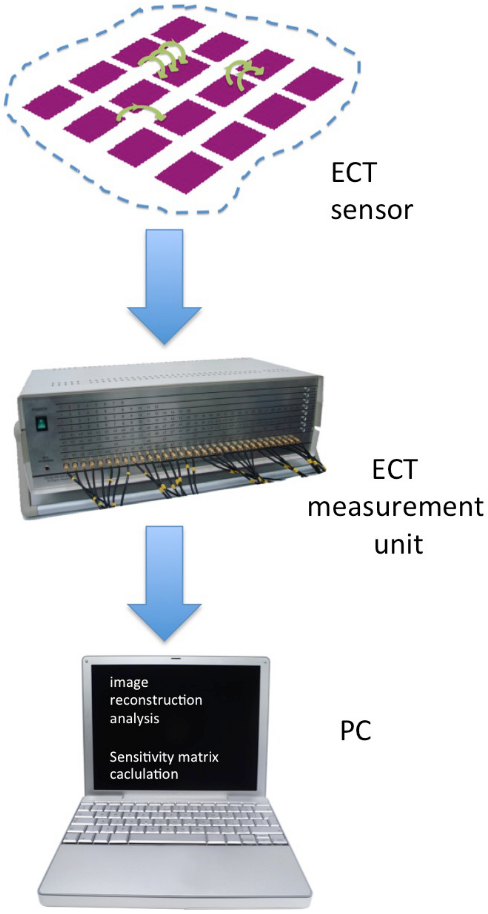

Fig. 2. Components of ECT

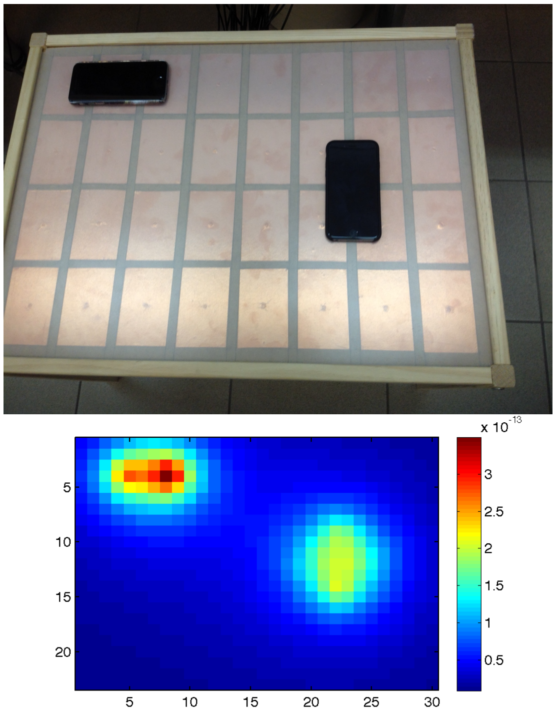

Fig. 3. Two iPhone 6 units placed on TomoTable and the resulting reconstructed image. Top: The phone on the upper left-hand side is located above the center of one electrode and covering two adjacent electrodes partially. The phone on the lower right-hand side is placed in between four adjacent electrodes covering only about one fourth of each of them. Bottom: The reconstructed 2D image of the device configuration view on top. The color scale show measurement intensity that varies empty space (blue) to the solid body of a device (dark red).

IV. PRELIMINARY RESULTS

Figures 3 and 4 show the reconstructed images of the distribution of the objects on the sensed surface. The examples shown here illustrate different possible configurations of devices and varying alignment with respect to the electrode array.

While it is apparent that an object is present on the sensed surface, its exact location is harder to determine. This is caused by the fact that the capacitance between adjacent electrodes (when the sensed surface is empty) increases with the distance between the electrodes. That is why a reference vector needs to be obtained before any object detection is performed.

Our next observation is that the introduction of mobile devices onto the sensed surface produced an easily sensed change in capacitance. The differences of capacitance we observed are in range of a few picofarads (from $6pf$ (empty space) to $14pf$ (space with a mobile device)). The advanced research system we used can detect differences in the range of fF and thus a lower grade device would be sufficient. Consequently, ECT sensing for mobile devices does not require highly accurate capacitance sensors, which creates opportunities for low-cost deployments. The number of elements into which the sensor plane was discretised in order to conduct the image reconstruction is relatively low and the resolution of the image is relatively low (e.g. compared to an interactive table). The image reconstruction procedure applied here was a simplified version of the LBP algorithm — a fairly naïve one that neglects the nonlinear character of the electrical field response to the objects present in the measurement space. Albeit using basic reconstruction method and choosing low resolution of the visualization (23x30 pixels) the size and orientation of the devices can be easily seen on the resulting reconstructed image. As a reference, we we show two cases with different orientation of the devices with respect to each other as well to the sensing electrodes area and the table itself (upper photos on Fig. 3 and Fig. 4) as well as the resulting reconstructed images of the distribution of the objects on the sensed surface (bottom pictures on Fig. 3 and Fig. 4). There are observable differences in the produced images depending on how the devices are positioned in relation to the electrodes and other devices. This showcases the potential of electrical capacitance tomography to provide accurate sensing for multi-device systems.

There are observable differences in the produced images depending on how the devices are positioned in relation to the electrode array and other devices. This showcases the potential of electrical capacitance tomography to provide accurate sensing for multi-device systems, namely we demonstrate

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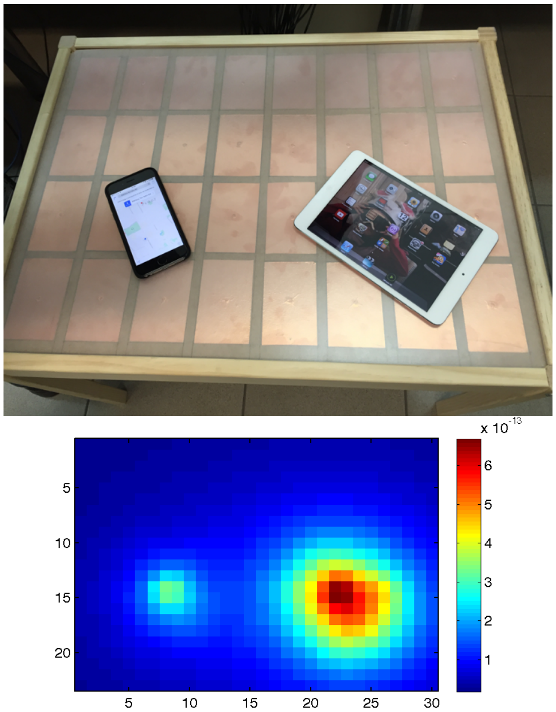

Fig. 4. An iPhone 6 and an iPad mini placed on TomoTable and the resulting reconstructed image. Top: The spatial arrangement of the devices is more chaotic and more likely in an in-the-wild scenario. The rotation of the devices is misaligned with TomoTable's electrode array. Bottom: The reconstructed 2D image of the two devices. The color scale show measurement intensity that varies empty space (blue) to the solid body of a device (dark red).

it is feasible to: (1) localize the position of the device (2) distinguish the size (3) detect the rotation angle and (4) sense several distinct devices.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we demonstrated that TomoSense detects on-top placed devices with ease; measurement records taken during experiments revealed significant changes in sensed capacitance and these varied from a few to over a dozen in the range of picoFarads (from 6pF for empty space to 14pF when sensing a device), while the ECT unit is capable to work in far more narrow range of femtoFarads. With this, we can conclude that it is possible to use a custom made device with lower sensitivity capacitance measurement devices for future wide deployment. One can observe that, even for the same type of devices, the particular position of the device with respect to electrode distribution (coverage over the distinct electrodes area) influences the values of reconstructed pixels (Fig. 2). This property may provide additional knowledge about devices orientation with respect to electrodes positions and hence shall improve the eventual spatial position calculations. ECT normally can produce tens up to hundreds of images per second for the all-inter-electrode measurement vectors. However, using contextual knowledge of the monitored process, such as the specific movements of mobile devices as reported here [5], we can adjust the measurement protocol. The protocol may support more rapid detection of spatial location with the aid of the "traveling measurement window" concept using a mask of 9 or 16 electrodes. While spatial awareness becomes an important feature in a class of applications such as sense making in a multi device environment, a question of a balance between required sensing accuracy vs. complexity and ease of application remains open. The proposed prototype offers limited spatial resolution compared to infrared based positioning. However, further research on refining the design (in terms of different electrode arrangements coupled with dedicated measurement protocols as well as contextual data processing algorithms) shall provide sufficient accuracy for spatial-aware based multi device applications. On the other hand, our design preserves the biggest advantage over the other modality systems, i.e. the possibility to be easily embedded into different surfaces and, therefore, to keep the promise of in-the-wild applicability. It will be interesting to test the device for advanced domain expert analytical meetings for last stage of scientific crowdsourcing applications [12]. Lastly, with the improved prototype, it is worth to conduct in-situ study on possible ways of interaction with various everyday objects.

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