

TUIC: Enabling Tangible Interaction on Capacitive Multi-touch Display

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ABSTRACT

We present *TUIC*, a technology that enables tangible interaction on capacitive multi-touch devices, such as iPad, iPhone, and 3M's multi-touch displays, without requiring any hardware modifications. TUIC simulates finger touches on capacitive displays using passive materials and active modulation circuits embedded inside tangible objects, and can be used with multi-touch gestures simultaneously. TUIC consists of three approaches to sense and track objects: *spatial*, *frequency*, and *hybrid (spatial plus frequency)*. The spatial approach, also known as 2D markers, uses geometric, multi-point touch patterns to encode object IDs. Spatial tags are straightforward to construct and are easily tracked when moved, but require sufficient spacing between the multiple touch points. The frequency approach uses modulation circuits to generate high-frequency touches to encode object IDs in the time domain. It requires fewer touch points and allows smaller tags to be built. The hybrid approach combines both spatial and frequency tags to construct small tags that can be reliably tracked when moved and rotated. We show three applications demonstrating the above approaches on iPads and 3M's multi-touch displays.

Author Keywords

TUI, tangible, tags, multi-touch, 2D marker, frequency tag, physical interaction, interactive surface

ACM Classification Keywords

H5.2 [Information interfaces and presentation]: User Interfaces: Input Devices and Strategies, Interaction Styles.

General terms: Design, Human Factors

INTRODUCTION

Tangible user interfaces (TUI) enable users to interact with digital information by directly interacting with physical

objects [11,12]. Multi-touch interface, another type of direct manipulation interface, can be combined with tangible user interface to provide seamless information representation and interaction that span both the physical and virtual worlds. Recent examples include Lumino [2] and SLAP Widget [30] that support tangible interaction on diffuse illumination (DI) tabletop systems. Diffuse illumination tabletop is a vision-based system that uses infrared (IR) light sources and IR cameras below the interaction surface to “see” finger touches and tangible object's markers [6,22,24].

Capacitive multi-touch displays are thinner and lighter than vision-based systems, and have enabled multi-touch interaction on mobile devices like iPad, iPhone, Google Android devices, and on desktop devices like 3M's 22-inch multi-touch displays. Because capacitive sensing technology is optimized to detect finger touches, current approaches to object sensing require additional sensors or cameras to be added. For example, Wacom's “pen and touch” tablets use electro-magnetic resonance sensing panels under the capacitive touch panels to sense pen input.

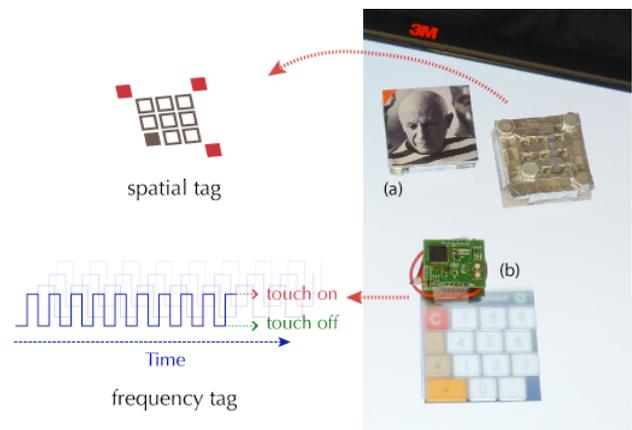


Figure 1: Examples of tangible objects embedded with TUIC tags, on unmodified capacitive multi-touch displays.

This paper presents TUIC, which enables tangible interaction on unmodified capacitive multi-touch panels. TUIC uses passive materials and active modulation circuits to simulate multi-touch gestures. These multi-point patterns

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and gestures are designed to be easily distinguishable from human gestures, and to encode object IDs. TUIC tags can be embedded inside tangible objects to sense the objects' identification, movement, and rotation.

There are several challenges to enable object sensing and tracking on unmodified capacitive multi-touch panels. The first challenge is creating self-contained tags that can simulate finger touches. TUIC creates capacitance change using both a passive approach and an active approach. One possible passive approach uses a coil coupled to an electric-conduction element to conduct current away from capacitive touch panels [4,16]. The active approach uses a battery-powered modulation circuit to simulate a finger touching and un-touching the panel.

The second challenge is reliable object identification and movement/rotation tracking. TUIC consists of three approaches to sense and track objects: *spatial*, *frequency*, and *hybrid (spatial plus frequency)*.

The *spatial approach*, called TUIC-2D, uses multi-point patterns to encode object IDs. TUIC-2D uses 3 registration points plus one or more payload points to encode its ID. The touch points are placed at a pre-defined distance and angle to make the patterns distinguishable from human gestures. Although the spatial tags are straightforward to construct using passive circuits, they require several touch points per tag. Capacitive multi-touch devices have a limitation on the total number of concurrent touch points (e.g. 10 for iPad and 20 for 3M), which places a limit on the total number of tags that can be used concurrently. In addition, there is a minimum distance required between each touch point (e.g. 0.5cm for iPad). For example, a 4-bit TUIC-2D tag is at least 2cm in size and uses up to 7 touch points.

In order to minimize the number of touch points required per tag, the *frequency approach*, called TUIC-*f*, encodes tag IDs in the time domain. Because the response rate of capacitive touch sensing is relatively fast (e.g. 15ms for iPad), the TUIC-*f* tags use a modulation circuit to generate high-speed touches in varying frequency that correspond to different tag IDs. The single touch point used by a TUIC-*f* tag, however, does not support tag orientation and rotation. In addition, fast movements of the tag may be difficult to distinguish from human gestures, making TUIC-*f* best suited for static objects.

The *hybrid approach*, called TUIC-hybrid, addresses these frequency tag issues by adding two positioning points to a frequency tag. The two positioning points enable movement and rotation tracking, while the frequency tag provides the ID.

To demonstrate the feasibility of three approaches, we have evaluated the three approaches on two different capacitive multi-touch displays, the Apple iPad tablet and the 3M M2256PW display. In addition, we implemented one application demonstrating each of the approaches.

Our contributions include the following: (1) TUIC enables object identification, sensing, and tracking on unmodified capacitive multi-touch panels by simulating and recognizing multi-touch gestures, (2) TUIC introduces the concept of frequency and hybrid tags, (3) TUIC supports simultaneous multi-touch gestures and tangible interaction on capacitive multi-touch panels.

The rest of the paper is organized as follows: The Related Work section describes prior object tracking approaches and the fundamentals of capacitive sensing technology. The Design and Implementation sections present the details of spatial, frequency, and hybrid tags, and their implementations on iPads and 3M's displays. We present three demo applications in the Application Examples section, and extensions to TUIC in the Discussion section. Since the benefits and user aspects of tangible interactions are well understood [2,9,13,24,32], we do not present a user study of tangible user interface in this paper.

RELATED WORK

We describe related work on object tracking technologies for TUI, the fundamentals of capacitive touch sensing, and TUI application on tabletops.

Object tracking solutions for tangible computing

For tangible user interfaces, vision-based tracking is the most popular approach. Domino Tag [18] uses a pattern of four positioning dots and eight payload dots for 8-bit IDs. It is designed to track objects placed on the Microsoft Surface, which is a diffuse illumination (DI) tabletop system. Both ARTag [6] and QR Code [22] are bi-tonal systems of square 2D markers, with interior region filled with matrices of black and white cells encoding their content. The location and presence of an ARTag is detected via its solid, black borders and a QR Code is detected via the three positioning points on its corners.

There are several other object tracking technologies. Bricks [7] use pulsed direct-current magnetic sensing and simulate graspable objects. Sensetable [20] tracks objects via electromagnetic sensing. mediaBlocks [26] embed distinct electronic ID tags inside each mediaBlock. Audiopad [21] attached two radio frequency tags on each puck to determine its position and orientation. Dolphin [17] uses of ultrasonic transmitters and receivers to locate people and the objects they interact with.

Capacitive sensing technologies

The capacitive multi-touch panels sense the change of capacitance by capacitive coupling effect [33]. There are two major types of capacitive touch technology: surface capacitive and projected capacitive. Surface capacitive touch panel is coated with conductive layer on one side of the insulator, and small voltage is applied to the layer. Once a conductor, such as human finger, touches the other side of insulator, a capacitor is formed. By means of measuring the change of capacitance from the four corners of the panel,

the panel's controller can determine the location of the touch. Currently, multi-touch devices are generally made by projected capacitive technology (PCT) [1]. Single conductive layer of X-Y grid or two separate, orthogonal conductive layers are etched on projected capacitive touch panel. The multi-touch controller of PCT sense changes at each point along the grid. In other words, every point on the grid generates its own signal and relays multi-touch points to the system. smartSkin [23] used capacitive sensing and a mesh-shaped antenna to detect multiple hand positions and object's shapes. Diamondtouch [5] developed at Mitsubishi Electric Research Laboratories, is another interactive table system based on capacitive sensing and supports the ability to distinguish among multiple users.

TUI applications on tabletops

Many pioneering projects have developed a variety of tangible applications on horizontal surfaces [21,27]. Sensetable [20] have physical dials and modifiers that can be plugged into objects to change the state of the objects. It allows users to share data between the tabletop interaction interface and the on-screen WIMP interface. reacTable [14] is a collaborative musical tabletop that allows several musicians to share the platform and control the instruments to perform. Urp [28] uses miniature architectural structures as tangible representation of digital building models, and those miniatures also serve as physical controller to configure underlying urban simulation of shadow, wind, etc. In PlayAnywhere [31], the camera identifies specific pattern and user's shadow to provide direct interaction. Then the system augments graphics model by a front projector. Manual deskterity [10] is a prototype digital drafting table that supports both pen and touch input. They explored the simultaneous use of pen and touch to support novel compound gestures. Lumino [2] demonstrates the tracking technology in 3D structures on tabletop surface and provide both multi-touch and tangible interactions seamlessly on an unmodified diffuse illumination table. SLAP [30] widgets introduced transparent tangibles that allow users get tactile feedbacks and see displays beneath them. However, the "footprints" of SLAP widgets required several markers of foam to be identified by the touch surface system which could limit the feasibility to further identify objects in smaller size due to restricted space. VoodooIO [3] is a system that allows users to construct their own physical interaction spaces to fit their personal preferences and requirements. It consists two main parts -- Voodoo Pins and a flexible substrate material on which users can freely pin Voodoo Pins to suit their purposes.

DESIGN

We present three types of tag designs, spatial, frequency, and hybrid, and describe each one's strengths and limitations.

1. Tag design based on spatial domain

The spatial approach, called TUIC-2D, uses a layout similar to vision-based systems like QR Code. Figure 2 shows a comparison of QR code and TUIC-2D. A TUIC-2D tag contains 3 positioning points, which have to be at a pre-defined distance at a 90-degrees angle, so that human gestures can be easily distinguished from a tag. These positioning points are also used to determine the orientation. The touch points inside are payload bits, with each touch point representing one bit. As an example, Figure 2c shows a TUIC-2D tag that can encode 9-bits of data, or 512 different object IDs.

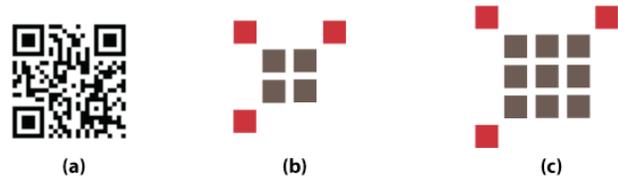


Figure 2: (a) QR code, (b) TUIC-2D: 4-bits tag, (c) TUIC-2D: 9-bits tag

TUIC-2D tags can be constructed using passive materials that are easy to maintain (e.g. a conductor such as a screw). Also, it can be detected as soon as it's placed on the capacitive panel. The quick detection time is important for interactions that require quick initial response time to insure perceptual coupling of physical objects to virtual world [11]. However, the spatial approach has two limitations. First, current capacitive devices such as Apple iPad and 3M's multi-touch displays support a limited number of simultaneous touches ranging from 10 to 20. This limits the number of spatial tags that can be used simultaneously. Second, these devices only report touch points that are at least 0.5-1cm apart, which puts a lower limit on the tag size.

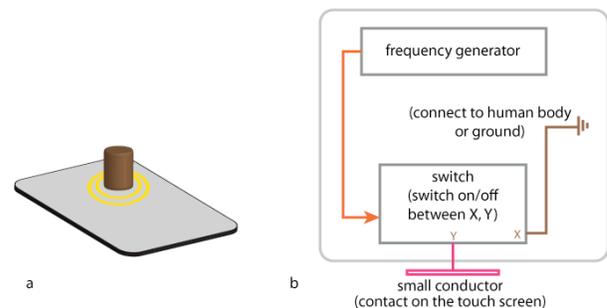


Figure 3: (a) a frequency tag on a touch panel, (b) a block diagram of modulation circuit that simulates high frequency touches.

2. Tag design based on time domain

The frequency approach, called TUIC- f , utilizes the fast response time supported by capacitive touch sensing. It encodes data in the time domain by simulating finger touches at the same location at various frequencies. Figure 3 shows the block diagram of the active modulation circuit

we have designed. The modulation circuit simulates high-frequency touches, and can control the touching (*on*) and un-touching (*off*) intervals.

Figure 4 shows that we collect m complete touch (on) and un-touch (off) cycles in time window W . T is the interval of each on and off phase, so a complete cycle is $2T$. Each unique T value is mapped to an ID. For example, $T_1=15\text{ms}$ represents ID=1, $T_2=20\text{ms}$ represents ID=2 and, so on. The largest value of T depends on the number of IDs that needs to be represented as well as the capacitive panels' timing resolution and consistency.

To ensure reliable detection, the first cycle is discarded because it may be incomplete. Also, m sets need to be observed to reduce the effect of measurement noise, and to ensure human are unlikely to accidentally touch the same pattern. With T_n representing the longest T , the longest wait time is $T_n * m$.

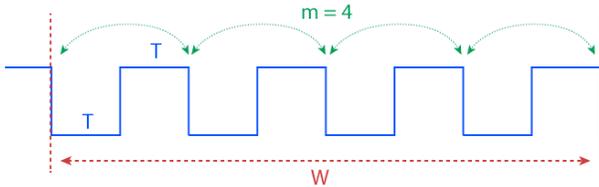


Figure 4: The concept of fixed-length touch frequency

There are two advantages of an active frequency tag. First, only a single touch point is required to encode data, enabling more tags to be used simultaneously. Also, it is possible to build a tag with a smaller footprint. Second, a tag can change its frequency dynamically and the corresponding object ID or state. This enables the tag to represent a button or a dial, supporting the types of tangible interaction in Sensetable and SLAP, for example.

There are several limitations to frequency tags. The first is the delay in sensing object IDs because several cycles may need to be observed. Second, fast movement causes a second touch point to be registered at a different location, and is difficult to distinguish from a human gesture. Third, a single touch point cannot provide orientation information. Since movement and rotation are important tangible interactions, we address these with hybrid tags.

3. Combining spatial and frequency tags

The hybrid approach combines spatial and frequency tag, with the spatial touch points providing the tag's position and orientation and the frequency tag providing its ID. Figure 5 shows the TUIC-Hybrid design with two positioning points accompanying one frequency tag. The physical tag boundary prevents interference from nearby touch points.

TUIC-Hybrid enables reliable tracking of tag movement and rotation, and requires a fixed, smaller number of touch points than TUIC-2D. For example, the 3M display

supports 20 simultaneous touch points, and up to six TUIC-Hybrid tags can be used at the same time as two-finger gestures such as zooming in and zooming out.

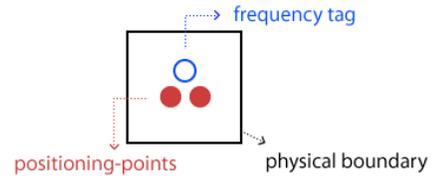


Figure 5: TUIC-Hybrid tag design that uses two positioning points and a frequency tag

IMPLEMENTATION

In this section, we describe the details of implementing the three TUIC approaches on two popular capacitive multi-touch devices: Apple iPad with 9.7-inch and the 22-inch 3M M2256PW Multi-Touch Display. The specific iPads we have evaluated are model MB292LL (the 16GB WiFi version) and run iOS 3.2. The iPad applications are written using the native CocoaTouch APIs included in iOS SDK 3.2. The 3M multi-touch display is driven by a PC with Intel Core 2 Duo T5450 CPU and 2GB RAM running Windows 7 Ultimate. The applications are written using Flash CS5 and the GestureWorks multi-touch gesture library.

TUIC-2D

Figure 6a shows TUIC-2D, which is a spatial tag design similar to 2D marker in vision-based systems. We have implemented a TUIC-2D tag containing a 5x5 grid of touch points within a square frame. Figure 6b shows three registration points, C_0 , C_1 , and C_2 , which are located in the corners of the grid and are used to determine location and orientation of the TUIC-2D object. Inside the payload area is a 3x3 grid of touch points, B_0 to B_8 , which can encode 9 bits of binary values. B_0 and B_8 represent the least-significant bit (LSB) and the most-significant bit (MSB), respectively.

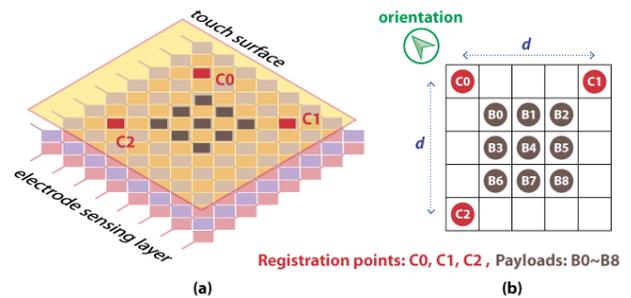


Figure 6: (a) TUIC-2D tag detected on capacitive multi-touch panel, (b) TUIC-2D tag design

Current capacitive touch screens like those used in iPad and iPhone are optimized for finger touches, and have a threshold on the minimum distance between two detected

touches. Capacitance readings separated by that threshold distance are reported as two distinct touch points. The threshold distance directly affects how closely we can place the simulated touch points and the resulting size of TUIC-2D tags. From our experiments, we have found the minimum distance between two reported touch points is 1.0cm on the 3M display and 0.5cm on iPad. As shown in Figure 7, the sample tag we made for the 3M display measures 5cmx5cm in size. The tag size, however, may be reduced if we are able to directly process the raw capacitance readings from the touch screen devices.

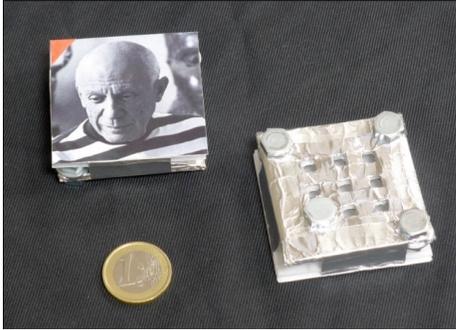


Figure 7: The real size of TUIC-2D tag

To recognize a TUIC-2D pattern, we have modified the multi-touch gesture in the open source gesture library from GestureWorks[8]. Figure 8 shows the state diagram of the TUIC-2D tag recognition algorithm. The detail of each state is described in the following paragraph.

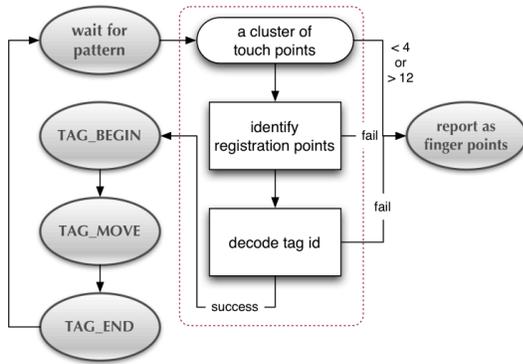


Figure 8: The state cycle of TUIC-2D

Wait for pattern

When a cluster of touch points is detected, we first check to see if the number of touch points is great than or equal to 4, which is the number of registration points plus one payload point. One or more payload points is required because we found users could accidentally trigger tag ID=0 by putting 3 fingers in predefined length, where as 4-finger gestures in the TUIC-2D pattern are extremely rare.

Identifying TUIC-2D tag registration points

To recognize TUIC-2D tags from touch points reported, we search for trios of touch points that have a geometry of the

right triangle as shown in Figure 6b, and report these trios as registration points. For each trio, touch points contained in the payload area created by the trio are used to decode the tag ID. Since the corner points are located outside of bit points, we check the distance of each pair of points from the three outside points. If the three distances are equal to d , d , and $\sqrt{2}d^2$ (Figure 6b), we have identified C_0, C_1, C_2 . If not, all touch points in the cluster will be reported as finger touches.

Decode tag id

If the registration points have been identified, we then extract a binary series from B_0 to B_8 in the payload area. B_0 is reported as 1 if there is a touch point found underneath the position. The tag ID then is decoded as $B_0 \cdot 2^0 + B_1 \cdot 2^1 + B_2 \cdot 2^2 + B_3 \cdot 2^3 + B_4 \cdot 2^4 + B_5 \cdot 2^5 + B_6 \cdot 2^6 + B_7 \cdot 2^7 + B_8 \cdot 2^8$. Given the 9 bits in the payload, the ID values range from 1 to 511.

Dispatching tag events

Tags recognized are in one of the three states: Tag_Begin, Tag_Move, and Tag_End. Once the tag ID has been decoded, the tag enters Tag_Begin state and reports the tag ID, the location of the tag center, and the tag orientation. We track the movement of registration points (C_0, C_1, C_2) and report Tag_Move events with the updated location and orientation. If the tag is removed from the touch screen, a Tag_End event state is reported along with the tag ID.

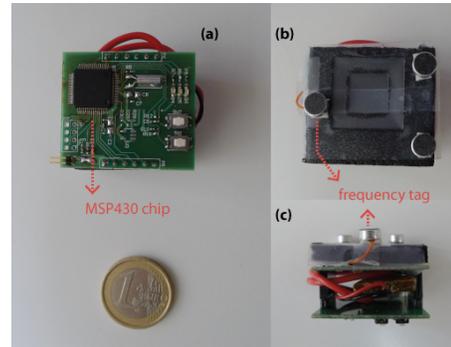


Figure 9: Modulation circuit with a built-in battery. (a) front view, (b) back view: one point is used for frequency tag, the other two are only used for support (c) side view

TUIC-Frequency

In order to generate touches in different frequencies, we have built an active modulation circuit, which is programmed using the IAR Embedded Workbench. The circuit diagram of our prototype is shown in Figure 3b. We choose the Texas Instruments MSP430 chip because its ultra-low power consumption. The battery-powered circuit controls the relay to on and off. The “on” signal conduct the frequency tag to human or ground end, to simulate a finger touch, as well as “off”. As shown in Figure 9, the size of the modulation circuit board is about $2 \times 3 \times 3 \text{ cm}^2$.

Experiments of frequency tag

We have tested the active modulation circuit on both iPads and 3M displays, varying the on/off interval T between 10ms to 45ms by 1ms. We collected 200 samples for each interval, which is 100 complete cycles. Figure 10 shows the measured interval values versus the input interval values on an iPad. The top charts show the “on” intervals and the middle charts show the “off” intervals. We have found that the measured intervals for both “on” and “off” signals vary significantly from the input signal sent by the modulation circuit. This might be caused by processing delay introduced by the software stack on the touch screen devices. We repeated the same experiment on 3M display and another iPad, and observed similar results.

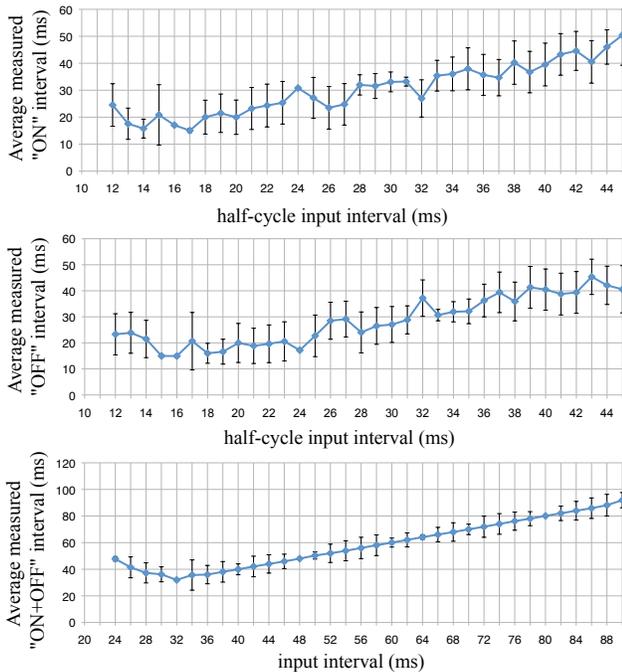


Figure 10: Average measured interval collected in iPad

As shown in the bottom charts in Figure 10, combining both the “off” and “on” intervals into a complete “off+on” cycle significantly reduces the measured variance for both the iPad and the 3M display. Our experimental results showed that the minimum interval is 15ms on the iPad, 12ms on the 3M display. We selected half-cycle interval values that can be reliably identified within a window: 15ms, 20ms, 25ms, 30ms, 35ms, 40ms and, 45ms averaged from a 5-cycle time window. Such a tag can represent IDs from 1 to 7, which is equivalent to a 3-bit TUIC-2D tag, and has a maximum startup delay of $45\text{ms} \times 2 \times 5 = 450\text{ms}$.

Because of the wait time, frequency-based tags are more suited for interactions that can tolerate a slight initially delay. For example, placing a miniature building to bring up its architectural model. In order to provide feedback during the wait time, we have designed an UI hint to inform users that the system is still functioning. Figure 11 shows

an animated progress ring appearing after a user puts a tangible object on the display. Once its ID is successfully detected, the ring fades while the system executes the appropriate actions.



Figure 11: Animated progress ring appears around the tangible object while the frequency tag is being identified

TUIC-Hybrid

The TUIC-Hybrid tag is an enhanced version of TUIC- f tags. As shown in Figure 12, we have added two spatial touch points next to one TUIC- f tag to indicate the orientation and help with movement tracking. The three touch points are arranged in an equilateral triangle in order to obtain reliable tracking of its orientation and location.

We have implemented two power saving techniques to reduce the power consumption. The first is a pressure-based power switch under the tag, and the second is a 1-second timeout for the modulation circuit. When a user holds the object in the air, the automatic power switch turns off the active circuit. When a user puts the object on a surface, the power switch is pressed by the object’s own weight, and activates the frequency tag. The modulation circuit is active for 1 second then stops the relay at the ground end, turning the frequency tag into a static touch point. The three static touch points can then be tracked for position and orientation.

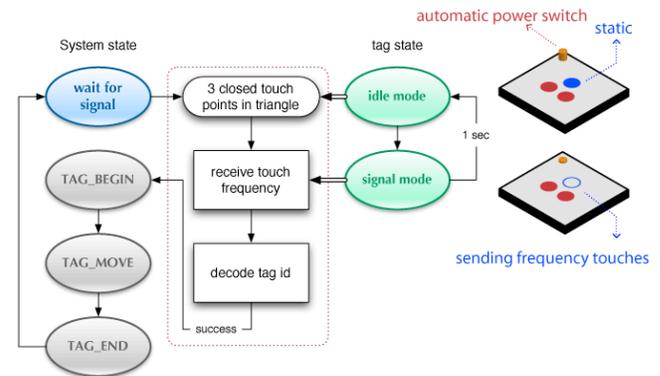


Figure 12: The state transition diagram of TUIC-Hybrid and the bottom view of a TUIC-Hybrid tag

Our prototype has a current consumption of 1.3mA (off) and 27.9mA (on). Therefore, the continuous run time of the active tag with 120mAh/3.7V battery is about 8.2 hours. Using our power-saving techniques, which keep the hybrid tag active for up to 1 second each time it is placed onto the

display, the battery can last approximately 90 days at 50 uses per day and 1 minute per use. The relays used in the current version of our prototype are big, noisy and power-consuming. We had experimented with a single BJT to replace the relay, and found that the BJT did not work. One possible explanation is that the offset voltage is 0.7V on the collector of BJT, which may be greater than the voltage on the drive electrode. We will continue to explore other circuit designs to improve the tags' size and power consumption.

APPLICATION EXAMPLES

We have developed three applications with tangible user interfaces to demonstrate the feasibility of the three TUIC tag designs. We describe user feedback at the end of each application.

Chronicle of famous painters

We implemented a tangible user interface for museum exhibitions to demonstrate that tangible objects work simultaneously with multi-touch gestures. Visitors can place tiles of famous painters on a kiosk to bring up their chronicle and associated paintings. The chronicle under the tile can be changed to different periods by rotating the tile. When users remove the tile, the paintings fade out and the kiosk returns to showing an introduction of the exhibition.

In a museum setting, the tangible object used in exhibitions should be unpowered and low maintenance. Therefore, we have selected TUIC-2D tags to implement this application. We used 9-bit tags to represent different famous artists including Pablo Picasso and Vincent van Gogh, as shown in Figure 13.



Figure 13: Chronicle demo that can support tangible and multi-touch interaction simultaneously

Users who used the kiosk commented that it was intuitive to use the tangible tiles to view each artist's paintings. Furthermore, switching between different artists was more efficient using the tiles without having to read, understand, than select menus or icons on the screen. Tangible user interface also reduced the UI elements necessary on the screen, which saved space to display more content on the capacitive touch screen that is smaller to typical tabletop systems.

Slap-on keypad

The SLAP keyboard [30] uses a thin, translucent skin to provide haptic feedback when typing on virtual keyboards on diffuse-illumination tabletop. We used TUIC-Hybrid tags to implement similar functionality on capacitive multi-touch screens, and added a physical frequency switch for switching between different keyboard layouts.

As shown in Figure 14, the frequency tag is attached to the corner of a translucent skin, and another fixed marker is used for tracking its position and orientation. As the system recognizes the skin's ID, location, and orientation, it properly displays the corresponding virtual keypad for a calculator.

We have extended the TUIC-Hybrid tag by adding two physical frequency switches on top of the tag. The switches change the frequency generated by the modulation circuit, change the calculator keypad to a character keyboard and change the LED to illuminate in different colors.

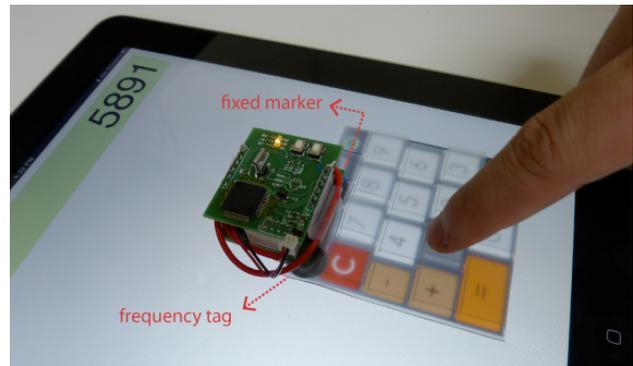


Figure 14: Slap-on keypad on capacitive multi-touch screen

Authentication key

In general, users encounter two problems while keying the PINs or passwords on mobile devices such as iPhone or iPad. First is pressing the wrong keys on the virtual keyboards. Second, entering passwords in public space, like a bus or elevator, potentially exposes the passwords to bystanders.

We use TUIC tags as authentication keys to replace PINs and passwords. In this scenario, users can carry these tags, say fastened to a keyring, and simply place the tags on a device's display for authentication. In addition, the key assures contact-based, secure authentication that prevents remote attacks. For example, vision-based tags can be easily viewed and copied, and RFID-based tags can also be read from a distance by an adversary using powerful readers.

By using multiple frequency tags embedded in an object, we can increase the amount of data encoded. For example, we can use 10 frequency tags, each with 7 possible frequencies, to represent 7^{10} bits. Applying the concept to authentication, we can create a tangible, authentication key equivalent to an 8-digit PIN. Such physical authentication

can be used in addition to manual PIN entry to further enhance security. Figure 15 shows an example application using an authentication key made with TUIC-*f* tag. When a user places it on the multi-touch screen, it unlocks protected documents for the user to access.

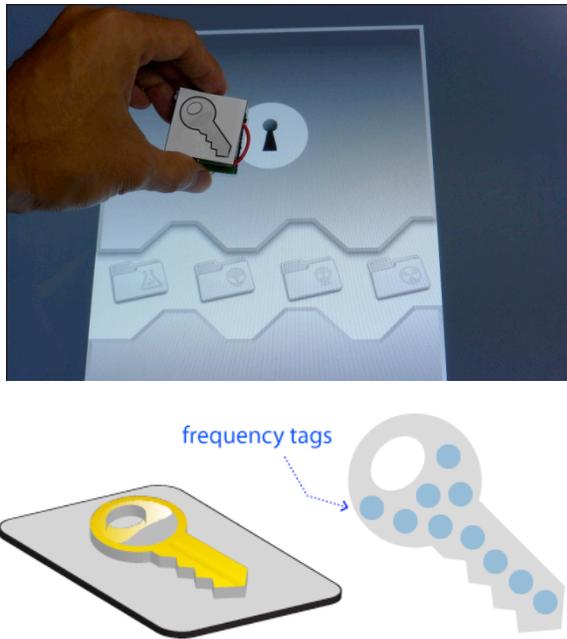


Figure 15: (top) Unlock secured files using an authentication key (bottom) The concept of authentication key with 10 frequency tags

Users liked the simplicity of using tangible authentication keys without having to enter anything using keyboards, but found the startup delay noticeable and distracting. We plan to improve the startup delay, and design appropriate UI to give user instant feedback and also show authentication progress.

DISCUSSIONS

We summarize and compare the three TUIC tag designs in Table 1. TUIC-2D has advantages of instant detection and is unpowered. Its movement and orientation changes are also easy to track. On current capacitive panels, the TUIC-2D tag is relatively large, and is proportional to the square root of the number of bits it needs to encode, as well as the minimum distance between two touch points. We believe the minimum distance can be reduced if the lower-level capacitance readings are accessible. The main disadvantage of TUIC-2D is that it requires many touch points per tag. The maximum number of touch points required is equal to the number of bits needed plus the three positioning points. This reduces the number of objects that can be used simultaneously. For example, only two to three 4-bit tags can be used on the 3M display, which currently supports the highest number of touch points of 20.

The TUIC-*f* and TUIC-Hybrid have active modulation circuits that enable them to change the IDs they encode, making it possible for the objects to be stateful. They also require fewer touch points than TUIC-2D. The concept of frequency tag could be extended to other systems such as resistive touch panels. Although the method to simulate a touch would be different, it provides an opportunity to enable object sensing on different sensing surfaces. However, frequency-based tags have a startup delay caused by encoding interval and jitter in the timing measurements. The delay is proportional to the number of reliably distinguishable intervals. We plan to try alternate approaches to select intervals, such as choosing intervals that are further apart that need fewer cycles to correctly distinguish them. As multi-touch panels improve their response rate and reduce jitter overtime, the delay may be shortened.

The coding technique we have proposed is easy to implement but leaves room for improvement. We plan to experiment with additional coding algorithms to encode more bits in less time, which should also help reduce the startup delay. We plan to collaborate with panel manufactures to gain access to lower-level panel signals to optimize frequency coding and 2D tag layout. Another disadvantage of frequency tags is that they require power. Timeouts and pressure-based power switches are two techniques that should dramatically reduce the duty cycles to extent their lifetime.

Tag design	TUIC-2D	TUIC- <i>f</i>	TUIC-Hybrid
Max # of IDs	2^n n: # of payload bits	n^m n: # of distinct intervals m: # of frequency tags	
Minimum Touch points	4	1	3
Size	Proportional to the minimum touch points and the resolution of touch sensors		
Power requirement	Passive	Active	
Orientation	Yes	No	Yes
Moveable	Yes	No	Yes
Robustness	Instant on	Startup delay is proportional to n.	
Important features	Unpowered	ID can be changed.	

Table 1. Comparison of TUIC tag designs

To compare different TUI technologies, Shaer and Hornecker [19] evaluated them in several dimensions and compared RFID, computer vision (CV) and microcontrollers. Here we summarize their properties and compare them with TUIC tags. In terms of physical

properties detected by sensors, TUIC-2D based on the 2D pattern inherits benefits of vision-based tags where the id, presence, orientation and position can be recognized. Because the TUIC-*f* and TUIC-hybrid are made by microcontrollers, the sensed physical properties can be extended by external sensors such as light, motion, or temperature. In terms of cost, TUIC-2D tags are as cheap as RFID and vision-based tags, but RFID and CV need a reader or a high-quality camera. We can remove the microcontroller in current prototype of TUIC-*f*, if the tag doesn't need to have programmability, thus the cost will be significantly lower in commercial production. In terms of performance, TUIC-2D tags work in real time just like RFID and is as accurate as vision-based tags and without the motion blur issues when tracking moving objects. TUIC-*f* and TUIC-hybrid have a startup delay proportional to the number of id encoded. In terms of aesthetics, TUIC tags are much bigger in size than RFID and vision-based tag. Since the size of TUIC tags is proportional to the resolution of capacitive touch screen, we expect it could be made much smaller with access to lower-level sensing data. In terms of robustness, reliability, setup and calibration, RFID can only be embedded in materials opaque to radio signals. CV might be affected by lighting condition, occlusion, lens settings, and projector calibration. TUIC-*f*, TUIC-hybrid have a drawback as other microcontrollers, they are powered by batteries. Regarding scalability, the number of TUIC tags that can be used simultaneously is limited by the maximum number of concurrent touch points sensed by capacitive display. For RFID, the number is limited by the reader.

POTENTIAL INTERACTIONS AND FUTURE WORK

Capacitive multi-touch displays have been rapidly adopted in recent years thanks to its direct manipulation interface. Its thin form factor and lightweight makes it especially ideal for portable devices. We propose the concept of clip-on widget, as shown in Figure 16 that physical controls are attached on the portable touch device while the TUIC-*f* tags are arranged on its inward side to contact the touch screen and send the status of the physical controls. Clip-on widgets can be easily used on the move and will not occlude the main display content.

Pen-based interaction [10] is important for tablet devices. Some commercial styluses are claimed to simulate finger-touch, but none of them allows the touch screen to distinguish pen touches from finger touches. As the startup delay and the size of TUIC-hybrid tag can be reduced in the future, a pen with a tiny tag attached on the tip can work with multi-touch interface. As we can adjust the frequency of the tag, the pen allows users to switch among colors or functions by hitting a button on the pen.

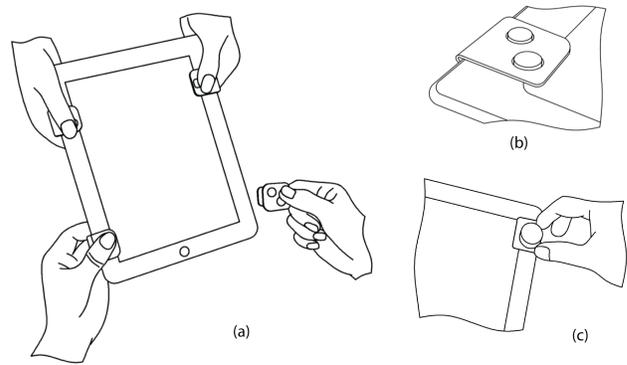


Figure 16: The concept of clip-on widget (a) gaming scenario: Clip and Play gamepad, (b) the widget overlays the edge (3~5mm) of the touch screen to sense input (c) audio mixing scenario: a knob provides eyes-free control to mix music

Unlike other sensing techniques, TUIC leverage the multi-touch display panel as the only sensor to significantly lower the complexity and cost of tangible UI systems. TUIC works in parallel with the standard multi-touch interactions, and on devices ranging from smartphones to tablets to tabletops (e.g. the AUO 32-inch capacitive display is larger than the Microsoft Surface tabletop, which is 30 inches). We will further explore the possible applications among different size of interactive surfaces and implement potential interactions.

CONCLUSION

We have presented TUIC, which enables tangible object sensing and tracking on off-the-shelf capacitive multi-touch devices. TUIC consists of three approaches to simulate and recognize multi-touch patterns using both passive and active circuits embedded inside objects. The spatial tag uses passive, unpowered circuits to create geometric touch patterns, and is ideal for applications that require fast detection and simple maintenance. The active frequency tag is smaller in size, use less touch points, and can change its ID and encode state. However, it does not support orientation or fast movement. The hybrid tag combines both spatial and frequency tags to support reliable tracking of tag translation and rotation. It is ideal for applications that can tolerate a slight startup delay, but require smaller tags or require multiple tags to be used concurrently. We have evaluated TUIC tags on two capacitive multi-touch devices, the iPad and 3M's 22-inch display. We demonstrate the feasibility of TUIC tags through three applications that utilize tangible interactions.

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