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Doctoral Dissertation

多指觸控顯示器之實體互動設計

Tangible Interaction Design on Multi-touch Display

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國立臺灣大學
敦品勵學・愛國愛人

中文摘要

實體使用者介面之研究已發展二十多年，此一概念改變了使用鍵盤滑鼠操作電腦的生硬刻板印象。利用實體物件自然地連結數位資訊或執行對應的功能，提供使用者操作電腦的便利性與直覺性，藉由碰觸或移動物體時的觸覺回饋，更增強使用者與系統溝通的互動歷程。傳統上，開發實體使用者介面大多利用影像偵測技術來達成實物辨識之功能，因此需要複雜的硬體建置；本篇論文首先提出基於電容式觸控之實物偵測技術，簡化系統複雜度，讓普及的電容式面板，不需增改硬體便能支援實體使用者介面開發。我們提出三種 TUIC 標籤可附加在實體物件上以提供電容式觸控面板感測物件的能力；TUIC 標籤使用低成本的導電材質模擬手指觸控訊號，並將其在空間及時間上的排列做為物件編碼之方式。

我們所發展的軟體讓電容式面板可分辨手指操作或是實體物件操作，結合多指觸控與實體使用者介面，我們提出兩種互動模型，分別呈現在大型互動桌及小型行動觸控裝置中。在互動桌上，我們開發一套支援多重顯示器之地圖導覽系統，使用者可使用象徵自己的人偶遊走在地圖上，並在前方顯示由人偶視角看到的街景圖，此系統讓街景視野與地圖方位有較好的連結，猶如使用者置身於虛擬世界中遊歷。在行動觸控裝置上，我們提出可延伸的實感觸控介面，藉由附加在裝置邊緣的延伸控制器，解決手指遮蔽畫面的問題，並提供觸覺回饋。更重要的是，此解決方案不需要電力且易於攜帶，有利於行動裝置之應用。

除了使用實體物件做為輸入裝置，本篇論文並提出可動式實體互動介面，以螢幕本身的光訊號來傳送指令，讓 TUIC 標籤以光感元件接收，進而驅動實體物件產生對應的動作。我們將此技術運用在社交玩偶上，玩偶附有馬達可帶動舉手等動作，使用者可將代表不同好友的玩偶放置在 iPad 上，做為好友來電提示功能，當好友在社群網路傳送訊息或更新狀態時，便能以其動作提醒使用者，增加互動的趣味性。最後我們提出具有應用潛力的互動模式，供未來研究及商品開發做為參考方向。

關鍵詞：實體使用者介面、多指觸控、互動桌、觸覺回饋輸入裝置、可動式實體互動介面、電容式觸控技術

ABSTRACT

This dissertation presents technologies and interaction models that combine tangible interaction with multi-touch UI. It describes *TUIC*, a technology that enables tangible interaction on capacitive multi-touch displays without requiring any hardware modifications. TUIC simulates finger touches on capacitive displays, such as iPad, iPhone, and 3M's multi-touch displays, using passive materials and active modulation circuits embedded inside tangible objects, and can be used with multi-touch gestures simultaneously. We demonstrate three TUIC approaches on iPads and 3M's multi-touch displays: passive (2D), active (frequency), and hybrid. In addition, we have extended TUIC to support bidirectional tangible interaction. For object tracking, we can use TUIC tags. For communication, we embed photodiodes into objects, and transmit data to them by programmatically changing the screen's brightness levels. We also present three novel tangible interaction models for tabletop-size and tablet-size multi-touch devices. First, our multi-display map touring system helps people use figurines to navigate through continuous panorama based on the street view, thus enhance better orientation perception and walkthrough experience. Second, Clip-on Gadgets solve the problem of fingers obscuring the screens and provide haptic feedback by extending the interaction area of multi-touch devices with unpowered physical controllers. Third, Social Toy uses motorized actuators to create ambient social awareness.

Our contributions include providing low-cost and easy-to-build techniques to enable tangible interactions on off-the-shelf multi-touch devices, empowering developers to explore and create diverse TUI applications, and making TUI accessible to end users.

Keywords: tangible user interface, multi-touch, 2D marker, frequency tag, physical interaction, interactive surface, tabletop, navigation, tactile input, bidirectional interfaces, active tangibles, capacitive sensing

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CHAPTER 1

INTRODUCTION

1.1 Background and motivation

Tangible user interfaces (TUI) enable users to interact with digital information by directly interacting with physical objects [21][34]. 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 [5] and SLAP Widget [98] that support tangible and multi-touch interactions 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 visual markers[17][75][77]. 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.

Although tangible user interaction has been studied for many years, there has been little work on enabling object sensing and tracking on capacitive multi-touch devices. In this dissertation, we present technologies we have developed to enable TUI capacitive displays, as well as several novel interaction models that combine TUI with multi-touch for tabletop and tablet interaction.

1.2 Dissertation statement and overview

We present novel object sensing, tracking, and two-way communication techniques involving tangible input/output on capacitive multi-touch displays. We propose TUIC tag designs that enable object sensing and tracking through spatial and temporal coding techniques. We also explore TUI applications on different forms of interactive surfaces from tabletops to mobile devices. We present a multi-display map touring system on tabletop and Clip-on gadgets on mobile devices based on TUIC tags. In addition, we propose TUIC+ to enable two-way communication for tangible objects. Thus, we are able to add motion or tactile feedback through the tangible output to compensate the limited visual feedback on the display. We have also designed Social Toys to transform the iPhone or iPad as an ambient display. By using these technologies, people are easy to build tangible interaction on the off-the-shelf multi-touch devices in low-cost way. We look forward to see more researches in this field in the near future.

Figure 1-1: Tangible interactions on unmodified capacitive multi-touch devices

1.3 Outline of the dissertation

In Chapter 2, we provide context for this research in the backdrop of previous work. We review related work in the areas of tangible user interface, interactive surfaces, unidirectional TUIs, bidirectional TUIs and capacitive multi-touch sensing technologies. In Chapter 3, we focus on the object sensing and tracking technologies on capacitive multi-touch panels that do not requiring any hardware modifications. We have developed passive, active, and hybrid tag designs that can be used on unmodified capacitive touch panels. The size of capacitive multi-touch display ranges 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). In Chapter 4, we focus on the problems on map navigation and mobile gaming, and develop the applications to solve these issues on different size of “interactive surfaces”. In Chapter 5, we go a step further to enable two-way communication for our tangible objects. We design a Social Toy by using our bidirectional tag to create ambient social awareness. We conclude this dissertation and provide the directions for future work in Chapter 6.

CHAPTER 2

RELATED WORK

The development of “Tangible User Interface” - TUI can be tracked back to the last two decades. In 1995, Fitzmaurice et al. [15] introduced the notion of a “Graspable Interface”, where graspable handles are used to manipulate digital objects.

Only a few years later, Ishii and his students introduced the notion of “Tangible Bits” which soon led to proposition of a “Tangible User Interface”[33]. Their vision centered on turning the physical world into an interface by connecting objects and surfaces with digital world. They attempt to change “painted bits” into “tangible bits” by taking advantage of multiple senses and the multimodality of human interactions with the real world. Figure 2-1 shows the concept of TUI. By giving tangible (physical) representation to the digital information, TUI makes information directly graspable and manipulable with haptic feedback. Intangible representation (e.g. graphical interface) may complement tangible representation by synchronizing with it.

In this chapter, we collect the major works of TUIs on the interactive surfaces and categorize them in two types. First are unidirectional TUIs, which use physical objects as input to control the digital information. Second are bidirectional TUIs, which not only use physical objects as input but also reflect the output by actuating the objects. We summarize the tracking techniques and actuated techniques in each section.

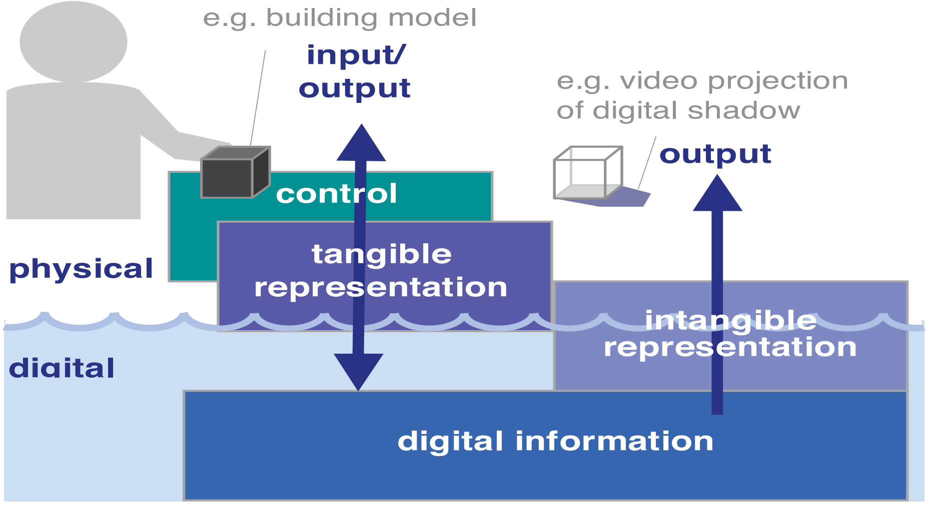


Figure 2-1: Tangible User Interface

2.1 Unidirectional TUIs

The prior influential TUI project is Urp (Urban Planning Workbench) [93] that 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 and etc. (Figure 2-2)

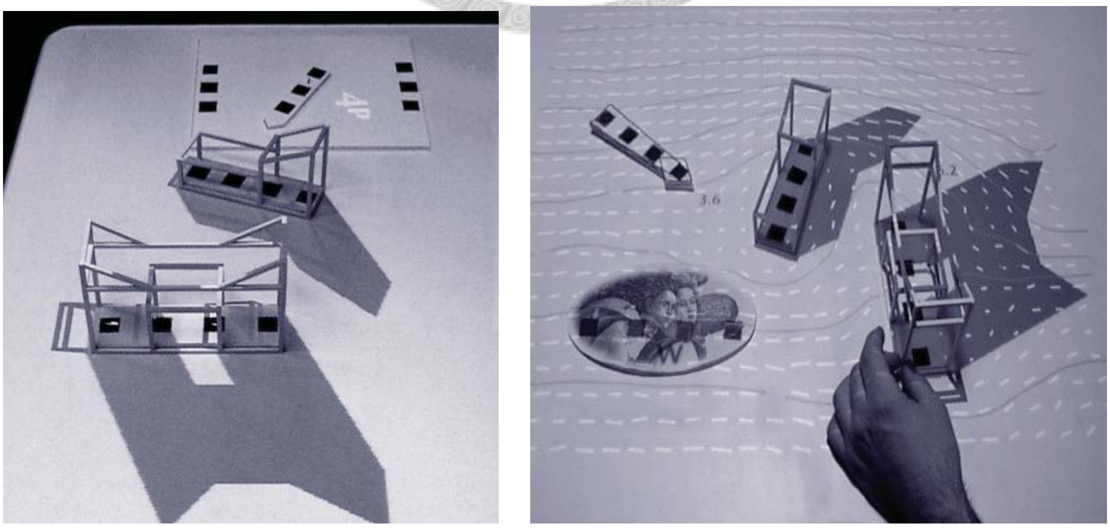


Figure 2-2: Urp, a TUI for urban planning with interactive simulation of winds.

Urp shows the advantages of TUI that tangible objects with physical constraints can make use of physical affordance to communicate interaction syntax and to limit the solution space. The TUI then soon was applied into different application domains. We describe several impact projects as following.

SandScape [34] is a tangible interface for designing and understanding landscapes through a variety of computational simulations using sand. The users can choose from a variety of different simulations that highlight the height, slope, contours, shadows, drainage or aspect of the landscape model. (Figure 2-3)

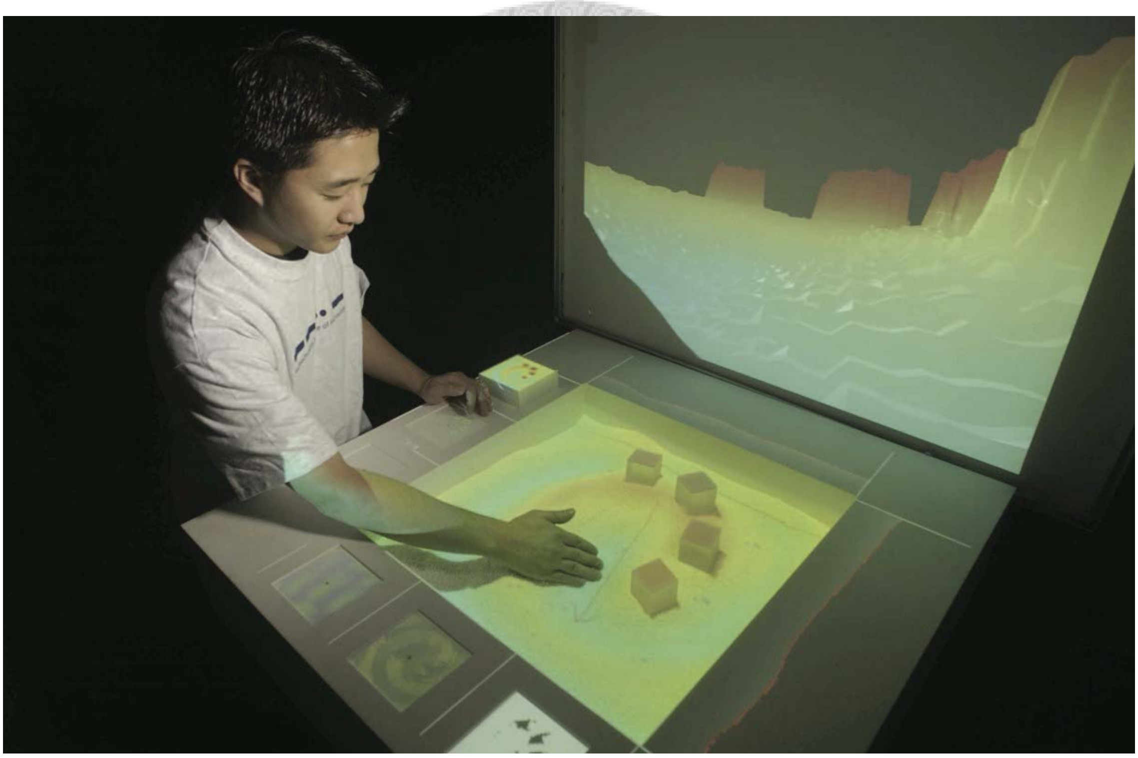


Figure 2-3: The Sandscape system

Tinkersheets [107] supports learning about warehouse logistics and enables users to set simulation parameters through interaction with paper forms where small black magnets are placed onto parameter slots. (Figure 2-4)

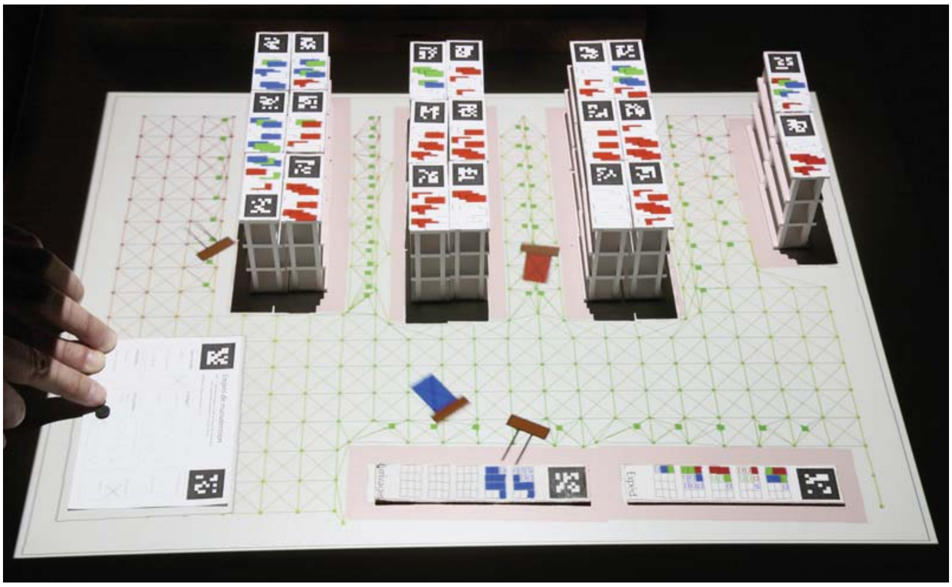


Figure 2-4: The Tinkersheets system

Ullmer et al. [90] developed tangible query interfaces that use physical tokens to represent database parameters (Figure 2-5). These tokens can be placed into physical constraints such as tracks and slots, which map compositions of tokens onto interpretations including database queries, filters, and Boolean operations.

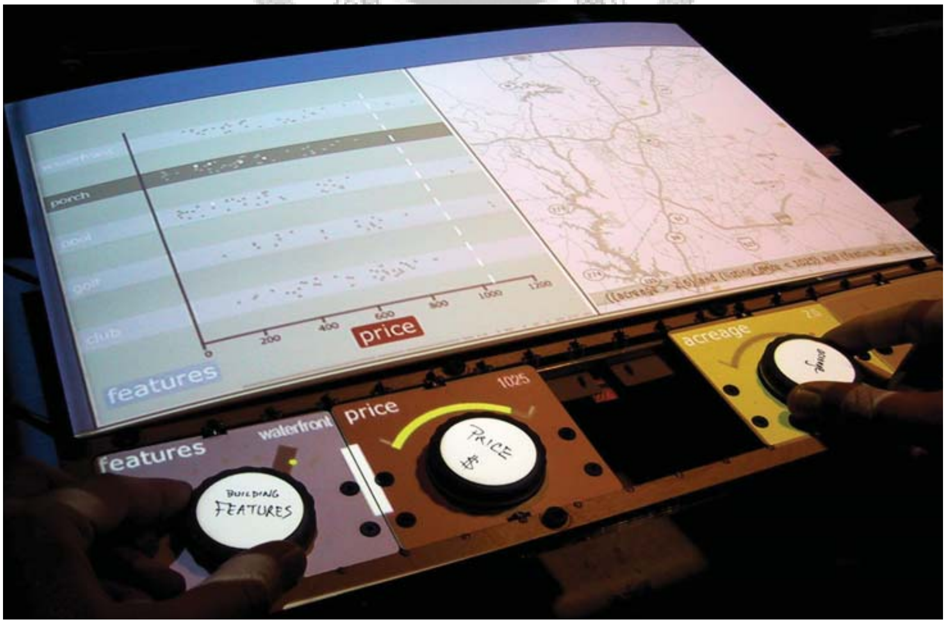


Figure 2-5: Tangible Query Interfaces

Sensetable[69] used electromagnetic sensing to determine the positions of objects. The physical dials and modifiers can be plugged into objects to change the state of the objects. Comparing to the vision-based tracking approaches, Sensetable tracks objects quickly and accurately without susceptibility to occlusion or changes in lighting conditions. (see Figure 2-6)

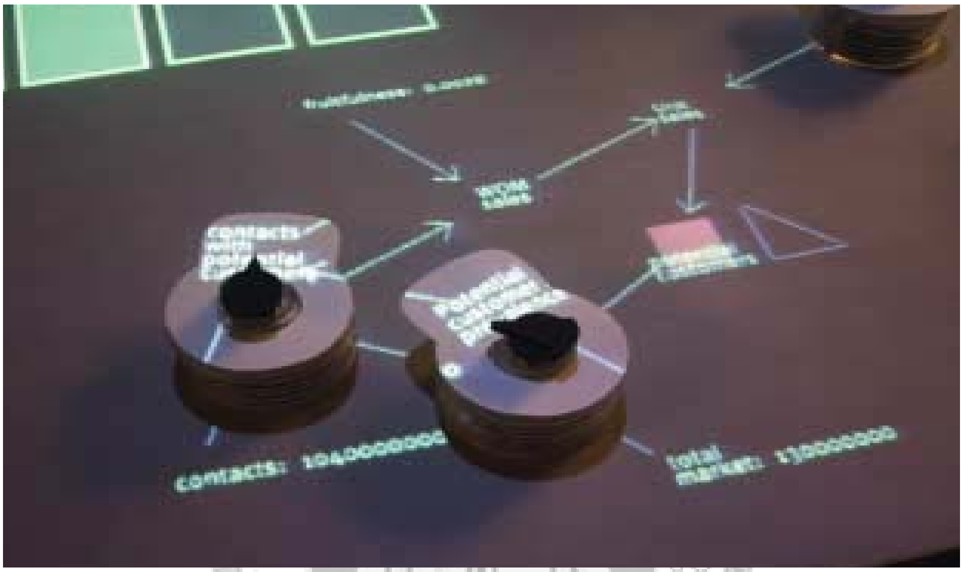


Figure 2-6: A system dynamics application running on top of Sensetable

Some pioneering projects have developed a variety of tangible applications on horizontal surfaces [68][91]. Digital Desk [99] is the pioneering work in this genre, and explored a variety of tabletop TUIs. Other examples such as: The metaDesk [91] developed graspable windows, icons and the more to represent the key ideas of AR: augmenting the user's surroundings with user interfaces, offering familiar interface elements as in a GUI. (Figure 2-7)

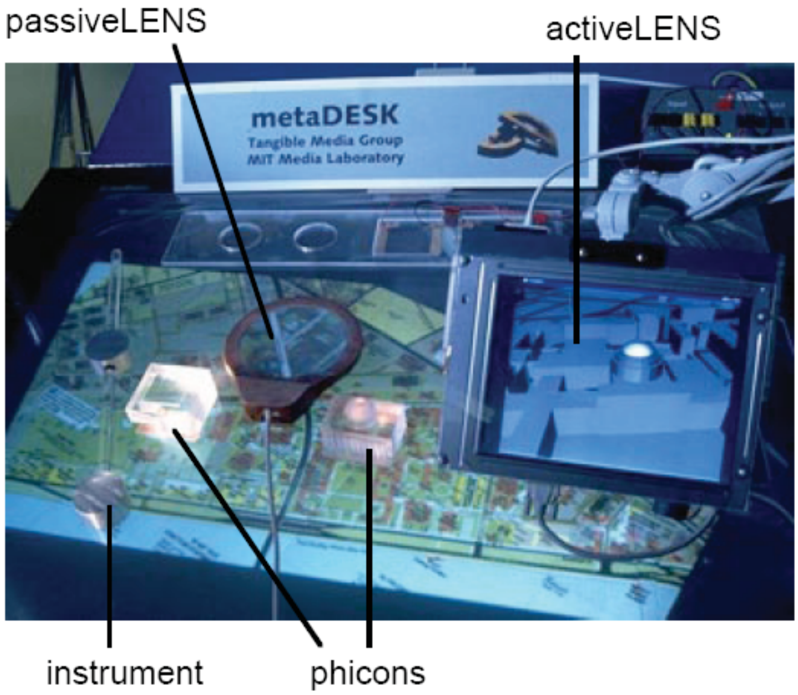


Figure 2-7: The metaDesk system

reacTable [40] is a collaborative musical tabletop that allows several musicians to share the platform and control the instruments to perform. It provides both multi-touch and tangible objects interaction by means of reacTIVision, an open-source, cross-platform computer vision framework for the tracking of fiducial markers and combined multi-touch finger tracking. (Figure 2-8)

Figure 2-8: The reacTable system

In PlayAnywhere[101], the camera identifies specific pattern and user's shadow to provide direct interaction. Then the system augments graphics model by a front projector to transform anywhere as interactive surface. (Figure 2-9)

Figure 2-9: The PlayAnywhere system

VoodooIO[6] 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. (Figure 2-10)

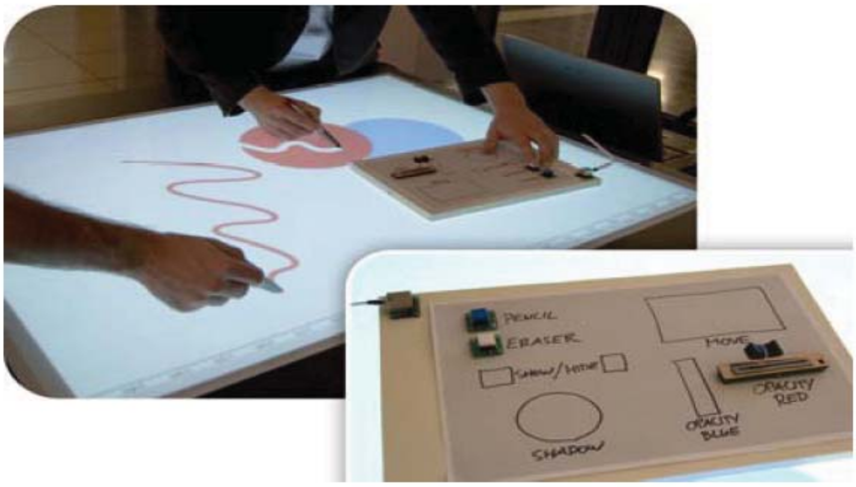


Figure 2-10: The VoodooIO system

i-m-Top (interactive multi-resolution tabletop) is a tabletop system [31], featuring not only multi-touch, but also multi-resolution display – for better accommodating to the multi-resolution characteristics of human vision. (Figure 2-11)

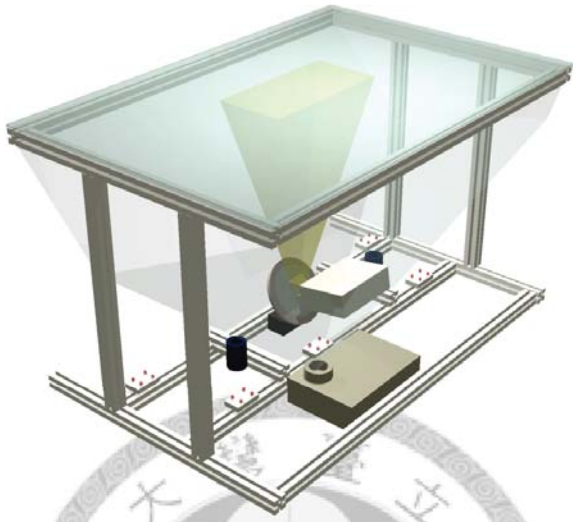


Figure 2-11: The imTop tabletop system

Microsoft Surface is a commercial tabletop product, consisting of a 30-inch reflective surface and has ability to sense both tags and fingers. It shows the vision of Natural User Interface (NUI) by supporting multi-touch and tangible interactions simultaneously. (Figure 2-12)

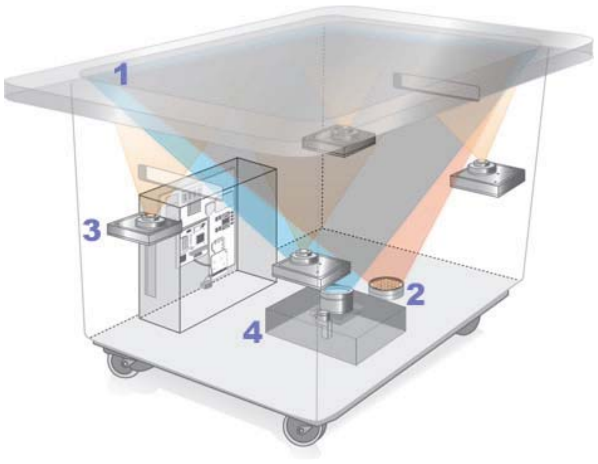


Figure 2-12: The Microsoft Surface

Manual deskterity [15] is a prototype digital drafting table that supports both pen and touch input based on MS Surface. They explored the simultaneous use of pen and touch to support novel compound gestures. (Figure 2-13)

Figure 2-13: The Manual deskterity prototype

Lumino [5] 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. (Figure 2-14)

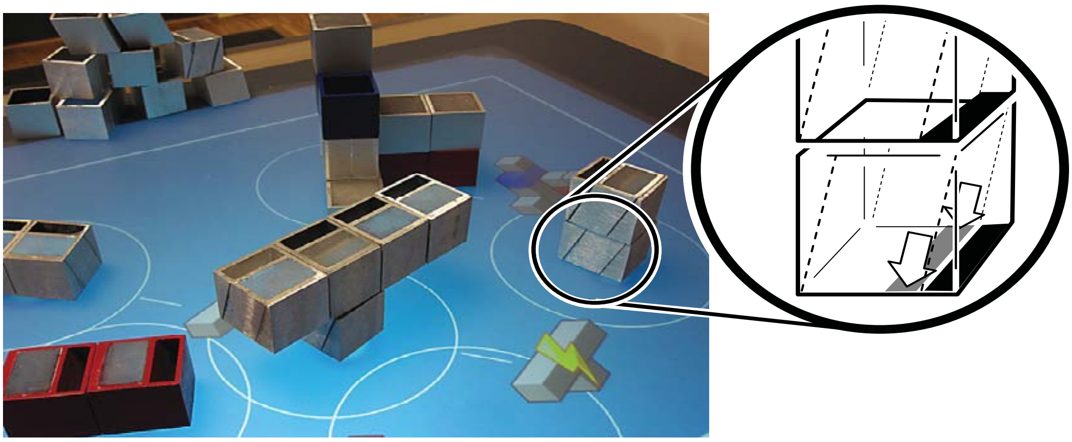


Figure 2-14: The Lumino system

SLAP [98] 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. (Figure 2-15)

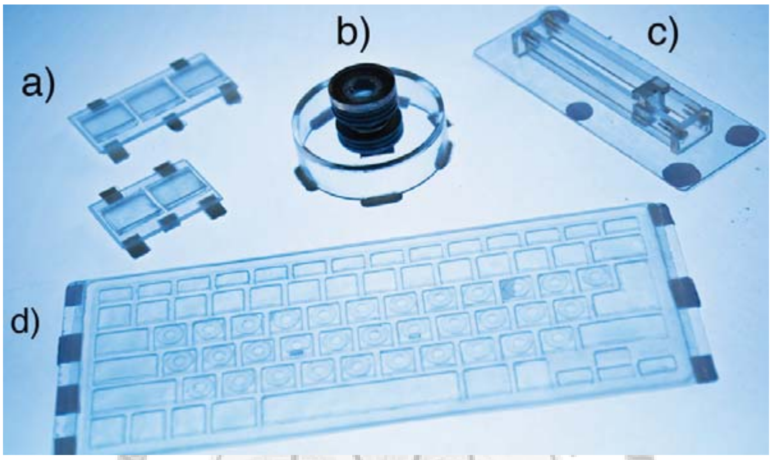


Figure 2-15: The SLAP widgets

2.1.1 Tracking techniques

Vision-based tracking is the most common approach in TUI projects because it makes the system able to see the objects. The system usually uses vision tag to identify the object's ID. Domino Tag[64] 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 [8] and QR Code[75] 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.

(a) (b)

Figure 2-16: The vision-based tags (a) domino tag (b) The examples of the markers from CyberCode, ARToolkit, ARToolkit Plus and ARTag (from L to R)

Radio-Frequency Identification (RFID) is a wireless radio-based technology that enables to sense the presence and identity of a tagged object when it is within the range of a tag reader. There are generally two types of RFID tags: active RFID tags, which contain a battery and thus can transmit a signal autonomously; and passive RFID tags, which have no battery and require an external source to initiate signal transmission.

Most RFID-based TUIs employ passive inexpensive RFID tags and hence consist of two parts: a tag reader that is attached to the surface and a set of tagged objects. Multiple examples of RFID-based TUIs include mediaBlocks[92], a TUI that consists of a set of tagged blocks that serve as containers for digital media; Senseboard [39], a TUI for organizing information using a grid that enables the placement of multiple tagged pucks on a white board (Figure 2-17); and Smart Blocks [22], an augmented mathematical manipulative that allows users to explore the concepts of volume and surface area of 3D objects. Martinussen and Arnall [8] discuss the design space for RFID-tagged objects, taking account of the aesthetics of tags and readers.

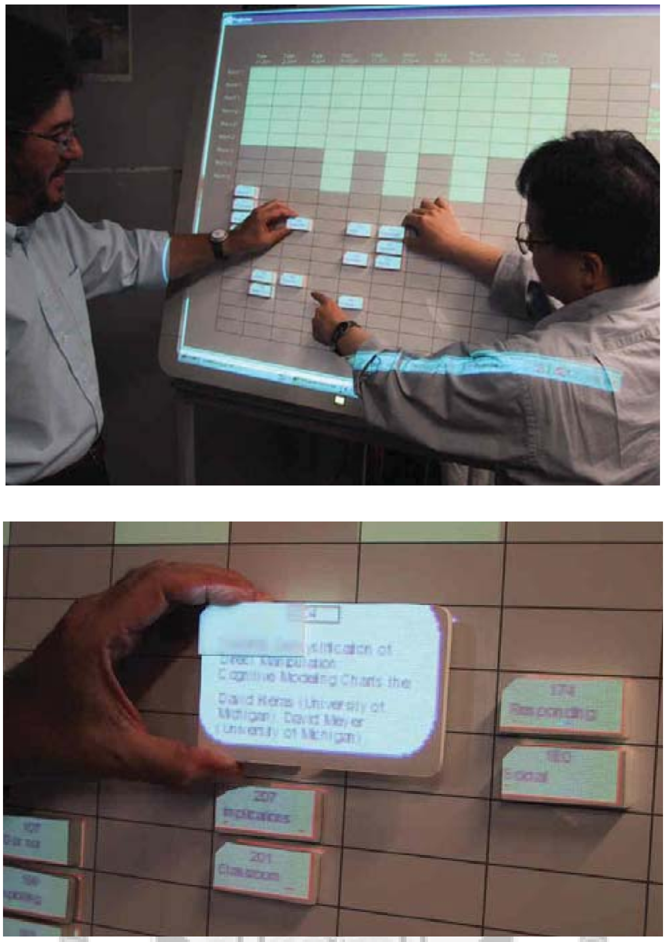


Figure 2-17: The Senseboard system

Other object tracking technologies are descried as following. Bricks[18] use pulsed direct current magnetic sensing and simulate graspable objects. Sensetable[69] tracks objects via electromagnetic sensing. Audiopad [68] attached two radio frequency tags on each puck to determine its position and orientation. Dolphin [31] uses of ultrasonic transmitters and receivers to locate people and the objects they interact with.

Capacitive multi-touch sensing technologies

The capacitive multi-touch panels sense the change of capacitance by capacitive coupling effect [106]. 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)[3]. 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. In this dissertation we uses specially designed circuits to induce capacitance change to simulate finger touches. Figure 2-18 shows the mutual capacitive sensing device.

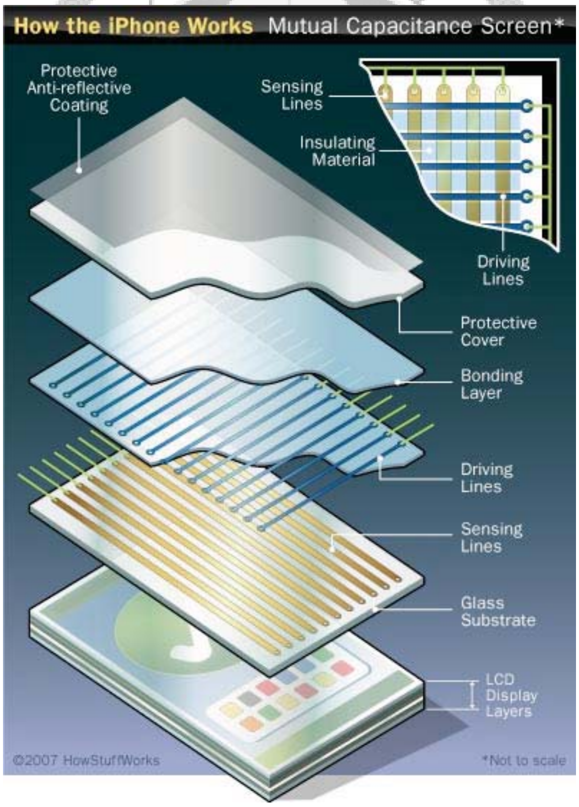


Figure 2-18: The mutual capacitance screen

SmartSkin [76] is the pioneer using capacitive sensing and a mesh-shaped antenna to detect multiple hand positions and the shapes of capacitance tag on the object.

2.2 Bidirectional TUIs

The early prototype of bidirectional TUI is PSyBench[8], which provides a generic shared physical workspace for distributed users. It is built by two motorized chessboards and uses electromagnet to actuate the magnet object. (Figure 2-19)

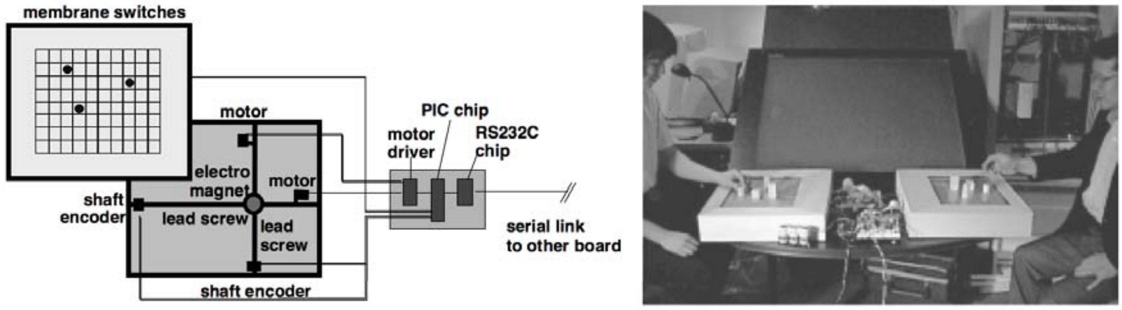


Figure 2-19: The PSyBench prototype

Actuated Workbench[66] and PICO[67] use electromagnet arrays to move pucks on a table in two dimensions but use different algorithm to actuate the moving object. Actuated Workbench uses anti-aliasing and PID control algorithms to provide smooth motion on the surface. PICO preserves the dynamic behaviors to support the concept of mechanical constraints. (Figure 2-20)

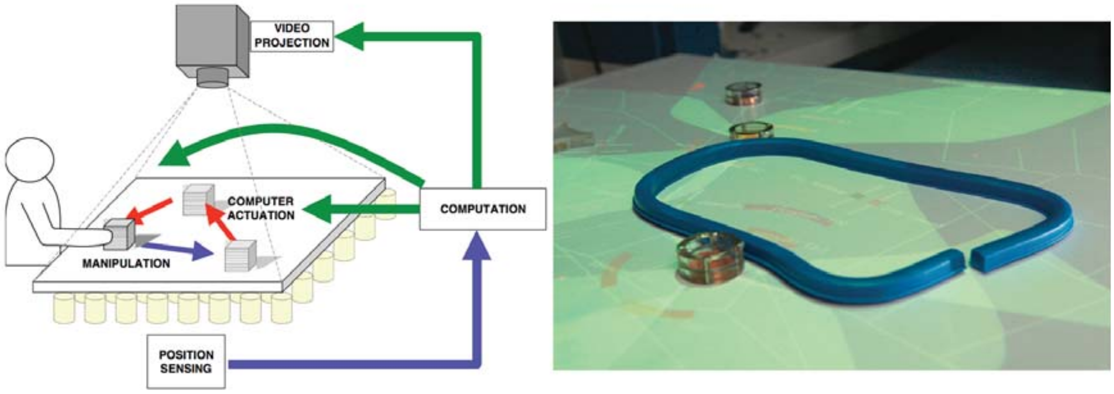


Figure 2-20: The architecture of Actuated Workbench and Pico system

Another implementation of the same idea is Madgets[83], but in addition to moving in 2D, it manipulated magnetic field to rotate magnet-embedded gear, repel the beater to hit the bell, and utilized the electromotive force generated by electromagnetic induction to light up the LED of induction Madget. (Figure 2-21)

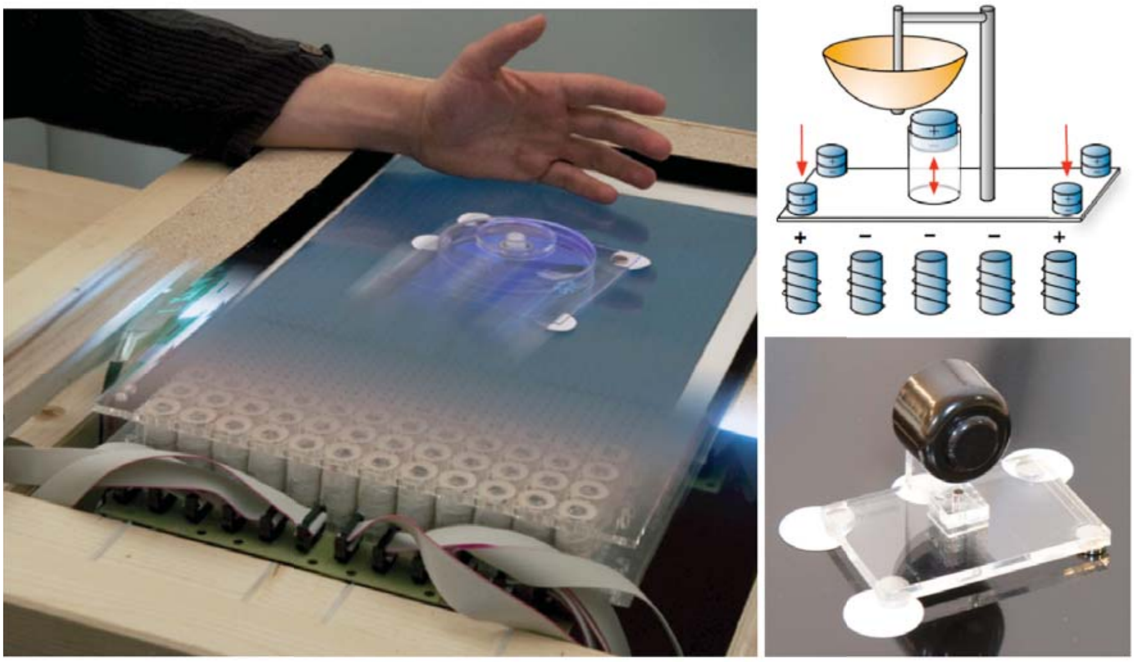


Figure 2-21: The Madgets

PMD (Planar Manipulation Display)[79] is a design support system for interior design where users can explore several alternative arrangements for furniture in a room. When users select a layout method, the application moves the active furniture into an arrangement dictated by the configuration type. (Figure 2-22)

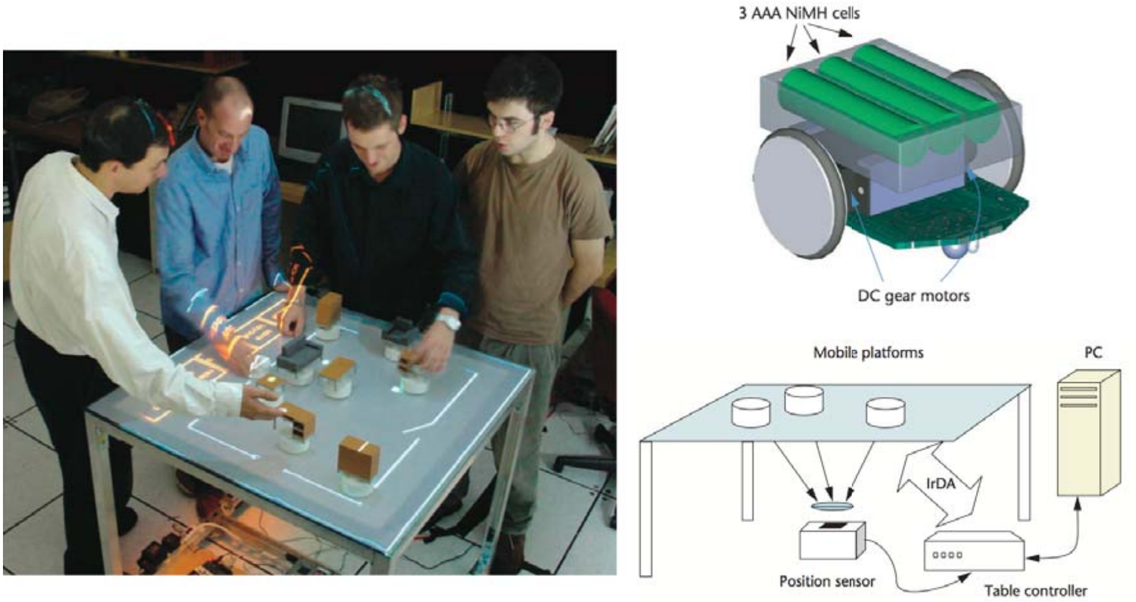


Figure 2-22: The PMD system

Augmented Coliseum[79] use DMCS (Display-based Measurement and Control System) to create an augmented reality game with small robots. The display-based measurement system is a 2 dimensional tracking system using a display device equipped with a few brightness sensors. (Figure 2-23)

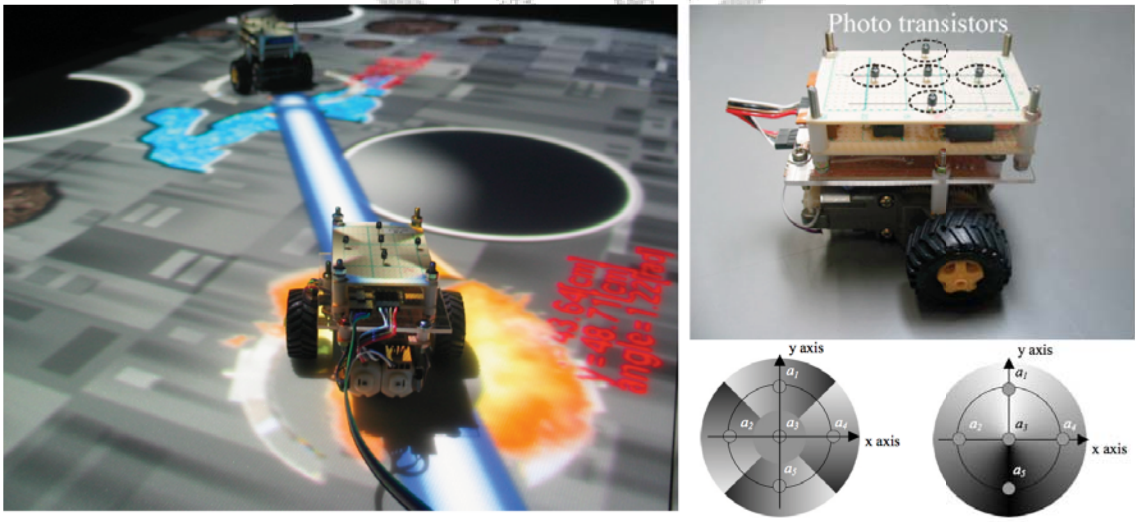


Figure 2-23: The Augmented Coliseum

Tangible Bots[70] use motorized tangibles to assist users by haptic changes, by correcting errors, by multi-touch control, and by allowing efficient interaction with multiple tangibles. (Figure 2-24)

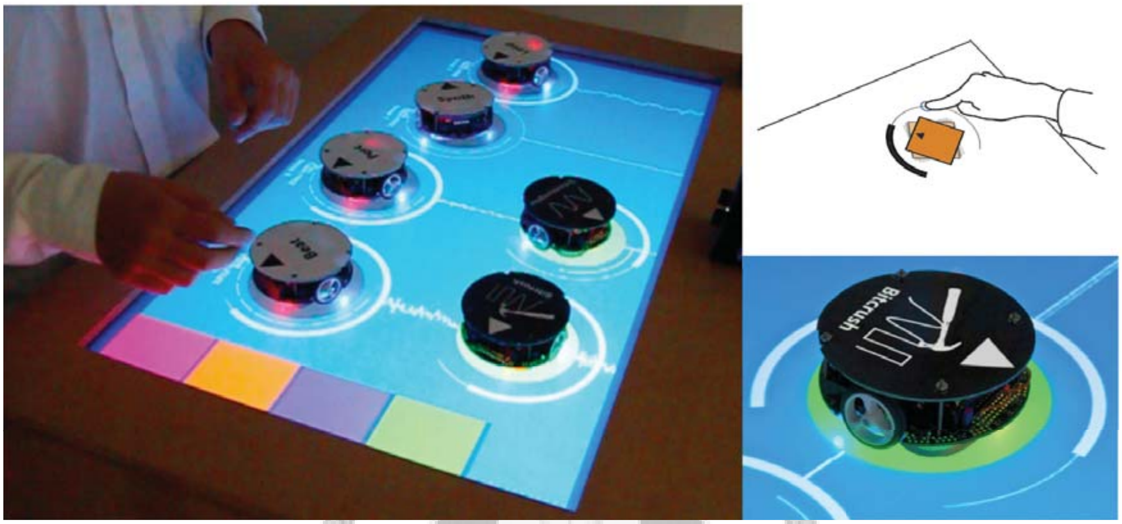


Figure 2-24: The tangible bots

2.2.1 Actuated techniques

Bidirectional tangible interfaces make virtual world and physical world closely coupled by actuating object's physical properties. In a range of Actuated TUIs, the actuated techniques can be loosely classified into two categories: surface-driven and self-driven.

Surface-driven actuated techniques are commonly install electromagnets into the surface to move the passive small objects. Examples are PSyBench[8], Actuated Workbench[66], PICO[67] and Madgets[83]. Each of them use different movement algorithm for their own purpose. Shape displays such as FEELEX[37] and Lumen[74] use more complex mechanism to move up and down in one dimension for each individual "pixel," and provide tactile feedback in addition to 2D visual presentation.

Because these tangible objects are actuated by the TUI system, which required complex mechanism to actuate, the sizes of these systems are generally very huge in size, and therefore need complicated configuration.

Other TUIs used robot-like tangibles that are self-actuated and battery-powered. Rosenfeld et al. implemented Planar Manipulation Display (PMD)[79] to produce a bidirectional user interface via a 115-kbps infrared communication link based on the IrDA physical layer. Each robot has two wheels driven by motors and is able to move around the table freely. Kojima et al. presented Display-based Measurement and Control System (DMCS)[49], which is a robot/tracking system on tabletop. Each robot uses five installed phototransistors to track its position by measuring light intensity and then send the data via a cable or radio to the system for controlling the its movement. Tangible Bots[70] uses off-the-shelf Pololu 3pi robot as active tangibles. The tabletop computer tracks robot's position by a vision marker and sends movement commands to robots via ZigBee. Most of bidirectional tangible interfaces are built upon tabletops and require complex additional hardware configuration. Thus, these systems are usually very big in size and not portable, in the other word, these bidirectional techniques limit the application domain. Navigational Blocks[10] are equipped with orientation sensors and electromagnetics, and able to give actuated feedback, repel or attract, in the interactive database query.

2.3 Summary

We have provided the major works in the fields of TUI. We also listed several tracking and actuating techniques that can be use in unidirectional and bidirectional TUIs. Comparing to the tabletop systems that are commonly used vision based camera to sense fingers and objects, there not seen another system that can provide tag recognition/localization on conventional capacitive touch screens. We address this problem and provide novel solutions in the following chapter.

Koleva et al. [50] conducted an analysis of TUI systems and found that most system supported only one-way communication. Although actuation had been a part of the vision of TUIs from the very start, given the technical difficulties, it is only lately emerging as a strong trend. It is an important means for increasing the malleability of physical objects, which normally are rigid and static [72]. We address this issue and propose a two-way communication approach on the capacitive touch displays. We describe the details in Chapter 5.

For tangible applications, we can see the interactive surfaces such as tabletop systems raise in the past years. Kirk et al. [47] survey existing interactive surface systems and show that there remains a strong desire to continue to incorporate tangibles into these interfaces. These systems therefore are not simply TUIs, but also “hybrid” surfaces. MS Surface and Reactable [40] are good examples: the surface on which tangible elements are manipulated is also an interactive touch surface for mixing, blending and playing. We believe this might be the trend for interactive surface. Therefore we explore techniques and applications to support tangible and multi-touch interactions simultaneously.

CHAPTER 3

TUIC: OBJECT SENSING AND TRACKING TECHNIQUES ON UNMODIFIED CAPACITIVE TOUCH PANELS

3.1 Introduction

In this chapter, 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.

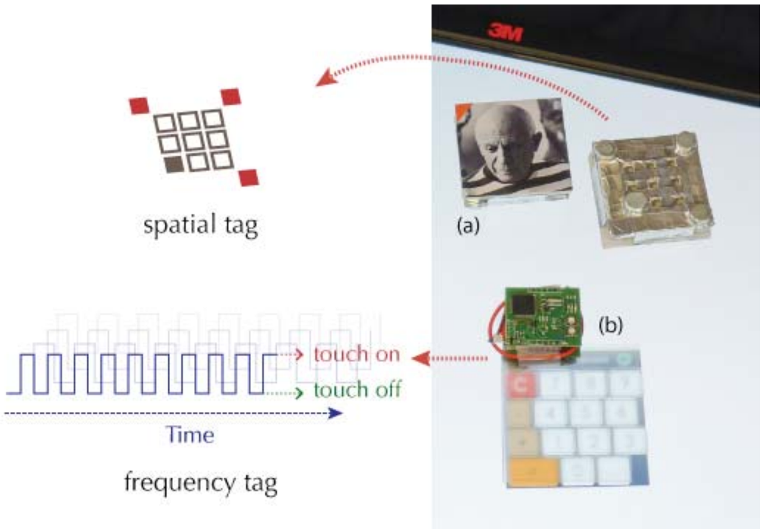


Figure 3-1: Examples of tangible objects embedded with TUIC tags, on unmodified capacitive multi-touch displays.

3.2 Motivation

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" [22] tablets use electro-magnetic resonance sensing panels under the capacitive touch panels to sense pen input. Since the great advantages of capacitive touch panels are its thin form factor and lightweight, adding any extra sensors or cameras will lose these advantages. Therefore, we target for the sensing solution on unmodified capacitive multi-touch displays.

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[12][28]. 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.

3.3 TUIC tag design

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

3.3.1 Tag design based on spatial domain

The spatial approach, called TUIC-2D, uses a layout similar to vision-based systems like QR Code. Figure 3-2 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 3-2c shows a TUIC-2D tag that can encode 9-bits of data, or 512 different object IDs.

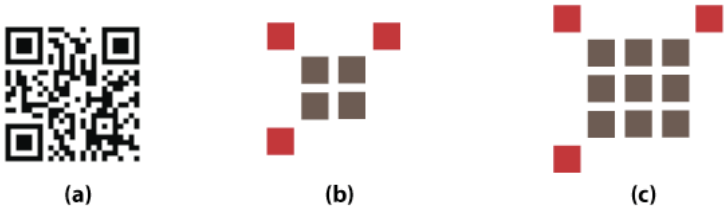


Figure 3-2: (a) QR code, (b) TUIC-2D: 4-bits tag, (c) TUIC-2D: 9-bits tag

TUIC-2D tags can be constructed using passive materials that are easy to maintain. 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[21].

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 due to the performance issue. 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.

3.3.2 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 3-3 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.

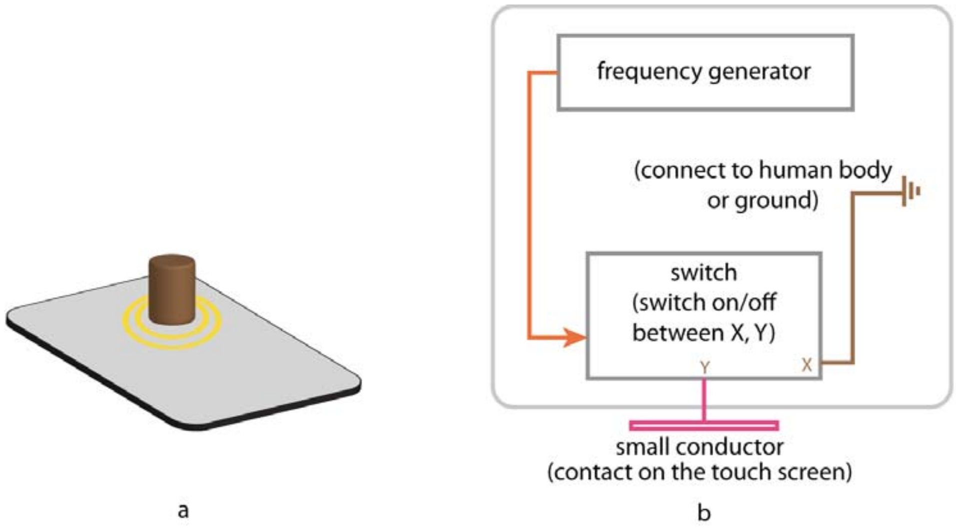


Figure 3-3: (a) a frequency tag on a touch panel, (b) a block diagram of modulation circuit that simulates high frequency touches.

Figure 3-4 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=15ms represents ID=1, T_2=20ms 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.

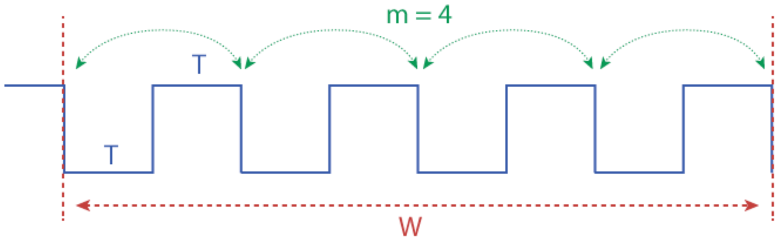


Figure 3-4: The concept of fixed-length touch frequency

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.

3.3.3 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 3-5 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.

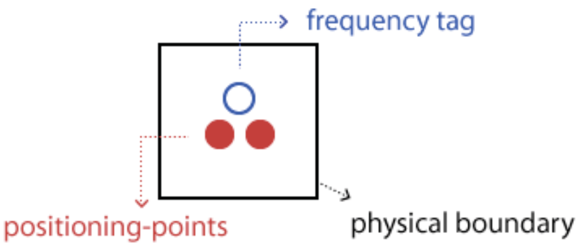


Figure 3-5: TUIC-hybrid tag design that uses two positioning points and a frequency tag

3.4 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.

3.4.1 TUIC-2D

Figure 3-6a 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 3-6b shows three registration points, C0, C1, and C2, 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, B0 to B8, which can encode 9 bits of binary values. B0 and B8 represent the least-significant bit (LSB) and the most-significant bit (MSB), respectively.

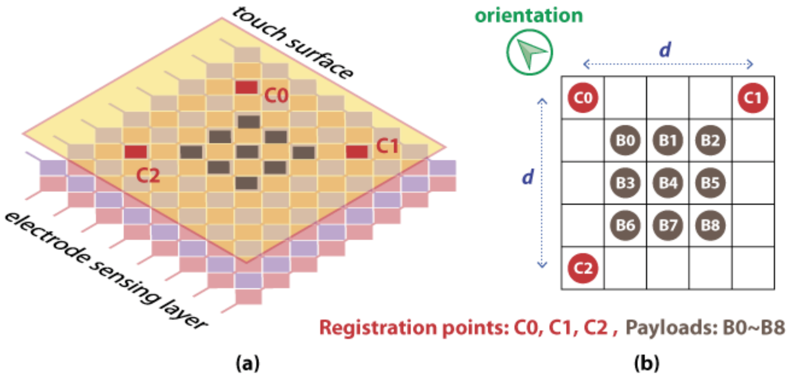


Figure 3-6: (a) Sensing signals on capacitive multi-touch panel, (b) TUIC-2D tag design

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 3-7, 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 3-7: 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[21]. Figure 3-8 shows the state diagram of the TUIC-2D tag recognition algorithm. The detail of each state is described in the following paragraph.

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 3-6b, 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.

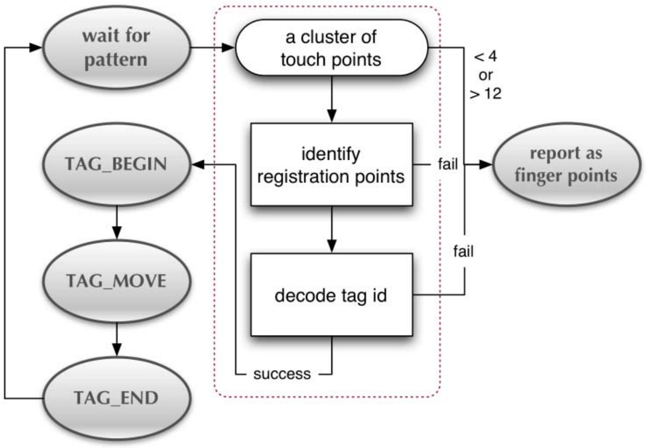


Figure 3-8: The state cycle of TUIC-2D

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 $\sqrt{2d^2}$ (Figure 3-6b), we have identified C0, C1, C2. 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 B0 to B8 in the payload area. B0 is reported as 1 if there is a touch point found underneath the position. The tag ID then is decoded as $B0 \cdot 2^0 + B1 \cdot 2^1 + B2 \cdot 2^2 + B3 \cdot 2^3 + B4 \cdot 2^4 + B5 \cdot 2^5 + B6 \cdot 2^6 + B7 \cdot 2^7 + B8 \cdot 2^8$. 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 (C0, C1, C2) 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.

3.4.2 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[32]. The circuit diagram of our prototype is shown in Figure 3-3b. We choose the Texas Instruments MSP430 chip [43] 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 3-9, the size of the modulation circuit board is about 2x3x3 cm^2.

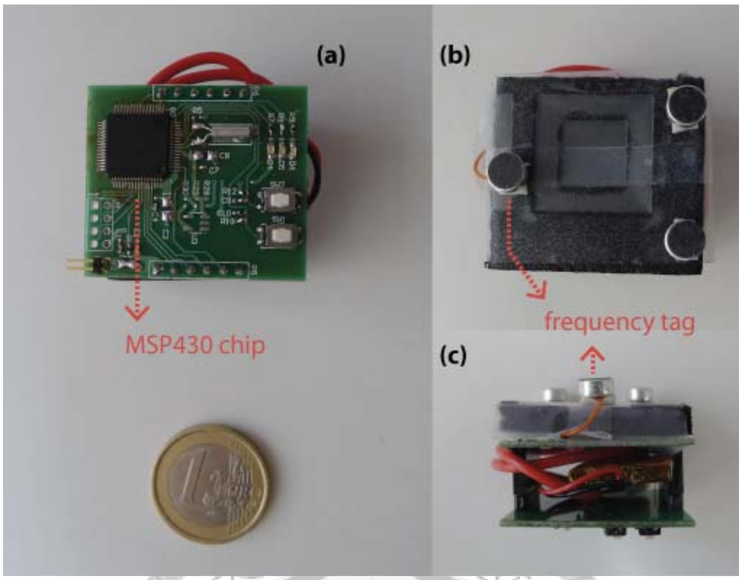


Figure 3-9: Modulation circuit with a built-in battery.

(a) front view, (b) back view: one point is used for frequency tag, the other two are only used for support (c) side view

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, and show the measured interval values versus the input interval values in Fig.10. 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, as reported by iPad and 3M, 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 another iPad and observed similar results.

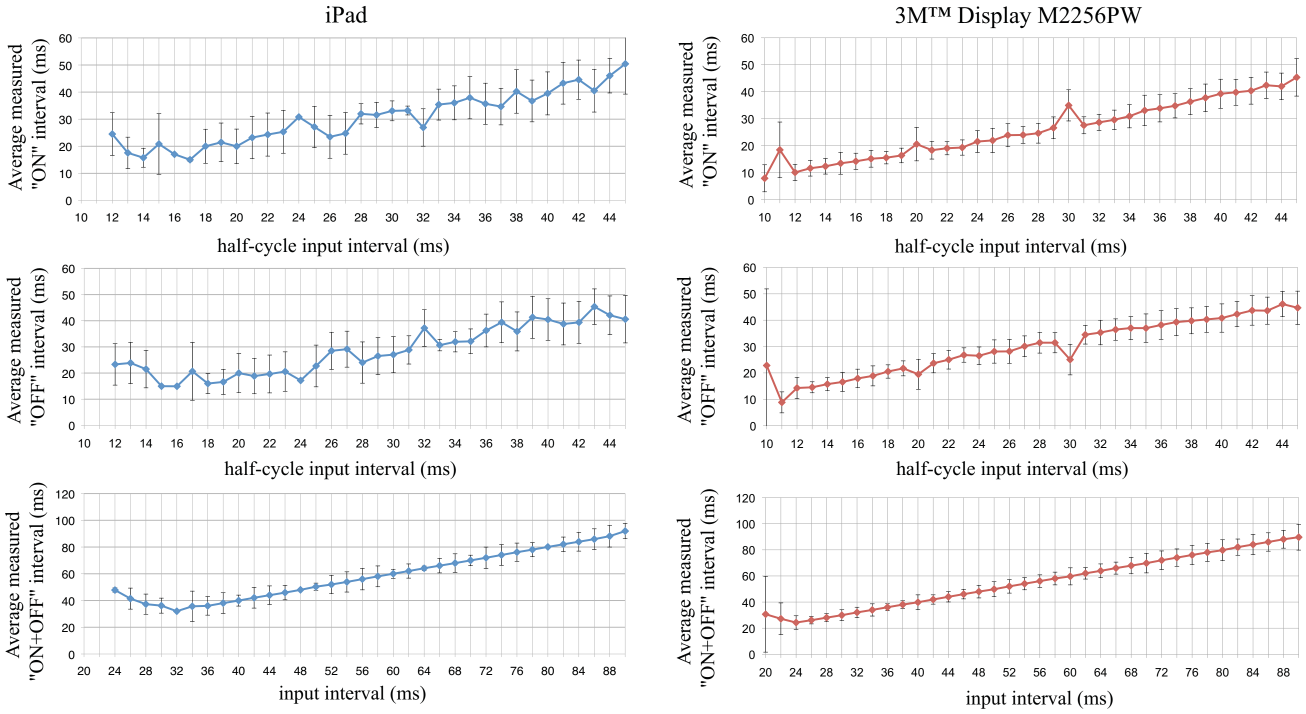


Figure 3-10: Average measured interval collected in iPad and 3M Multi-touch Display.

As shown in the bottom charts in Figure 3-10, 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. Based on the experimental results, 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 45ms x 2 x 5 = 450ms.

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 3-11 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.

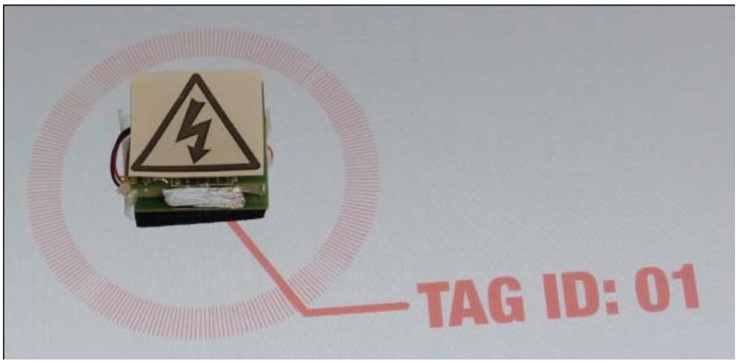


Figure 3-11: Animated progress ring appears around the tangible object while the frequency tag is being identified

3.4.3 TUIC-hybrid

The TUIC-hybrid tag is an enhanced version of TUIC-*f* tags. As shown in Figure 3-12, 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.

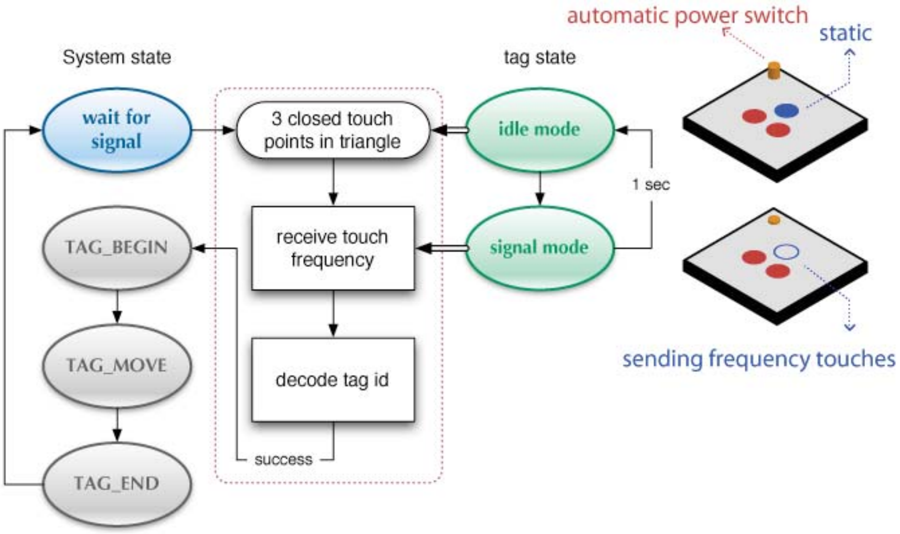


Figure 3-12: The state transition diagram of TUIC-hybrid and the bottom view of a TUIC-hybrid tag

3.5 Application examples

We have developed three applications with tangible user interfaces to demonstrate the feasibility of the three TUIC tag designs.

3.5.1 Chronicle of famous painters

We have implemented a tangible user interface suitable for museum exhibitions. 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.

The TUI in this scenario reduces the UI elements on the screen, and users no longer have to switch modes by selecting menus or icons. Visitors can intuitively select the appropriate tile matching their interests, reducing the cognitive load of learning menu systems or remembering different gestures[98].

In a museum setting, the tangible object used in exhibitions should be unpowered and low maintenance because many visitors will manipulate it. 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 3-13.

Figure 3-13: Chronicle of famous painters

3.5.2 Slap-on calculator

The SLAP keyboard [98] uses a thin, translucent skin to provide haptic feedback when typing on virtual keyboards on diffuse-illumination tabletop. We use TUIC-hybrid tags to implement similar functionality on capacitive multi-touch screens, called slap-on keyboard. As shown in Figure 3-14, 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.

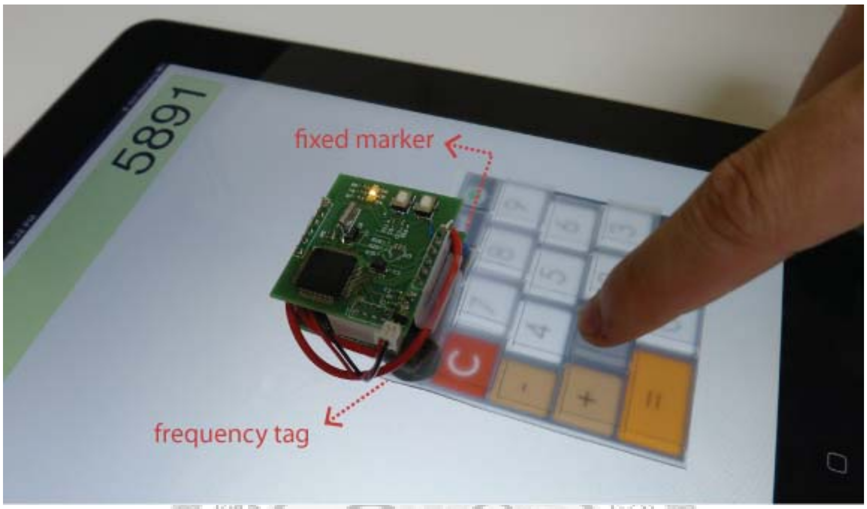


Figure 3-14: Slap-on calculator on capacitive multi-touch screen

3.5.3 Slap-on 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 3-15 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. 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.

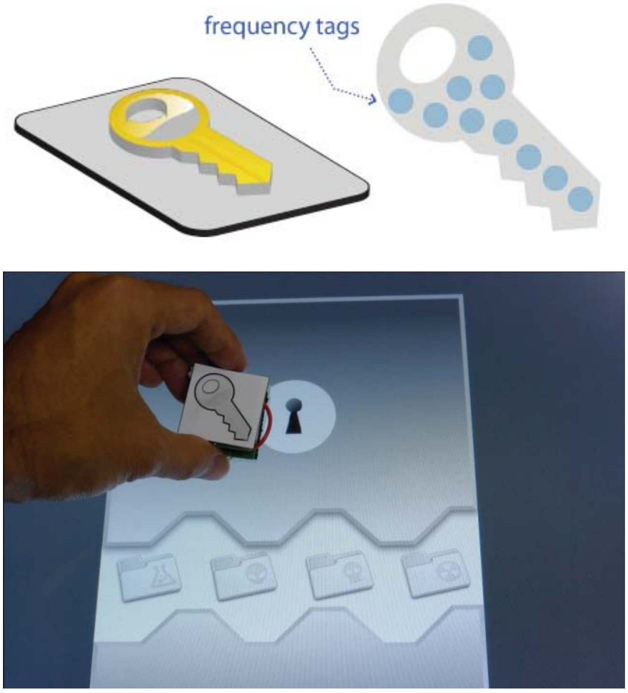


Figure 3-15: (top) The concept of a Slap-on authentication key with 10 frequency tags (bottom) Unlock secured files using a Slap-on authentication key

3.6 Discussion

We summarize and compare the three TUIC tag designs in Table 3-1. 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.

Tag design	**TUIC-2D**	**TUIC-*f***	**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 3-1: Comparison of TUIC tag designs

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.

To compare different TUI technologies, Shaer and Hornecker [65] 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 make 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.

3.7 Summary

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.

CHAPTER 4

DESIGNING UNIDIRECTIONAL TANGIBLE INTERACTIONS FROM TABLETOP TO MOBILE DEVICE

Tangible tabletop interaction combines interaction techniques of multi-touch interfaces and TUIs. The interactions might be varied between different types of interactive devices. In this chapter, we apply our TUIC technologies on two typical forms of interactive surfaces: tabletop and portable multi-touch devices, and demonstrate a novel application on each of them.

4.1 Multi-display map touring system for interactive tabletop surfaces

Many map systems are created to help the user finding a place or define a route to follow. Google Map extends the concept of ”surfing the map” by adding a street view that allows the user to explore a place from real pictures, creating the same feeling of walking through the streets. The horizontal 2D map and vertical panoramic street view, however, cause usability problems, while operating with traditional computer mouse and keyboards and presenting by single vertical or horizontal display. This section presents a new map touring system composed of a horizontal tabletop screen and a vertical screen. The map view and the street view are displayed on the horizontal and vertical displays of our system respectively. Users can place the tangible pawn on the 2D map to have direct access of the street view from the pawn's point of view.

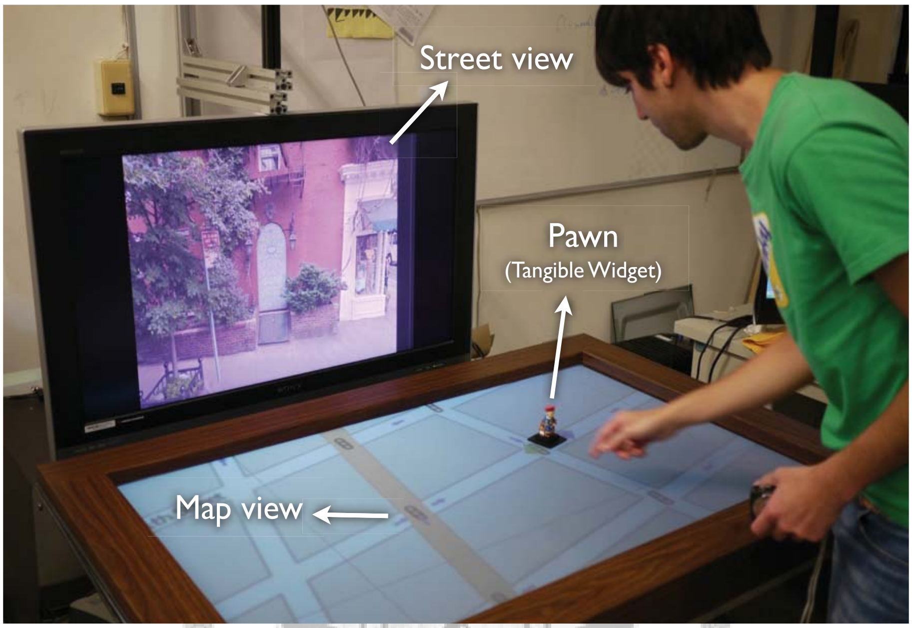


Figure 4-1: Map touring system on interactive tabletop surface

4.1.1 Motivation

Navigation is ”the process whereby people determine where they are, where everything else is, and how to get to particular object or places” [45][89]. As we all know this is a common problem and many are solutions proposed during the years. The common goal of all these applications is to improve the navigational knowledge of the user, so he or she can find the direction also in an unknown space. However this concept of knowledge can be divided into subcategories. The two on which we want to focus our attention now are called: route knowledge and survey knowledge. The first is gained through personal exploration and allows reaching a destination just through a known route while the second de- scribes the relationship among locations and can be gained through the study of a map.

In the Google Map web application there are two views called street and map, as shown in Figure 4-2. The map view is focused on the street topography while the street view is made by pictures taken from the streets and shows the real appearance of the city. Using a combination of these two views the user can acquire both route and survey knowledge in the same moment, simply using a PC. Studies about human navigation [60] show the importance of landmarks for routing and way finding. The landmarks are particularly recognizable elements of various kind (e.g. buildings, signboards....), normally used to easily remember a path. The street view, being made by pictures from the city, can truly help the user identifying those landmarks and exploit the advantages given from their use.

Figure 4-2: Map view and street view of the Google Map application

However, with Google Map, surfing the street view using the mouse directly on it or using the mouse to move the virtual character on the map view requires users who have good recognition on correlation between virtual character, map and street view. This motivation pushes us to create a Tangible User Interface on map touring applications. Our goal is to provide simplicity and intuitiveness on this system.

4.1.2 Survey of map touring systems

Fallahkhair et al.[16] created a system composed by multiple devices, discussing the potentials of this choice. The design constraints are more fluid, there are more input/output options and the designer can take advantage from the characteristics of each device to model a better interaction between system and user. When we talk about maps the first type of interaction that we normally think about are the hands; we use our fingers to move, rotate or follow a street on the paper. To be able to perform the same type of interaction in the virtual world we need a touch screen device. Smartphones and PDAs have the advantage of being small and portable, in the other hand the dimension of the screen and the input/output possibilities are limited. If portable is not our goal, devices like tabletops can solve the dimension and interaction problem. The screen dimension is much bigger that any portable device and the interaction with the system can include not only fingers but also TUI (tangible user interfaces). Maher and Kim [57] presented a 3D design system that uses tabletop and TUI to improve the perception of space and the relation between the elements in the scene. They discuss the advantages of using physical objects into virtual world; how manipulability, tactile feedback and kinesthetic information can improve the interaction between user and system. In Wagner[95] compare TUI and GUI, showing the advantages called double feedback loop and persistency of tangibles given from the use of TUI.

All the following systems show how the interaction with an application like Google EarthTM can be revisited using devices like screens, tabletops or projectors and different kind of input methods. S. Kim et al.[46] presented a system based on a tabletop device that allows the user to completely control the map using hand gestures.

Kim, Cho, Park, Han[53] focused their attention on TUI interactions. They create a device called SmartPuck that can be used to substitute all the mouse (or finger) interactions with the map, introducing in the system all the advantages given by the use of tangible widgets. More connected to immersible 3D experience is Liquid Galaxy[26]. The system is controlled by a special joypad and is composed by eight screens that provide the sensation of immersion in the virtual world. A mix between art and technology is The Earthwalk [23]. The map is projected on the floor and the interaction is driven by the feet through the use of footpads. The user is not just browsing the map, but has also the feeling of walking on it.

All the projects we just mentioned are presenting different kind of interaction, but all of them are focused on just one type of map. What we want to do is to improve the interaction for a system that uses two maps in the same time, taking the benefits from the use of different types of visualization. In [19] lines et al. present a solution for this issue of interacting simultaneously with different views of the same map. However the goal of this system is analyze the map and incentive the collaboration between users during this analysis. The navigation needs more grades of freedom and this affects the system usage, which is therefore more complicated. We want to present a way of showing and interacting with these two maps that is focused on simplicity, intuitiveness and allows the user to navigate and remember more easily the environment.

4.1.3 System design

Our system is composed by tabletop system, a vertical display and tangible UI. We implement a tabletop system that can detect fingers and tags on capacitive multi-touch screen. The Tangible UI is a pawn with a TUIC-2D tag applied on the bottom. A vertical display shows the street view corresponding to the current point of view of the pawn. What we decided to do is to split the two views into two devices. As shown in Figure 4-1, the map view is shown on the table while the street view is shown on the LCD screen, positioned vertically in front of the table. The management of the two views is done by two different programs, each responsible for controlling the corresponding view and maintaining the consistency between the two views.

The 2D map view is shown on the tabletop surface. Users can interact with the map by using their fingers and the pawn. The recognized finger actions are two: move and zoom and are used to control the map view. The movements that the user has to do to perform these actions are exactly the same movements presented by S. Kim, Arif, J. Kim and Lee [95] for the same actions.

What we have to control, however, is not only the map view but also the street view. The first possibility is to increment the number of gestures. Nevertheless this idea make it possible to use only the hands to control both views, it increases the complexity of the system. This because the user need not only to learn a new set of gestures, but also how to perform them correctly to manipulate the system. What we decided to do is to use a pawn. This not only simplifies the number of gestures required to use the system but also exploits a mental process known as recognition over recall [53]. The shape of the pawn is exactly like a person, including the face. Therefore, It's easy for the user to associate the rotation of the pawn to the rotation of the view on the screen and the movement of the pawn with the change of the panorama's image. The functionalities connected to the pawn are two: move and rotate. When the user places the pawn on the surface of tabletop the closest panorama is shown on the screen; moving the pawn the panorama changes according to the new location, rotating the pawn is possible to see all the 360 degrees of the current panorama.

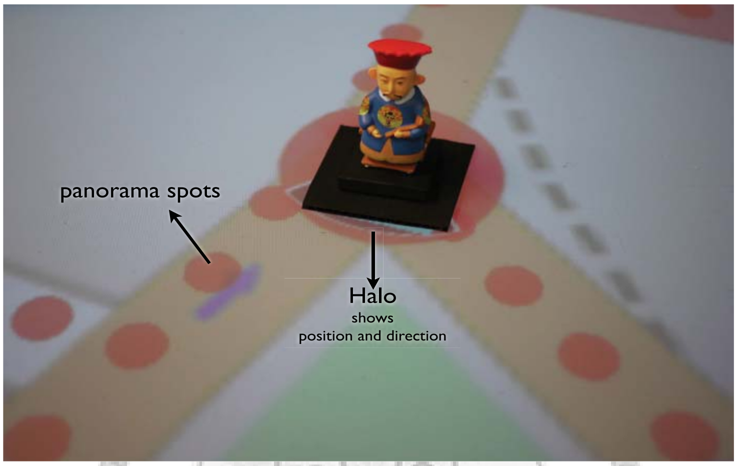


Figure 4-3: The visual user interface on the map view

As the pawn is placed on the map, some visual hits are shown under the pawn (Figure 4-3). One is a halo that indicates the position and direction. Another is the panorama spot. Since the Google map street view are discrete panorama pictures, the red spots can notices user how far will the street view is going to change on vertical display.

4.1.4 Discussion

We describe our findings as following aspects:

Direct mapping V.S. Indirect mapping

One important characteristic of TUI is physical contact of the widget. When holding the real widget, users get a better understanding about orientation, position and they can control the street view angle without focusing on the widget. In map navigation, the street view and the map view are separated in different region and moving or rotating the avatar is frequently involved. We observed a very much higher frequency of re-focusing with mouse-keyboard than with tangible widget. In addition, participants manipulated the movement of the widget more intuitively under our horizontal setting of the map view.

Place-and-direct

Tangible widget offers an important feature, that it can specifies both the position and the orientation. This characteristic is especially crucial in controlling the virtual navigation. Users have to specify the pose frequently in map navigating application. In our experiment, participants completed repositioning more efficiently with the tangible widget than the mouse and keyboard.

Physical widget in virtual world

Mapping the position and the orientation of the real widget to the virtual world brings convenient operating manners. But it has a problem that how to map the virtual position and orientation back to the real world. Moving and rotating the map will lead to the disorder of the street view and the widget. In our application, we fix the map position and orientation when the widget is placed. An alternative way is to display visual aid to help user understand the relationship between the shifted map and the real widget. Using the tangible widget brings a serious problem when users scale the map. Once the map zoomed, the region and the distance between neighboring panorama spots also scaled. However, the real widget is not able to perform resizing to keep the consistency. In our observation, we found a common mistaken idea if we use a constant size widget. Participants tried to move the widget a relatively tiny step which is out of the resolution that the device can provide. In our experiment, we ask participants to utilize the zoom function to avoid such problem. We are planning to introduce level of detail concept to the map system. If the level of detail is integrated properly, users can manipulate fixed size widget under different scale level and obtain important information as well.

4.2 Clip-on gadgets for portable multi-touch devices

Comparing to the large tabletop systems, the mobile devices are tend to be small and portable. The smaller panel size cannot hold too many tangible objects simultaneously, and the tangible objects should be easy to carry as well as the portable devices. In this section, we focus on the other type of tangible inputs – physical controllers, and develop a SDK for developers to create applications with better tactile experience.

4.2.1 Motivation

Virtual keyboards and controls commonly used on mobile multi-touch devices but they have several user interaction issues. First, virtual controls and users' "fat fingers"[82] occlude content of interest. Figure 4-4a shows the Street Fighter iPhone game UI with a virtual joystick and four buttons, which obscure 22~40% of the screen. Second, virtual controls provide no tactile feedback and require visual attention.

External, tactile controllers have been designed to address these issues. Both wired and wireless controllers eliminate occlusion and provide tactile feedback. However, wireless controllers, typically based on Bluetooth, require batteries to operate and are expensive. In addition, they require pairing to use with a device, and also un-pairing if users would like to control a different device. Wired controllers draw power from the mobile devices themselves. They have to route wires from the devices' connectors to the controls, and are generally more bulky. Another type of controller attaches directly to the screen to provide tactile feedback[86]. It makes the occlusion problem worse by completely obscuring the area occupied by the virtual controls.

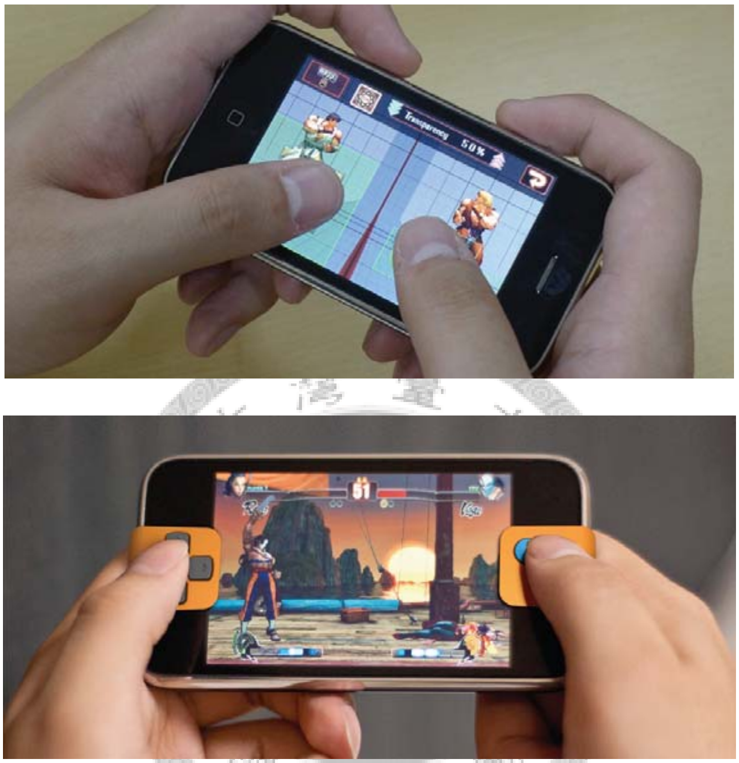


Figure 4-4: (top) Virtual keyboards and controls, commonly used on mobile multi-touch devices, occlude content of interest and do not provide tactile feedback. (bottom) Clip-on gadgets map user input to touch points on edges of screens to reduce occlusion and enhance tactile feedback

4.2.2 Survey of virtual controls

Past studies have reported several typing problems on virtual keys and proposed various solutions[56][85]. We surveyed the Top 10 arcade games in Apple App Store and found that there are two types of virtual controls (Figure 4-5(a) (b)). One is virtual joystick, and another is virtual keypad/buttons. Users move characters around by moving fingers in different directions on the screen. The direction of movement is determined by the relative position of touch point and the center of the controller. Without tactile feedback, the virtual joystick sometimes does not function as expected because users' fingers traverse the center unknowingly. All virtual controls introduce occlusion problem. Not only do virtual controls overlay on top of the content, users' fingers also occlude the display. Base on our calculation, while playing games with thumbs, the occlusion ratio is about 22~40% on iPhone and 12~14% on iPad, respectively.

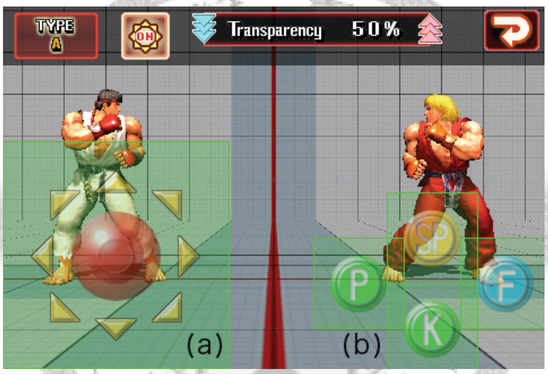


Figure 4-5: Virtual controls (a) virtual joystick, (b) virtual keypad / buttons

These are several mobile input techniques try to solve the fat finger problem[82] on smaller mobile devices. Offset Cursor[71] is designed to avoid finger occlusion on targets and improve selection accuracy. However, the offset between the cursor and the actual touched point makes it difficult to select contents at the bottom. To solve this problem, callout is usually used to display the occluded area. Shift[94] further improves it by avoiding unnecessary callouts, but, still, fingers block part of the touch screen. The backside of the devices has also been used to eliminate occlusion[4][30][44][82][85]. Some other approaches provide tactile feedback, but do not address the occlusion issue.

Several actuator solutions have been proposed to generate vibration at the touch position[9][20][51][63][73]. E-Sense[80] passes an ultra-low current into the pixel to create a small force to fingertips. Tactile Plus[28] pastes transparent haptic buttons on the screen to provide tactile feeling of buttons. Fling game controllers[86] directs stick on the screen with suction cups. Inside of the controller is a spiral that suspends an electrically conductive joystick to match the virtual controls

4.2.3 System design

Capacitive multi-touch screens sense changes of capacitance by the capacitive coupling effect[106]. When a conductor is placed on the screen and is connected to human body or ground, it changes the capacitance and the position of the conductor is sensed. We utilize this characteristic to build Clip-on gadgets. Figure 4-6 shows the design diagram of Clip-on gadgets. While pressing the button, the conductive rubber connects user’s finger to the contact points and registers as a touch event on the edge of the touchscreen. We decode the touch events to identify the corresponding buttons. The Clip-on gadgets are un-powered and are easy to carry. They transform the on-screen touch interactions into off-screen tactile interactions, reducing the occlusion ratio down to 5.8~9.6% on iPhone and 0.7~1.2% on iPad.

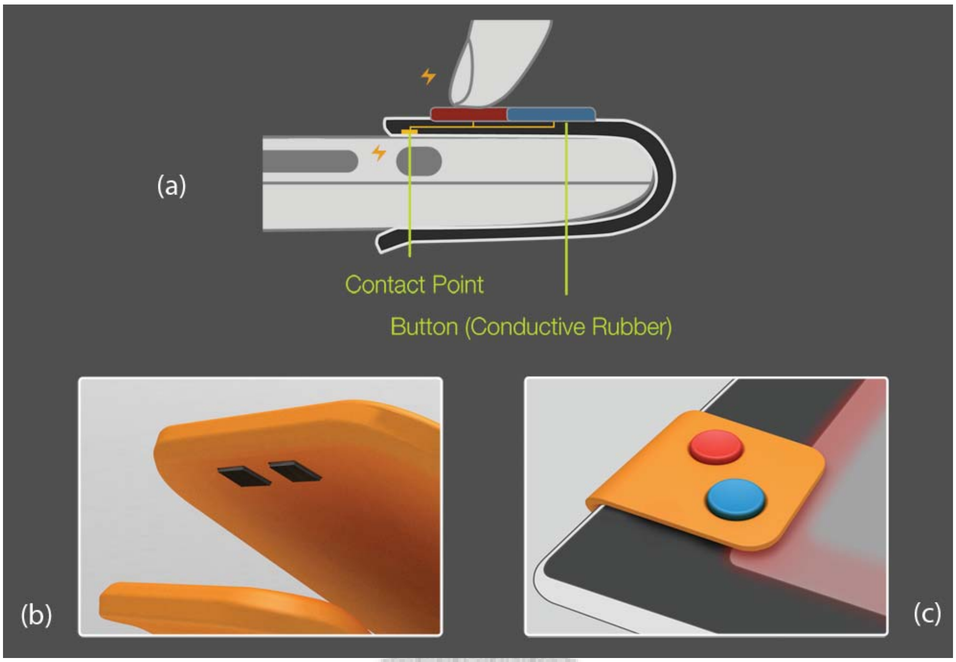


Figure 4-6: The design of Clip-on gadget (a) the contact points are conductors and connected to the corresponding buttons, (b) the contact points are arranged on the inward side to contact the touch screen and send the status of buttons, (c) the gadget overlays the edge (3~5mm) of the screen to trigger the touch input

Hardware prototyping

Figure 4-7 shows our clipper-style prototype. In order to provide better tactile feedback, we use physical buttons and switches. We connect one end to the tack, the other to the metal clipper. The tacks are one to one mapping to the buttons and re-arranged linearly to contact the edge of the touch screen. The size of tack is about 5mm to simulate finger touches. We chose median sized clipper as the control holder and attach some foam on the edge to ensure its stability while clipping to the devices. When the user holds the metal clipper, all the ground ends of the buttons are connected to the human body. Once the user presses the button, it causes touch event at the corresponding contact point (tack). In our experiment on iPad, the minimal size of contact points should be at least 3mm in diameter and the minimal gap between each point is 5mm. These values might be applicable to other touch screens with slightly difference.

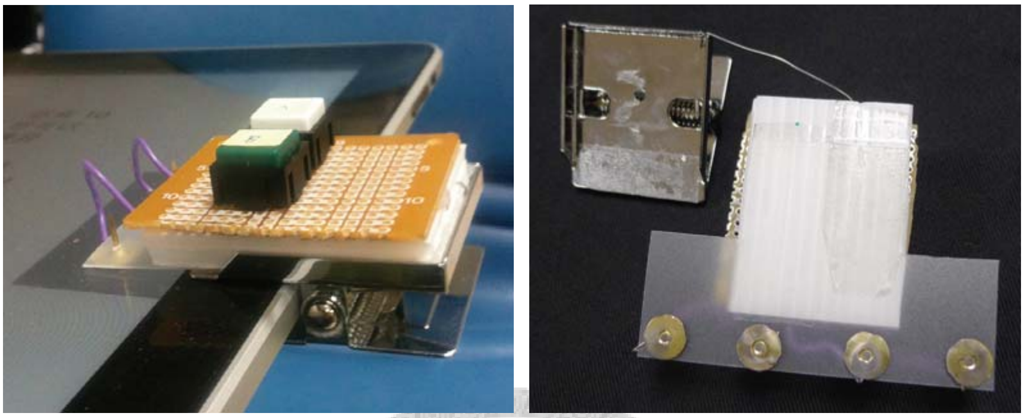

(a) (b)

Figure 4-7: The implementation of clipper-style prototype (a) side view, (b) exploded view

Software architecture

We developed a toolkit for iOS 4-based devices, written using Objective-C and CocoaTouch APIs included in iOS SDK 4.3. Our prototype devices are Apple iPad 1 and iPad 2 running iOS 4.3. The software architecture consists of three layers and two main components. The three layers works as follows: 1) iOS SDK dispatching touch events to Clip-on toolkit. 2) Clip-on toolkit translating the touch events to the tactile events and dispatches them to the application. 3) The application dispatching the tactile event to the callback functions to perform application-specific logic. The two main components are 1) Clip-on object 2) Detector object.

Clip-on object

The Clip-on object is the abstract object of the tactile controls. It includes two parameters: 1) a set of contact points on the screen, 2) the corresponding tactile events triggered by the contact points. The developer can load a predefined control in their application or customize one.

Predefined controls

Because some controls are commonly used by many applications, we built several predefined controls. For example, a D-pad can be used to control the direction and a knob can be used to control the rotation. Each predefined control maps to a physical Clip-on gadget. For example, a Clip-on D-pad has four buttons: left, right, up, down. So the D-pad object will trigger corresponding events when users click the physical buttons. The four contact points are also arranged in predefined order and distance. (Figure 4-8)

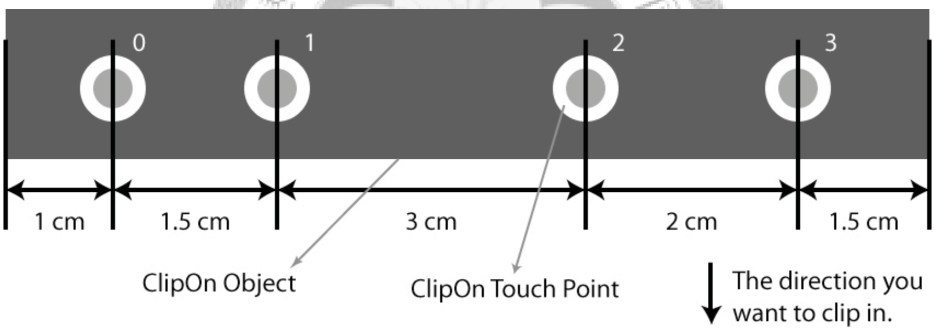


Figure 4-8: The layout of contact points

Detector object

The detector object contains an event listener, an event dispatcher and a visual UI element (DetectorView). The detector object is used to detect the touch event triggered by the DetectorView and then dispatch the tactile event to the application. The DetectorView shows the sensing area under the contact points and are used to notify the user to attach Clip-on gadget at that position. The width of sensing area on the edge of the screen is about 5mm, the smallest area for which touch events can be reliably detected. The detector object loads the parameter of Clip-on object to assign the height of sensing area. We also define two modes of the detector object: 1) fixed-position mode, 2) dynamic-position mode. In fixed-position mode, the screen shows a connector symbol on the left side of the iPhone and enforce user to clip the controller at that position (Figure 4-9(a)). In dynamic-position mode, the sensing area is any position along the edges of the devices (Figure 4-9(b)), so users can clip gadgets anywhere.

(a) (b)

Figure 4-9: two modes of Detector object. (a) Fixed-position mode: clip-on gadget has to be attached to specific positions. (b) Dynamic-position mode: clip-on gadget can be attached to arbitrary positions on the edge.

Calibration Procedure

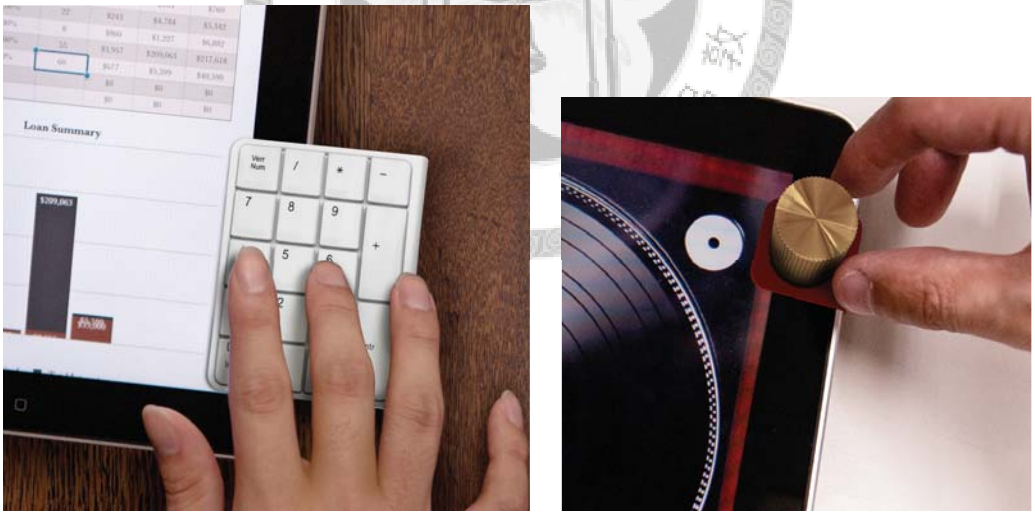
In dynamic-position mode, we assume user can clip the controller at any position on the edge. In order to match the controller and the application, we design a simply calibration procedure. Figure 4-10 show that the user is asked to press the "up" button of the clip-on gadget. After user pressed the "up" button, the color of the button will be changed to green and user will be asked to press the other buttons sequentially.

(a) (b)

Figure 4-10: User calibration procedure for dynamic-position mode

4.2.4 Discussion

The concept of Clip-on gadgets is very straightforward. We can expand the same idea on different forms of controllers. For example, we can design a Clip-on Numpad to help users enter numbers more efficiently (Figure 4-11a). Or a mechanical knob improves tuning accuracy when adjusting volume, tone, and balance. (Figure 4-11b)



(a) (b)

Figure 4-11: (a) Clip-on Numpad, (b) Clip-on knob

Current version of Clip-on gadget is one-to-one mapping from physical buttons to touch points. We will enhance coding technique to encode more information in the future.

4.3 Summary

We build a multi-display map touring system on tabletop. User can intuitively use multi-touch gestures and tangible pawn to walk through a city. Our tangible user interface provides better orientation mapping through the pawn and horizontal 2D map. The street view on the vertical display also help user to see the real city from the pawn's point of view.

As the tabletop system has larger space to place tangible objects, the mobile device is not friendly for traditional TUIs because of its tiny screen. But the demand of physical controllers is still needed. We propose a Clip-on gadget solution for tablets and mobile devices and a SDK for application developers to build attractive games or productivity tools. Clip-on Gadgets enable physical controllers to be used with these devices, without requiring wiring, battery, or wireless connections. User simply clips a physical controller to an edge of the device and start interacting with it. These expandable tactile controllers are easy to carry. The physical keys can be used with minimal visual attention by augmenting the sense of tactile.

CHAPTER 5

TUIC+: ENABLING BIDIRECTIONAL TANGIBLE INTERACTION ON CAPACITIVE MULTI-TOUCH DISPLAYS

5.1 Motivation

Tangible User Interfaces (TUIs) interlink digital information with the physical world[33]. While most TUIs are uni-directional, where an object's ID, location, and orientation are used as inputs to the system, several bidirectional approaches have been proposed to enable TUIs that are capable of both physical input and output[81]. These TUIs are mostly based on tabletop system[70][83][97], which typically use vision-based tracking and require external cameras that are relatively complex to set up and occupy significant space. We present TUIC+, a low-cost and low-power technique to enable bidirectional tangible interaction on unmodified capacitive multi-touch displays. These displays combine both sensing and display capabilities into a thin and light packaging, and have been widely used in mobile devices, such as iPad and iPhone, and large public displays such as 3M multi-touch display. In order to sense and track objects on capacitive multi-touch displays, TUIC+ utilizes multiple conductive points to encode object ID, location, and orientation[100]. Because the object location can be precisely tracked, it becomes possible to embed photodiodes into objects, and to transmit data to the objects by programmatically changing the brightness of the screen area directly below the photodiodes.

Compare to previous approaches, TUIC+ significantly reduces system complexity, power consumption, and cost because it does not require external cameras to sense and track objects, or wireless radios to send and receive data (e.g. ZigBee, Bluetooth, or Wi-Fi).

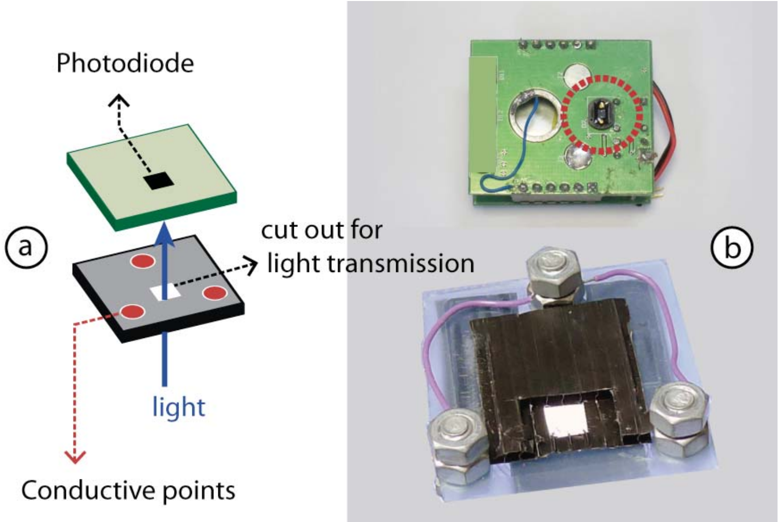


Figure 5-1: (a) TUIC+ design showing photodiode for receiving data and conductive points for object sensing and tracking. (b) TUIC+ prototype photodiode circuit board and conductive points.

5.2 TUIC+ tag design

Our TUIC+ prototype has two main hardware components, as shown in Figure 5-1a. First is a small photodiode circuit board, used to measure light level and decode data transmission. Data is encoded by changing the pixels directly beneath the photodiode to black to represent 0 and white to represent 1. The second part is a set of conductive points that simulate multiple finger touches. The pattern encodes object ID and orientation, and its position can be tracked. An opaque board with a cutout is placed between the circuit board and the display to minimize light leak. The cutout has the same dimension and is at the same location as the photodiode.

Our prototype circuit board, as shown in Figure 5-1b, has a dimension of 3x3cm and is powered by a 120mAh/3.7V battery. We use Texas Instruments' MSP430F1611 micro-controller because of its ultra-low power consumption and its ability to control analog and digital I/O channels. It can also be easily extended to support more sensors and actuators. We use a Hamamatsu S1087 photodiode on the circuit board to read the light signal from the multi-touch display below. The reason we use an analog photodiode instead of a binary phototransistor is that we can determine the lighting threshold in software. Figure 5-2 shows the block diagram of our circuit. The ADC on MSP430F1611 is 12-TUIC+, and the voltage reference is set to 2.5V.

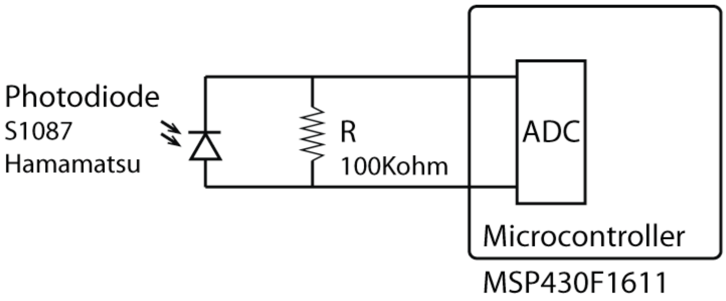


Figure 5-2: Block diagram of the photodiode to detect lighting level.

Experiments of light transmission

We measured the voltage reported by the photodiode at the lowest and at the highest brightness settings, and on three different devices: iPhone, iPad and iPad 2.

Figure 5-3 shows the voltage levels for black at both brightness settings are about 2mV for all three devices. At the highest brightness setting, the threshold can be set at

25mV to distinguish between black and white. We decide not to support the lowest brightness condition in our prototype because the voltage difference is not enough. We will add an amplifier to enhance the resolution in the future. We also measured the response time of the photodiode when the pixels go from black to white and vice versa. The results show that it can keep up with the display's refresh rate of 60Hz.

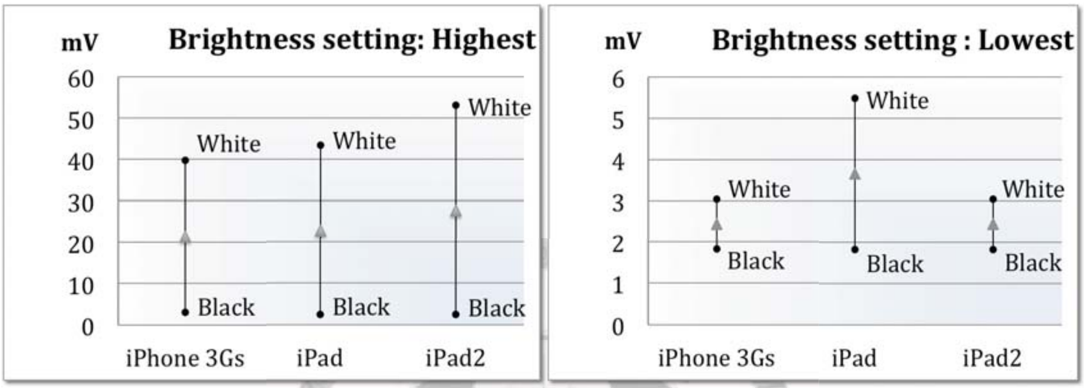


Figure 5-3: voltage reported by the photodiode on iPhone, iPad, and iPad 2.

5.3 Application example: Social Toy

Although multi-touch has become a natural way to interact with capacitive displays, the information we can read or manipulate is still virtually and bounded inside the flat display. In this section, we transform an iPhone or iPad as an *ambient display* that can reflect information through physical figurine. By using bidirectional tangible interaction, we make social communication more emotional and playful to enhance remote intimacy.

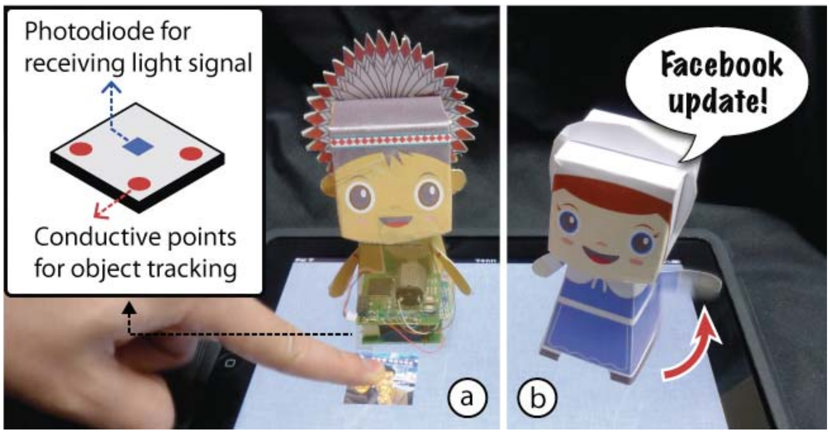


Figure 5-4: (a) Social Toys that have a bidirectional tag inside to transform iPad as an ambient display. (b) Social Toy raises arm as tangible output to inform Facebook update

5.3.1 Scenario

We use Facebook a lot to social with tons of people. For the closer friends, we not only send them a digital message, but also eager for more sensitive way to communicate with them. For example, we sometimes give them a real gift as a souvenir. And friends like to place the souvenir on the desk so that it can recall our faces to their mind. Several projects[43][52] explored the possible design to show different prototypes of *tangible social network*. We design a Social Toy that is an active figurine and can be represented as an important friend on Facebook. As the mobile device could be seen as a plate to get in touch with our friends, we further use it as a tray of physical ambient display. When the active figurine has been put on one's iPad or iPhone, it will automatically filter the wall's update from the represented person and raise its hand to notify the update. And then we can see the update message displayed on the screen. Once the user hugs the active figurine, it will send a poke to friend's wall. We can even have multiple figurines and send them photos by dragging a picture to their territory.

5.3.2 Active figurine as ambient display

Weiser first brought up the concept of "Calm Technology" and illustrated it with the dangling string[96]. Later, in their "Tangible Bits" vision, Ishii et al. envisioned ambient displays, which communicate digital information to human in physical or graphical manner on the periphery of user's attention without distraction. Some examples are ambientROOM[36], Water Lamp[14], Pinwheels[14]. Besides leveraging ambient displays to help awareness on the periphery, a number of researches are also used to support social communication. Kuzuoka and Greenburg[52] have designed a few digital but physical surrogates as media to mediate awareness and communicate with remote people. Based on their distinct designated functions, each surrogate selectively indicates the position, activity, degree of interest, and availability of remote people. Also, they react to user's explicit moving or grabbing, or implicit activity of getting close or far from them by controlling the communication capability of a media space naturally Connectibles[43] implemented a system of tangible social network focusing on group interaction to support remote awareness of friends. It utilizes gift-giving customs between friends to enhance mutual intimacy via the tangible Connectibles system and also allows data accessing with a GUI application. Other researches to enhance remote intimacy by using physical objects with different sensory modalities such as [7][11][13][83][100].

5.3.3 Social toy prototyping

Figure 5-5 shows the function blocks of Social Toy. As tangible interaction and multi-touch can both be used for a rich and natural interaction with interactive surfaces, we classify four types of interactions: *touch input*, *tangible input, screen output* and *tangible output*. Since the touch input is about manipulating virtual objects, we use the term: *digital input* instead. And we also use *digital output* to substitute screen output. We label four types onto each function block to show our design consideration.

Base on this classification, we can consider what type of input/output is best fit for certain interaction. For example, for the function of ambient display, notification of wall's update can form as tangible output: raising figurine's hand, to enhance the awareness. On the other hand, the update message is applicable to display on screen (digital output) and it's easy to thumb up that message by hitting the figurine (tangible input). Additionally, the classification helps us to distinguish the tasks for multi-touch device and active tangible. Thus, it helps to setup bidirectional communication during the development process.

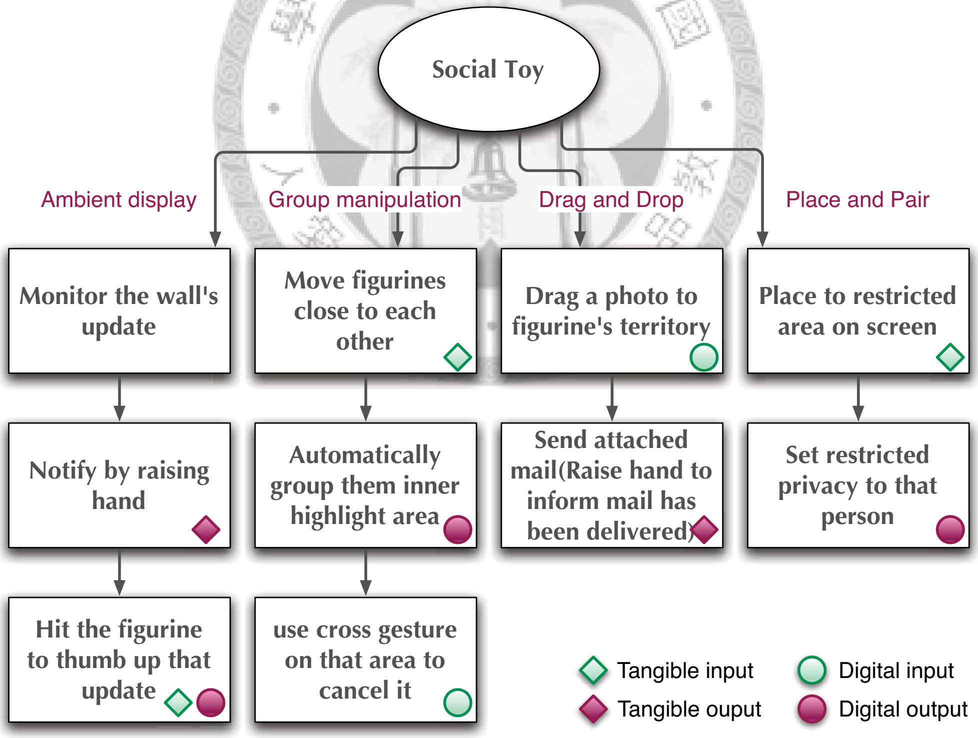


Figure 5-5: Function blocks of Social Toy

Group manipulation allows multiple figurines to work in parallel. When we move figurines close to each other, the system groups them automatically. So that we can send message to the group or do other group settings. When we want to exit the group mode, we just use cross gesture on the highlight area to cancel it. Drag and drop has been used a lot in GUI, it's easy to extend this concept to TUI with touch interface. Moreover, we can actuate the figurine to produce stronger feedback. Place and pair is another tangible interaction technique that has often been adopted in TUI systems. In the privacy setting mode, we can put different figurines onto different screen area to determine what level of notification for the represent people.

The Social toy was made by three main parts (Figure 5-6). First part is the paper figurine that can be customized by users. Second part is the conductive points for object sensing. Third part is a small photodiode circuit board, which attach a DC motor to control the arm's up and down actions.

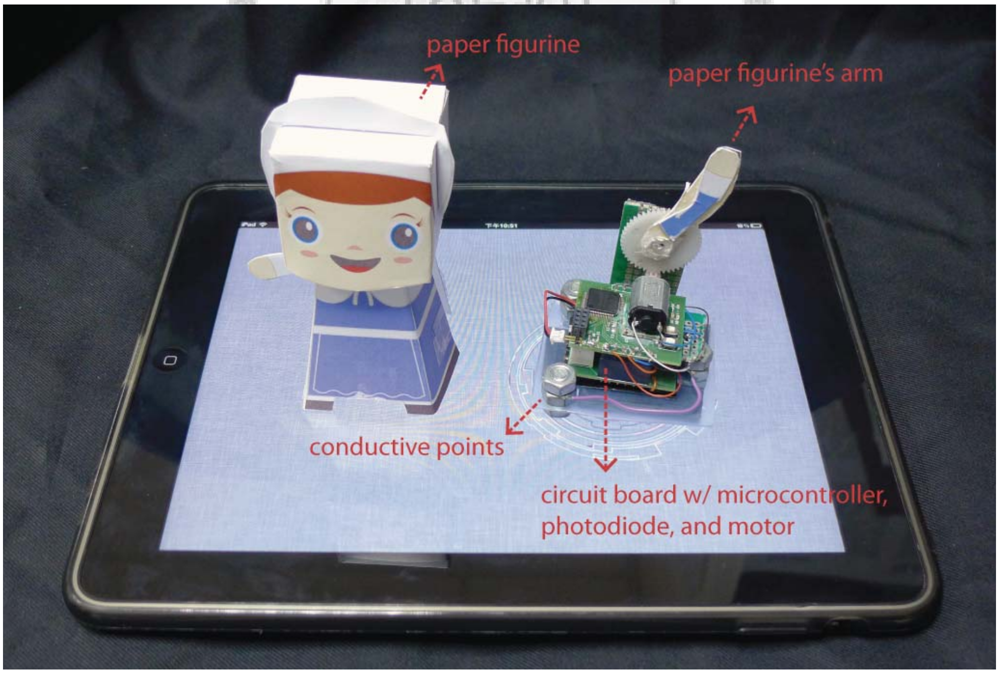


Figure 5-6: Exploded view of Social toy

We build an app with Facebook SDK. Users can use drag and drop manipulation to assign Facebook id to the Social Toy. And the app starts to monitor the wall's update.

Once the person represented by figurine posts the message, the figurine will raise its arm. Since the notification of wall's update does not require hard real-time response, we use a simple coding technique in this prototype. The app controls the light transmission area to flash 8 times per second and then Social toy raises arm. If the user has read the message and tapped it on the screen, the area flash 4 times per second to tell the Social toy lower down its arm.

5.4 Discussion

In this section we compare our technique with former bidirectional techniques that are used in interactive surfaces (e.g., tabletop system). Table 5-1 shows the primary techniques and their limitations. The TUIC+ has many advantages on size, configuration and cost. Most of all, it can seamlessly work on capacitive multi-touch displays. If we don't attach too many actuated parts on tangible object, the technique is sufficient for low-bandwidth communication. However, if we need high-bandwidth to transmit large data onto tangible object, our technique would cost user to wait too long. In this case, we suggest adding more photodiodes to expand the channels or enhancing the coding techniques.

As for the Social Toy application, we found users like active figurine very much because the figurine can embody the communication channel, and the contents of the channel can be mediated seamlessly through the Social Toy. The Social Toy can be treated as a message-filtering tool. The figurines we put on the iPad are whom we care more about. However, the size of capacitive touch devices is smaller than tabletop systems, we plan to design an advance UI for representing one Social Toy for multiple friends.

	TUIC+	Tangible Bots [70]	DMCS [49]	PMD [79]	Madgets and etc. [7][66] [67][97]
Object Detection	Conductive points	Visual marker	Projection light	Infrared	Visual marker or electro-magnetic
Communication	Light from screen	Zigbee	Projection light, need a Serial link	Infrared	None. (actuated by table)
Size of tangible tag	2x3x3 cm	~9.5cm^2	143x 108 cm	6x7 cm	Smallest is 1.5x1.5cm
Tag's Power Consumption	Low	Medium	Medium	Medium	None
Configuration	None	Wireless pairing	Complex	Complex	Complex
System Cost	Very Low	Low	-	-	Object is cheap but the table is expensive

Table 5-1: Comparison of bidirectional designs

5.5 Summary

We have presented TUIC+, a low-cost and low-power technique to enable bidirectional tangible interaction on unmodified capacitive multi-touch displays. It enables researchers to easily build and experiment with bidirectional TUIs on popular multi-touch devices. TUIC+ uses multiple conductive points for object tracking and sensing. For object communication, TUIC+ embeds photodiodes into objects, and transmits data to them by programmatically changing the screen’s brightness levels. We have demonstrated TUIC+ through a prototype implemented on iPhone and iPad and the same techniques can be used in different display systems.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Summary of the dissertation

Capacitive multi-touch displays support direct manipulation interface, have thin form factor, and are lightweight, and have been rapidly adopted in devices ranging from smartphones, tablets, to large interactive displays. We present TUIC, which enables 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 TUIC spatial tag uses passive, unpowered circuits to create geometric touch patterns, and is ideal for applications that require fast detection and simple maintenance. The TUI active frequency tag is smaller in size, use fewer 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 evaluate 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.

The size of capacitive multi-touch display ranges from smartphones to tablets to tabletops. Base on the TUIC techniques, we investigate two common forms of interactive surfaces: tabletop and portable multi-touch devices (e.g. tablets and mobile phones) and show the possible applications with TUIs + multitouch interactions.

We present a multi-display map touring system on tabletops. The system composes of a horizontal tabletop screen and a vertical screen. The map view and the street view are displayed on the horizontal and vertical displays of our system respectively. Users can place the tangible pawn on the 2D map to have direct access of the street view from the pawn’s point of view.

We present Clip-on gadgets as an Expandable Tactile Controllers for portable multi-touch devices. Clip-on gadgets enable physical controllers to be used with these devices, without requiring wiring, battery, or wireless connections. Users simply clip a physical controller to an edge of the device and start interacting with it. Developers can use our SDK to create games or productivity tools with Clip-on gadgets support.

Finally, we present TUIC+, which enable two-way communication for tangible interaction. We describe the design and implementation of a TUIC+ using iPads, and our experience with an application scenario, called Social Toys, that uses a motorized actuator to create ambient social awareness.

6.2 Future directions

The capacitive sensing techniques have brought multi-touch into the mass market. Through our TUIC and TUIC+ technology, we can enable tangible interactions on off-the-shelf multi-touch devices, empowering developers to explore and create diverse TUI applications, and making TUI accessible to end users.

For the technical side, we plan to dramatically reduce the size of TUIC and TUIC+ tags using more advanced circuit design and packaging. The largest obstacle to reducing size is probably the resolution of capacitive touch screens, because they are generally tuned to detect finger touches and have “finger-sized” resolution. We plan to collaborate with panel manufacturers to get lower-level sensing data to optimize the tag designs. For the application side, we explore several interactions based on Clip-on gadgets and TUIC+ tags, focusing on enhancing entertainment and education.

1. Better learning with haptics

Learning with haptic sensation has been shown to improve learning effectiveness[56]. We propose a piano-learning concept as shown in Figure 6-1(a). We can build a low-cost keyboard that is unpowered and contains only haptic keys. By using Clip-on technique, each key is mapped to a touch point on the lower edge of the touchscreen.

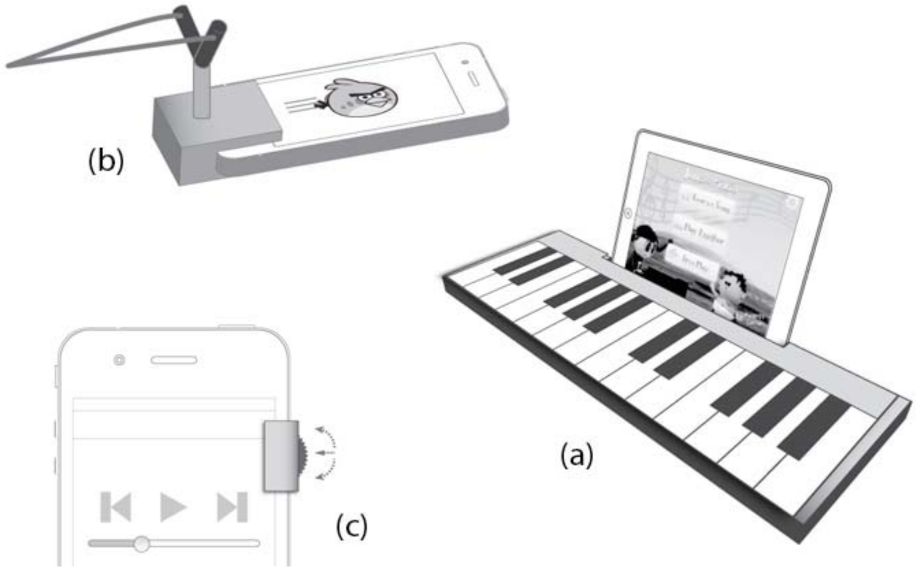


Figure 6-1: (a) Clip-on piano keyboard, (b) Clip-on Slingshot with force feedback, (c) Clip-on dial

2. Force feedback

Although software can generate visual effects, the feedback is still virtual. Haptic controls can provide *force feedback* to enhance experience in certain scenarios. As shown in Figure 6-1(b), a Clip-on slingshot can augment user experience by providing stretching force feedback in Angry Bird-style games. Users can change the weapon on the touch screen by swiping it and pull the slingshot to fire.

3. Single-hand usage

Mobile phones are often used with one hand, especially while walking or holding items in the other hand. Karlson et al. revealed that the vast majority of users want to use one hand for interacting with mobile devices, but the touchscreens are not designed to support dedicated single-handed use [44]. This is because some areas are hard to reach by the thumb while holding the phone. We propose a Clip-on dial that can provide up, down and click status. As shown in Figure 6-1(c), the dial can be used to control e-book reading, music playing, and the basic navigation. By combining the audio feedback, we can even use the device in the pocket to provide eye-free control.

4. Collaboration

Larger touch screens support collaborative work and gaming with multiple people. However, having more fingers on the screen leads to worse occlusion problems. Since the Clip-on gadgets can be easily attached next to the screens, they enhance sharing experience. Figure 6-2 shows four Clip-on gamepads are attached to an iPad to support 2-player games.

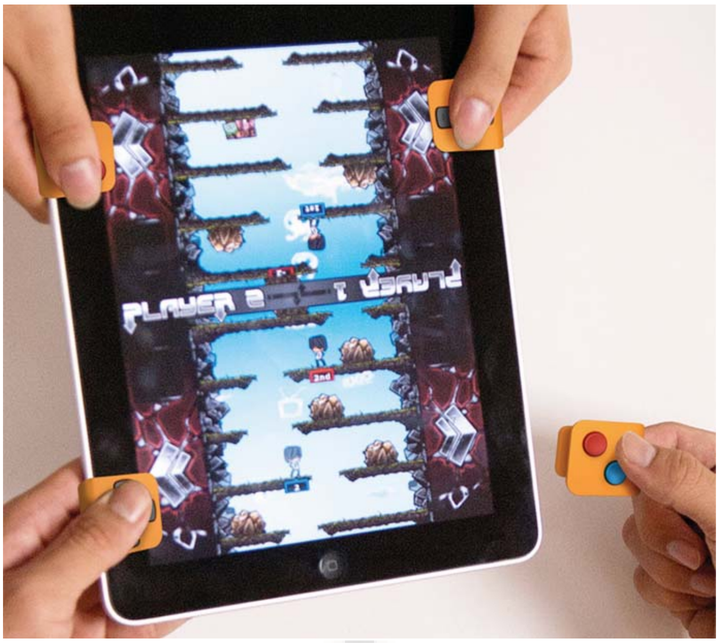


Figure 6-2: Collaborative gaming

5. Music box dancing doll

With adding more actuated joints and wheels on the active tangibles, we can create a dancing bots (Figure 6-3). While putting it on the portable device, it turns out as a music box dancing doll. For the social communication, people can design their own steps for the doll and their friends can see the doll dancing for them with unique steps. In order to guide the movement for the bot, we can connect 4 photodiodes in each direction to provide real-time moving command through the directional signals.

Figure 6-3: The concept of music box dancing doll

6. Storytelling toy

Children love to play dolls while they listen a story. For the eBook application, we can create storytelling pets. Children will not only use their hands to play with the virtual content on the touch display, but also use storytelling pets to interact with it. For example, children can use a puppet dog to smell virtual flowers, and then the puppet dog reflects its emotion through the actuated nose.

Figure 6-4: The concept of storytelling toy

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