PERCs: Persistently Trackable Tangibles on Capacitive Multi-Touch Displays

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ABSTRACT

Tangible objects on capacitive multi-touch surfaces are usually only detected while the user is touching them. When the user lets go of such a tangible, the system cannot distinguish whether the user just released the tangible, or picked it up and removed it from the surface. We introduce PERCs, persistent capacitive tangibles that 'know' whether they are currently on a capacitive touch surface or not. This is achieved by adding a small field sensor to the tangible to detect the touch screen's own, weak electromagnetic touch detection probing signal. Thus, unlike previous designs, PERCs do not get filtered out over time by the adaptive signal filters of the touch screen. We provide a technical overview of the theory behind PERCs and our prototype construction, and we evaluate detection rates, timing performance, and positional and angular accuracy for PERCs on a variety of unmodified, commercially available multi-touch devices. Through their affordable circuitry and high accuracy, PERCs open up the potential for a variety of new applications that use tangibles on today's ubiquitous multi-touch devices.

Author Keywords

Tangible user interfaces; tabletop interaction; capacitive multi-touch

ACM Classification Keywords

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

INTRODUCTION

Tangible objects in combination with multi-touch surfaces have been shown to be useful in a large variety of application scenarios [11], from music creation [4], to collaborative search [3], to medical teaching simulations [14]. The haptic experience and tactile feedback provided by tangibles guides user input and allows for eyes-free interaction [15]. In the past, most of these tangibles have been designed for visual multi-touch systems [15, 4]. However, since such systems are often bulky and sensitive to external lighting conditions, modern touch screens increasingly use capacitive sensing.

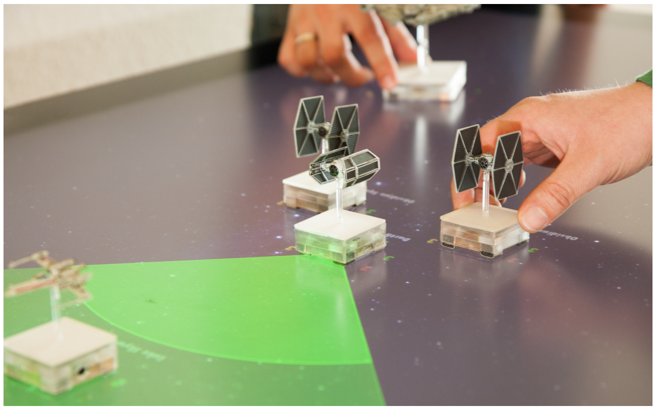

Figure 1. PERC tangibles used as Star Wars ships in an interactive board game on a capacitive touch screens.

Capacitive touch screens detect touches by creating an electric field above their surface. When an object with high capacitance, such as a human finger, comes close to the surface, this electric field changes. The touch screen measures this change and reports a touch. Tangibles on touch screens, such as Capstones [1] or TUIC [16], normally use electrically conductive material on their bottom and sides, so that a user touching them increases their capacitance enough to register as a touch. However, this means that for the tangible to be detected, the user has to continue touching it. As soon as the user releases the tangible, the capacitance drops, and the system fails to detect the tangible—even if it remains on the surface. This makes it impossible to distinguish whether a tangible has been picked up and removed from the touch screen, or whether the user has just let go of the tangible, leaving it on the touch screen.

PUCs [13] addressed this issue by introducing tangibles that ground themselves through currently inactive sensor electrodes of the capacitive touch screen, thereby increasing their capacitance beyond the detection threshold. However, most touch screens have adaptive filtering mechanisms that remove touches that have been stationary for too long. This causes the touches by stationary, untouched PUC tangibles to disappear after a short while (5–30 seconds), leading again to the problem that we cannot determine from the touch screen output

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if a tangible was actively removed from the table or merely filtered out by the system. Touch hardware and controllers also require certain minimum sizes and distances for the pads that make up a PUC footprint. Since PUCs use their footprint for identification, the number of uniquely identifiable PUCs is rather limited.

In this paper, we propose PERC tangibles, an extension of the PUCs concept. An integrated sensor in each PERC detects the signal emitted by the capacitive touch screen's electric probing field. This allows the tangible to determine whether it is currently placed on a capacitive touch surface or not, even when its touches are being filtered out by the touch system. That status is communicated from the PERC tangible to the system via Bluetooth; the communication channel also assigns a unique ID to each tangible independent of its touch pattern, solving the identification problem with PUCs. With the sensor electronics being contained in the tangible, PERCs can be used on a variety of unmodified, commercially available devices including capacitive multi-touch tables, smartphones, and tablets.

In all, this paper makes the following contributions:

1. We provide a detailed description of the concepts behind PERC tangibles, and of our prototype PERCs.
2. We report the results from a large-scale technical evaluation of PERCs on a number of unmodified, commercially available capacitive touch screens. Our evaluation included measuring the detection rate, detection time, and detection accuracy from over 70000 individual tangible placements.

SAMPLE SCENARIO AND REQUIREMENTS

Figure 1 shows a sample gaming scenario using tangibles. The game is an adaptation of the *X-Wing Miniatures*[1] tabletop board game. Two players each control a fleet of space ships, with the goal of destroying the opposing player's fleet. Each ship has specific movement patterns, weapons ranges, and talents, and is represented by a miniature that acts as a tangible. For the system to support this kind of game, for example by automatically determining and displaying if a ship's weapon can reach an opponent, the tabletop has to be able to identify each individual tangible, and continually determine its position and orientation on the touch surface with high accuracy. When a player moves a ship, it will change position rapidly. Most of the time, however, ships will be stationary.

This scenario already motivates a number of requirements for a system using tabletop tangibles:

1. At any time, the system has to be able to determine which tangibles are currently placed on the interactive surface, whether they are being touched or not.
2. Each tangible has to be uniquely identifiable.
3. The system needs to be able to detect the exact position and orientation of each tangible.
4. Position and orientation updates of fast-moving tangibles should be detected without noticeable delays.

RELATED WORK

To detect tangibles on touch screens, vision-based tracking is still a popular approach. URP [12] detects a specific dot pattern on top of each tangible. SLAP [15] and ReacTable [4] use diffuse illumination (DI) to detect reflective markers attached to the bottom of each tangible. Most of these systems fulfill all four requirements. However, vision-based interactive surfaces suffer from impaired reliability under many lighting conditions, and are mostly rather voluminous.

Because of this, several projects have explored alternative tracking technologies: Audiopad [9] attached two radio frequency tags to each tangible to determine its position and orientation. Bricks [2] uses an existing input device as a tangible. Sensetable [8] uses electromagnetic sensing to track tangibles. All of these systems fulfill the first two requirements, but not requirements 3 and 4, since they cannot detect the exact position and orientation of tangibles. Gausstones [6] track magnetic tangibles using a hall sensor grid below the touch display. Since the small magnetic tangibles can only be detected over a very short range, this technique only works in combination with thin touch screens.

Tangibles on capacitive screens can usually only be detected while the user is touching them. SmartSkin [10] showed how tangibles can be tracked on custom-made capacitive touch displays, by simulating touch points that mimic a human touch. However, these touch points can only be simulated while a user is touching the tangible. CapWidgets [5] applied this concept to commercially available capacitive touch displays such as the Apple iPad. Capstones [1] extended this concept by allowing the user to stack tangibles onto each other. To distinguish a large number of tangibles, Yu et al. [16] created active tangibles that can be uniquely identified by enabling and disabling the touch points with a specific time based pattern. All these capacitive systems violate requirement 1, since the system cannot tell if a tangible is still present on the screen or not when the user stops touching it.

In contrast to these systems, PUCs tangibles [13] can simulate touches without a user touching the tangible, due to their specific marker pattern. However, due to different filtering algorithms in capacitive touch displays, stationary PUCs tangibles are filtered out over time. This again violates requirement 1, since the system cannot determine whether a filtered tangible is still on the surface.

Our goal was to develop a concept for tangibles on capacitive touch screens that fulfill all four requirements. Our approach combines the PUCs marker design [13] with an additional sensor inside the tangible that can detect if the tangible is close to a capacitive touch screen.

PERC TANGIBLES

Our Persistently Trackable Tangibles on Capacitive Multi-Touch Displays (PERCs) build upon the PUCs marker concept [13], which has two weaknesses that have to be addressed: Firstly, without modifications, PERCs would—just like PUCs markers—suffer from the aforementioned issue that stationary touch points are eventually filtered out by the capacitive touch screen [13], prohibiting us from determin-

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[1] fantasyflightgames.com

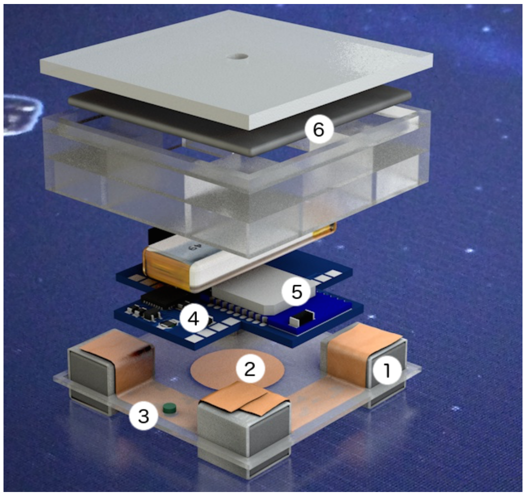

Figure 2. The six main components of a PERC tangible: (1) marker pattern, (2) field sensor, (3) light sensor, (4) micro controller, (5) Bluetooth element, and (6) lead plate.

ing if a stationary tangible has been removed from the touch screen or if its touches have just been filtered out. This problem, fortunately, only occurs if the tangible is stationary for at least several seconds. As soon as a tangible is moved across the surface, all touch points are immediately detected again. However, this behavior still breaks requirement 1. Secondly, PUCs tangibles are identified by their geometric touch pattern, limiting the number of uniquely identifiable tangibles by the size of their footprint and the number of different marker constellations that can be accommodated by it. This limits the fulfillment of requirement 2.

For our PERC tangibles, we solve these problems by adding a sensor to each tangible that detects if it is placed on a capacitive touch surface or not. During operation, this information is constantly communicated via Bluetooth 4.0 (BLE) to the system. With this approach, we are able to fulfill both requirements: PERCs communicate that they are still on the touch surface even when the touches have been already filtered out, satisfying requirement 1. Each PERC can also be identified through its own unique BLE UUID, satisfying requirement 2.

TECHNICAL IMPLEMENTATION

A PERC tangible consists of three main components: A PUCs marker pattern, the field sensor, and a light sensor (Fig. 2). In addition to these main components each PERC also includes a microcontroller, a Bluetooth 4.0 chip, a battery, and a lead plate on top of the tangible to increase the tangible's weight for better touch detection.

Marker Pattern

The marker pattern consists of three 8x8 mm pads connected via conductive copper foil (Figure 2). Each pad creates a touch point that is detected by the capacitive touch screen. For the pads, we use a soft conductive weave that is usually used as EMS shielding[2]. This has the benefit that the pads do not create any scratches on the touch surface, and that they remain in good contact with the surface.

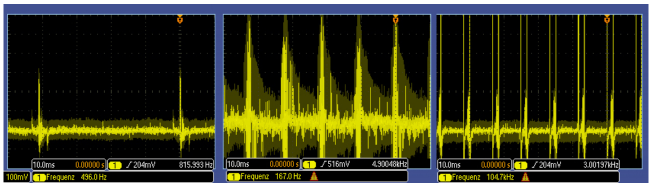

Figure 3. Touch detection signals by (left to right) iPad 4, 3M screen, and Microsoft 55" capacitive screen.

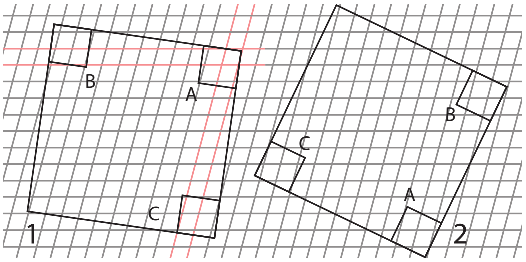

Figure 4. PERCs tangibles on the transmitter and receiver electrodes of the Microsoft 55" capacitive screen. For (1) marker a is not detectable due to the alignment of the electrodes. In (2) all markers are detected reliably.

Field Sensor

The field sensor is the part of a PERC tangible that actively determines if the tangible is placed on a touch surface at any given time or not. For this purpose, an antenna at the bottom of the tangible picks up the signature of the electric field above the surface, which is created by every capacitive touch screen. We have measured the fields of several commercially available devices (Figure 3), and found that all signals exhibit a regular pattern of strong peaks at a fixed frequency, which can be easily distinguished from the noise component of the signal. In our current implementation, the threshold of the field sensor is set to detect the capacitive touch screen if the distance between the touch surface and the tangible falls below 1 mm.

Whenever the field sensor detects the presence of a capacitive touch surface, the tangible sends a *set* event via BLE to the system. The system correlates this message temporally to newly appearing touches in order to link the UUID to the tangible's position. Since the *set* event and the touches arrive at the system within 144 ms in over 99% of the cases, setting the time window for grouping UUID and location to 150 ms eliminates most false negatives. False positive groupings that could result from multiple PERCs being set down on the table within this time window are resolved using a light sensor, as described below. Until the tangible recognizes the absence of the electric field and sends a corresponding *lift* event, the system considers it as being on the table even if its touches are filtered out.

While the combination of our marker pattern and the field sensor lets the system reliably detect which tangibles are on the surface, we found that if a PERC tangible is placed on the touch surface at certain angles, only two of the three marker

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[2] www.we-online.com

pads are detected. The reason for this is a combination of the marker pattern and the arrangement of the transmitter and receiver electrodes of the capacitive surface. Whenever a tangible is oriented as shown in Figure 4.1, the corner pad A is located at the crossing of two electrodes that are also covered by the outer pads B and C. In this case, the capacitive touch surface will not detect a touch at pad A, which is consistent with observations made by Voelker et al. [13]. Because pads B and C are still detected reliably, the system is able to determine the location and the angle of the tangible, but only modulo a 180° orientation ambiguity. Similar to the situation with multiple tangibles being placed on the capacitive touch surface at the same time, these ambiguities can be resolved using the PERCs' light sensor.

The exact angles at which pad A is not detected depend on the geometric configuration of the electrodes in the touch surface. On many common capacitive touch screens the electrodes are aligned orthogonally to each other. Therefore, for our marker setup, angles around full 90° rotations are critical. On other devices, such as our main test screen, one set of the electrodes is rotated by 15°, so the critical angles for our marker setup are shifted by this amount (see Fig. 5).

Light Sensor

The light sensor is responsible for resolving the two ambiguities—UUID assignment for mutliple PERCs that are set on the surface simultaneously and when only two of the three touches of a PERC are registered by the touch surface—that can occur during normal operation. The sensor is mounted underneath the tangible, offset to one side from the diagonal line between the pads B and C.

The off-axis position ensures two different possible locations of the light sensor when both the position and the angle of the tangible are known but the orientation is unknown. Whenever the system receives a *set* event accompanied by only two touches that have the expected distance between two touch points as B and C, the system sends a 'visual ping' to one of these possible light sensor locations by locally changing the brightness of the display momentarily. This approach is similar to how Touchbugs work [7]. If this brightness change is detected by the light sensor, the tangible communicates this via BLE to the system. Consequently, if the light sensor does not detect the visual ping, it must be located on the other side of the diagonal between the pads B and C. Either way, the system can recover the orientation of the tangible.

Note that this process is only ever necessary immediately after setting a tangible down on the capacitive touch surface at one of the critical angles, where pad A is not detected. As soon as the tangible is moved, all three pads are detected reliably, and the exact orientation of the tangible can be determined without the overhead of additional communication to the tangible. In the cases where this disambiguation procedure is necessary, the whole process increases detection duration by roughly 100 ms (see Fig. 6).

Apart from resolving the orientation ambiguity, the light sensor also serves to tell apart multiple tangibles if they where placed on the capacitive touch surface within the 150 ms time window between receiving the *set* event via BLE and detecting the touches of the tangible. In this case, a sequence of visual pings is sent—one ping to the location of the light sensor of each tangible in question—and the sequence of BLE answers resolves the UUID assignment ambiguities.

Components and power consumption

Our PERC tangibles are built from cheap, off-the-shelf components. For the current implementation, we used an MSP430G2553 microcontroller, a BLE112 Bluetooth module, a TEMD6200FX01 light sensor, and a Renata LIPO battery (3.7 V, 175 mAh). The total cost of all parts including the acrylic frame and the marker pads is less than US$25.

The tangibles operate in BLE-master/slave mode; the limiting factor for the maximum number of tangibles is the number of touches that can be detected at the same time, rather than the Bluetooth connection. We successfully connected all our 27 prototype tangibles to the PC-based system and 10 tangibles to an iPad.

PERCs have very low energy consumption: one battery charge yields approximately 60 hours of continuous use. Making the tangibles issue a warning via bluetooth when they need to be recharged would be a straightforward extension to our current prototype. Similarly, the recharging mechanism could easily be changed from cable-based to inductive power transfer, allowing the tangibles to recharge in their storage tray or box.

EVALUATION

We performed a series of automated experiments to technically evaluate the capabilities of the PERCs tangibles and the degree to which they fulfill the four requirements identified above. For this purpose, a robot (Video Figure) performed a large number of test cycles on three different capacitive touch screens: a Microsoft 55" capacitive touch screen (MS display), a 27" Perceptive Pixel display (PPI display), and an iPad 4 (iPad). Each cycle consists of setting down a PERC tangible (40 mm by 40 mm) at a specified location and angle, waiting for one second, and then lifting up the tangible before changing the angle for the next cycle. This resulted in testing 73 distinct angles at nine different positions on each touch screen.

For each cycle, we measured and logged the positions and time stamps of all touches reported by the touch screen as well as the time stamps and event types for all incoming BLE communication. Whenever the tangible was detected, the system calculated the position and angle, compared both to the expected values for the cycle, and logged the positional and angular detection errors.

The reasons for performing the experiment with a robot are twofold: First, using a robot allowed us to gather a much larger sample size of measurements and granted exact repeatability of each individual placement cycle. Secondly, when setting down the tangible manually, the parasitic capacitance of the experimenter's hand actually results in much more accurate touch locations (even though there is no conductive connection to the pads). Therefore, the experimental

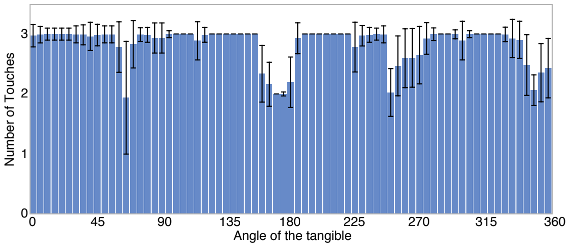

Figure 5. Number of marker points found depending of the orientation of the tangible. The Whiskers denote the standard deviation. Results were measured on the MS display.

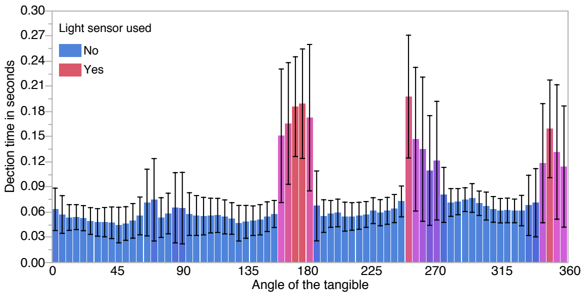

Figure 6. Average duration from receiving the information that the tangible is close to a capacitive screen via BLE until the tangible is correctly detected. The red colored bars indicates the usage of the light sensor to determine orientation of the tangible. The whiskers denote the standard deviation. Results were measured on the MS display.

setup we used allows us to give a very conservative 'worst case' estimate for the detection accuracy of the system.

For this evaluation, we ran the 65700 cycles on the MS display (900 per angle) at nine different positions on the screen. In addition to that, we performed 2190 cycles on both the iPad and the PPI display (30 trials per angle). This adds up to a total amount of over 70000 trials; given an average number of 64 detection reports from the touch screens over each cycle, we recorded about 4.4 million data points.

Results

The detection rate of our newly introduced field sensor was at 100 % across all trials and all touch screens. The field sensor was always able to detect if a tangible was placed on the surface and if it was lifted from the surface. The average time difference between the *set* event and the *lift* event is 1.3 s with a standard deviation of 0.038 s.

As expected, the detection rate of the PUCs marker points depends on the angle of the tangible. As shown in figure 5, around 75°, 165°, 255° and 345°, sometimes only touch points for pad B and C are detected. On the iPad and the PPI we found similar results at 0°, 90°, 180° and 270°. As explained earlier, these angles reflect the alignment of transmitter and receiver electrodes of the capacitive surface.

The average detection duration reflects the use of the light sensor and the additional communication overhead in these cases. Figure 6 shows the detection duration for successfully detected tangibles, cases where the light sensor had to be used are highlighted in red.

Display	Detection time	Detection time (light sensor)	Position error	Angle error	Single touch detection
MS	50ms	190ms	1.5mm	-0.78°	2.2%
PPI	65ms	176ms	2.1mm	-1.84°	2.5%
iPad	55ms	167ms	2.5mm	-1.94°	3.5%

Figure 7. Average measurements of the evaluation.

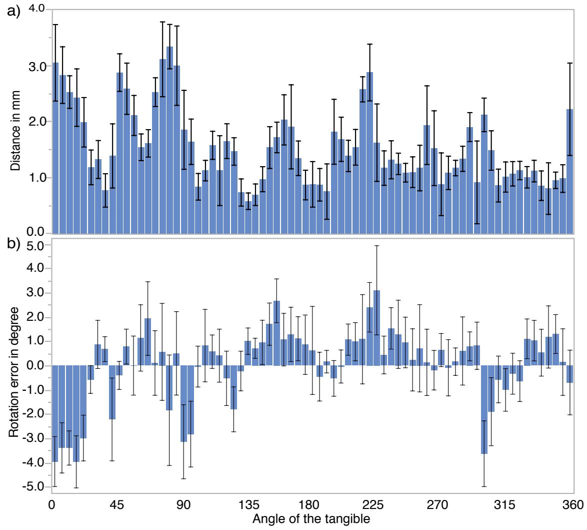

Figure 8. Average tangible position (a) and rotation (b) error depending of the orientation of the tangible. The whiskers denote the standard deviation. Results were measured on the MS display.

The average detection time if all three markers were detected, the detection time if the light sensor was used, the displacement and angular errors, and the percentage of trials in which only one marker was detected for all three tested touch displays are show in Figure 7. More detailed results are show in Figure 8. These results suggest that the displacement and the angular error of a tangible depends on the orientation of the tangible.

Discussion

From the evaluation of the PERC tangibles, the following observations can be made:

Regarding requirement 1, PERCs can reliably detect (with 100 % accuracy) if they are located on a capacitive touch surface. Through the application of the PUCs marker concept, about 98 % of the tangibles are correctly detected on a MS display. This detection is independent of user's touch since we use the PUCs technology to create the touch points. Our newly introduced field sensor counters the problem of stationary touch points being filtered out over time. Therefore, our system can reliably decide if a tangible was removed from the surface or just filtered out.

PERCs also fulfill requirement 2, since every tangible has its own Bluetooth UUID. If two *set* events occur at very close temporal proximity, the light sensor acts as a fallback mechanism for disambiguation. Therefore, our system is able to uniquely identify each tangible at any given point in time.

Position and angle of PERCs can be detected with high fidelity: the mean position error on the MS display is 1.5 mm, the mean angular error is -0.78°. Therefore, PERCs fulfill requirement 3. Both, position and angular accuracy can be further improved upon by employing machine learning algorithms to the collected results.

Requirement 4 is fulfilled as well, since all three of a PERC's touch points are reliably detected as soon as the tangible is moved over the capacitive surface. At this point, positional and angular information are obtained directly from the touches, which are updated with the capacitive touch surface's scan rate. The tracking performance for fast moving tangibles can possibly be even further improved on by employing predictive filtering mechanisms based on dynamic movement models (e.g., kalman filters).

SUMMARY AND FUTURE WORK

In this paper, we presented PERCs, Persistently Trackable Tangibles on Capacitive Multi-Touch Displays. PERCs are detected even when they are not touched by a user and, unlike previous designs, they do not get filtered out over time by the adaptive signal filters of the touch screen. This is achieved by adding a field sensor that detects the electric field of the touch surface. PERCs can be easily and affordably constructed from off-the-shelf components, and they work on a variety of commercially available touch screen models.

While we were able to show that PERC tangibles can be reliably detected on a number of common capacitive touch screens, there is still potential to improve upon their accuracy and detection rate. For example, we plan to apply machine learning algorithms to minimize the displacement and angular error during the tangible detection. A more detailed look into how the pattern of detected markers is geometrically skewed on different touch surfaces and at different angles could yield more precise estimations for the tangibles' positions.

Since the different touch screen models exhibit specific characteristics in how they pulse their electric field, the field sensor could be used to detect on which touch screen model a tangible is currently placed. This would allow us to adapt thresholds, timeouts and error correction functions specifically tuned for each screen model.

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