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Detection of Ungrounded Objects on Mutual Capacitance Touch Screens

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***Abstract*—Mutual capacitance touch screens are responsible for detecting billions of human fingers touching them around the world every day. Being able to use such screens for detection of ungrounded objects as well, would make it easier develop compatible tangible user interface objects that could extend the functionality of the screens. We present results from both simulations and experiments showing that the sensing principle used in these screens are able to detect ungrounded objects.**

I. Introduction

In recent years, touch screens have become one of the most common human computer interfaces. Touch screens offer more direct and intuitive interaction with the information displayed on the screen, as well as being space saving and independent of external input devices. However, they do not offer the haptic feedback of traditional user interfaces. Tangible User Interface for touch screens, where interaction happens through manipulation of physical objects on the screen is one possible way of bringing haptic feedback to touch screens. Such an interface has been demonstrated for rear camera based optical touch screens [1], [2]. These screens are susceptible to interference from ambient light. It is therefore of interest to look into designing tangible user interface for other touch screen technologies.

In the consumer market, mutual capacitance touch screens [3] has become the most applied touch screen technology and is found in nearly all smart phones and tablets. It offers true multi-touch detection and compared to resistive screens, no physical force is required to trigger touches. However, the controllers for these screens are specifically designed to detect human fingers by the fingers' property of acting as grounded objects. A grounded touch causes a reduction in mutual capacitance between the digitizer electrodes at the point of touch. Thus, grounded tangibles may be used with these screens. Several methods for grounding exists. Grounding through the operator allows the screen to detect the tangible [4], but only as long as it is touched by the operator. Grounding by a tether cable offers detection at all times, but has the disadvantage of the ground tether. Lastly, grounding through the screen itself has been explored [5], but has not proven sufficiently reliable for all applications and also restricts the possible spatial patterns used to differentiate between tangibles. Being able to detect ungrounded objects would therefore be of great value in designing tangibles.

Mutual capacitance touch screens works by sampling an image of the mutual capacitance between the intersecting electrodes embedded in the screen. With a few exceptions [6], [7], such images are not frequently seen in literature. Our question is then: Can such a capacitance image be used to detect ungrounded objects on the screen? With a lack of raw data from commercial devices, we designed a simple touch controller based on an ARM32 microcontroller as a platform to study mutual capacitance touch screens. This device showed an increase in mutual capacitance when a small ungrounded object was present on the screen. To investigate the case of ungrounded touch further, we applied electrostatic Finite Element Analysis, FEA, to 3D models of touch screen digitizers. We here focus on the FEA results for a digitizer similar to that of a commercial device we have been able to obtain raw data from and present a comparison of data from simulation and experiment.

II. Finite Element Analysis

The open source multiphysical simulation software Elmer [8] was used for electrostatic FEA of a 3D model of a touch screen digitizer consisting of five electrodes in both x- and y-direction with an air volume of thickness $10\,\mathrm{mm}$ above the surface, Figure 1. We chose the model parameters, Table I to be close to that of the commercial device of section III-B. To determine the electrode layout and dimensions, we used bright field microscope images of the digitizer of that device. A conductive disc on the glass surface of the digitizer represented the object on the screen, with displacement and radius varied in the simulations

The model differs from the real device in that rx- and tx-electrodes are considered to be in the same layer at the bottom side of the glass in the model. At the intersections of the rx- and tx-electrodes, we made a cut through the tx-electrodces, with an extra gap of 0.05 times the rx-electrode pitch to each side of the rx-electrode. This means that the layer between the electrodes, which in reality contributes strongly to their mutual capacitance, is not included in the model. However, objects present on the surface of the screen does not influence the electric field in this region much, and it mostly contributes a fixed parallel plate capacitance to the total mutual capacitance. The real digitizer also features small square patches of floating conductors in the gaps between the rx-electrodes, which are not included in the model. The glass thickness was measured for the glass on a spare digitizer and does not include the layer of polymer film with the electrodes. The relative permittivity of the glass was not measured.

We used Gmsh mesh generator [9] to define the model

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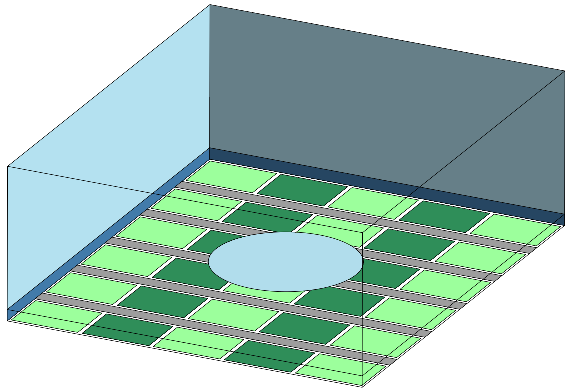

Figure 1. 3D model of digitizer used in simulations. Tx-electrodes are shown in alternating colors.

Table I. SIMULATION PARAMETERS

Parameter	Value	Unit
Glass thickness, t	0.8	mm
Electrode pitch tx	5.08	mm
Electrode ptich rx	5.20	mm
Width of tx-electrode	4.76	mm
Width of rx-electrode	1.07	mm
Relative permittivity of glass, ε_r	4.0	

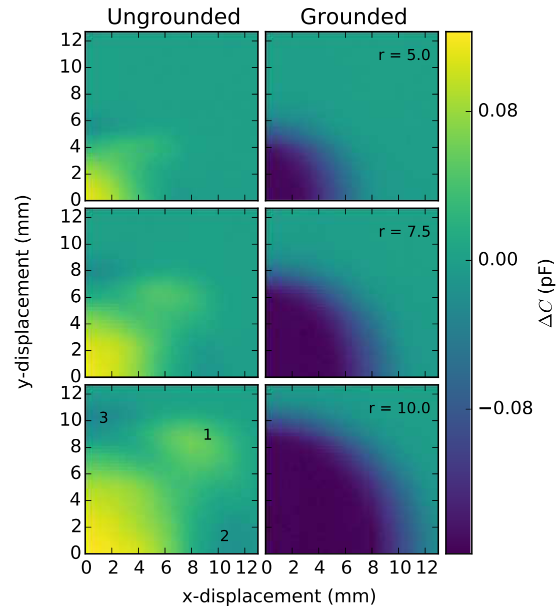

Figure 2. Results of FEA for three different pad radii (mm), showing the relative mutual capacitance of an electrode intersection where the pad center is displaced in x- and y-direction from the electrode intersection. The numbers mark regions of interest. The tx-electrodes are parallel to y-axis.

geometry and create the mesh and Python scripts to control the parameters. The capacitance matrix option in the electrostatic solver in Elmer provides capacitances between all the individual electrodes and the pad. The mutual capacitance between the electrodes under the condition of grounded pad is given directly by this capacitance matrix. By assuming the pad to be a floating conductor, the mutual capacitance between electrodes for the ungrounded case can be determined.

Let C_{tx} and C_{gnd} be the capacitance between the pad and respectively the active tx-electrode and ground, and let V_{tx} be the voltage of the active tx-electrode. The voltage of the pad is then given by a capacitive voltage divider as

$$V_{\mathrm{pad}} = \frac{C_{\mathrm{tx}}}{C_{\mathrm{tx}} + C_{\mathrm{gnd}}} V_{\mathrm{tx}}. \tag{1}$$

Now with C_{rx} as the capacitance between pad and chosen rx-electrode, the charge on that electrode is given by:

$$Q_{\mathrm{rx}} = V_{\mathrm{pad}} C_{\mathrm{rx}} \tag{2}$$

Finally the capacitance between active tx-electrode and the chosen rx-electrode is given as

$$C_{\mathrm{tx-rx}} = \frac{Q_{\mathrm{rx}}}{V_{\mathrm{tx}}} = \frac{C_{\mathrm{rx}} C_{\mathrm{tx}}}{C_{\mathrm{tx}} + C_{\mathrm{gnd}}} \tag{3}$$

Assuming all but the active tx-electrode to be kept at ground potential, C_{gnd} is simply the sum of the capacitances between the pad and all electrodes except the active tx-electrode.

Processing the results from displacing the center point of the pad up to one half of the electrode pitch in both x- and y-direction away from the middle electrode intersection, by utilizing symmetry, we constructed the result of displacements up to 2.5 electrode pitches in both directions by using data from all electrodes. The resulting plots shown in Figure 2 compare grounded and ungrounded touch for different pad radii. For the $10\,\mathrm{mm}$ pad, the maximum capacitance decrease for grounded touch was $0.154\,\mathrm{pF}$ and the maximum capacitance increase for ungrounded touch was $0.120\,\mathrm{pF}$, or $78\,\%$ of the grounded touch capacitance decrease.

In a spare digitizer obtained for the same device, the rx-electrode each consisted of a pair of strips. Modeling of this digitizer showed a weaker response to ungrounded touch compared to grounded touch. For the $10\,\mathrm{mm}$ pad, the maximum capacitance decrease for grounded touch was $0.15\,\mathrm{pF}$, while the maximum capacitance increase for ungrounded touch was $0.04\,\mathrm{pF}$ or $27\,\%$ of the grounded touch capacitance decrease.

In order to determine how parameters influence grounded and ungrounded touch differently, we simulated the result of changing the relative width of the rx-electrodes, the glass thickness and the relative permittivity of the glass, Figure 3. Electrode pitch was kept constant. Variation of the air volume thickness did not influence the results until it was reduced below $3\,\mathrm{mm}$.

III. EXPERIMENTAL RESULTS

A. ARM32 Based Controller

Our touch controller is based on an STM32F103C8T6 development board combined with a replacement touch screen digitizer panel for a device called ONDA VX610W. This 7" digitizer has rx-electrodes on the top surface of the glass and tx-electrodes on the bottom surface, both with a pitch of about $1\,\mathrm{cm}$. Each rx-electrode consists of a pair of strips with a bridge between them at the center of each tx-electrode.

We connected the rx-electrodes to analog inputs and the tx-electrodes to digital outputs of the microcontroller. Before each

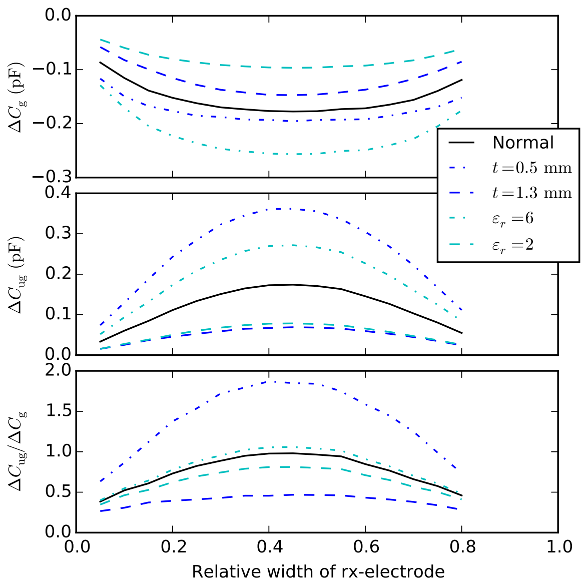

Figure 3. Results of FEA of capacitance changes ΔC_{g} and ΔC_{ug} for grounded and ungrounded touch, when varying rx-electrode width, glass thickness t and relative permittivity of the glass, ε_r. Rx-electrode width is given relative to rx-electrode pitch. Pad radius is $7.5\,\mathrm{mm}$.

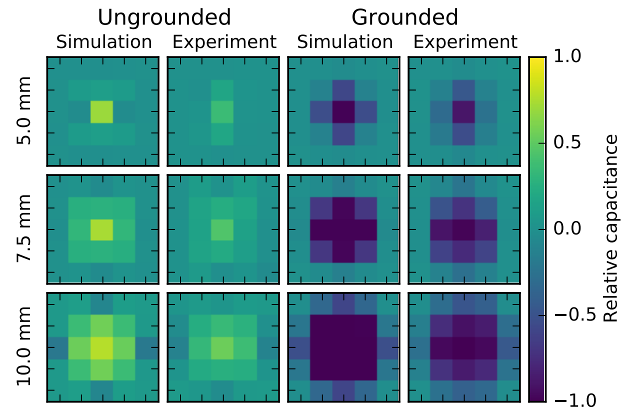

Figure 4. Simulation and experimental results for different pad radii on an area of 5 by 5 electrodes. Capacitances are normalized to the maximum values for grounded touch for both simulation and experiment.

measurement, all electrodes are set low for a short duration to bring them to a fixed potential. The rx-electrodes are then switched back to analog input, one tx-electrode is set high and the rx-electrodes are sampled using the ADC. This is repeated for all tx-electrodes. The sum of 20 scans are sent to a computer by virtual COM port over USB. With this configuration, we achieve $75\,\mathrm{Hz}$ refresh rate. The maximum change in output value for a $10\,\mathrm{mm}$ pad is 860 counts decrease for grounded touch and 260 counts increase for ungrounded touch or $30\,\%$ of that for grounded touch.

B. Commercial Device

The tablet device Samsung Galaxy Note 10.1 (GT-N8010) features an Atmel maXTouch mxt1664S controller, which is compatible with the mxt-app[1] open source command line utility provided by Atmel. Executing[2] mxt-app as root on the device gives access to the debug features of the touch controller, including the matrices of capacitance reference levels and capacitance deltas. The latter being the difference between measured capacitance and the reference level. Operating the mxt-app in bridge mode, this data can be transfered by network to a computer for further processing. The controller reports a matrix size of 32 x 52; however the digitizer only has 27 x 42 electrodes, where the 27 long electrodes are the tx-electrodes.

As the controller continuously makes updates to the reference levels, for each measurement we make, we extract both reference values and deltas. We then sum the two to get the measured capacitance. We use this method to first acquire our own reference level when the screen is untouched and subtract this from subsequent measurements for various touch conditions. Although oscilloscope measurements show that the controller scans the screen at a rate of about 90 Hz, having to transfer two sets of data for each update results in a refresh rate about $1\,\mathrm{Hz}$. It should also be noted that data is transferred as pages, and one update does not represent the data from one single scan cycle, but rather a combination of data from several cycles.

We used circular pads made of conductive aluminum tape cut to size and stuck to a piece of cardboard to generate data from grounded and ungrounded touches. The pad was carefully centered above an electrode intersection in the digitizer, by means of observing the output image and shifting the pad to obtain symmetry in both x- and y-direction about one center pixel. These measurements were conducted with the device connected by the USB-cable to a grounded computer. We achieved grounded touch simply by touching part of the conductive tape on the back side of the pad with a finger. Figure 4 shows a side by side comparison of data from the FEA and data from the experiment for both grounded and ungrounded touch. Grounded touch resulted in a decrease of 701 counts and ungrounded touch resulted in an increase of 385 counts for the experiment, or $55\,\%$ in terms of grounded touch.

IV. Discussion

Both simulations and experiments show an increased capacitance for ungrounded touch. For ungrounded touch, the pad acts as a shortcut for the electric field from tx-electrode to rx-electrode. The coplanar capacitor formed by the tx- and rx-electrodes is to some degree turned into a two layer parallel plate capacitor, where the pad makes up the middle plate. As the pad also overlaps other electrodes, it has capacitive coupling to ground as well, reducing the mutual capacitance between the two electrodes.

Both for simulations and experiment, the shape of the ungrounded capacitance image is not circular as for the grounded case. For both region 2 and 3 in Figure 2, the pad is overlapping the electrode intersection, thus reducing the direct mutual capacitance. As most of the pad is overlapping other electrodes, it has a considerable coupling to ground and weak coupling to one of the two electrodes. Thus, the indirect mutual

[1] https://github.com/atmel-maxtouch/mxt-app
[2] command line argument: -d "i2c-dev:3-004a"

capacitance through the pad is less compared to when the pad is centered on the intersection. This can explain the slight reduction in total mutual capacitance.

When the pad center is displaced diagonally away from the electrode intersection, region 1 in Figure 2, the pad is overlapping both electrodes but not the intersection. The pad then still acts as a bridge for the electric field, but since it is not overlapping the intersection, it does not affect the direct mutual capacitance between the electrodes. This explains the increased mutual capacitance observed for this case.

When designing tangible tags, the choice of pad radius for the touch points is critical to achieve reliable accurate detection, while at the same time limiting the size. A larger pad will in general offer more accurate interpolation, and there is a minimum size required to achieve reliable detection no matter how the pad is positioned relative to the electrodes. Considering Figure 2, the requirement for detection corresponds to a capacitance above detection threshold up to a displacement of half the electrode pitch in both directions. This is clearly satisfied for the grounded touch of all the selected radii, however for ungrounded touch the capacitance increase for $5\,\mathrm{mm}$ radius may not be sufficient depending on the threshold required to avoid false detections. The shape of the capacitance image for ungrounded touch also makes interpolation for accurately determining the position more challenging.

The result from the parameter sweep in Figure 3 shows that rx-electrode width influences the sensitivity to grounded and ungrounded touch differently. In addition, reduced glass thickness and increased permittivity increases the capacitance change for both grounded and ungrounded touch. As seen from the ratio of capacitance changes, glass thickness and rx-electrode width has more influence on ungrounded touch.

The ungrounded touch was less sensitive than expected from the FEA when compared to grounded touch. Our analysis for the replacement digitizer, featuring a different electrode layout, indicates that the relative sensitivity to ungrounded touch depends on the electrode layout. The difference between simulation and experiment may thus be due to inaccurate modeling of the real digitizer. Although our value for relative permittivity was simply chosen to a realistic value for glass, we see from our results that it has little influence on the capacitance ratio. We modeled the electrodes as being in the same plane, with an in-plane gap between them instead of an out-of-plane gap. This gap and uncertainty in the actual glass thickness are possible causes of the difference between model and actual device. We have also assumed the device to report a count linearly dependent on capacitance change.

Although we are able to extract the raw capacitance data from a commercial device, the refresh rate is too slow to be of any use in a practical interactive application. The fact that the data acquired is not from a single scan means that for moving objects, we will also have an effect similar to screen tearing. Holz et al. [7] reported a refresh rate of 30 Hz for an LG Nexus 5 phone. This would be sufficient for most interactive applications. However, the small display size 4.95" limits the usefulness for tangible interfaces. Our microcontroller-interfaced digitizer has a sufficient refresh rate, but the size combined with large pixel size also limits the usefulness of this digitizer for tangible interfaces. Although an ARM32 controller with more analog inputs could be interfaced with a larger digitizer using this simple design, signal level and refresh rate would suffer when scaling it up.

V. Future Work

In order to speed up the development of ungrounded tangibles, it would be beneficial to develop a faster simulation tool. We propose doing this by estimating the capacitance matrix as a function of intersection area covered by the pad, using capacitance per unit area covered to determine the different couplings. FEA of different conditions for one single electrode intersection can be used to determine per unit area capacitances.

VI. Conclusion

By simulations and experiment, we have demonstrated the feasibility of using mutual capacitance touch screens to detect ungrounded objects, as they cause an increase in mutual capacitance. We have also shown that there is a difference in shape and size of the capacitance image of a grounded versus an ungrounded conductive pad. Finally, we have seen that changes in digitizer layouts and glass thicknesses affects the sensitivity towards grounded and ungrounded objects differently.

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