A Framework for Tangible User Interfaces

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ABSTRACT
This paper extends our understanding of tangible user interfaces (TUIs) by considering the different ways in which physical and digital objects can be computationally coupled. It proposes a framework based around the degree of coherence between physical and digital objects. Links between physical and digital objects are described in terms of a set of underlying properties (transformation, sensing, configurability, lifetime, autonomy, cardinality and link source). We use our framework to classify a representative selection of existing TUI systems. This classification raises key implications for the field of tangible computing. In particular our focus on enriching physical-digital links highlights the need to consider the asymmetry of these links, issues surrounding their configuration and the need to represent their nature to developers and users.

Categories and Subject Descriptors
H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *theory and methods.*

General Terms
Design, Theory

Keywords
Tangible user interfaces, design framework, interaction models

1. INTRODUCTION
Tangible computing [11] allows users to interact directly with computational artifacts by manipulating everyday physical objects rather than using traditional graphical interfaces and dedicated physical interface devices such as mice and keyboards. A variety of systems have been developed to date that illustrate the tangible interface principle. Some notable examples include:

- The TangibleGeospace application of the metaDesk [22], where physical representations of geographical features are used to manipulate a digital map;
- Illuminating Light [24], where physical models of optical elements are used to create a simulated optical layout;
- The Passage system [16], which provides a mechanism for transporting digital information by linking it to physical objects;
- WebStickers [10], where everyday physical object act as bookmarks for web pages;
- The tangible tools (tongs, eraser and magnet) provided by the Surface Drawing system [21];
- Illuminating Clay [20] where users interact directly with a clay model of a landscape and observe the effects of geometric changes.
- Storytent [8], where physical balloons are used as identifiers for virtual balloon objects and flashlights are used as pointing devices for manipulating them.

Just as concrete examples of tangible user interfaces (TUIs) are proliferating, so conceptual frameworks are also emerging to help researchers, designers and developers classify what constitutes a TUI and to understand the various ways in which physical objects can be combined with digital information. Like the MVC interaction model for GUIs [4] and the PAC interaction model for dialog design [5], these frameworks seek to highlight the main components of TUIs.

Ullmer and Ishii have proposed the model-control-representation (physical and digital) (MCRpd) interaction model for tangible interfaces [23], which highlights the integration of physical representation and control with this type of interface. Holmquist et al have suggested a broader taxonomy of how physical and digital objects can be coupled [10]. They propose the categories of *containers* as generic objects for moving information between devices or platforms, *tokens* as objects for accessing stored information (the nature of which is physically reflected in the token) and *tools* as object for manipulating digital information.

This paper aims to further extend our understanding of the different ways in which physical and digital objects can be computationally coupled. It introduces a framework that is based around the idea of the "degree of coherence" between physical and digital objects. This is further broken down into the concept of *links* between physical and digital objects that are described in terms of a set of underlying *properties*. We use our framework to classify a representative selection of TUI systems. In turn, this classification raises key implications for the field of tangible computing.

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2. DEGREE OF COHERENCE

The first concept that we introduce as a means of distinguishing between different types of tangible UIs is "degree of coherence". It is proposed that relationships between physical and digital objects can be rated along a coherence continuum, where the level of coherence represents the extent to which linked physical and digital objects might be perceived as being the same thing. That is whether the physical and the digital artifact are seen as one common object that exists in both the physical and the digital domain or whether they are seen as separate but temporarily interlinked objects. Figure 1 shows the coherence continuum along with some proposed categories of TUI types.

Interface objects that establish the weakest level of coherence with the computational artefacts they operate are termed "general purpose tools". Using such a tool a user can select to manipulate any one of many digital objects and perform different transformations (depending on the application). Examples include traditional physical interface devices such as mice and joysticks.

The next category along the coherence continuum, named "specialised tools", encompasses interface objects that have a more specialised function but still temporarily connect to potentially many different digital objects. Examples include the tongs, eraser and magnet from the Surface Drawing system [21] and the optical instruments, such as mirrors, beam-splitters, lenses etc., from the Illuminating Light system [24].

The "identifier" category represents interface objects which act as bookmarks for retrieving computational artefacts. The passenger objects in the Passage system [16] and the bar-coded everyday objects in the WebSticker system [10] are examples of this category. Here the physical object is a token representing a digital artefact and the two are often more permanently coupled.

Interface objects that belong to the "proxy" category are even more coherent with the digital objects they are coupled to. This is because proxies are more permanently associated with, and allow a more extensive manipulation of, their digital counterpart (more than identification for subsequent retrieval). Examples include the physical building models in the Geospace application of the metaDesk [22] and the pucks on the Senseboard as used to represent conference papers [14].

The "projection" category encompasses relationships where the digital artefact is seen as a direct representation of some properties of the physical object and so its existence is dependent on the physical object. An example is the representation of human activity in a physical foyer as a digital pattern projected on the wall of the ambientRoom [12].

Finally we can create the illusion that two coupled objects are one and the same if they are visible only one at a time, making smooth transitions between the physical and the digital space. For example a physical object may pass though a traversable interface [15] and appear as a virtual object on the other side of the display (in the virtual space) or the spaces can be superimposed in such a way that all actions appear coherent (e.g. highly registered augmented reality).

Unpacking this idea of coherence a bit further, we propose that what distinguishes the different categories are underlying differences in what interactions are sensed, the type of effects mediated between the coupled objects, the duration of the coupling, autonomy of the digital artefact and configurability of the coupling. The following section develops this idea further, proposing a detailed set of properties that we can use to describe and design different types of links.

3. COHERENCE AND LINK PROPERTIES

3.1 Transformation

This property describes whether the effect mediated between linked objects is literal or transformed. If actions are mediated literally, movement of the physical object for example, will result in the same movement of the digital object. This is the case with the phicons and virtual building models in Tangible Geospace [22] and the manipulation of the CUBIK interface [17]. Here the shape of a physical cube is altered by pushing and pulling its sides and these manipulations are directly mediated to a virtual cube whose shape changes in a corresponding manner.

On the other hand, the effect between linked objects can be transformed. For example positioning a physical object on a predefined place may trigger an animation of a digital object and/or for the digital object to emit sounds. Another example is the magnet tool in the Surface Drawing system [21], which changes the meaning of the drawing action to that of altering existing geometry. Waving the magnet near the region of a drawing pulls that region closer to the magnet.

3.2 Sensing of Interaction

This property describes what interactions with the interface object and its surrounding environment are sensed and transmitted to the destination object. This can range from detecting and responding to the presence of the source object in a specified area [16] to mediating manipulations in the full 6 degrees of freedom. E.g. translations and rotations in a plane are sensed for the metaDesk phicons [22] and for the CUBIC interface [17] scaling in the X, Y and Z axes are transmitted. An example of sensing actions in the surrounding environment is using video processing to detect gestures such as pointing at the physical objects, e.g. the DigitalDesk [26].

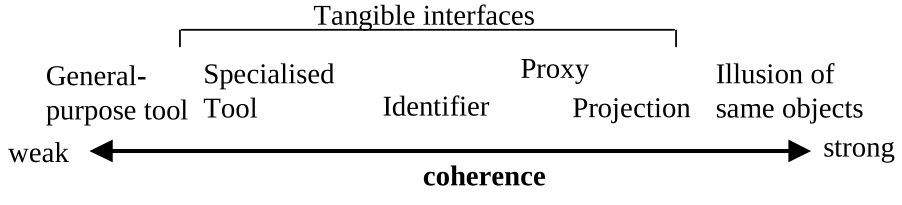

Figure 1: TUI categories along the coherence continuum

3.3 Configurability of Transformation

This property describes whether the transformation mediated between two linked objects remains fixed for the lifetime of the link or whether it is configurable over time. For example in the Illuminating Light system [24] each tangible object has a fixed transformation associated with it. E.g. a representation of an optical-grade mirror always has the effect of reflecting the virtual beams of light. On the other hand the pen for interacting with the Toshiba tablet PC changes its effect from a left to a right click on a digital objects when its button is pushed down.

3.4 Lifetime of link

This property describes for how long a physical and a digital object remain linked. A physical object may be consecutively linked to different digital artefacts in the lifetime of the application. For example a flashlight in the Storytent [8] can be used to select different balloon objects. Alternatively, the physical and digital object may remain linked for the lifetime of the application. This is exemplified in the Tangible Geospace [22] where the phicons are permanently bound to their digital counterparts. Finally, a link may retain its nature across many applications, potentially even permanently.

3.5 Autonomy

This property describes to what extent the existence of the destination object is reliant upon the existence of the link and the source object. For example, a digital object may be created only as a result of its link to a physical object. This is the case with the balloon objects in the Storytent – a virtual balloon is created whenever a physical balloon is brought into the tent and then it is deleted when that physical balloon leaves the tent. The destination object may also be a representation/projection of some of the characteristics of the source object, e.g. the digital pattern projected on the wall of the ambientRoom [12] reflects human activity in a physical space. In such cases if the source object ceases to exist, the destination object would also disappear or become meaningless.

3.6 Cardinality of Link

This describes whether an object is linked to one or more objects. One-to-one relationships seem to be most common. For example in the Tangible Geospace application on the metaDesk [22] each phicon, a small physical model of a particular building, was bound to the digital representation of that building. However it is also possible to link a physical object to multiple digital objects, e.g. Passage objects [16] could have been implemented so that a single physical "passenger" can identify a selection of digital documents (i.e. play the role of a folder). We can describe such a configuration by saying that a link has multiple destinations.

3.7 Link Source

So far we have only discussed cases where there is a physical interface object that mediates transformations to a digital object. However, it is also possible for digital objects to affect the state of the physical world. For example, haptic interfaces such as the PHANToM [18] provide a tangible feedback to the person manipulating digital objects and ambient displays such as Natalie Jeremijenko's Live Wire [25] provide tangible feedback of activities in digital space (Ethernet traffic in this case) through physical motion, sound and touch.

The link source property describes whether the source of the effect is the physical or the digital object.

4. REVIEWING CURRENT SYSTEMS

We now use our proposed link properties to classify current TUIs. First, we use the link source property to broadly divide systems into those where the source is a physical object and those where the source is a digital object. Thus Table 1 summarises the properties of the example TUI systems that have been discussed for far in which physical objects control digital ones. Table 2, on the other hand, introduces systems where the source is a digital object that has an effect in physical space. The examples in both tables are broadly listed in order of increasing coherence.

As object relationships with a cardinality of one to many are rare in current systems, this property has been omitted from the tables and all examples illustrate links where a single physical object is coupled to a single digital artefact.

5. IMPLICATIONS FOR TUIs

Our framework is based on unpacking the nature of the links between tangible and digital objects and using this to classify TUIs. This represents a shift in focus from many of the current perspectives. Not unsurprising much of the existing work on tangible interfaces has tended to focus on realising the physical artefacts associated with tangible interfaces. Current frameworks such as those proposed by Ullmer and Ishii [23] and Holmquist [11] while based on a connection between physical and digital tend to leave the nature of this connection as implicit with little reflection on the different ways in which this connection may be manifest. Understanding TUIs based on the richness of potential links between the digital and the physical provides us with a slightly different perspective on their nature and outlines a number of significant future research directions. In this section we briefly reflect on three initial examples by considering the asymmetry of the links, the configuration of the links involved and the need for users and developers to understand the nature of the link between the physical and the digital.

5.1 Tangibles that Push Back

Comparing tables 1 and 2 reveals a significant asymmetry in how the physical and digital are linked. While there are many examples of using physical objects to control digital objects, tangible interfaces that react to changes in digital information are relatively rare – there are few examples of tangible interfaces that "push back". It is therefore a challenge to develop techniques that will allow us to create digital artefacts that will push back on the physical space. These will be useful for providing tactile information, maintaining synchronisation between digital and physical objects and showing or monitoring digital activity through physical movement.

Examples of push back technologies from related fields include haptic devices for virtual reality such as the PHANToM [18], tangible interfaces for remote collaboration such as the PsyBench [3], and also ambient displays such as Pinwheels [6] and Table Fountain [7]. However, it remains a challenging problem as to how to push back through everyday objects such as blocks on a table or post-it notes on a board. Promising approaches include the use of airflow, waterflow, electromagnets and actuator arrays [13].

5.2 Mobility, Reconfiguration and TUIs

Many of the examples of tangible interfaces have tended to be based on stable arrangements between the physical and digital. TUIs such as the MetaDesk [22] have tended to be constructed as installations to be experienced by users as stand alone applications. However, TUIs have also become closely associated with Ubiquitous computing and examples such as the ambientROOM [12] outline the potential of TUIs and demonstrate how the digital may be physically manifest. However, less consideration has been given to the ubiquity of information and what happens when the physical element of TUI moves from one context into another. The main use of mobility of physical object has been to act as a token to access digital data.

How do the physical devices within the Ambient Room act when they are placed within a second room? Do their existing connections with the digital material in one ambient room persist into the second room offering remote availability or are new links established reflecting different digital effects? Considering the lifetime, autonomy and configurability within the potential links allow us to chart and understand this design space and consider how we may support the mobility of TUIs.

5.3 Understanding the effects of TUIs

Our turn to reasoning about the links between the digital and the physical within TUIs also seeks to develop a richer understanding of the interactive nature of TUI. As Bellotti et al argue existing work on sensed environments have tended to not provide mechanisms to allow users to make sense of the interaction [2]. Essentially, as we establish richer forms of links between the physical and the digital we need to carefully consider how the variability inherent in these different links are conveyed to users and how they might make sense of their interactions with TUIs.

This issue is manifest both within toolkits to realise tangible user interfaces and how TUIs present themselves to users. Toolkits such as Phidgets [9] provide a rich set of physical objects linked to digital objects. The connection between the real and physical is manifest through only one mechanism. Few structures are given to manage a variety of forms of link. The iStuff toolkit [1] exploits different types of events within an event heap to allow a richer set of connections to be established. However, it is unclear which of these connections are desirable and how these should be structured. We would suggest our framework offers a way of exploring this design space.

In order for the link between the physical and the digital to be intelligible to the user we must carefully consider how these effects are conveyed to users. What feedback is provided? How might users understand the extent of physical manipulation? How might the properties of the link be presented to users and how these properties might be explored? Previous work has considered how the properties associated with boundaries between real and virtual environments might be presented to users [15] and we would suggest similar explorations are needed for TUIs.

Category	Example	Transf.	Scope of Interaction	Config.	Lifetime	Autonomy
General purpose tool	mouse	Transformed	Translations in X-Z plane	Configurable	Temporary	Autonomous
	Tablet pen	Transformed	Drag, tap, tap with button pressed	Configurable	Temporary	Autonomous
Specialised Tool	tongs, eraser, magnet	Transformed	Translations in X-Z plane	Fixed	Temporary	Autonomous
	Storytent torches	Literal (ish)	Translations in X-Y plane	Fixed	Temporary	Autonomous
	Illuminating Light	Literal	Translations in X-Z plane and rotations Y	Fixed	Temporary	Autonomous
Identifier	Passage	Literal	Presence	Fixed	Semi perm.	Autonomous
	WebStickers	Literal	Presence	Fixed	Permanent	Autonomous
	Storytent ballons	Literal	Presence	Fixed	Permanent	Dependent
Proxy	metaDesk phicons	Literal	Translations in XZ plane and rotations around Y	Fixed	Permanent	Autonomous
	CUBIC	Literal	Scaling in X, Y and Z axis	Fixed	Permanent	Autonomous
Projection	Display in ambientRoom	Transformed	Human movement	Fixed	Permanent	Dependent
Illusion of same object	Traversable interface	Literal	Crossing boundary	Fixed	Permanent	Dependent

Table 1: Classification of systems with links with a physical source

Category	Example	Transf.	Scope of Interaction	Config.	Lifetime	Autonomy
Proxy	PSyBench objects	Literal	Translations in X-Z plane	Fixed	Permanent	Autonomous
Projection	Pinwheels LiveWire	Transformed	LAN traffic	Fixed	Permanent	Dependent
Illusion of same object	Traversable interface	Literal	Crossing boundary between virtual and physical space	Fixed	Permanent	Dependent

Table 2: Classification of systems with links with a digital source

6. CONCLUSIONS

We have proposed a framework for TUIs based around the idea of the *degree of coherence* between physical and digital objects. This was further broken down into the concept of *links* between physical and digital objects that are described in terms of a set of underlying *properties*. We used this proposed framework to classify current TUIs, which raised a number of broad implications for the field of tangible interaction. The focus on enriching the link between physical and digital highlighted the need to consider the asymmetry of these links, issues surrounding the configuration of these links and the need to represent the nature of these links to developers and users. We suggest that these areas represent potentially fruitful directions for future research.

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