# PUCs: Detecting Transparent, Passive Untouched Capacitive Widgets on Unmodified Multi-touch Displays

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## ABSTRACT

Capacitive multi-touch displays are not designed to detect passive objects placed on them—in fact, these systems usually contain filters to actively reject such touch data. We present a technical analysis of this problem and introduce *Passive Untouched Capacitive Widgets (PUCs)*. Unlike previous approaches, PUCs do not require power, they can be made entirely transparent, they are detected reliably even when no user is touching them, and they do not require internal electrical or software modifications of the touch display or its driver. We show the results from testing PUCs on 17 different off-the-shelf capacitive touch display models, and provide initial technical design recommendations.

## Author Keywords

Tangible user interfaces; transparent widgets; passive widgets; tabletop interaction; capacitive multi-touch

## ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces Input Devices and Strategies

## INTRODUCTION

Most commercially available multi-touch devices today, in particular tablets, use capacitive touch technology. Tangible widgets on such capacitive touch screens have been explored for over a decade [5], but they generally rely on the user's body to provide the capacitance needed for touch detection. Their major limitation is that, to maintain widget detection, the user needs to keep touching the conductive parts of a widget. This leads to several problems: the system cannot reliably distinguish whether an object has been removed from the table, or whether a user just stopped touching it. Furthermore, if a widget is moved but not touched (e.g., by inertia from a flicking gesture or by being touched indirectly through a non-conductive material), this movement is not detectable by the system and leads to input desynchronization.

**Figure 1. PUC widgets on an iPad: a transparent Bridge PUC (left) and a Ring PUC (center). The clip to permanently ground a touch point and override the iPad's adaptive filter can be seen on the right.**

After a review of related work, we provide a technical analysis of why capacitive touch screens usually ignore these objects, and introduce *Passive Untouched Capacitive Widgets (PUCs)*—simple physical widgets that can be detected constantly by unmodified capacitive touch displays. We show how to make these widgets optically completely transparent to avoid occlusion issues and, based on a preliminary evaluation, introduce some design recommendations for PUCs.

## RELATED WORK

In 2002, Rekimoto first proposed a basic concept to design tangibles for capacitive displays [5]. Since then, the concept has been extended to using tangibles on tablets and smartphones [4, 8, 3], enhanced with actively modulated touch signals [7], and even resulted in commercial products[1], but their common challenge is that these capacitive widgets are detected only while a user touches them. This causes inconsistency between actual and recognized positions since the system cannot sense the movement of untouched widgets. Furthermore, it makes it impossible to distinguish whether a user picks up a widget from the surface, or whether they just stop touching it. A heuristic of simultaneous vs. sequential disappearance of touch points may distinguish widget removal from hand removal [2], but this approach still cannot detect widgets moving without being touched, such as after a flicking gesture.

Our goal is to create capacitive widgets that are detected constantly on unmodified, commercially available touch displays without the need for a user to touch them. The widgets should be *passive*, i.e., require no built-in active electronics, because

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[1] *Fling* game controller, tenonedesign.com

this leads to practical issues such as battery maintenance, and it makes the widgets more expensive and complex to build.

## TRACKING LOSS ON CAPACITIVE TOUCH DISPLAYS

Capacitive touch displays sense the presence of a grounded electrical conductor, typically a human finger, in close proximity to the screen, using transparent electrodes located above the display panel. We distinguish two main sensing techniques, self capacitance and mutual capacitance [1]. Mutual capacitance is best suited and most commonly used in multi touch displays today, and is thus the principle targeted by our marker design.

The typical electrode configuration of a mutual capacitance display consists of a set of rows and a set of columns. One set acts as transmitters ($Tx$) and the other as receivers ($Rx$) [5]. When a signal is applied to one of the $Tx$ electrodes, the capacitance between this $Tx$ electrode and an intersecting $Rx$ electrode couples the signal to the $Rx$ electrode [6]. By measuring the signal from each of the $Rx$ electrodes, the touch controller determines the capacitance between the active $Tx$ electrode and each of the $Rx$ electrodes. Activating one $Tx$ electrode at a time (time multiplexing), the controller is able to measure this capacitance at all the $Tx - Rx$ electrode intersections on the display.

When a grounded conductor like a finger gets close to one of these $Tx - Rx$ electrode intersections, capacitance between the two electrodes is reduced as the electric field between them is disturbed by the conductor [9]. With a typical electrode pitch of 5 mm, a finger touching the display will affect more than one intersection. Using interpolation, the controller is able to accurately determine the center of the touched area and reports this as a touch event. Since controllers are designed to detect finger touches, they search for elliptical shapes about the size of a fingertip. Other touch shapes and sizes are either ignored or may cause unpredictable touch events to be reported.

In summary, to make the controller report a touch event, (1) the $Tx - Rx$ electrode capacitance needs to be reduced below a certain threshold, and (2) this needs to happen over an elliptic area about the size of a fingertip.

In this paper, we refer to a *widget* as a complete tangible object. A widget contains one or more *markers* on its underside that communicate its ID, position, rotation and possibly other operational parameters (like slider positions or button presses) to the underlying touch surface. Each marker, in turn, consists of one or more *pads* that are detected by the underlying surface.

## HOW PUCS WORK

To be detected by the display, a widget marker pad has to fulfill the two requirements above. The first requirement can be fulfilled by grounding the widget marker. The second requirement can be fulfilled by shaping the marker pad as a round pad of a particular size. The size of the pad depends on the electrode grid resolution of the display. We will explain this in detail in the next section.

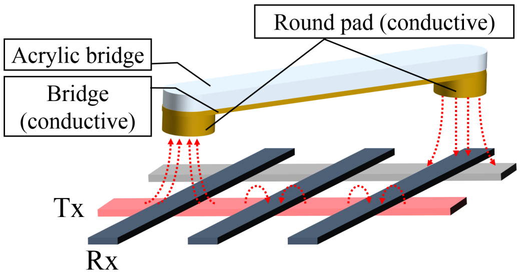

**Figure 2. Basic concept of a Bridge marker. Red connections indicate capacitive coupling between marker and electrodes.**

The straightforward way to ground a pad is to use the body capacitance of a user as proposed by Rekimoto [5]. This requires that a user touches the widget, that the pads of the widget are conductive, and that they are electrically connected to the part of the widget touched by the user. In this case, the widget simply functions as an electrical conductor between user and touch surface. However, in this approach, as soon as the user lets go of the widget, the display cannot detect it anymore.

One approach to replace the user as electrical ground is to use a conductive wire that permanently connects the widget to a relatively grounded object, for example, the battery ground connector of a tablet computer. However, permanently wired widgets are not a very practical setup for experiments, user studies or interaction design prototypes.

*PUCs*, therefore, use a different technique that allows them to be detected without the need to be grounded or touched by the user while still remaining passive (Fig. 1): they utilize the capacitive coupling to a second area on the display as ground. Through several pads on each PUC marker that are electrically connected to each other, currently active intersections on the touch screen are coupled to other, currently inactive intersections that serve as ground. This is the key technological insight that allows us to create PUCs.

The simplest example of this principle is a “Bridge” PUC that creates two touch points (Fig. 2). Its marker consists of two round pads that are used to fulfill the first requirement. The pads are connected to each other using a conductive material. When a $Tx$ electrode under one pad is active and the $Tx$ electrodes under the other pad are inactive (at ground level), then this second pad has a capacitive coupling to ground. This ground coupling is sufficient to reduce the $Tx - Rx$ intersection capacitance under the first pad to below the threshold for touch detection. Similarly, when the $Tx$ electrodes are active under the second pad (when the touch screen scanning algorithm reaches that area), the $Tx$ electrodes under the first pad are no longer active, and thus couple to ground. This lets the Bridge PUC generate one touch event for each of the two pads, without the aid of external grounding.

However, if both pads are aligned with the $Tx$ electrodes, both will couple to the same $Tx$ electrode, and the marker will no longer have a sufficient coupling to ground to bring the $Tx - Rx$ capacitance down. Similarly, if both pads are aligned with the $Rx$ electrodes, the Bridge provides an addi-

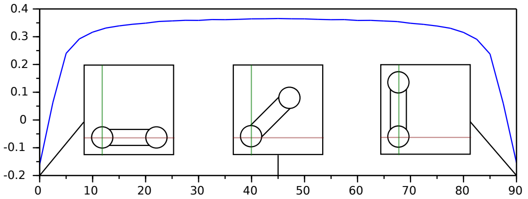

**Figure 3. Simulated decrease in intersection capacitance below a pad for different orientations of a Bridge marker. Scale: 0 is base capacitance, 1 is capacitance for grounded conductor in contact with display.**

tional coupling from $Tx$ to $Rx$. This time the coupling goes through the Bridge from the active $Tx$ electrode to a second point on the $Rx$ electrode. In both cases, the $Tx - Rx$ capacitance at each pad will not drop below the detection threshold, and may in fact increase, as it does for a single unconnected pad. Since electrodes in touch screens are laid out in a horizontal-vertical grid, this means that in practice, a two-pad marker like the Bridge PUC will disappear when its position on the screen is horizontally or vertically aligned.

To support our approach, we modeled the capacitances between two crossing electrodes in a touch display and between electrodes and conductive pads contacting or hovering above the screen. This was done using 2D electrostatics models in the FEMM[2] software tool for finite element method simulation of electromagnetics. The resulting capacitances were used to calculate intersection capacitances for different marker geometries as seen by the touch display controller.

Figure 3 shows how the simulated decrease in capacitance below one end of a Bridge marker is changing as the marker is rotated. This corresponds well with our observation that the marker was undedectable when aligned with either set of electrodes, as the graph shows an increase in capacitance above the base level for this condition.

To address the horizontal and vertical alignment problem we created a “Ring” marker (shown in Figure 1) that can be detected continuously independent of its orientation. This marker consists of a set of pads that are connected with a ring-shaped conductive material that hovers very closely above the display surface. Since the electrical field reaches out of the display, this material also creates a capacitive coupling with the intersections under it. This setup ensures that at least one area of the marker is always capacitively coupled with several inactive intersections, independent of its orientation. The hovering ring does not fulfill the area requirement, so it does not create false touch points.

The Ring marker is a simple example. Any other arrangements that cover multiple $Tx$ and $Rx$ electrodes are possible starting points to design a marker. For example, even markers that create only a single touch are possible: to create a Bridge marker that only creates a single touch point, we connected one pad to a conductive layer hovering above the surface.

To make a Bridge marker that is completely transparent (Fig. 1), we used an *indium tin oxide (ITO)* foil for the pads and connecting material mounted underneath an acrylic base. ITO is the same material that a touch screen’s electrodes are made of, and is available as a thin plastic foil that is electrically conductive on one side while insulated on the other side. It can be processed easily using a lasercutter, although care should be taken not to bend the material too sharply as its conductive coating may break.

## EVALUATION AND DESIGN GUIDELINES

**Basic detection.** In our first experiment, we tested our PUCs marker technology with 17 different commercially available multi-touch devices, ranging from smartphones to tabletops.[3] While these all use the same fundamental physical effect, we expected differences in how these devices implement their touch detection and filtering thresholds.

We placed a Bridge marker (two 10 mm pads, length 50 mm, placed diagonally) and a Ring marker (three 10 mm pads, radius 40 mm) on each device for ten seconds. On all devices, both markers were detected for the entire time without a user touching the marker. This indicates that our basic concept works for many widely used types of capacitive multi-touch display hardware.

**Electrode grid spacing.** In our second experiment, we measured electrode grid spacing of six different multi-touch devices (iPad 1 & 3, iPhone 4 & 4S, and Perceptive Pixel 27”), to understand how homogeneous their hardware characteristics are, and to correlate our findings to electrical characteristics of the various devices.

Using an oscilloscope, we were able to pick up the drive electrode $Tx$ signal by connecting the probe to a small 5 mm wide strip of conductive material that spans across the touch screen surface. With this setup, we measured the duration of the signal from one drive electrode and the duration of the complete scan through all drive electrodes, and could thus easily determine the number of drive electrodes without disassembling the touch screen. Electrode pitch was then determined by dividing the physical screen area by the number of electrodes in the corresponding direction. With this method we found that the distance between electrodes is 5 mm for all tested devices. This suggests that the hardware varies less than expected between different devices, and that there is a decent chance that other touch screens feature similar technical specifications.

**Pad size and distance ranges.** In our third experiment, we varied pad size and length (or radius) of the hovering conductive material and tested detection on the same six devices from Experiment 2, in order to better understand the space of possible marker designs.

We placed 2-pad Bridge and 3-pad Ring markers with different pad diameters and lengths or radii onto each device (Fig. 1). Pads were connected with conductive copper foil that hovered 1 mm above the display surface. We tested pads with diameters of 4–10 mm in steps of 2 mm, and lengths of 10–30 mm for the Bridge markers and radii of 20–50 mm for

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[2] www.femm.info

[3] Tested devices: Apple iPad 1, 2, 3 & 4, Apple iPhone 3, 3S, 4, 4S & 5, Google Nexus 4 & 7, Perceptive Pixel 27”, MS Surface tablet, and touch pads in current Apple, Asus, Samsung & Sony laptops.

the Ring markers. Distance between pads on the Ring was always at least 10 mm. Each PUC was placed onto the display ten times, and we counted how often the display was able to detect all pads for at least 5 seconds.

The Bridge markers had a detection rate of 90–100% for pads of 7–10 mm with a minimal length of 20 mm. Below 7 mm, detection dropped to 0%. Reducing length to 10 mm shifted the 90% detection threshold to 8 mm diameter and above.

The Ring markers had a detection rate of 90–100% for pads of 6–10 mm with a minimal radius of 50 mm. Below 6 mm, detection dropped to 0%. Reducing radius to 30 mm shifted the 90% detection threshold to 7 mm diameter and above.

These results provide some design parameters when creating PUCS markers. They also show that different pad diameters can also be used to encode information if the SDK provides touch diameter data, as Apple and Perceptive Pixel do.

We excluded laptop touch pads from our experiments 2 and 3 because being opaque, their technology works somewhat differently. However, informal testing indicates that touch pads can detect even smaller PUCs down to a pad size of 2 mm.

Finally, informal observations indicate that squares or other pad shapes may confuse the touch detection algorithms, limiting PUC pads to round shapes. This is a limitation compared to visual multi-touch systems that researchers and designers should take into account.

**Long-term detection.** Many capacitive touch systems adapt their filtering algorithms to changing electrical background noise over time. Since PUCs push the limits of touch detection on these systems, they are likely to fall under this adaptation. To explore this, we left our Bridge marker from experiment 1 on an iPad 1 and on a Perceptive Pixel 27” display.

On the iPad’s one to three, all marker pads disappeared after 20 seconds at the same time, indicating a global adaptation of the detection threshold over time. We solved this problem by simulating a “permanent touch” through a conductive clip that connected one corner of the display to its aluminum back, thereby permanently grounding that touch point (Fig. 1). With the clip in place, our PUC was still visible on the iPad after 48 hours. The concept of this clip is another key insight to make PUC widgets work on real-world devices. However, this problem does not occure on the latest iPad using iOS 7.

On the Perceptive Pixel display, the markers sometimes began to disappear after 1–10 min, but always with distinct gaps of at least 10 s between each pad, indicating a local adaptation algorithm. An application could distinguish this behavior from a regular disappearance of the PUC widget, in which all markers disappear at essentially the same time. As soon as the PUC is handled again in any way, it reappears.

**Touch point count.** Commercial capacitive touch displays are frequently limited in the number of simultaneous touch points they can detect (Perceptive Pixel: 100; iPad: 11). Since a widget needs at least three touch points to encode its type, position, and orientation, this limits the number of widgets that can be used on those capacitive displays. However, if necessary this number can be increased by using active markers that encode this information with a time-multiplexed pattern instead of the spatial arrangement [7].

## CONCLUSION

We proposed *PUCs,* tangible widgets for capacitive multi-touch screens that (a) are *passive* and require no batteries; (b) can be detected even when *untouched*; (c) can be completely *transparent*; and (d) work with *unmodified* off-the-shelf multi-touch screens. Our contributions also include (e) the new approach of grounding a widget marker via a second pad or hovering conductive material plane, and (f) the solution of attaching a calibration clip to devices like the iPad to override their adaptive filtering. We hope that cutting the Gordian Knot of creating widgets with these qualities enables researchers and practitioners to explore a rich new design space of tangible interfaces for multi-touch screens.

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