INVITED PAPER

Tangible Bits: Beyond Pixels

Hiroshi Ishii
Tangible Media Group
MIT Media Laboratory
ishii@media.mit.edu

ABSTRACT
Tangible user interfaces (TUIs) provide physical form to digital information and computation, facilitating the direct manipulation of bits. Our goal in TUI development is to empower collaboration, learning, and design by using digital technology and at the same time taking advantage of human abilities to grasp and manipulate physical objects and materials. This paper discusses a model of TUI, key properties, genres, applications, and summarizes the contributions made by the Tangible Media Group and other researchers since the publication of the first Tangible Bits paper at CHI 1997. http://tangible.media.mit.edu/

Author Keywords
Tangible User Interfaces, Augmented Reality, Ubiquitous Computing, Ambient Media, Interaction Design

ACM Classification Keywords
H5.2. Information interfaces and presentation: User Interfaces.

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 cannot 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.

TO MAKE BITS TANGIBLE
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. Tangible User Interfaces (TUIs) are built upon those skills and situate the physically-embodied digital information in physical space. The design challenge is a seamless extension of the physical affordances of the objects into the digital domain [24, 49].

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. GUIs have been in existence since the 70's and first appeared commercially in the Xerox 8010 Star System in 1981 [44]. 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 bit-mapped 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 manipulation of building blocks or the 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 vision of Ubiquitous Computing of weaving digital technology into the fabric of a physical environment and making it invisible [54]. 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 paper introduces the basic concept of TUI in comparison with GUI, early prototypes of TUI that highlight the basic design principles, and discusses design challenges that TUI needs to overcome.

URP: AN EXAMPLE OF EARLY TUI

To illustrate basic TUI concepts, we introduce Urp (Urban Planning Workbench) as an example of TUI [53]. Urp uses scaled physical models of architectural buildings to configure and control an underlying urban simulation of shadow, light reflection, wind flow, etc. (Figure 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 the 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.

In Urp, physical models of buildings are used as tangible representations for 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 for 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.

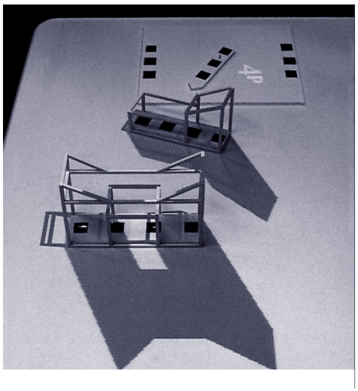

Figure 1. Urp and shadow simulation. Physical building models casting digital shadows, and a clock tool to control time of day (position of the sun).

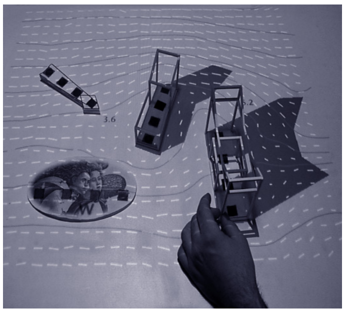

Figure 2. Urp and wind simulation. Wind flow simulation with a wind tool and an anemometer.

BASIC MODEL OF TUI

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 *representations* are perceived with the human senses. In the Smalltalk-80 programming language [7, 20], 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

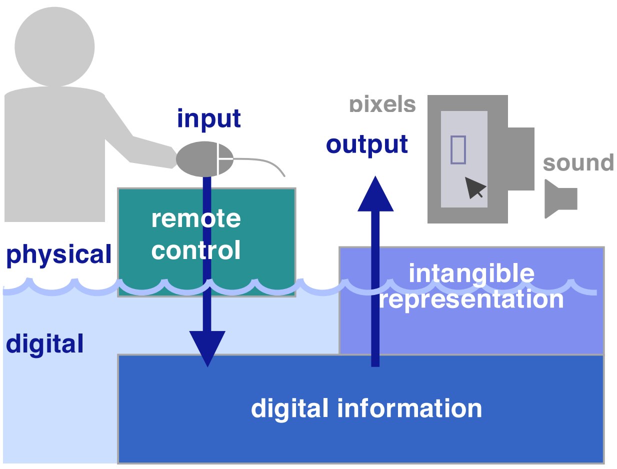

Figure 3. Graphical User Interface. **GUI represents information with intangible pixels on a bit-mapped display and sound. General-purpose input devices allow users to control those representations.**

perceivable by the human senses that include visual, hearing and tactile senses.

GUI

Figure 3 illustrates the current GUI paradigm in which generic input devices allow users to remotely interact with digital information. Using the metaphor of a seashore that separates the sea of bits from the land of atoms, the digital information is illustrated at the bottom of the water, and the mouse and screen are above sea level in the physical domain. Users interact with the remote controls, and ultimately experience an intangible, external representation of digital information (display pixels and sound).

TUI

Tangible User Interface aims at a different direction from GUI by using tangible representations of information that also serve as the direct control mechanisms 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 4 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 digital worlds. Also notice that the tangible representation is computationally coupled to the control of the underlying digital information and computational models. Urp illustrates examples of such couplings, including 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 of 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.

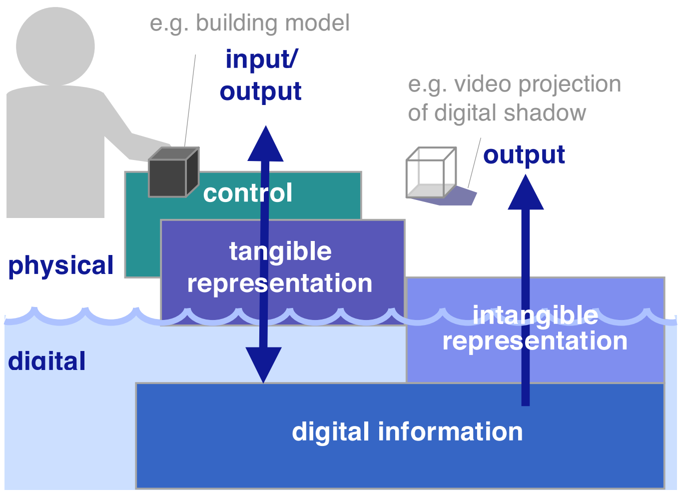

Figure 4. Tangible User Interface. **By giving tangible (physical) representation to the digital information, TUI makes information directly graspable and manipulable with haptic feedback. Intangible representation (e.g. video projection) may complement tangible representation by synchronizing with it.**

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 change in 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, 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 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 realtime response are important requirements to accomplish this goal.

KEY PROPERTIES OF TUI

While Figure 3 illustrates the GUI's clear distinction between graphical representation and remote controls, the model of TUI illustrated in Figure 4 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 [49].

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 on 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 form 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 [35]. When a puck is used as a dial to control a simulation parameter, graphical feedback is given to complement the information, such as the 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 [34].

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 [26]. 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 realtime 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. This convinces users of an illusion that the shadows are cast from the building models (rather than the video projector).

Related Work Defining TUI

Since we introduced TUI in 1997 [24] there have been a number of papers written by our research group and others to continue defining and understanding the design space for tangible interfaces. A full account of this work is beyond the scope of this paper though we will briefly call the readers attention to some of this research here. Holmquist et al. [22] and Fishkin [14] provide categories and metrics for understanding tangibles, the MVC model was expanded in [49] and Hornecker proposes a framework for tangible interaction [23]. Most recently Jacob et al.'s work in Reality-Based Interaction [28] places TUI within a larger framework to unite post-WIMP interfaces. The TUI idea has continued to grow through innovations from many researchers and inventors, the formation of the first conference dedicated to tangible interaction (TEI, http://tei-conf.org/) in 2007 promises to continue this growth into the future.

GENRES OF TUI APPLICATIONS

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 the paragraph above as well as

Zuckerman et al. [56] which provides a useful taxonomy and frameworks to analyze the design space of TUIs in education.

1) Tangible Telepresence
One such genre is an inter-personal 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, allowing 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 [6], HandJive [16], and ComTouch [10] are such examples.

2) Tangibles with Kinetic Memory
The use of kinesthetic gestures and movement to promote learning concepts is another promising domain. Educational toys to materialize record & play concepts have been also explored using actuation technology and taking advantage of i/o (input/output) 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 story telling. Curlybot [19] and topobo [38] are examples of toys which distill ideas relating gestures and form to dynamic movement, physics and storytelling.

3) 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 [1, 2] for thermal performance analysis, and Frazer developed a series of intelligent modeling kits such as Universal Constructor [17, 18] for modeling and simulation. Recent examples include GDP [3], AlgoBlock [46], Triangles [21], Blocks [4], ActiveCube [29], and System Blocks [57]. Topobo [38] is an unique instance that inherit the properties from both "constructive assemble" and "tangibles with kinetic memory".

4) Tokens and Constraints
"Tokens and constraints" is another TUI approach to operate abstract digital information using mechanical constraints [51]. 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 [12] is a classic example which influenced many following research. mediaBlocks [48], LogJam [11], DataTiles [41], and Tangible Query Interface [50] are other recent examples of this genre of development.

5) Interactive Surfaces—Tabletop TUI
Interactive surfaces are another promising approach to support collaborative design and simulation that 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 onto the surface of the workbench keeping input/output space coincidence. This genre of TUI is also called "tabletop TUI" or "tangible workbench".

Digital Desk [55] 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 surfaces. Examples are metaDesk [47], InterSim [5], Illuminating Light [52], Urp [53], Build-It [40], Sensetable [35], AudioPad [36], and IP Network Design Workbench [31].

One limitation of the 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 [34], 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.

6) Continuous Plastic TUI
A 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 relationships among them but not the form of the individual objects themselves.

Instead of using predefined discrete objects with fixed forms, the new type of TUI systems that utilize continuous tangible material such as clay and sand were developed for rapid form giving and sculpting for landscape design. Examples are Illuminating Clay [37], and SandScape [27]. Later this interface was applied to the browsing of 3D volumetric data in the Phoxel-Space project [39].

7) 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 [45], musicBottles [26], HandScape [32], LumiTouch [9], Designers' Outpost [30], and I/O Brush [43]. 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.

8) 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:

1. Allowing users to "grasp & manipulate" foreground information by coupling bits with physical objects, and
2. 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 [8]. 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 their peripheral attention. If it was convenient, they 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 [24].

The ambientROOM is a project that explores the ideas of ambient media constructing a special room equipped with embedded sensors and ambient displays [25]. This work was a preliminary investigation into background/peripheral interfaces, and lead to the design of standalone ambient fixtures such as Pinwheels and Water Lamp that make users aware of "digital wind" and "bits of rain" at their peripheral senses [13].

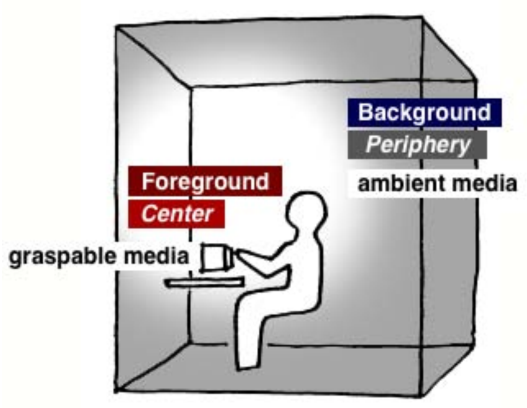

Figure 5. Center and periphery of user's attention within physical space.

Strictly speaking, ambient media is not a kind of TUI since in many cases there are no direct interactions. Rather, ambient media serves as background information displays that complement tangible/graspable media that users manipulate in their foreground. TUI's approach to ambient media is concerned with the design of simple mappings that gives easy-to-understand form to cyberspace information and representing 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 architectural or physical spaces into an ambient and calm information environment. Another design space is low attention interfaces for interpersonal communication through ambient media [9]. 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/).

CONTRIBUTION OF TUI

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 Interaction 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 Figure 6.

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 or 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 the user uses a mouse with a GUI computer, he or she has to wait for the visual feedback (2nd loop) to complete an action.
2. The 2nd 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 2nd loop takes longer than the 1st 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.[1]

Persistency of Tangibles

As physical artifacts, TUIs 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 underling 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.

[1] Actuation technology introduced in Actuated Workbench will contribute to add another loop, that of physical actuation. Figure 7 illustrates the 3rd loop introduced into the TUI model by computer-controlled actuation and sensing. The 3rd loop allows the computer to give feedback on the status of the digital information as the model changes or responds to internal computation.

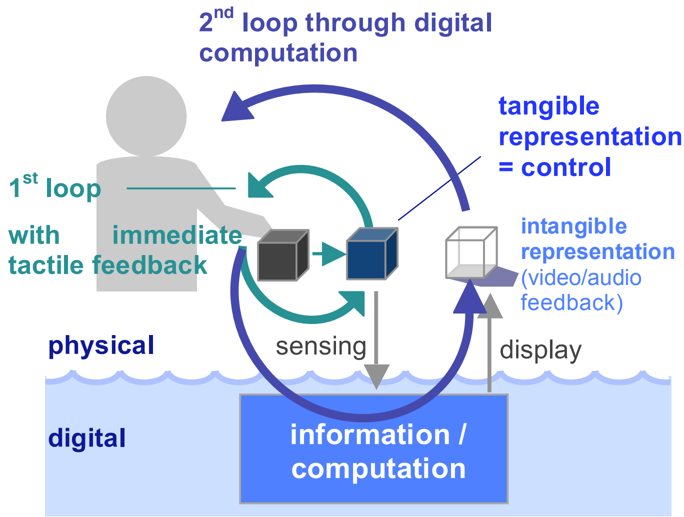

Figure 6. TUI's Double Feedback Loops. TUI provides two feedback loops: 1) 1st immediate tactile feedback, and 2) 2nd feedback through digital processing with possible delay.

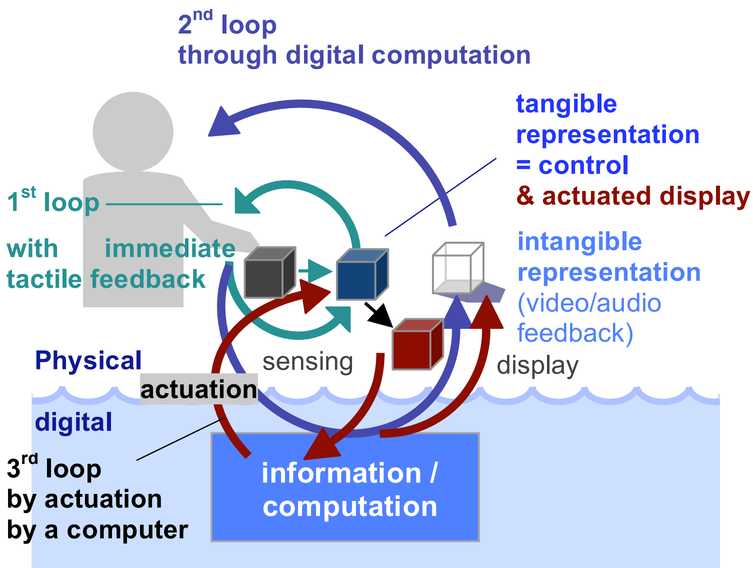

Figure 7. TUI with Actuation. Computational actuation provides another loop for the computer to control the position of objects (tangible representation) on the workbench.

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.

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 [24]. An example of this seamless coupling is Underkoffler's Urp [53]. 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 [37] and SandScape [27] demonstrates 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 (Figure 1). Likewise, he or she can change the orientation of the weather vane to control the direction of the wind (Figure 2).

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 cannot be reused for most 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 [15]. Each tangible representation serves as a dedicated controller occupying its own space, and encourages two-handed & multi-user simultaneous interaction with underlying computational models. 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 [34].

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 and the position and orientation of the moved building is also synchronized. This synchronization of distributed workbenchs allows both teams to discuss changes to the situation in realtime, and provides a common reference for otherwise ethereal qualities such as wind, time, and shadows.

CONCLUSION

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

Second, the simple and transparent mechanical structure of the abacus (without any digital black boxes) provides rich physical affordances [33] 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 paper 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, scalable TUI 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 seminal paper on Ubiquitous Computing [54] 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 the promising paths to his vision of invisible interface.

ACKNOWLEDGEMENTS

The author would like to thank to many of the former and current TMG students and colleagues in the MIT Media Lab for their contributions to the TUI research in the past 12 years at the MIT Media Lab. Especially thanks are due to Dr. John Underkoffler, Dr. Brygg Ullmer, Dr. Kimiko Ryokai, Dr. James Patten, Angela Chang, Hayes Raffle, Amanda Parkes, Oren Zuckerman, and Jamie Zigelbaum. Jamie Zigelbaum helped me to refine my draft paper and compress it into 12 pages. Thanks are also due to Things That Think and Digital Life Consortia at the Media Lab fore their support of our research. The author also would like to thank Professor Bill Buxton and Dr. George Fitzmaurice for our collaboration on the Bricks project in 1994 at University of Toronto [15] which laid the foundation of TUI, and Professor Mitchel Resnick for his vision of Digital Manipulatives [42] which influenced on our design of educational TUI applications.

REFERENCES

1. Aish, R. 3D input for CAAD systems. *Computer-Aided Design 11, 2,* (1979). 66-70.
2. Aish, R., and Noakes, P. Architecture without numbers - CAAD based on a 3D modeling system. *Computer-Aided Design 16, 6*, (1984)*,* 321-328.
3. Anagnostou, G., Dewey, D., and Patera., A. Geometry-defining processors for engineering design and analysis. *The Visual Computer 5,* (1989). 304-315.
4. Anderson, D., Frankel, J. L., Marks, J., Agarwala, A., Beardsley, P., Hodgins, J., Leigh, D., Ryall, K., Sullivan, E., and Yedidia, J. S. Tangible interaction + graphical interpretation: a new approach to 3D modeling. *Proc. SIGGRAPH 2000*, ACM Press/Addison-Wesley Publishing Co. (2000), 393-402.
5. Arias, E., Eden, H., and Fisher, G. Enhancing communication, facilitating shared understanding, and creating better artifacts by integrating physical and computational media for design. *Proc. DIS 1997,* ACM Press (1997), 1-12.
6. Brave, S., and Dahley, A inTouch: A Medium for Haptic Interpersonal Communication. *Ext. Abstracts CHI 1997,* ACM Press (1997), 363-364.
7. Burbeck, S. Applications Programming in Smalltalk-80(TM): How to use Model-View-Controller (MVC), 1992.
8. Buxton, W. Integrating the Periphery and Context: A New Model of Telematics. *Graphics Interface 1995*, 239-246.
9. Chang, A., Resner, B., Koerner, B., Wang, X., and Ishii, H. LumiTouch: an emotional communication device. *Ext. Abstracts CHI 2001*, ACM Press (2001), 313-314.
10. Chang, A., O'Modhrain, S., Jacob, R., Gunther, E., and Ishii, H. ComTouch: design of a vibrotactile communication device, *Proc. DIS 2002*, ACM Press (2002), 312-320.
11. Cohen, J., Withgott, M., and Piernot, P. LogJam: a tangible multi-person interface for video logging. *Proc. CHI 1999,* ACM Press (1999), 128-135.
12. Crampton Smith, G. The Hand That Rocks the Cradle. *I.D.* (1995), 60-65.
13. Dahley, A., Wisneski, C., and Ishii, H. Water Lamp and Pinwheels: Ambient Projection of Digital Information into Architectural Space. *Conference Summary CHI 1998,* ACM Press.

14. Fishkin, K. P. A taxonomy for and analysis of tangible interfaces. *Pers. Ubiq. Comput. 8*, (2004), 347-358.
15. Fitzmaurice, G. W., Ishii, H., and Buxton, W. Bricks: Laying the Foundations for Graspable User Interfaces. *Proc. CHI 1995,* ACM Press (1995), 442-449.
16. Fogg, B., Cutler, L. D., Arnold, P., and Eisbach, C. HandJive: a device for interpersonal haptic entertainment, *Proc. CHI 1998*, ACM Press/Addison-Wesley Publishing Co. (1998), 57-64.
17. Frazer, J. H., Frazer, J. M., and Frazer, P. A. Intelligent physical three dimensional modeling system, *Computer Graphics 1980.* 359-370.
18. Frazer, J. An Evolutionary Architecture. Architectural Association, London. 1994.
19. Frei, P., Su, V., Mikhak, B., and Ishii, H. curlybot: designing a new class of computational toys. *Proc. CHI 2000*, ACM Press (2000), 129-136.
20. Goldberg, A. Smalltalk-80: The Interactive Programming Environment. Addison-Wesley, 1984.
21. Gorbet, M., Orth, M., and Ishii, H. Triangles: Tangible Interface for Manipulation and Exploration of Digital Information Topography. *Proc. CHI 1998,* ACM Press (1998), 49-56.
22. Holmquist, L. E., Redstr, J., and Ljungstrand, P. Token-Based Access to Digital Information. *Proc. Handheld and Ubiquitous Computing 1999*, Springer-Verlag (1999), 234-245.
23. Hornecker, E., and Buur, J. Getting a grip on tangible interaction: a framework on physical space and social interaction. *Proc. CHI 2006,* ACM Press (2006), 437-446.
24. Ishii, H. and Ullmer, B. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. *Proc. CHI 1997*, ACM Press (1997), 234-241.
25. Ishii, H., Wisneski, C., Brave, S., Dahley, A., Gorbet, M., Ullmer, B., and Yarin, P. ambientROOM: Integrating Ambient Media with Architectural Space (video), *Conference Summary CHI 1998,* ACM Press.
26. Ishii, H., Mazalek, A., and Lee, J. Bottles as a minimal interface to access digital information, E*xt. Abstracts CHI 2001,* ACM Press (2001), 187-188.
27. Ishii, H., Ratti, C., Piper, B., Wang, Y., Biderman, A., and Ben-Joseph, E. Bringing clay and sand into digital design - continuous tangible user interfaces. *BT Technology Journal 22, 4,* (2004), 287-299.
28. Jacob, R. J. K., Girouard, A., Hirshfield, L. M., Horn, M. S., Shaer, O., Treacy, E. S., and Zigelbaum, J. Reality-Based Interaction: A Framework for Post-WIMP Interfaces. To appear in *Proc. CHI 2008*, ACM Press (2008).
29. Kitamura, Y., Itoh, Y., and Kishino, F. Real-time 3D interaction with ActiveCube. *Ext. Abstracts CHI 2001*, ACM Press (2001), 355-356.
30. Klemmer, S. R., Thomsen, M., Phelps-Goodman, E., Lee, R., and Landay, J. A. Where do web sites come from?: capturing and interacting with design history. *Proc. CHI 2002,* ACM Press (2002), 1-8.
31. Kobayashi, K., Hirano, M., Narita, A., and Ishii, H. A tangible interface for IP network simulation. *Ext. Abstracts CHI 2003*, ACM Press (2003), 800-801.
32. Lee, J., Su, V., Ren, S., and Ishii, H. HandSCAPE: a vectorizing tape measure for on-site measuring applications. *Proc. CHI 2000*, ACM Press, 137-144.
33. Norman, D. A. Affordance, conventions, and design. *Interactions 6, 3*, (1999), ACM Press, 38-43.
34. Pangaro, G., Maynes-Aminzade, D., and Ishii, H. The actuated workbench: computer-controlled actuation in tabletop tangible interfaces, *Proc. UIST 2002*, ACM Press (2002), 181-190.
35. Patten, J., Ishii, H., Hines, J., and Pangaro, G. Sensetable: a wireless object tracking platform for tangible user interfaces. *Proc. CHI 2001*, ACM Press (2001), 253-260.
36. Patten, J., Recht, B., and Ishii, H. Audiopad: A Tag-based Interface for Musical Performance. *Proc. NIME 2002,* 1-6.
37. Piper, B., Ratti, C., and Ishii, H. Illuminating clay: a 3-D tangible interface for landscape analysis. *Proc. SIGGRAPH 2002*, ACM Press (2002), 355-362.
38. Raffle, H. S., Parkes, A. J., and Ishii, H. Topobo: a constructive assembly system with kinetic memory. *Proc. CHI 2004,* ACM Press (2004), 647-654.
39. Ratti, C., Wang, Y., Piper, B., Ishii, H., and Biderman, A. PHOXEL-SPACE: an interface for exploring volumetric data with physical voxels. *Proc. DIS 2004,* ACM Press (2004), 289-296.
40. Rauterberg, M., Fjeld, M., Krueger, H., Bichsel, M., Leonhardt, U., and Meier, M. BUILD-IT: a planning tool for construction and design, *Proc. CHI 1998*, ACM Press (1998), 177-178.
41. Rekimoto, J., Ullmer, B., and Oba, H. DataTiles: a modular platform for mixed physical and graphical interactions. *Proc. CHI 2001*, ACM Press (2001), 269-276.
42. Resnick, M., Martin, F., Berg, R., Borovoy, R., Colella, V., Kramer, K., and Silverman, B. Digital manipulatives: new toys to think with. *Proc. CHI 1998*, ACM Press/Addison-Wesley Publishing Co., 281-287.
43. Ryokai, K., Marti, S., and Ishii, H. I/O brush: drawing with everyday objects as ink. *Proc. CHI 2004*, ACM Press (2004), 303-310.

44. Smith, D. Designing the Star User Interface, *Byte*, (1982), 242-282.

45. Stifelman, L. J. Augmenting real-world objects: a paper-based audio notebook. *Conference companion on Human factors in computing systems* 1996, ACM Press (1996), 199-200.

46. Suzuki, H. and Kato, H. AlgoBlock: A tangible programming language -- a tool for collaborative learning. *The 4th European Logo Conference* (1993), 297-303.

47. Ullmer, B., and Ishii, H. The metaDESK: Models and Prototypes for Tangible User Interfaces. *Proc. UIST 1997,* ACM Press (1997), 223-232.

48. Ullmer, B., Ishii, H., and Glas, D. mediaBlocks: physical containers, transports, and controls for online media. *Proc. SIGGRAPH 1998*, ACM Press (1998), 379-386.

49. Ullmer, B., and Ishii, H. Emerging frameworks for tangible user interfaces. *IBM Systems Journal 39, 3&4*, (2000), 915-931.

50. Ullmer, B., Ishii, H., and Jacob, R. J. K. Tangible Query Interfaces: Physically Constrained Tokens for Manipulating Database Queries. *INTERACT 2003*, IFIP.

51. Ullmer, B., Ishii, H. and Jacob, R. J. K. Token+constraint systems for tangible interaction with digital information. *TOCHI 12, 1,* (2005), ACM Press, 81-118.

52. Underkoffler, J. and Ishii, H. Illuminating Light: An Optical Design Tool with a Luminous-Tangible Interface, *Proc. CHI 1998,* ACM Press/Addison-Wesley Publishing Co. (1998), 542-549.

53. Underkoffler, J., and Ishii, H. Urp: a luminous-tangible workbench for urban planning and design. *Proc. CHI 1999*, ACM Press (1999), 386-393.

54. Weiser, M. The computer for the 21st Century. *Scientific American 265, 3,* (1991), 94-104.

55. Wellner, P. Interacting with Paper on the DigitalDesk. *Communications of the ACM 36, 7,* (1993), 87-96

56. Zuckerman, O., Arida, S., and Resnick, M. Extending tangible interfaces for education: digital montessori-inspired manipulatives, Proc. CHI 2005, ACM Press (2005), 859-868.

57. Zuckerman, O., and Resnick, M. Hands-on modeling and simulation of systems. Proc. IDC 2004, ACM Press (2004), 157-158.