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TANGIBLE USER INTERFACES

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INTRODUCTION

Where the sea meets the land, life has blossomed into a myriad of unique forms in the turbulence of water, sand, and wind. At another seashore, between the land of atoms and the sea of bits, we are now facing the challenge of reconciling our dual citizenships in the physical and digital worlds. Our visual and auditory sense organs are steeped in the sea of digital information, but our bodies remain imprisoned in the physical world. Windows to the digital world are confined to flat square screens and pixels, or "painted bits." Unfortunately, one can not feel and confirm the virtual existence of this digital information through one's hands and body.

Imagine an iceberg, a floating mass of ice in the ocean. That is the metaphor of Tangible User Interfaces. A Tangible User Interface gives physical form to digital information and computation, salvaging the bits from the bottom of the water, setting them afloat, and making them directly manipulatable by human hands.

FROM GUI TO TUI

People have developed sophisticated skills for sensing and manipulating their physical environments. However, most of these skills are not employed in interaction with the digital world today. A Tangible User Interface (TUI) is built upon those skills and situates the physically embodied digital information in a physical space. Its design challenge is a seamless extension of the physical affordance of the objects into digital domain (Ishii & Ullmer, 1997, 2000).

Interactions with digital information are now largely confined to Graphical User Interfaces (GUIs). We are surrounded by a variety of ubiquitous GUI devices such as personal computers, handheld computers, and cellular phones. The Graphical User Interface (GUI) has been in existence since the 1970s and the first appeared commercially in the Xerox 8010 Star System in 1981 (Smith, 1982). With the commercial success of the Apple Macintosh and Microsoft Windows, the GUI has become the standard paradigm for Human Computer Interaction (HCI) today.

GUIs represent information (bits) with pixels on a bitmapped display. Those graphical representations can be manipulated with generic remote controllers such as mice and keyboards. By decoupling representation (pixels) from control (input devices) in this way, GUIs provide the malleability to emulate a variety of media graphically. By utilizing graphical representation and "see, point, and click" interaction, the GUI made a significant improvement over its predecessor, the CUI (Command User Interface) which required the user to "remember and type" characters.

However, interactions with pixels on these GUI screens are inconsistent with our interactions with the rest of the physical environment within which we live. The GUI, tied down as it is to the screen, windows, mouse, and keyboard, is utterly divorced from the way interaction takes place in the physical world. When we interact with the GUI world, we cannot take advantage of our dexterity or utilize our skills for manipulating various physical objects, such as building blocks, or our ability to shape models out of clay.

Tangible User Interfaces (TUIs) aim to take advantage of these haptic interaction skills, which is a significantly different approach from GUI. The key idea of TUIs is to give physical forms to digital information. The physical forms serve as both representations and controls for their digital counterparts. TUI makes digital information directly manipulatable with our hands, and perceptible through our peripheral senses, by physically embodying it.

Tangible User Interface serves as a special-purpose interface for a specific application using explicit physical forms, while GUI serves as a general-purpose interface by emulating various tools using pixels on a screen.

TUI is an alternative to the current GUI paradigm, demonstrating a new way to materialize Mark Weiser's (1991) vision of Ubiquitous Computing of weaving digital technology into the fabric of a physical environment and make it invisible. Instead of making pixels melt into an assortment of different interfaces, TUI uses tangible physical forms that can fit seamlessly into a users' physical environment.

This chapter introduces the basic concept of TUI in comparison with GUI, early prototypes of TUI that highlight the basic design principles, and design challenges that TUI needs to overcome.

URP: AN EXAMPLE OF TUI

To illustrate basic TUI concepts, we introduce "Urp" (Urban Planning Workbench) as an example of TUI (Underkoffler & Ishii, 1999). Urp uses scaled physical models of architectural buildings to configure and control an underlying urban simulation of shadow, light reflection, wind flow, and so on. (Photo 24.1). In addition to a set of building models, Urp also provides a variety of interactive tools for querying and controlling the parameters of the urban simulation. These tools include a clock tool to change the position of sun, a material wand to change the building surface between bricks and glass (with light reflection), a wind tool to change the wind direction, and an anemometer to measure wind speed.

The physical building models in Urp cast digital shadows onto the workbench surface (via video projection), corresponding to solar shadows at a particular time of day. The time of day, representing the position of the sun, can be controlled by turning the physical hands of a "clock tool" (Photo 24.2). The building models can be moved and rotated, with the angle of their corresponding shadows transforming according to their position and the time of day.

Correspondingly, moving the hands of the clock tool can cause Urp to simulate a day of shadow movement between the situated buildings. Urban planners can identify and isolate intershadowing problems (shadows cast on adjacent buildings), and reposition buildings to avoid areas that are needlessly dark,or maximize light between buildings.

A "material wand" alters the material surface properties of a building model. By touching the material wand to a building

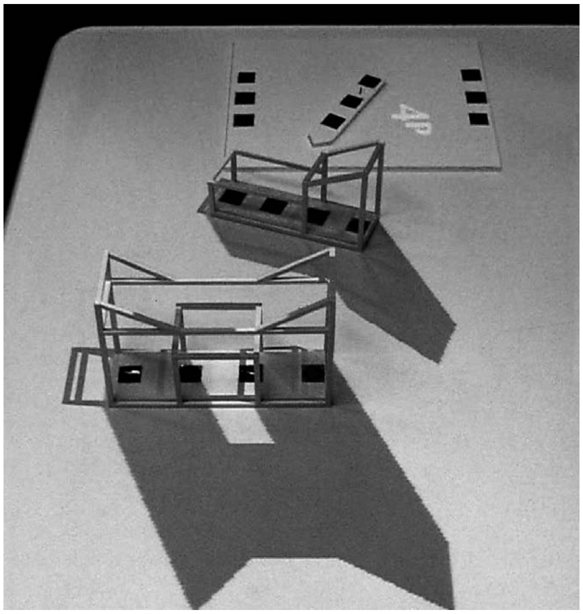

PHOTO 24.1. Urp and shadow stimulation.

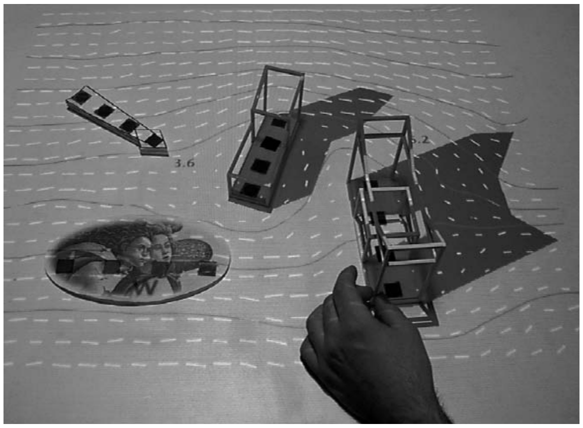

PHOTO 24.2. Urp and wind stimulation.

model, the building surface material is switched from bricks to glass, and a projected reflection of sunlight appears to bounce off the walls of the building. Moving the building allows urban designers to be aware of the relationship between the building reflection and other infrastructure. For example, the reflection off the building at sundown might result in distraction to drivers on a nearby highway. The designer can then experiment with altering the angles of the building to oncoming traffic or moving the building further away from the roadway. Tapping again with the material wand changes the material back to brick, and the sunlight reflection disappears, leaving only the projected shadow.

PHOTO 24.3. inTouch.

By placing the "wind tool" on the workbench surface, a wind flow simulation is activated based on a computational fluid dynamics simulation, with field lines graphically flowing around the buildings. Changing the wind tool's physical orientation correspondingly alters the orientation of the computationally simulated wind. Urban planners can identify any potential wind problems, such as areas of high pressure that may result in had-to-open doors or unpleasant walking environments. An "anemometer" object allows point monitoring of the wind speed (Photo 24.3). By placing the anemometer onto the workspace, the wind speed of that point is shown. After a few seconds, the point moves along the flow lines, to show the wind speed along that particular flow line. The interaction between the buildings and their environment allows urban planners to visualize and discuss inter-shadowing, wind, and placement problems.

In Urp, physical models of buildings are used as tangible representations of digital models of the buildings. To change the location and orientation of buildings, users simply grab and move the physical model as opposed to pointing and dragging a graphical representation on a screen with a mouse. The physical forms of Urp's building models, and the information associated with their position and orientation upon the workbench, represent and control the state of the urban simulation.

Although standard interface devices for GUIs, such as keyboards, mice, and screens, are also physical in form, the role of the physical representation in TUI provides an important distinction. The physical embodiment of the buildings to represent the computation involving building dimensions and location allows a tight coupling of control of the object and manipulation of its parameters in the underlying digital simulation.

In Urp, the building models and interactive tools are both physical representations of digital information (shadow dimensions and wind speed) and computational functions (shadow interplay). The physical artifacts also serve as controls of the underlying computational simulation (specifying the locations of objects). The specific physical embodiment allows a dual use in representing the digital model and allowing control of the digital representation. In the next section, the model of TUI is introduced in comparison with GUI to illustrate this mechanism.

BASIC MODEL OF TANGIBLE USER INTERFACE

The interface between people and digital information requires two key components: input and output, or control and representation. *Controls* enable users to manipulate the information, while *external representations* are perceived with the human senses. Figure 24.1 illustrates this simple model of a user interface consisting of control, representation, and information.

In the Smalltalk-80 programming language (Burbeck, 1992; Goldberg, 1984), the relationship between these components is illustrated by the "model-view-controller" or "MVC" archetype, which has become a basic interaction model for GUIs.

Drawing from the MVC approach, we have developed an interaction model for both GUI and TUI. We carry over the "control" element from MVC, while dividing the "view" element into two subcomponents: tangible and intangible representations, and renaming "model" as "digital information" to generalize this framework to illustrate the difference between GUI and TUI.

In computer science, the term *representation* often relates to the programs and data structures serving as the computer's internal representation (or model) of information. In this article, the meaning of "representation" centers upon external representations—the external manifestations of information in fashions directly perceivable by the human senses that include visual, hearing, and tactile senses.

GUI

In 1981, the Xerox Star workstation set the stage for the first generation of GUI (Johnson et al., 1989; Smith, 1982), establishing the "desktop metaphor" which simulates a desktop on a bitmapped screen. The Star workstation was the first commercial system that demonstrated the power of a mouse, windows, icons, property sheets, and modeless interaction. The Star also set several important HCI design principles, such as "seeing and pointing vs. remembering and typing," and "what you see is what you get (WYSIWYG)." The Apple Macintosh brought this new style of HCI to the public's attention in 1984, creating a new trend in the personal computer industry. Now, the GUI is widespread, largely through the pervasiveness of Microsoft Windows, PDAs, and cellular phones.

GUI uses windows, icons, and menus made of pixels on bitmapped displays to visualize information. This is an intangible representation. GUI pixels are made interactive through general "remote controllers" such as mice, tablets, or keyboards. In the pursuit of generality, GUI introduced a deep separation between the digital (intangible) representation provided by the bitmapped display, and the controls provided by the mouse and keyboard.

Figure 24.2 illustrates the current GUI paradigm in which generic input devices allow users to remotely interact with digital information. Using the metaphor of seashore that separates a sea of bits from the land of atoms, the digital information is illustrated at the bottom of the water, and mouse and screen are above sea level in the physical domain. Users interact with the remote control, and ultimately experience an intangible external representation of digital information (display pixels and sound).

TUI

Tangible User Interface (TUI) aims at a different direction from GUI by using tangible representations of information that also serve as the direct control mechanism of the digital information. By representing information in both tangible and intangible forms, users can more directly control the underlying digital representation using their hands.

Tangible Representation as Control

Figure 24.3 illustrates this key idea of TUI to give tangible (physical and graspable) external representation to the digital information. The tangible representation helps bridge the boundary between the physical and physical worlds. Also notice that the tangible representation is computationally coupled to the control to the underlying digital information and computational models. Urp illustrates examples of such couplings, including

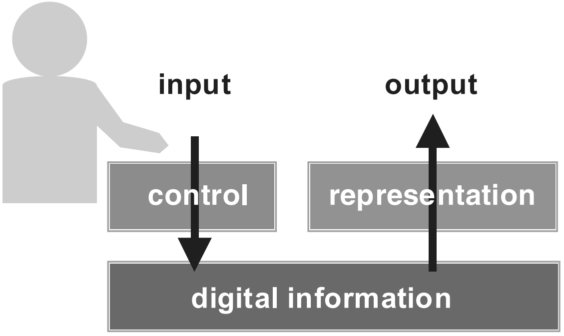

FIGURE 24.1. User interface model.

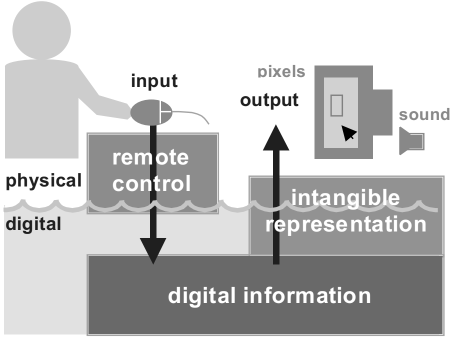

FIGURE 24.2. GUI model.

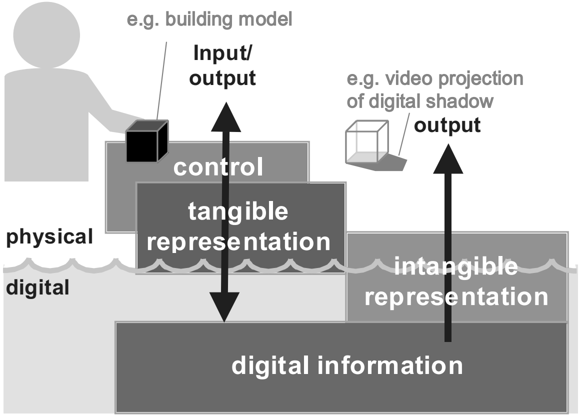

FIGURE 24.3. TUI model.

the binding of graphical geometries (digital data) to the physical building models, and computational simulations (operations) to the physical wind tool. Instead of using a GUI mouse to change the location and angle graphical representation of a building model by pointing, selecting handles, and keying in control parameters, an Urp user can grab and move the building model to change both location and angle.

The tangible representation functions as an interactive physical control. TUI attempts to embody the digital information in physical form, maximizing the directness of information by coupling manipulation to the underlying computation. Through physically manipulating the tangible representations, the digital representation is altered. In Urp, changing the position and orientation of the building models influences the shadow simulation, and the orientation of the "wind tool" adjusts the simulated wind direction.

Intangible Representation

Although the tangible representation allows the physical embodiment to be directly coupled to digital information, it has limited ability to represent or change many material or physical properties. Unlike malleable pixels on the computer screen, it is very hard to change a physical object in its form, position, or properties (e.g., color or size) in real time. In comparison with malleable "bits," "atoms" are extremely rigid, taking up mass and space.

To complement this limitation of rigid "atoms," TUI also utilizes malleable representations, such as video projections and sounds, to accompany the tangible representations in the same space to give dynamic expression of the underlying digital information and computation. In the Urp, the digital shadow that accompanies the physical building models is such an example.

The success of a TUI often relies on a balance and strong perceptual coupling between the tangible and intangible representations. It is critical that both tangible and intangible representations be perceptually coupled to achieve a seamless interface that actively mediates interaction with the underlying digital information, and appropriately blurs the boundary between physical and digital. Coincidence of input and output spaces and real-time response are important requirements to accomplish this goal.

Note: There exist certain types of TUIs which have actuation of the tangible representation (physical objects) as the central mean of feedback. Examples are inTouch (Brave, Ishii, & Dahley, 1998), curlybot (Frei, Su, Mikhak, & Ishii, 2000), and topobo (Raffle, Parkes, & Ishii, 2004). This type of force-feedback-TUI does not depend on "intangible" representation since active feedback through the tangible representation serves as the main display channel.

Key Properties of TUI

While Fig. 24.2 illustrates the GUI's clear distinction between graphical representation and remote controls, the model of TUI illustrated in Fig. 24.3 highlights TUI's integration of physical representation and control. This model provides a tool for examining the following important properties and design requirements of tangible interfaces (Ullmer & Ishii, 2000).

Computational coupling of tangible representations to underlying digital information and computation. The central characteristic of tangible interfaces is the coupling of tangible representations to underlying digital information and computational models. One of the challenges of TUI design is how to map physical objects and their manipulation to digital computation and feedback in a meaningful and comprehensive manner.

As illustrated by the Urp example, a range of digital couplings and interpretations are possible, such as the coupling of data to the building models, operations to the wind tool, and property modifiers to the material wand.

Deciding the embodiment and mapping of the controller is dictated by the type of application envisioned. We give example cases in which a range of specificity of embodiment is used. In some applications, more abstract forms of physical objects (such as round pucks) are used as generic controllers that are reusable to control a variety of parameters by rotating and pushing a button (Patten, Ishii, Hines, & Pangaro, 2001). When a puck is used as a dial to control a simulation parameter, graphical feedback is given to complement the information, such as scale of the dial.

Embodiment of mechanisms for interactive control with tangible representations. The tangible representations of TUIs serve simultaneously as interactive physical controls. Tangibles may be physically inert, moving only as directly manipulated by a user's hands. Tangibles may also be physically actuated, whether through motor-driven force-feedback approaches (e.g., inTouch, Curlybot) or magnet-driven approaches such as Actuated Workbench (Pangaro, Maynes-Aminzade, & Ishii, 2002).

Tangibles may be unconstrained and manipulated in free space with six degrees of freedom. They may also be weakly constrained through manipulation on a planar surface, or tightly constrained, as in the movement of the abacus beads with one degree of freedom.

In order to make interaction simple and easy to learn, TUI designers need to utilize the physical constraints of the chosen physical embodiment. Because the physical embodiment, to some extent, limits the interaction choices, a designer must design the interaction so that the actions supported by the object are based on well-understood actions related to the physical object. For example, if a bottle shape is chosen, then opening the bottle by pulling out a cork is a well-understood mechanism (Ishii, Mazalek, & Lee, 2001). This understanding of the culturally common manipulation techniques helps disambiguate the users' interpretation of how to interact with the object.

Perceptual coupling of tangible representations to dynamic intangible representations. Tangible interfaces rely on a balance between tangible and intangible representations. Although embodied tangible elements play a central, defining role in the representation and control of a TUI, there is a supporting role for the TUI's intangible representation. A TUI's intangible representation—usually graphics and audio—often mediate much of the dynamic information provided by the underlying computation.

The real-time feedback of the intangible representation corresponding to the manipulation of the tangible representation is critical to insure perceptual coupling. The coincidence of inputs and output spaces (spatial continuity of tangible and intangible representations) is also an essential requirement to enhance perceptual coupling. For example, in Urp, the building models (tangible representation) are always accompanied by a "digital shadow" (intangible representation) without noticeable temporal or spatial gaps. That convinces users of an illusion that the shadows are cast by the building models (rather than by the video projector).

Genres of TUI Applications

By giving physical form to digital information to enhance an experience, TUIs have a wide variety of application domains. This section gives an overview of seven genres for promising TUI applications. For a more exhaustive survey of TUIs in a historical context, I would encourage the readers to refer to Ullmer and Ishii (2000), Holmquist, Redstr, and Ljungstrand (1999), and Fishkin (2004). Zuckerman, Arida, and Resnick (2005) also provided a useful taxonomy and frameworks to analyze the design space of TUIs.

Tangible Telepresence

One such genre is an interpersonal communication taking advantage of haptic interactions using mediated tangible representation and control. This genre relies on mapping haptic input to haptic representations over a distance. Also called "tangible telepresence," the underlying mechanism is the synchronization of distributed objects and the gestural simulation of "presence" artifacts, such as movement or vibration, which allow remote participants to convey their haptic manipulations of distributed physical objects. The effect is to give a remote user the sense of ghostly presence, as if an invisible person was manipulating a shared object. InTouch (Brave & Dahley, 1997), HandJive (Fogg, Cutler, Arnold, & Eisbach, 1998), and ComTouch (Chang, O'Modhrain, Jacob, Gunther, & Ishii, 2002) are examples of this.

Tangibles with Kinetic Memory

The use of kinesthetic gestures and movement to promote learning concepts is another promising domain. Educational toys to materialize, record, and play concepts have been also explored using actuation technology and taking advantage of i/o coincidence of TUI. Gestures in physical space illuminate the symmetric mathematical relationships in nature, and the kinetic motions can be used to teach children concepts relevant to programming and differential geometry as well as storytelling. Curlybot (Frei et al., 2000) and topobo (Raffle et al., 2004) are examples of toys which distill ideas relating gestures and form to dynamic movement, physics, and storytelling.

Constructive Assembly

Another domain is a constructive assembly approach that draws inspiration from LEGO™ and building blocks, building upon the interconnection of modular physical elements. This domain is mainly concerned with the physical fit between objects, and the kinetic relationships between these pieces that enable larger constructions and varieties of movement.

Constructive assembly was pioneered by Aish and Frazer in the late 1970s. Aish developed BBS (Aish, 1979; Aish & Noakes, 1984) for thermal performance analysis, and Frazer developed a series of intelligent modeling kits such as "Universal Constructor" (Frazer, 1994; Frazer, Frazer, & Frazer, 1980) for modeling and simulation. Recent examples include GDP (Anagnostou, Dewey, & Patera, 1989), AlgoBlock (Suzuki & Kato, 1993), Triangles (Gorbet, Orth, & Ishii, 1998), Blocks (Anderson et al., 2000), ActiveCube (Kitamura, Itoh, & Kishino, 2001), and System Blocks (Zuckerman & Resnick, 2004). Topobo (Raffle et al., 2004) is a unique instance that inherits the properties of both "constructive assemble" and "tangibles with kinetic memory."

Tokens and Constraints

"Tokens and constraints" is another TUI approach to operate abstract digital information using mechanical constraints (Ullmer, Ishii, & Jacob, 2005). Tokens are discrete, spatially reconfigurable physical objects that represent digital information or operations. Constraints are confining regions within which tokens can be placed. Constraints are mapped to digital operations or properties that are applied to tokens placed within their confines. Constraints are often embodied as physical structures that mechanically channel how tokens can be manipulated, often limiting their movement to a single physical dimension.

The Marble Answering Machine (Crampton Smith, 1995) is a classic example which influenced many following research. MediaBlocks (Ullmer, Ishii, & Glas, 1998), LogJam (Cohen, Withgott, & Piernot, 1999), DataTile (Rekimoto, Ulmer, & Oba, 2001), and Tangible Query Interface (Ullmer, Ishii, & Jacob, 2003) are other recent examples of this genre of development.

Interactive Surfaces—Tabletop TUI

Interactive surfaces are another promising approach to support collaborative design and simulation which has been explored by many researchers in the past years to support a variety of spatial applications (e.g., Urp). On an augmented workbench, discrete tangible objects are manipulated and their movements are sensed by the workbench. The visual feedback is provided on the surface of the workbench, keeping input/output space coincidence. This genre of TUI is also called "tabletop TUI" or "tangible workbench."

Digital Desk (Wellner, 1993) is the pioneering work in this genre, and a variety of tabletop TUIs were developed using multiple tangible artifacts within common frames of horizontal work surface. Examples are metaDesk (Ullmer & Ishii, 1997), InterSim (Arias, Eden, & Fisher, 1997), Illuminating Light (Underkoffler & Ishii, 1998), Urp (Underkoffler & Ishii, 1999), Build-It (Rauterberg et al., 1998), Sensetable (Patten et al., 2001), AudioPad (Patten, Recht, & Ishii, 2002), and IP Network Design Workbench (Kobayashi, Hirano, Narita, & Ishii, 2003).

One limitation of above systems is the computer's inability to move objects on the interactive surfaces. To address this problem, the Actuated Workbench was designed to provide a hardware and software infrastructure for a computer to smoothly move objects on a table surface in two dimensions (Pangaro et al., 2002), providing an additional feedback loop for computer output, and helping to resolve inconsistencies that otherwise arise from the computer's inability to move objects on the table.

Continuous Plastic TUI

Fundamental limitation of previous TUIs was the lack of capability to change the forms of tangible representations during the interactions. Users had to use predefined finite sets of fixed-form objects, changing only the spatial relationship among them but not the form of individual objects themselves.

Instead of using predefined discrete objects with fixed forms, the new type of TUI systems utilizing continuous tangible material such as clay and sand were developed for rapid form-giving and sculpting for the landscape design. Examples are Illuminating Clay (Piper, Patti, & Ishii, 2002), and SandScape (Ishii, Ratti, Piper, Wang, Biderman, & Ben-Joseph, 2004). Later this interface was applied to the browsing of 3D volume metric data in PhoxelSpace project (Ratti, Wang, Piper, Ishii, & Biderman, 2004).

Augmented Everyday Objects

Augmentation of familiar everyday objects is an important design approach of TUI to lower the floor and to make it easy to understand the basic concepts. Examples are the Audio Notebook (Stifelman, 1996), musicBottles (Ishii et al., 1999), HandScape (Lee, Su, Ren, & Ishii, 2000), LumiTouch (Chang, Resner, Koerner, Wang, & Ishii, 2001), Designers' Outpost (Klemmer, Thomsen, Phelps-Goodman, Lee, & Landay, 2002), and I/O Brush (Ryokai, Marti, & Ishii, 2004). It is a challenge for industrial designers to improve upon a product by adding some digital augmentation to an existing digital object. This genre is open to much eager interpretation by artists and designers, to have our everyday physical artifacts evolve with technology.

Ambient Media

In the early stages of TUI research, we were exploring ways of improving the quality of interaction between people and digital information. We employed two approaches to extending interaction techniques to the physical world:

- Allowing users to "grasp and manipulate" foreground information by coupling bits with physical objects;
- Enabling users to be aware of background information at the periphery using ambient media in an augmented space.

At that time, HCI research had been focusing primarily on foreground activity on the screen and neglecting the rest of the user's computing environment (Buxton, 1995). However, in most situations, people are subconsciously receiving ambient information from their peripheral senses without attending to it explicitly. If anything unusual is noticed, it immediately comes to their attention, and they could decide to bring it to the foreground. For example, people subconsciously are aware of the weather outside their window. If they hear thunder, or a sudden rush of wind, the user can sense that a storm is on its way, out of his or her peripheral attention. If it was convenient, the user could then look outside, or continue working without distraction.

Ambient media describes the class of interfaces that is designed to smooth the transition of the users' focus of attention between background and foreground. Natalie Jeremijenko's Live Wire in 1995, at Xerox Parc, was a spinning wire that moved to indicate network traffic. Designing simple and adequate representations for ambient media using tangible objects is a key part of the challenge of Tangible Bits (Ishii & Ullmer, 1997).

The ambientROOM is a project that explores the ideas of ambient media constructing a special room equipped with embedded sensors and ambient displays (Ishii et al., 1998). This work was a preliminary investigation into background/peripheral interfaces, and led to the design of standalone ambient fixtures such as Pinwheels and Walter Lamps that make users aware of "digital wind" and "bits of rain" at their peripheral senses (Dahley, Wisneski, & Ishii, 1998).

Strictly speaking, ambient media is not a kind of TUI since in many cases there are no direct interactions. Rather, ambient media serve as background information displays that complement tangible/graspable media that users manipulate in the foreground. TUI's approach to ambient media is concerned with the design of simple mappings that give easy-to-understand form to cyberspace information and represent change in a subtle manner. We started experimenting with a variety of ambient media such as sound, light, airflow, and water movement for background interfaces for awareness of cyberspace at the periphery of human perception.

This concept of "ambient media" is now widely studied in the HCI community as a way to turn the architectural/physical spaces into an ambient and calm information environment. Another design space is low-attention interfaces for interpersonal communication through ambient media (Chang et al., 2001). Ambient devices further commercialized the domain of low-attention ambient media interfaces by developing the Ambient Orb and Weather Beacon, exploring the new genre of "glanceable interfaces" (http://www.ambientdevices.com/).

TUI Instances

In this section, 10 TUI examples are presented to illustrate the potential application domains described in a previous section, and to highlight unique features of TUIs. However, given the limited space and rapid growth of TUI research in HCI community in recent years, the collection of examples introduced here can only cover a relatively small portion of the representative works of TUIs.

InTouch: Tangible TelePresence Through Distributed Synchronized Physical Objects

InTouch is a project to explore new forms of interpersonal communication over distance through touch by preserving the physical analog movement of synchronized distributed rollers (Brave & Dahley, 1997; Brave et al., 1998). Force-feedback is employed to create the illusion that people, separated by distance, are interacting with a shared physical object. The "shared" object provides a haptic link between geographically distributed users, opening up a channel for physical expression over distance.

Two identical mechanisms were built with three freely rotating rollers (Photo 24.3). Each roller is synchronized to the corresponding roller on the distant mechanism using force-feedback, so that when one roller is moved the other corresponding roller also moves. If the movement of one roller is held, then the roller transmits that resistance to the other roller. They are in a sense connected by a stiff computational spring. Two users separated by distance can then play, moving or tapping the rollers or more passively feeling the other person's manipulation of the object. The presence of the other person is represented tangibly through physical interaction with the inTouch device.

Force-feedback is conventionally used to allow a user to "touch" virtual objects in the computer screen through a single point. InTouch applies this technology to realize a link for interpersonal haptic communication, instead of just touching virtual objects. InTouch allows people to feel as if they are connected through touching the rollers, to another person. Instead of touching inanimate objects, each person is touching a dynamic, moving object that is shared.

Important features of inTouch from HCI points of view can be summarized as follows:

1. No boundary between "input" and "output" (i/o coincidence: the wooden rollers are force displays as well as input devices);
2. Principal human input/output organs are hands, not eyes or ears (with the sense of touch being the primary mode);
3. Information can be sent and received simultaneously through one's hand.

Past communication media such as video-telephony set themselves the ultimate goal of reproducing the voice or the image of the human face and body as realistically as possible in order to create the illusion of "being there" for each interlocutor. InTouch takes the opposite approach by making users aware of the other person without ever rendering him or her in bodily terms, and creating what we call a "tangible presence" or "ghostly presence." By seeing and feeling an object being moved in a human fashion on its own, we imagine a ghostly body. The concept of the ghostly presence provides us with a different approach to the conventional notion of telepresence.

Curlybot: A Toy to Record and Play

Curlybot is a toy that can record and play back physical motion (Photo 24.4). As one plays with it, it remembers how it has been moved and can replay that movement with all the intricacies of the original gesture; every pause, acceleration, and even the shaking in the user's hand, is recorded. Curlybot then repeats that gesture indefinitely, creating beautiful and expressive patterns. Children can use curlybot to gain strong intuition for advanced mathematical and computational concepts, like differential geometry, through play outside of traditional computers (Frei et al., 2000).

The forced-feedback technology used for real-time simultaneous communication in inTouch was employed in curlybot for the recording and playback of gestures. Two motors equipped with an optical encoder enable free rotation in addition to forward and backward movement.

When the user presses the button a red LED is illuminated to indicate the recording mode. The user then moves the curlybot around; meanwhile an encoder is recording this gesture information. Pushing the button a second time terminates recording and a green LED alights to indicate the playback mode. The microprocessor compares the current position with the stored positions and instructs the motors to retrace the steps recorded in the curlybot's memory.

PHOTO 24.4. Curlybot.

This project contributes to both interface design and education. As a tangible interface it blurs the boundary between input and output, as inTouch does. Curlybot itself is both an input device to record gestures and a physical display device to reenact them. By allowing the user to teach it gestures with his or her hand and body, and then reenacting those gestures in a physical space around the body, curlybot enables a strong connection between body and mind not obtainable from anything expressed on a computer screen.

From an educational standpoint, curlybot allows very young children to explore "advanced" mathematical and computational concepts. Curlybot supports new ways of thinking about geometric shapes and patterns. Children can also use curlybot to explore some of the basic ideas behind computational procedures, like how complexity can be built from simple parts. This is similar to what is possible with the Logo programming language, but does not require children to read or write and thus makes advanced ideas accessible to younger children. Curlybot also draws strongly on children's intuition about their own physical actions in the world to learn—what Seymour Papert called "body syntonic learning" (Papert, 1980). In addition, the direct input and beautifully expressive patterns that result through curlybot's repetition of the gestures keep children playing and engaged.

Topobo: 3D *Constructive Assembly With Kinetic Memory*

Topobo, a combination of "topology" and "robotics," is a 3D constructive assembly system with kinetic memory, and the ability to record and play back physical motion (Raffle et al., 2004). By snapping together a combination of passive (static) and active (motorized) components, people can quickly assemble dynamic biomorphic forms like animals and skeletons with Topobo. Topobo allows users to animate those forms by recording the movement of pushing, pulling, and twisting them, and later observe the system play back those motions repeatedly. This "record and play" function was inherited from the prior curlybot project, and the constructive assembly function was inherited from the commercial toy, Zoob™.

For example, a dog can be constructed and then taught to gesture and walk by twisting its body and legs. The dog will then repeat those movements and walk repeatedly. The same way people can learn about static structures playing with regular building blocks, they can learn about dynamic structures by playing with Topobo. Topobo works like an extension of the body, giving one gestural fluency. Topobo embeds computation within a dynamic building system so that gestural manipulation of the material becomes a programming language (Photo 24.5).

Topobo was inspired by current trends in computational media design and by artists and empiricists using visual explorations and models of natural phenomena to more deeply appreciate patterns found in the natural world. In this spirit, Topobo is designed to allow people to use experimentation, play, and self-expression to discover and explore common natural relationships between natural forms and dynamic motion. Building toys and educational manipulatives have been used for years by children to learn about the world though model making.

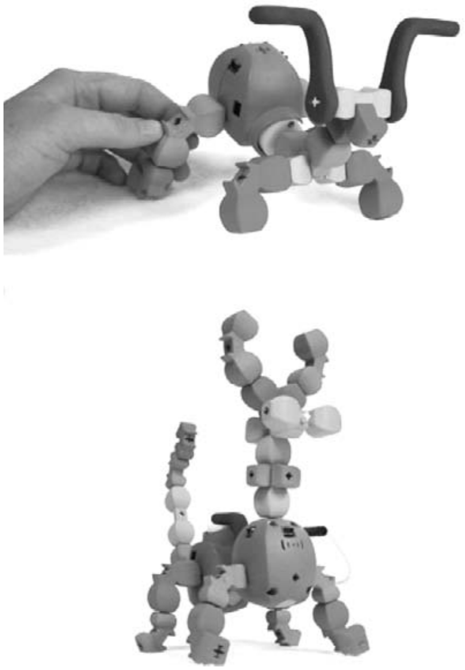

PHOTO 24.5. Topobo.

Unique among modeling systems is Topobo's coincident physical input and output behaviors (which is also common to inTouch and curlybot). The system is comprised of 10 different primitives that can be snapped together in a variety of ways. Nine of these primitives are called "passive" because they form static connections. These static connections constrain the form and the range of motion available to the structure. One "active" primitive is built with an embedded encoder and motor which is programmed by demonstration. These motorized components are the only ones that move, so the system is able to faithfully record and replay every dynamic manipulation to the structure.

mediaBlocks: Token and Constraint Approach

The mediaBlocks system is a tangible interface for manipulating lists of online digital media such as video clips and images (Ullmer et al., 1998). Whereas Urp provides a spatial interface for leveraging object arrangements consistent with real-world building configurations, the mediaBlocks system provides a relational interface for manipulating more abstract digital information.

The mediaBlocks are small, digitally tagged blocks, dynamically bound to lists of online media elements. The mediaBlocks support two major modes of use. First, they function as capture, transport, and playback mechanisms for moving online media between different media devices. In this mode, conference room cameras, digital whiteboards, wall displays, printers, and other devices are outfitted with mediaBlock slots. Inserting one of the mediaBlocks into the slot of a recording device (e.g., a camera) activates the recording of media into online space, and the dynamic binding of the media to the physical block.

Similarly, inserting one of the bound mediaBlocks into a playback device (e.g., video display) activates playback of the associated online media. Inserting mediaBlocks into slots mounted on computer monitors provides an intermediate case, allowing mediaBlock contents to be exchanged bi-directionally with traditional computer applications using the GUI drag-and-drop operation.

The second functionality of mediaBlocks uses the blocks as physical controls on a media-sequencing device (Photo 24.6). A mediaBlock "sequence rack" (partially modeled after the tile racks of the Scrabble game) allows the media contents of multiple adjacent mediaBlocks to be dynamically bound to a new mediaBlock carrier. Similarly, a second "position rack" maps the physical position of a block to an indexing operation upon its contents. When mediaBlocks are positioned on the left edge of the position rack, the first media element of the block is selected. Intermediate physical positions on the rack provide access to later elements in the associated media list of the block.

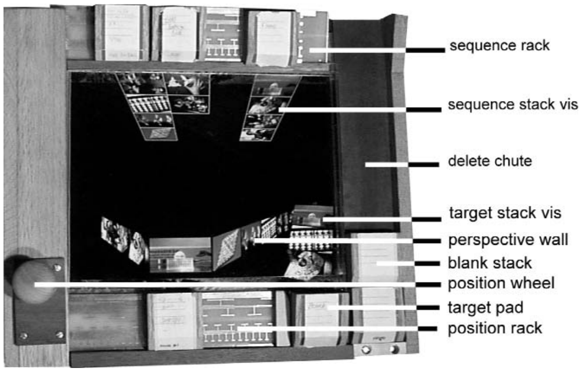

PHOTO 24.6. mediaBlocks: media sequencing device.

PHOTO 24.7. AudioPad running on Sensetable platform.

Digital Desk: Pioneer of Tabletop TUI

Digital Desk (Wellner, 1993) is a pioneering work to demonstrate a way to integrate physical and digital document processing on a table. Wellner brought some of the functionality we typically associate with GUIs onto the physical desktop. This table used a camera and a microphone to detect finger presses on a graphical interface displayed on a desk with a video projector. Wellner used this desk for tasks such as graphic design and spreadsheet computations on physical paper. This system also employed some physical props, such as a scanner that would scan items and place them directly on the tabletop interaction surface.

Wellner's research pointed the way toward enabling the computer to perform some of the operations we traditionally associate with GUIs in a tabletop environment. The Digital Desk also illustrates some of the compelling reasons for considering computer interfaces based on horizontal interactive surfaces. Because many work surfaces in our environment are already planar, horizontal or nearly horizontal surfaces, integrating computer interfaces into these surfaces may provide an opportunity for new types of relationships between computation and physical objects, and may help create computer systems that are more relevant to problem domains with established work practices based on tabletops.

The Digital Desk inspired many tabletop tangible interfaces including the Luminous Room project (Underkoffler, Ullmer, & Ishii, 1999) from which Urp (Underkoffler & Ishii, 1999) was created. Sensetable (Patten et al., 2001) is another example.

Sensetable and AudioPad: Tabletop TUI *for Real-Time Music Performance*

Sensetable (Patten et al., 2001) is a system that wirelessly tracks the positions of multiple objects on a flat display surface. The Sensetable serves as a common platform for a variety of tabletop TUI applications such as Audio Pad and IP Network Design Workbench.

Audiopad (Patten et al., 2002) is a composition and performance instrument for electronic music which tracks the positions of objects on a tabletop surface and converts their motion into music. One can pull sounds from a giant set of samples, juxtapose archived recordings against warm synthetic melodies, cut between drum loops to create new beats, and apply digital processing all at the same time on the same table. Audiopad not only allows for spontaneous reinterpretation of musical compositions, but also creates a visual and tactile dialogue between itself, the performer, and the audience.

Audiopad is based on the Sensetable platform that has a matrix of antenna elements which track the positions of electronically tagged objects on a tabletop surface. Software translates the position information into music and graphical feedback on the tabletop. Each object represents either a musical track or a microphone (Photo 24.8).

Experience of Audiopad with tangible user interface through a series of live performances suggests that interacting with electromagnetically tracked objects on a tabletop surface with graphical feedback can be a powerful and satisfying tool for musical expression. The integration of input and output spaces gives the

PHOTO 24.8. IP network design workbench running on Sensetable platform.

performer a great deal of flexibility in terms of the music that can be produced. At the same time, this seamless integration allows the performer to focus on making music, rather than using the interface. Spatial multiplexed inputs of TUI also supported two performers play music simultaneously and collaboratively (Photo 24.8).

IP Network Design Workbench: Event Driven Simulation on Sensetable

The IP Network Design Workbench (IPNWDWB) is the collaborative project between NTT Comware and the Tangible Media Group. The IP Network Design Workbench supports collaborative network design and simulation by a group of experts and customers (Kobayashi et al., 2003). This system is also based on the Sensetable platform which can wirelessly detect the location and orientation of physical pucks. Simulation engine is based on the event-driven simulation model. Using the Sensetable system, users can directly manipulate network topologies for modeling, control simulation parameters of nodes and links using physical pucks on the sensing table, and simultaneously see the simulation results projected onto the table in real time (Photo 24.9).

The goal of IPNWDWB is to make simulation tools more accessible for non-experts, so that they can join the network design process and interact with experts more easily than using traditional GUI computer. This system was commercialized and has been used for collaborative network design with customers to ensure their understanding of the performance and cost of network enhancements dealing with the increases of network traffic caused by Voice over IP and/or streaming video, for example. Because of the large tiling horizontal work surface and TUI interaction that invites all the participants to touch and manipulate pucks simultaneously, the process of decision making becomes much more democratic and more convincing than ordinary PowerPoint presentations through conventional GUI.

If we compare IPNWDWB with Urp, we notice a big difference in the nature of applications. In Urp, we used physical scale models of buildings, which humans have used for thousands of years to design cities, as tangible representations of urban models. Therefore, it is very natural to apply TUIs to such domains (e.g., urban planning, landscape design) in which physical models have been used long before the birth of digital computers.

In contrast, IP Network Design is based on event-driven simulation models which are quite abstract and new. This modeling technique requires digital computers. IPNWDB is important

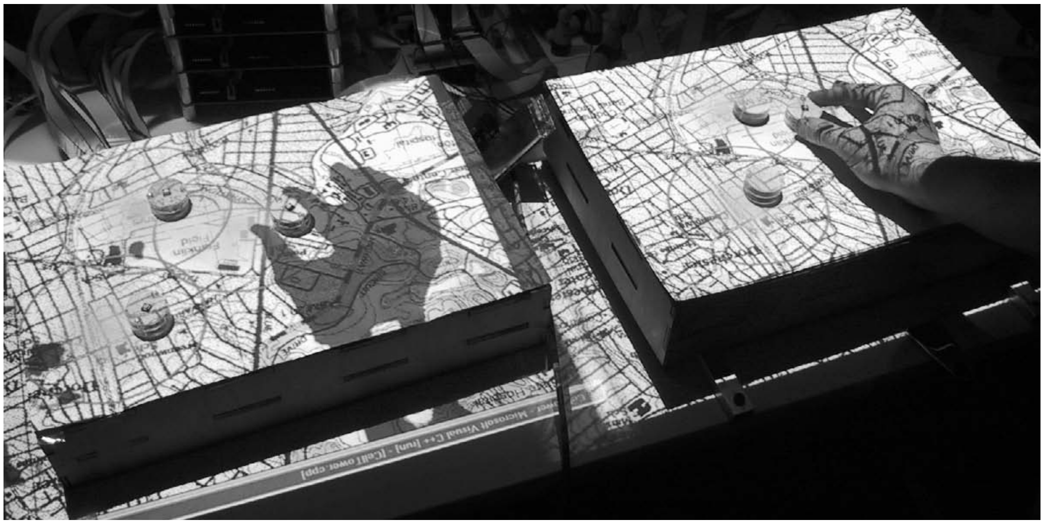

PHOTO 24.9. Actuated workbench used for distributed collaboration.

since it demonstrated that TUI can empower the design process even in abstract and computational application domain which does not have straight-forward mappings from abstract concepts to physical objects. There are a wide range of modeling and simulation techniques such as System Dynamics and Event-Driven Simulation that uses 2D graph representation. We learned that many of these abstract computational applications can be supported by Sensetable-like TUI platforms in the collaborative design sessions. For example, simultaneously changing parameters, transferring control between different people or different hands, and distributing the adjustment of simulations dynamically are interactions enabled by TUI.

Actuated Workbench: Closing a Loop of Computational Actuation and Sensing

The aforementioned tabletop TUI systems share a common weakness. While input occurs through the physical manipulation of tangible objects, output is displayed only through sound or graphical projection on and around the objects. As a result, the objects can feel like loosely coupled handles to digital information rather than physical manifestations of the information itself.

In addition, the user must sometimes compensate for inconsistencies when links between the digital data and the physical objects are broken. Such broken links can arise when a change occurs in the computer model that is not reflected in a physical change of its associated object. With the computer system unable to move the objects on the table surface, it cannot undo physical input, correct physical inconsistencies in the layouts of the objects, or guide the user in the physical manipulation of the objects. As long as this is so, the physical interaction between human and computer remains one-sided.

To address this problem, the Actuated Workbench was designed to provide a hardware and software infrastructure for a computer to smoothly move objects on a table surface in two dimensions (Pangaro et al., 2002).

The Actuated Workbench is a new technology that uses magnetic forces to move objects on a table in two dimensions. It is intended for use with existing tabletop tangible interfaces, providing an additional feedback loop for computer output, and helping to resolve inconsistencies that otherwise arise from the computer's inability to move objects on the table.

Actuation enables a variety of new functions and applications. For example, a search and retrieve function could respond to a user query by finding matching data items and either moving them to another place on the tabletop or wiggling them to get the user's attention. A more powerful function would be one in which the computer could physically sort and arrange pucks on the table according to user-specified parameters. This could help the user organize a large number of data items before manually interacting with them. As a user makes changes to data through physical input, he or she may wish to undo some changes. A physical undo in this system could move the pucks back to their positions before the last change. It could also show the user the exact sequence of movements she had performed. In this sense, both "undo" and "rewind" commands are possible.

One advantage that tabletop tangible user interfaces offer is the ease with which multiple users can make simultaneous changes to the system. Users can observe each other's changes, and any user can reach out and physically change the shared layout without having to grab a mouse or other pointing device. This is not the case, however, when users are collaborating remotely. In this scenario, a mechanism for physical actuation of the pucks becomes valuable for synchronizing multiple, physically separated workbench stations (Photo 24.9). Without such a mechanism, real-time physical synchronization of the two tables would not be possible, and inconsistencies could arise between the graphical projection and the physical state of the pucks on the table.

In addition to facilitating the simple synchronization of these models, the Actuated Workbench can recreate remote users' actual gestures with objects on the table, adding greatly to the "Ghostly Presence" (Brave et al., 1998) sought in remote-collaboration interfaces.

Actuated Workbench is helpful in teaching students about physics by demonstrating the attraction and repulsion of charged particles represented by pucks on the table. As a student moves the pucks around on the table, the system could make them rush together or fly apart to illustrate forces between the objects.

SandScape: Continuous TUI for Landscape Design

SandScape (Ishii et al., 2004) is a tangible interface for designing and understanding landscapes through a variety of computational simulations using sand. Users view these simulations as they are projected on the surface of a sand model that represents the terrain. The users can choose from a variety of different simulations that highlight the height, slope, contours, shadows, drainage, or aspect of the landscape model (Photo 24.10).

The users can alter the form of the landscape model by manipulating sand while seeing the resultant effects of computational analysis generated and projected on the surface of sand in real time. The project demonstrates how TUI takes advantage of our natural ability to understand and manipulate physical forms while still harnessing the power of computational simulation to help in our understanding of a model representation.

The SandScape configuration is based on a box containing 1 m-diameter glass beads lit from beneath with an array of 600 high-power infrared LEDs. Four IR mirrors are placed around the LED array to compensate for the uneven radiance distribution on the boundary. A monochrome infrared camera is mounted 2 m above the surface of the beads and captures the intensity of light passing through the volume. The intensity of transmitted light is a function of the depth of the beads and a look-up table can be used to convert surface radiance values into surface elevation values. The system has been calibrated to work with a specific bead size and the optical properties of the material used (absorption and scattering coefficients) are critical to its successful functioning. Owing to the exponential decay of the IR light passing through the glass beads (or any other material) the intensity at the top surface can vary greatly and sometimes exceed the dynamic range of the video camera. This problem can be solved by taking several images with different exposure times

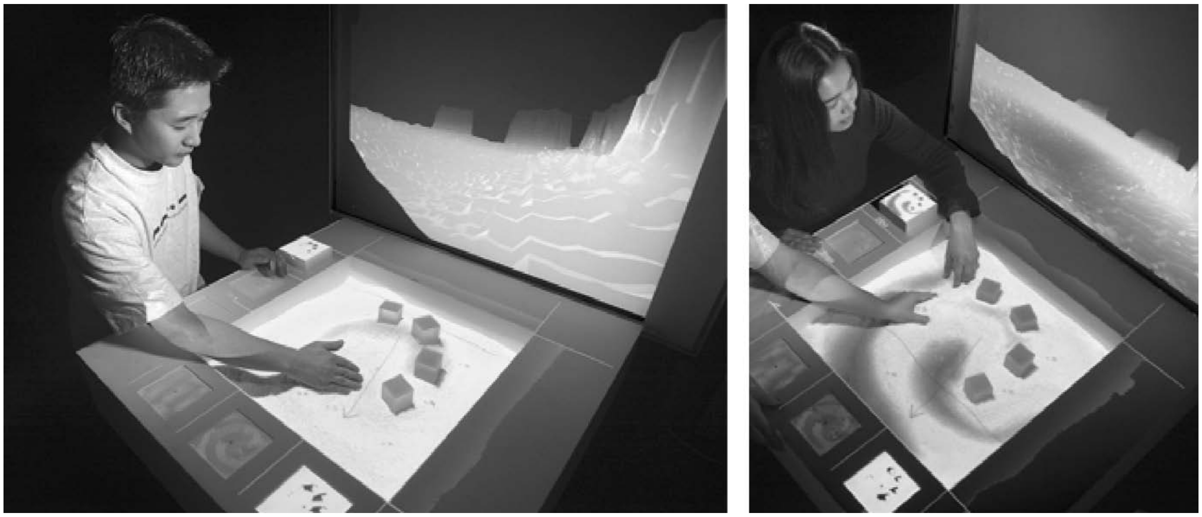

PHOTO 24.10. SandScape.

and combining them to recover the effective radiance of the scene. SandScape is less accurate than its predecessor Illuminating Clay, which used laser rangefinders to capture the geometry of a clay model (Piper et al., 2002).

SandScape and Illuminating Clay show the potential advantages of combining physical and digital representations for landscape modeling and analysis. The physical clay and sand models convey spatial relationships that can be intuitively and directly manipulated by hand. Users can also insert any found physical objects directly under the camera. This approach allows users to quickly create and understand highly complex topographies that would be difficult and time-consuming to produce with conventional CAD tools. We believe that this "Continuous TUI" approach makes better use of our natural abilities to discover solutions through the manipulation of physical objects and materials.

At the same time, the projected graphics give the user real-time feedback. While tracked physical models interfaced with a computer are not a novelty, we believe that SandScape and Illuminating Clay offer a new contribution, by using the continuous surface geometry of the model itself to act as the input/output mechanism. In so doing we hope to give the projected information the same tangible immediacy as the clay/sand material itself and allow quantitative data to support the intuitive understanding of the landscape.

Landscape architecture, as well as urban and architectural design, requires the collaboration of a number of specialists. These include earth engineers, water engineers, agrarian managers, land economists, and transport engineers—to name just a few. In the current process of design, the collaboration happens at different stages, and sometimes without much direct and synchronous interaction. SandScape and Illuminating Clay provide a common platform for collaboration, centered on the table workspace. Numerous representations and analyses can be combined in a single design environment, potentially offering a greater cohesion between different specialists and streamlining the process of design.

musicBottles: Transparent Interface Based on Augmented Glass Bottles

musicBottles introduces a tangible interface that deploys bottles as containers and controls for digital information (Photo 24. 11). The system consists of a specially designed table and three corked bottles that "contain" the sounds of the violin, the cello, and the piano in Edouard Lalo's Piano Trio in C Minor, Op. 7. Custom-designed electromagnetic tags embedded in the bottles enable each one to be wirelessly identified.

When a bottle is placed onto the stage area of the table, the system identifies each bottle, and lights up the stage to show that the bottles have been recognized. The opening and closing of a bottle is also detected, and as the cork is removed, the corresponding instrument becomes audible. A pattern of colored light is rear-projected onto the table's translucent surface to reflect changes in pitch and volume for each instrument. The interface allows users to structure the experience of the musical composition by physically manipulating the different soundtracks.

Humans have used glass bottles for thousands of years. Through the seamless extension of physical affordances and metaphors of the bottles into the digital world, the bottles project explores the transparency of the interface (Ishii, 2004).

A wide variety of contents, including music, weather reports, poems, and stories have been designed to test the concept (Ishii et al., 1999). The bottles lined up on a specially designed table, the feel of the glass as we open them, and the music and light from the LED lamps that come out of them together create a unique aesthetic experience. This is a pleasure not to be had from the mere click of a mouse.

Potential applications are not limited to music alone. One might imagine perfume bottles filled with poetry or wine bottles that decant stories (Mazalek, Wood, & Ishii, 2001). More practical applications might include a medicine chest full of bottles that tell the user how and when to take them and let the hospital

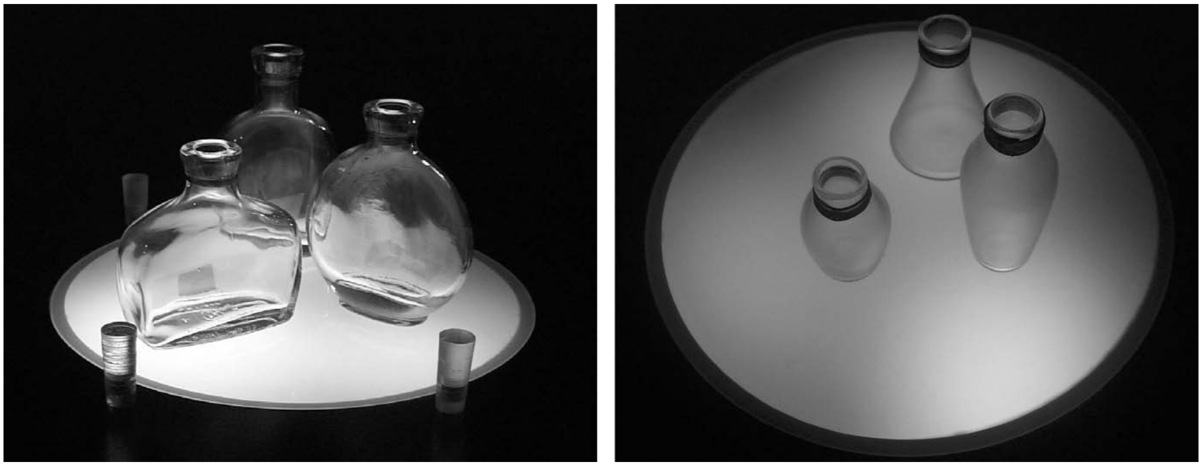

PHOTO 24.11. musicBottles.

know when they do. As an intimate part of our daily lives, glass bottle interfaces offer a simple and transparent interface.

Pinwheels: Ambient Interface to Information

Pinwheels are an example of ambient media that demonstrate a new approach to interfacing people with online digital information through subtle changes in sound and movement, which can be processed in the background of awareness. Pinwheels spin in a "bit wind" and represent an invisible flow of digital information such as network traffic as physical movement within an architectural spaces (Photo 24.12).

Nature is filled with subtle, beautiful, and expressive ambient media that engage each of our senses. The sounds of rain and the feeling of warm wind on our cheeks help us understand and enjoy the weather even as we engage in other activities. Similarly, we are aware of the activity of neighbors through passing sounds and shadows at the periphery of our attention. Cues like an open door or lights in an office help us subconsciously understand the activities of other people, and communicate our own activity and availability.

Current personal computing interfaces, however, largely ignore these rich ambient spaces, and squeeze vast amounts of digital information into small rectangular screens. Information is presented as "painted bits" (pixels) on flat screens that must be in the center (foreground) of a user's focus to be processed. In order to broaden the concept of "display" to make use of the entire physical environment as an interface, using ambient media, information can be manifested as subtle changes in form, movement, sound, color, smell, temperature, or light. We call them "ambient displays."

The Pinwheels evolved from the idea of using airflow as ambient media. However, we found that the flow of air itself was difficult to control and to convey information. As an alternative, we envisioned that a visual/physical representation of airflow based on the "spinning pinwheels" could be legible and poetic.

PHOTO 24.12. Pinwheels.

The Pinwheels spin in the "bit wind" at different speeds based upon their input information source.

Ambient displays are envisioned as being all around and suited to the display of

1. People's presence (awareness of remote people's status/activities);
2. Atmospheric and astronomical phenomena;
3. General states of large and complex systems (e.g., an atomic power plant).

For instance, an atmospheric scientist might map patterns of solar wind into patterns of Pinwheel spins in a room.

There are many design challenges surrounding ambient displays. One of them is the mapping of information to the physical motion and other ambient media. A designer of ambient displays must transform the digital data into a meaningful pattern of physical motion that successfully communicates the information. The threshold between foreground and background is another key issue. Ambient displays are expected to go largely unnoticed until some change in the display or user's state of attention makes it come into the foreground of attention. How to keep the level of display at the threshold of a user's attention is an open design issue.

Contributions of TUIs

TUI is generally built from systems of physical artifacts with digital coupling with computation. Taken together as ensembles, TUI has several important advantages over traditional GUI as well as limitations. This section summarizes those contributions of TUIs and required design considerations.

Double Interactions Loop: Immediate Tactile Feedback

One important advantage of TUI is that users receive passive haptic feedback from the physical objects as they grasp and manipulate them. Without waiting for the digital feedback (mainly visual), users can complete their input actions (e.g., moving a building model to see the interrelation of shadows).

Typically there are two feedback loops in TUI, as shown in Fig. 24.4:

1. The passive haptic feedback loop provides the user with an immediate confirmation that he or she has grasped and moved the object. This loop exists within a physical domain, and it does not require any sensing and processing by a computer. Thus, there is no computational delay. The user can begin manipulating the object as desired without having to wait for the second feedback loop, the visual confirmation from the interface. In contrast, when user uses a mouse with a GUI computer, he or she has to wait for the visual feedback (second loop) to complete an action.
2. The second loop is a digital feedback loop that requires sensing of physical objects moved by users, computation based on the sensed data, and displaying the results as visual (and auditory) feedback. Therefore, this second loop takes longer than the first loop.

Many of the frustrations of using current computers come from the noticeable delay of digital feedback as well as a lack of tactile confirmation of actions taken by computers. We believe the double loops of TUI give users a way to ease those frustrations.

Note: Actuation technology introduced in Actuated Workbench will contribute to add another loop, that of physical actuation. Figure 24.5 illustrates the third loop introduced into the TUI model by computer-controlled actuation and sensing. The third loop allows the computer to give feedback on the status of the digital information as the model changes or responds to internal computation.

Persistency of Tangibles

As physical artifacts, TUI tangibles are persistent. Tangibles also carry physical state, with their physical configurations tightly coupled to the digital state of the systems they represent. The physical state of tangibles embodies key aspects of the digital state of an underlying computation.

For example, the physical forms of the Urp building models, as well as their position and orientation on the workbench of the system, serve central roles in representing and controlling the state of the underlying digital simulation system. Even if the mediating computers, cameras, and projectors of Urp are turned off, many aspects of the state of the system are still concretely expressed by the configuration of its physical elements.

In contrast, the physical form of the mouse holds little representational significance because GUIs represent information almost entirely in visual form.

Coincidence of Input and Output Spaces

Another important feature (and design principle) of TUI is coincidence of input and output spaces to provide seamless information representation that spans both tangible (physical) and intangible (digital) domains.

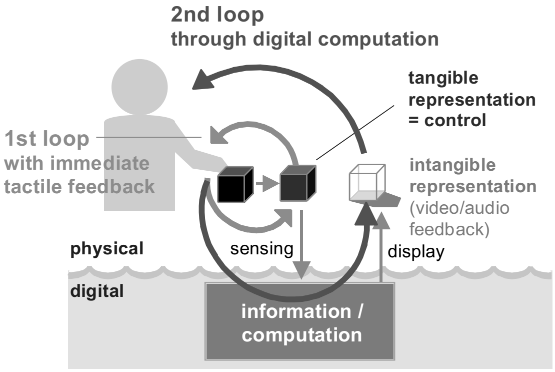

FIGURE 24.4. TUI's double feedback loops.

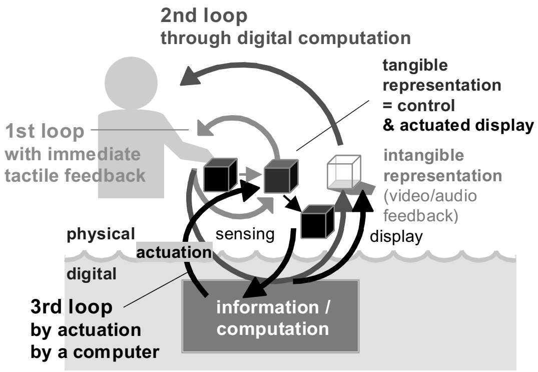

FIGURE 24.5. TUI with actuation (Actuated workbench).

GUI utilizes the mouse and keyboard as generic "remote" controllers (input), and the screen serves as main output medium. Thus, there is spatial discontinuity between those two spaces. There is also multimodal inconsistency, as touch is the main input while vision is the only output.

TUI tries to coincide inputs space and output space as much as possible to realize seamless coupling of physical and digital worlds (Ishii & Ullmer, 1997). An example of this seamless coupling of is Underkoffler's Urp (Underkoffler & Ishii, 1999). A series of architectural models serve as the input devices, and output in the form of a wind-and-shadow simulation is projected down onto the same tabletop surface, on top of and around the building models. Illuminating Clay (Piper et al., 2002) and SandScape (Ishii et al., 2004) demonstrate another example of i/o coincidence using continuous flexible material: sand. Curlybot and topobo demonstrate the same concept using the contact surface of the tangibles as input and output to digitize the person's physical motion.

Special Purpose vs. General Purpose

GUIs are fundamentally general-purpose interfaces that are supposed to emulate a variety of applications visually using dynamic pixels on a screen and generic remote controllers such as the mouse and keyboard. On the other hand, TUIs are relatively specific interfaces tailored to certain type of applications in order to increase the directness and intuitiveness of interactions.

The selection of the correct and specific application domain is critical to apply TUI successfully to take advantage of existing skills and work practices (e.g., use of physical models in urban planning).

One notable aspect of Urp is its use of objects with very application-specific physical forms (scaled building models) as a fundamental part of the interface. Physical building models represent the buildings themselves in the interactive simulation. Thus they give the user important visual and tactile information about the computational object they represent. Indicators such as a clock and weather vane work in reverse in the Urp system. Instead of the clock hands moving to indicate the passage of time, the user can move the clock hands to change the time of day for the shadow study (Photo 24.1). Likewise, he or she can change the orientation of the weather vane to control the direction of the wind (Photo 24.2).

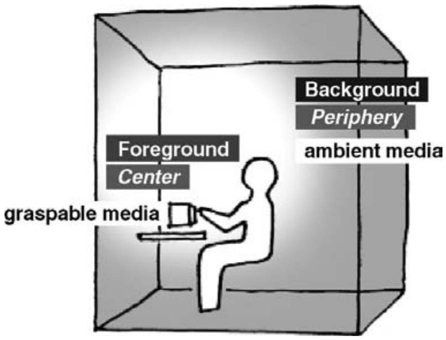

FIGURE 24.6. Center and periphery of user's attention within physical space.

In the design of TUI, it is important to give an appropriate form to each tangible tool and object so that the form will give an indication of the function available to the users. For example, the clock hands allow people to automatically make the assumption that they are controlling time.

Of course, this special-purpose-ness of TUIs can be a big disadvantage if users would like to apply it to a wide variety of applications since customized physical objects tailored to certain application can not be reused for most of other applications. By making the form of objects more abstract (e.g., a round puck), you lose the legibility of tangible representation and the object will become a generic handle rather than the representation of underlying digital information. It is important to attain a balance between specific/concrete vs. generic/abstract to give a form to digital information and computational function.

Space-Multiplexed Input

Another distinct feature of TUI is space-multiplexed input (Fitzmaurice, Ishii, & Buxton, 1995a). Each tangible representation serves as a dedicated controller occupying its own space, and encourages two-handed and multi-user simultaneous interaction with underlying computational model. Thus, TUI is suitable for collocated collaboration allowing concurrent manipulation of information by multiple users.

GUI, in contrast, provides time-multiplexed input that allows users to use one generic device to control different computational functions at different points in time. For instance, the mouse is used for menu selection, scrolling windows, pointing, and clicking buttons in a time-sequential manner.

TUI can support not only collocated collaboration, but also remote collaboration using actuation mechanism to synchronize the physical states of tangibles over distance. Actuated Workbench is an example of such a technology that extends TUI for remote collaboration (Pangaro et al., 2002).

In the Urp scenario, applying the Actuated Workbench technology, it is possible to have two distributed Urp tables in different locations, connected and synchronized over the Internet. One Urp can be in Tokyo, while the other Urp can be in Boston, and the shadows are synchronized as the urban planning team moves the buildings around the Urp space. The movement of buildings can be also synchronized by the actuation mechanism. When the building planner moves a building location, both the local and the remote shadow will update simultaneously; position and orientation of moved buildings is also synchronized. This synchronization of a distributed workbench allows both teams to discuss changes to the situation in real time, and provides a common reference for otherwise ethereal qualities such as wind, time, and shadow.

CONCLUSION

The author met a highly successful computational device called the "abacus" when he was two years old (Photo 24.13). He could enjoy the touch and feel of the "digits" physically represented as

PHOTO 24.13. Abacus.

arrays of beads. This simple abacus was not merely a digital computational device. Because of its physical affordance, the abacus also became a musical instrument, imaginary toy train, and a backscratcher. He was captivated by the sound and tactile interaction with this simple artifact.

His childhood abacus became a medium of awareness too. When his mother kept household accounts, he was aware of her activities by the sound of her abacus, knowing he could not ask her to play with him while her abacus made its music.

This abacus suggests to us a new direction of Human-Computer Interaction (HCI) that we call Tangible User Interfaces (TUI). First, it is important to note that the abacus makes no distinction between "input" and "output." Instead, the beads, rods, and frame serve as physical representations of numerical information and computational mechanism. They also serve as directly manipulatable physical controls to compute on numbers.

Second, the simple and transparent mechanical structure of the abacus (without any digital black boxes) provides rich physical affordances (Norman, 1999) so that even children can immediately understand what they can do with this artifact without reading a manual.

TUI pursues these features further into the digital domain by giving physical form to digital information and computation, employing physical artifacts both as representations and controls for computational media. Its design challenge is a seamless extension of the physical affordances of the objects into the digital domain.

This chapter introduced the basic concept of TUI and a variety of examples of TUI applications to address the key properties of TUI and its design challenges. TUI is still in its infancy, and extensive research is required to identify the killer applications, scalableTUI toolkits, and a set of strong design principles.

The research of TUI which gives physical forms to digital information/computation naturally crosses with the paths of industrial/product design as well as environmental/architectural design. It has also made an impact on the media-arts/interactive-arts community. The author hopes that TUI design will contribute to promote those interdisciplinary design research initiatives in the HCI community to bring strong design culture as well as media-arts perspective to the scientific/academic world.

Mark Weiser's (1991) seminal paper on ubiquitous computing started with the following paragraph: "*The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.*"

I do believe that TUI is one of promising paths to his vision of invisible interface.

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