Successful Physical Interaction Design on Tangible User Interfaces Framework and Novel Device Design

ABSTRACT

For nearly a decade various tangible user interfaces (TUI) frameworks have emerged to enhance understanding of physical-digital linkage. Whilst others have focused principally on the ubiquitous perspective in the design stage, this paper takes a slightly different approach. We analyze successful design in everyday physical artifacts in order to extract principles of effective physical interaction and so to inform the next generation of interfaces. We will briefly describe the principles of design success, and examine these against a broader range of tangible interfaces within the context of a TUI framework finding that many of the broad design guidelines are followed by tangible interfaces. We also use the conceptual principles to analyze design choices for a novel interaction device, the Cubicle. This approach enables us to see that novel interactions whilst different in detail, share much with more mundane everyday appliances, and so sheds lights on the design of tangible devices.

Author Keywords

Tangible user interface, ubiquitous computing, consumer appliances, physical interaction, fluidity, affordances.

ACM Classification Keywords

H5.2. User Interfaces – Input devices and strategies, Interaction styles, Style guides.

INTRODUCTION

The vision of the creation of tangible devices in the era of ubiquitous computing, linking the physical-digital worlds, is shared by many these days. The term "Tangible User Interfaces" (TUI), first proposed by Ishii in 1997 [11], introduced the world of computing to the possibility of linking physical artifacts with digital information; and the research work on TUI has grown much since.

Frameworks, conceptual theories and tangible device developments have significantly emerged which aimed at gaining a better understanding of the subject, such as [13, 21, 22], whilst [2, 7, 18] look at ubiquitous interaction in general.

Whilst others looked at and even developed tangible devices in search of tangible design guidelines, we are examining our physical design principles [8] to test the principles' compatibility and their impact on the TUI framework [13], which has extended our understanding of computationally-coupled physical and digital objects.

The design principles were based on our study of understanding the features of physical interaction and of the physical-logical mapping of everyday artifacts that make them comprehensible and natural, which has given us insights to understand the design of novel tangible and ubiquitous devices. What motivated us is the fact that we can learn much by studying these appliances that would be hard or impossible to learn by extensive especially with novel devices.

Here, we will also see how we used the conceptual principles to suggest appropriate mappings onto a novel tangible interface device, the Cubicle.

PRINCIPLES OF DESIGN SUCCESS

The success of good design has materialized from our study of day-to-day devices and consumer appliances, which its aim was to understand how natural interactions can be used effectively in the design of tangible devices. We analyzed and represented some of the rich physical interactions available on mundane appliances including a washing machine and speaker volume control. The motivations, descriptions and techniques of this particular work have been elaborated carefully in [8].

We observed that in most of the appliances, the explicit design of the physical object enables the user to understand how to manipulate the devices as they exhibit strong affordances. However, we saw that there are additional aspects of these devices that exploit the physical form of the device to inform the users' interaction with the logical function they control. In some cases we saw that this is not the case and then the devices employ various 'recovery' strategies to make the non-physical aspects more obvious.

Following are the design features, or principles, emanated from the study of good physical design success.

Exposed State

Physicality of the device exposes some aspects of state. We may not know to what the switch (light or air conditioning) is connected, or whether up means off or on, but still there is very visibly two states. This exposed physical state of a device is often used to create very natural interactions by directly mapping the physical device states to logical states.

As noted above, there is a separate issue as to whether the user knows this mapping - is up off or on?, or how the user gets to know the mapping - affordances, labels?. However, note that the user can make a reasonable guess that it is a two-state thing being controlled, and because of the simple relationship between physical device state and logical controlled-system state the user is in a good position to infer the mapping with use. This ability of the user to manage without necessarily knowing mappings ahead of time is typical of physically natural interactions. Obviously, the visible state of a control can only be used when there are a corresponding number of internal states although this can be quite large.

In contrast to exposed state, there are controls where the physical appearance does not indicate any obvious state – *hidden state*. Sometimes this is the result of aesthetic rather than usability decisions, but also hidden state controls can be useful where the logical system has large numbers of states, or where the calibration between device state and logical state needs to be dynamic. For example, if the dial could turn completely round several times to increase or reduce volume there would be no one-to-one relationship between location and volume. Also if the same control is used to manipulate different aspects of the logical state in different modes or there are large numbers of internal states, then it may be impossible to have a simple mapping.

Tangible Transitions

Some physical controls provide the naturalness of interaction by embedding a sense of feltness when manipulating the controls. This may augment exposed state or in the case of hidden state provide while-use exposure. In the example of the speaker control, the physical control has a palpable bump so that the user can feel it go past the on/off position. This does not give the user knowledge of the current state before grasping the control, but whilst manipulating the device, the user is made aware of critical transitions.

Bounce Back

Some control devices return to their initial position soon after we release our fingers or hands from the knobs/buttons. This particular effect is what we call 'bounce back'.

The bounce back control, such as the on/off power button on many PCs, has aspects of both exposed and hidden states. It is exposed in that it is clearly 'in' or 'out'. However, the 'in' state is a *transient state*, it only stays in the state while a finger is actually pressing it. As soon as the pressure is released it bounces back to the 'out' state and so there is only a single stable exposed state. This lack of a meaningful exposed state means that bounce-back buttons typically rely on a screen display or some other sort of indication to show the present state the system is currently in after the physical manipulation has taken place.

Inverse Actions

Physical controls such as dials have rotary knobs that afford turning clockwise and anti-clockwise that gives two opposite results. This, exploits natural physical inverse actions – if you push a cup across the table you can also push it back in the opposite direction; unless it falls off the edge, opposite pressures have opposite effects.

It is not just that an inverse exists with physical devices, but that the inverse exploits a natural physical inverse such as push/pull, twist clockwise/anti-clockwise, or push up/down. In the best cases this is intrinsic to the device, but may also be made apparent using visual or tactile decoration.

Inverse action is especially important if the user does not have a perfect knowledge of the physical–logical mapping; the user can experiment with the physical control but recover effortlessly if things go wrong. A particular case of this is when a physical control may manipulate more than one logical function. Inverse actions, in some other cases, work together with exposed state to deliver natural interaction.

The naturalness of inverse actions' interaction may only be achieved when the user gets immediate feedback. However, feedback is sometimes delayed. As we discussed, temporal locality is one of the features of physical interaction, and not surprisingly these delays are not dealt with naturally.

Compliant Interaction

Some of the physical controls which exhibit a good exposed state do also exhibit symmetry of interaction – the user sets the program by turning the dial, but the system also turns the dial itself as the program advances.

Exposed state and compliant interaction differ in that compliant interaction displays mechanical movement that changes the control in the same way as the user would interact. The control does not solely depend on the user's interaction.

Compliant interaction means that the user can easily learn the relationship between the state of the control and the state of the device. The naturalness of compliant interaction enables expert users to use the device to exert fine control over the system's action.

EXISTING TANGIBLE DEVICES

It is clear that good design of day-to-day appliances should offer benefits for the design of tangible devices. Having understood the principles of physical design, we now look at examples of tangible devices that embody the principles, and look at where in the design space of tangible interaction the principles can contribute to improving design.

Collaborage [15], Marble Telephone Answering Machine [3] and Illuminating Light [24] are good examples that exploit the *exposed state* principle. Collaborage uses badges, which are the tagged tokens that can be moved between the In/Out columns and on the In/Out/Away board located in the hallway to trace the users' positions. The changes are tracked by the system and are updated in the database. In the Marble Telephone Answering Machine, a marble is used as the device control to play the message by dropping the marble into an indentation in the machine. The marble is also used to dial the caller automatically by placing it onto the augmented telephone. Of the three examples, the Illuminating Light exploits the exposed state principle the most. Physical models of optical elements (prism etc.) are used to create a simulated optical layout. The system then simulates the corresponding light patterns. The simulated optical layout is not just about control and feedback, but is a direct representation of the actual thing.

As we already know, to ensure the natural interaction exists in *hidden state*, we have to provide additional information in order to assist the user to understand how to manipulate the device. In tangible devices, the situation is a bit different; the examples that follow seem to be using hidden state not because of the constraints of the interface but for specific purposes. The Storytent by Fraser [6] uses UV light to reveal the hidden writing on an electronically tagged paper to make the experience of unearthing the logical functions (digital) more interesting. Rather like the Drift Table uses a 'bad' neutral state for ludic effect the Storytent uses hiddenness in an exploratory experience. Super Cilia Skin [17] is also focused on the aesthetic. It is a computationally enhanced membrane, which is actuated by electromagnets, coupling together tactile/kinaesthetic input with tactile/visual output. It attempts to make the tangible-logical mapping more exciting. Both examples have aspects of natural interaction as the UV light directly points onto the surface of the turntable, and the tactile aspects of the membrane draw the users to touch it. Hartson calls these sensory affordances [10].

Most tangible devices exploit *inverse actions*, which allow the users to undo and reverse the actions, for example, Phicons in metaDesk [23] and Senseboard [12]. At one level the invertibility is there by virtue of the physicality of the tokens being used to control the manipulation. However, it is not a necessary property of the augmented system but depends on there being a functional relationship between the state of the physical tokens and the state of the logical system. For example, Senseboard has been used to organise conference paper sessions. It is designed to show conflicts, but an alternative design might have had the users manipulating just some of the papers physically and others being reorganised by the system to maintain constraints. When a paper is moved by the user the system would reorganise the rest, but then it could easily be the case that moving a paper and then moving it back did not lead to the same overall situation. The same thing occurs with a word processor if you move the cursor down and then up when at the bottom of the screen. It is relatively 'easy' to make tangible interfaces obey the inverse action principle, but still needs to be considered explicitly in design.

Although these systems support inverse action, they do not have a real 'undo' in that they do not provide or represent the actual "path" of movements that have been made. Thus the user performs the reverse action(s) depending solely on what they can remember. One example that actually records and displays the history of the movement to allow inverse action is Outpost [5], which is about organising information of Post-it notes that are used as the physical media. Note that this exposes several purposes of 'undo' or invertible actions in GUI systems that are usually elided: (i) to correct slips immediately, (ii) to allow 'homing' actions such as mouse movement or rapid cursor movement, (iii) to allow low risk exploration of alternatives, (iv) to 'turn back the clock' when after several actions some problem is found. In a GUI (iv) requires some form of multi-step undo menu, (ii) and (iii) are typically achieved using invertible actions, although using an explicit 'undo' button for (iii) is possible, and (i) may be achieved using either invertible actions or undo depending on the erroneous action. However, (iv) is most needed when there are large amounts of hidden state, or complicated computations so less relevant for TUIs. The focus in tangible interfaces is less about backward error recovery, restoring a past state, and instead more about forward error recovery, moving on from where you are towards a goal [1].

It was quite difficult to find examples of tangible devices that have all of the properties that make one have *compliant interaction*. Most of the existing tangible devices let the user easily learn the relationship between the physical and logical states that enable the user to have control over the system actions. Often these system actions are virtual (e.g. projections as in Illuminating Light), but there are examples of physical effects being produced. For instance, Actuated Workbench [16] is a device that uses magnetic forces to move objects on a table in two dimensions. The user controls the graphical output by manipulating the physical input, which is composed by positions and movements. The input is tracked and responded to by the workbench. Pinwheels [4] use an ambient display that shows the presence and state of digital activity within a space through changes in airflow. The speed of Pinwheels is based upon their input information source – users' activities. However it is rare to have the same physical effect controlled by both user and system. The only example that we have found conforming to compliant interaction principle is Rototack

[25]. Besides allowing the user to have control over the system's action, it also exhibits symmetry of interaction. Rototack is a small computationally-enhanced tack that provides a source of programmable rotational motion provided by a small stepper motor. The user has control over the tack, i.e. by writing a program for the tack. The tack then in response runs its program. The user can stop the program at any point; even this means that the tack has not yet completed its cycle.

The above examples show that the physical design principles can be used to analyse existing tangible devices and expose where they exhibit natural interaction. We now will see how these findings fit more broadly within a tangible user-interface framework.

A TUI FRAMEWORK

We chose the TUI framework by Koleva et al. [13], among others, because it is based around the idea of the "degree of coherence" between the physical and digital objects. As there is a variety of tangible systems that have been developed to date that illustrate tangible interface principle, we were keen to learn what are the characteristic or features that these tangible systems have as we go along the coherence level, against our design principles, which is aimed at producing natural interaction.

The framework places TUI objects into six proposed categories of TUI types that depict the relationship of physical and digital objects. These categories are positioned along a 'coherence' scale based on five properties that are used to describe the physical-digital links.

The TUI categories are as follows moving from low coherence to high coherence:

- *General-purpose tool* – a tool that gives the user a choice to manipulate any one of many digital objects and perform different transformations. It establishes the weakest level of coherence
- *Specialised tool* – objects that have a more specialised function, yet still temporarily connect to potentially various digital objects
- *Identifier* – interface objects that act as bookmarks for retrieving computational artefacts
- *Proxy* – interface objects that are of proxy category are more permanently associated with, and allow a more extensive manipulation of their digital counterpart
- *Projection* – digital artefact that is seen as a direct representation of some properties of the physical object. Its existence is dependent on the physical object
- *Illusion of same objects* – this category has the strongest coherence. Objects that fall into this category give the illusion that the two coupled objects are one and the same

The physical-digital links can also be described in terms of their five properties:

- *Transformation* – this describes whether the effect mediated between linked objects is literal or transformed
- *Sensing of interaction* – this describes what interactions with the interface object and its surrounding environment are sensed and transmitted to the destination object
- *Configurability of transformation* – this describes whether the transformation mediated between two linked objects remains fixed for the lifetime of the link or whether it is configurable over time
- *Lifetime of link* – this describes for how long a physical and a digital object remain linked
- *Autonomy* – this describes to what extent the existence of the destination object is reliant upon the existence of the link and the source object

Although individual TUI objects and applications exhibit differing spectra of properties, there is a general correlation between the scales giving rise to an overall 'level of coherence' continuum. This is illustrated in figure 1. A range of TUI applications and devices, including most of those examined in the last section, are placed into the categories.

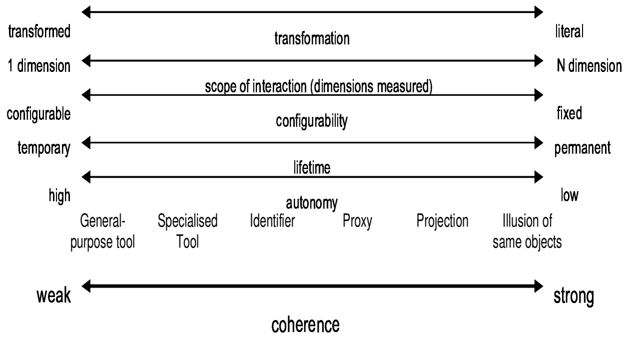

Figure 1. TUI categories along the coherence continuum (from [13]).

IMPACT ON TUI FRAMEWORK

Just as individual TUI objects vary in their spectra of coherence properties, they clearly also differ in the extent to which they satisfy the various physical design principles. In general, high coherence and satisfaction of 'good' principles are related; however, some of the principles seem particularly related to particular categories. So, we will explore the findings from the previous sections against the properties and categories of figure 1.

Exposed State – Collaborage (identifier), Marble Telephone Answering Machine (specialised tool), Illuminating Light (specialised tool), Actuated Workbench (proxy), Pinwheels (projection) and Rototack (projection) all exhibit exposed state. However, when we categorise them according to the TUI categories (see brackets) the categories that exhibit exposed state the most have both strong physical-digital links and natural interaction and range from the ‘proxy’ category, to ‘illusion of same objects’ category. In addition, the examples that fall within these categories all have fixed configuration and permanent lifetime. The stronger the coherence, the more dependent autonomy the objects have (Rototack has dependent autonomy, whilst Actuated Workbench is autonomous) and of course exposed state is most effective with a fixed relationship between device state and logical state.

The Cubicle used to control the feed into the situated display in the seating area has each of the sides labelled with the possible feeds into the display. It thus exhibits the fixed configuration property suggesting the proxy category. However, this relationship between labels and functions is highly symbolic and is also malleable in the long term, rather like written labels on function keys on a keyboard. The Cubicle thus has a ‘feel’ more of a specialised tool. Although it has an exposed state the affordances are exposed linguistically rather than through its intrinsic properties.

Hidden State – Identifier, Specialised tool and Generalised-purpose tool categories tend to exploit the hidden state principle because they are likely to be mapping the same physical device to different logical states. The Storytent for example, belongs to ‘specialised tool’, whilst the Super Cilia Skin belongs to the ‘identifier’ category. The nature of these three categories is that the mapping of the representation of the physical and digital is not that direct, comparing to the proxy categories and beyond. The weak coherence that the objects exhibit, for example, the Storytent, is also indicated by fixed configuration, temporary lifetime and autonomous properties.

A different experimental use of the Cubicle as AV controller uses an unlabelled cubicle and gestures to navigate between feeds and to control options for each feed (e.g. navigate in web browser, adjust volume of video playback, etc. This is clearly an example of hidden state and more clearly belongs to the specialised tool category as it temporarily connects to many different digital objects, for example, TV tuner and fixed computer. Being able to consecutively link to different digital objects in the lifetime of the application shows that the Cubicle has the temporary lifetime property. The cubicle also embodies the fixed configuration property.

Note how the Cubicle’s classification depends on its visual decoration and application context. Both the physical interaction principles and the TUI framework properties are not about a device in isolation, but about the device in an interaction context.

Inverse Actions – All tangible devices from ‘identifier’ category to ‘illusions of same objects’ category seem to exploit the inverse actions principle. Howver, previously we have seen that most of the tangible devices that fall in these categories do not provide the user with the actual ‘path’ to perform undo/redo actions, but rather a more local ability to simply ‘move back’. This gives rise to a strong physical-digital mapping and exhibits natural interaction. For example, Outpost, in particular, has a literal transformation in that its physical movement gives an effect of moving the digital object, with permanent lifetime. As we discussed when looking at consumer appliances, the inverse action principle is very important when the user does not have a clear idea of the effect of the action, allowing exploratory interaction; that is where configurability is high and lifetime low. Paradoxically inverse effects are exhibited most in high coherence objects, but perhaps required most in low coherence.

Compliant Interaction – As we saw, compliant interaction is related to exposed state, which is common in TUI applications. However, in addition to this, those tangible devices that exploit this principle show a strong and symmetric coupling of the physical and digital link. The examples that most closely exhibit this, the Actuated Workbench, Pinwheels and Rototack, are of the ‘proxy’ and ‘projection’ categories. In general, the tangible devices that fall in ‘proxy’ category to ‘illusion of same object’ category are most likely to exhibit compliant interaction. However, as we have seen few of the tangible devices exhibit really symmetric interactions, due partly to the difficulty of engineering haptic feedback on untethered devices.

Figure 2 shows the property settings and level of coherence from figure 1 amended based on the impacts made by the physical design principles. From the diagram, we can conclude that the stronger the coupling of the physical and digital, the more natural the interaction.

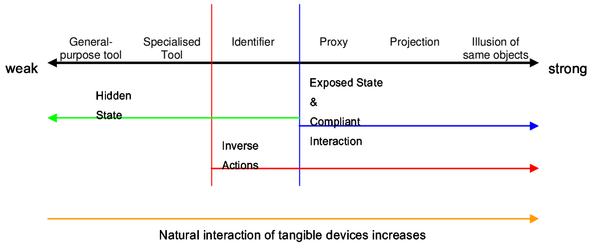

Figure 2. Principles of naturalness and levels of coherence.

GUIDELINES FOR TANGIBLE CONTROL

The analysis has given us the understanding of in what way the design for tangible control can be realised. We have summarised some of the broad guidelines which illustrates the situations or contexts where the principles, or the design characteristics can be applied.

Exposed State:

- The ideal design
- to provide simple interaction, i.e. one-to-one mapping of logical-physical

- to provide more complex interaction (c.f. compliant interaction)

Hidden State:

- when there is some kind of constraints – limited space / restricted interface
- must supplement the device controls with additional information
- making interaction interesting/exciting

Inverse Action:

- to allow undo, or backward action to recover immediate mistakes
- to allow exploration of the device, esp. when the physical–logical mapping is variable
- to allow overshoots in ‘homing’ or rapid target selection tasks

Compliant Interaction:

- to express the meaning of the states of a control (because it shows current state)
- to expose the physical control’s movement (because it shows changes)
- to allow the expert users to have control over the system (e.g. intervene in the programme)

Bounce Back:

- to map to a variable number of states
- to map to large number of states
- when there is limitation of space
- with a neutral position for direction of movement or velocity control

Tangible Transition:

- when designing haptic interaction
- to make the users aware of the transition that they are making
- when the user can only glance when manipulating the control

FLUIDITY OF NOVEL INTERACTIONS

We have already used these principles in studying novel devices, in particular a novel input device, the Cubicle [9]. Here we will illustrate how we used the conceptual categories to suggest appropriate mappings.

Cubicle

Cubicles are cubes of various sizes that are instrumented with different kinds of sensors so that properties such as orientation, location etc. can be detected [14]. These sensed attributes can then be used to control various devices.

Cubicles are being developed as part of the EQUATOR project investigating the integration of digital and physical life and use Smart-It technology to allow rapid prototyping of sensor-based systems [20].

One example of a Cubicle is of a small cube with sides approximately 3 in (7.5 cm) that is used to control the feed into a large situated display in the seating area of the Lancaster Innovative Interactions Laboratory. Each of the sides is labelled with one of the possible feeds into the display: TV tuner, laptop cable, fixed computer, etc. The cube sits on the coffee table and is simply turned over to select a particular feed. Inside the cube is a standard Smart-Its main board with micro controller and wireless communications. A small Smart-Its plug-in module has accelerometers to detect orientation.

Other Cubicle designs have included much smaller or larger cubes and also cubes with different physical properties: soft ones that can be squeezed, furry ones that can be stroked. Separate work has investigated how these factors affect the way people choose to interact with Cubicles [19].

Visible State

In the screen-control Cubicle there is a very clear one-to-one mapping between the visible state of the Cubicle (the uppermost face) and the logical state of the situated display. However, like an on-off switch, this only allows the control of six-state applications. Also the unique labelling of the sides mean that it is largely a single purpose device. It is interesting to note however how subtle changes in the decoration of the Cubicle change the number of visible states and the way they can be used in interaction.

If a labelled Cubicle is placed on a flat surface and there is no preferred direction on the surface, then there are only 6 states corresponding to the uppermost face. In a situation like the communal coffee table this is exactly what we have.

If, however, there is a preferred direction, perhaps the direction of the display, then we can also distinguish the orientation of the cube. In principle, there are 360 degrees of orientation that could be detected, and if the Cubicle were a flat plate with an arrow inscribed on top, then these would all be potentially usable.

In fact, the strong rectilinear visual affordance of the cube suggests that states with a face or possibly corner facing towards the screen are preferred, so, for illustrative purposes we'll consider the cube as 'normally' in aligned face positions which means that strictly there are 24 states: 6 possibilities for the uppermost face and 4 further orientations.

In the case of the screen controller the fact that the faces were labelled with text (which suggests a single ‘correct’ orientation) and the lack of relation between the sides meant that this was effectively reduced to 6. An alternative decoration of the sides, for example, a squared-off globe would suggest treating the orientation as significant and hence allow all 24 states to be used.

Both the text labels and globe decoration are very much single purpose. One of the goals of Cubicles is also to use them as generic controllers, so we also consider more open decorations.

One extreme is a fully labelled cube, for example with each side a different colour, or as in the case of a normal die, a number. Here all 24 states are in principle available, although in the case of the die there are strong cultural suggestions that one should consider it a 6 state device.

More minimal labellings include colouring one half of the cube so that one side becomes significant or painting one corner only (see Figure 3). In the former case there are 6 states (painted side down or up and 4 'sideways' states) although there are strong visual suggestions to regard these as 3 major states: face up, face down and sideways, with 4 orientation 'sub-states' when sideways. When the corner is painted there are 8 possible states although there is some suggestion that the corner could be used as a pointer, so possibly this may be used as a 360-degree controller.

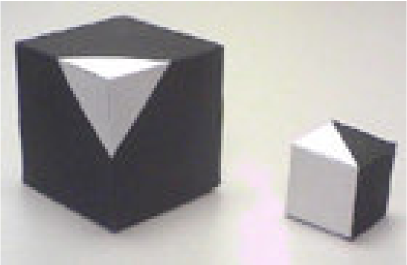

Figure 3. Coloured Cubicles.

Notice that some of the visible states of the Cubicle are given by its physical properties, but others depend on cultural or contextual factors.

Inverse Action

The simplest decoration of all is an entirely unlabelled cube, which has no distinguishable states whatsoever. Although this sounds not very useful it means that it can be used in the same way as a mouse or joystick can, where the absolute location is not important: it is the relative movements (rotating, twisting) that are significant.

For example, given a menu structure, tipping the cube from side-to-side can be used to cycle through options and tipping it forward can be used to select an option.

Depending on the sensors in the Cubicle, slowly tipping in a direction can be distinguished from a quick 'flick' in a direction or actually turning in the same direction. The desire to return to the 'natural' orientation of the cube with flat face up, suggests that the tipping action, rather like a sprung joystick, affords more continuous velocity effects, whereas a flick or turning of the face is a discrete action, more like cursor keys.

Whilst movements like this can be used to make a Cubicle into a universal controller, there are problems of registration. Which way is 'forwards'? For the users this would probably be tipping the cube away from them, but if the Cubicle does not have any absolute location or orientation sensors (which are more difficult than tilt sensors) then this may not agree with the Cubicle's 'own' idea of 'forward'. Also a new user coming to the Cubicle, perhaps finding it on a coffee table, would need to learn the interactions.

Just as in the appliances we have studied, these are exactly the situations where natural inverse actions can help. The use of opposing directions for moving in different directions through a menu list means that tipping the cube in one direction can be undone by the opposite movement. Similarly if tipping forward is selection of an alternative, tipping backward should be the 'go back' action. So long as this is the case a user picking up the Cubicle in the 'wrong' direction can learn up the effects and if desired then re-orientate the Cubicle. Where the inverse action breaks down, for example when selecting an option has an irreversible effect, then some sort of orientation independent action, such as a sharp tap of the Cubicle, will be necessary.

Compliant Action and Haptic Feedback

As we have seen compliant action is comparatively rare, but very powerful when used appropriately as in the washing machine dial, or on-off buttons on electric kettles.

Cubicles are predominantly passive and untethered input devices, so do not naturally suggest control back from the application. However, some potential designs have a small display on each side. This would allow interactions where the user could rotate a particular face upwards, but this could then change over time under the applications control. For example, if the Cubicle is used to control a menu system, then the system could gradually 'fall back' into a standard state after a period of inaction.

Haptic feedback is even more problematic although a heavy gyroscope could be used to give controllable resistance to rotation or even used to autonomously flip the cube.

More practically a ball-bearing moving within a face-centred octahedral void within the Cubicle would enhance the 'joystick' effect – as one tipped the cube, even in mid air, it would be trying to get back to a face down state. Alternatively having a ball bearing roll within the cube itself would tend to suggest holding it with a corner pointing down and hence radically change its interaction affordances.

DISCUSSION

In this paper we have explored the thesis that the design features of current day-to-day appliances can be used to inform next generation interfaces. We have focused on the aspects of the physical controls that correspond to natural physical interactions in the world. Studying these day-to-day devices has led to a number of principles and issues of physical interaction. This has enabled us to examine a particular novel interaction device, the Cubicle, and also to see how these principles correspond to generic categories of tangible interface object.

We also have summarized some of the broad guidelines that emerge from this discussion although we would not regard these as definitive. These guidelines emerged from examining the day-to-day artifacts and were largely followed by many of the tangible interfaces. Amongst the issues that arose a few are worth noting especially.

Exposed state and inverse action seem to almost follow by course from the physicality of tangible interface objects. However, this only follows for their own physical state and not the logical functions and state influenced by them. These need to be explicitly considered during TUI design not left to chance.

Compliant interaction seems to be extremely powerful where it is employed in consumer devices leading to clear state, ease of discovery and natural control. It effectively emulates the symmetry when we as people collaboratively manipulate an object with each other. However, the difficulty of symmetric haptic feedback means that few current interfaces make use of this powerful technique.

Although some of the principles are generally ‘good’ ones: exposed state, inverse action, compliant interaction; there are circumstances where they are and should be broken. For example, if there are many states or a variable mapping then exposed state is not possible. Furthermore, we saw that ‘bad’ interaction is sometimes good interaction for ludic purposes.

Some broader methodological issues also emerge from this work.

We have seen that many of the physical design principles and the TUI coherence properties relate not just to a device in isolation, but instead to a device with an associated physical–logical mapping. Because of the experimental nature of tangible interfaces and more broadly ubiquitous computing, it is frequently the case that a device is used in one application only. It is therefore easy to elide the intrinsic properties of a device or mode of interaction with the application for which it is used.

Our investigative approach has combined what can be thought of as an epidemiological study of devices that are extant, more psychological analysis of device use, common knowledge about good and bad design and detailed formal analysis. Most of the devices we have studied exhibit several ‘good’ and ‘bad’ properties and the effectiveness is a combination of designed and accidental properties of the device combined with skilled human behaviors arising from cultural, learnt and innate causes. To attempt to disentangle completely all these issues would not be productive for design purposes and our multi-paradigm approach has allowed a broad analysis. However, attempting to obtain some purchase on the complex interactions and trade-offs of physical design does lead not only to insight but also potential directions for more detailed experimental studies of individual effects.

This study offers new ways to understand the design with regard to tangible controls. The ubiquitous vision may seem to be far removed from the devices we see today, but perhaps they are not so different after all.

ACKNOWLEDGMENTS

REFERENCES

1. Abowd, G. and Dix, A. (1992). Giving undo attention. Interacting with Computers, 4(3): 317-342.
2. Benford, S., Schnadelbach, H., Koleva B., Gaver, B., Schmidt, A., Boucher, A., Steed, A., Anastasi, R., Greenhalgh, C., Rodden, T., and Gellersen, H. (2003). Sensible, Sensable and Desirable: A Framework for Designing Physical Interfaces. Technical Report Equator-03-003, Equator (www.equator.ac.uk).
3. Crampton, S.G. (1995). The Hand that Rocks the Cradle, I.D., May/June 1995, pp. 60-65.
4. Dahley, A., Wisneski, C., and Ishii, H. (1998). Water Lamp and Pinwheels: Ambient Projection of Digital Information into Architectural Space, Short paper in Conference on Human Factors in Computing Systems, CHI 98, Los Angeles, April 1998, ACM Press, pp. 269 270.
5. Everitt, K., Klemmer, S., Lee, R. and Landay, J. (2003). Two World Apart: bridging the gap between physical and virtual media for distributed design collaboration. Proceedings of CHI 2003. ACM Press. pp. 553–560.
6. Fraser, M., Stanton, D., Ng, K., Benford, S. D., O'Malley, C., Bowers, J., Taxn, G., Ferris, K., Hindmarsh, J. (2003). "Assembling History: Achieving Coherent Experiences with Diverse Technologies", Proceedings of ECSCW 2003 Helsinki, Finland, Kluwer.
7. Gaver, W., Beaver, J., and Benford, S. (2003). "Ambiguity as a Resource for Design". CHI 2003, Florida, ACM Press.
8. Ghazali, M. and Dix, A (2005). “Knowledge of Today for the Design of Tomorrow”, Proceedings of the 2nd International Design and Engagability Conference (IDEC), September 6th 2005, Edinburgh.
9. Ghazali, M. and Dix, A. (2005). “Visceral Interaction”, Proceedings of BCS-HCI 2005 Volume 2, September 8th 2005, Edinburgh.

10. Hartson, H.R. (2003). “Cognitive, Physical, Sensory, and Functional Affordances in Interaction Design”, Behaviour & Information Technology, September-October 2003, Taylor & Francis Ltd, pp. 322
11. Ishii, H. and Ullmer, B. (1997) “Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms”, Proceedings of CHI 1997, March 1997, Atlanta, USA.
12. Jacob, R., Ishii, H. Pangaro, G. and Patten, J. (2002). A Tangible Interface for Organizing Information Using a Grid. Proceedings of CHI 2002. ACM Press. pp. 339–346.
13. Koleva, B., Benford, S., Kher Hui Ng and Rodden, T. (2003). A Framework for Tangible User Interfaces. Physical Interaction (PI03) - Workshop on Real World User Interfaces, a workshop at the Mobile HCI Conference 2003. Udine (Italy).
14. Kortuem, G. et al. (2003). Cubicle – tangible cuboid interfaces. Lancaster UbiComp Group. http://ubicomp.lancs.ac.uk/cubicle/
15. Moran, T.P., Saund, E., Melle, W.V., Gujar, A.U., Fishkin, K.P., and Harrison, B.L. (1999). Design and Technology for Collaborage: Collaborative Collages of Information on Physical Walls, UIST 99, North Carolina, USA, 1999.
16. Pangaro, D., Maynes-Aminzade, D., and Ishii, H. (2002). The Actuated Workbench: Computer-Controlled Actuation in Tabletop Tangible Interfaces, Proceedings of UIST 02, Oct. 27 30, 2002.
17. Raffle, H., Joachim, M.W., and Tichenor, J. (2003). Super Cilia Skin: An interactive membrane, Proceedings of CHI 2003, April 5-10, 2003, Florida, USA.
18. Schmidt, A. (2000). Implicit Human Computer Interaction through Context. Personal Technologies Volume 4 (2&3).
19. Sheridan, J.G., Short B.W., Kortuem, G., Van-Laerhoven K., Villar, N. Exploring Cube Affordance: Towards A Classification Of Non-Verbal Dynamics Of Physical Interfaces For Wearable Computing. Proceedings of EuroWearable 2003, HP Labs, Bristol.
20. Smart-Its Project. URL accessed Oct 2003. http://www.smart-its.com/
21. Svanæs, D., Verplank, W. "In Search of Metaphors for Tangible User Interfaces", DARE'2000, ACM, 2000
22. Ullmer, B. and Ishii, H. (2000). “Emerging Frameworks for Tangible User Interfaces”. IBM System Journal, Volume 39, Numbers 3 & 4, 2000. p. 915.
23. Ullmer, B. and Ishii, H. (1997). “The metaDESK: Models and Prototypes for Tangible User Interfaces”. Proceedings of UIST 1997, October 1997, Canada.
24. Underkoffler, J., and Ishii, H. (1998). Illuminating Light: An Optical Design Tool with a Luminous Tangible Interface, Proceedings of CHI 98, Los Angeles, USA, April 1998, pp. 542 549.
25. Wrensch, T., Blauvelt, G. and Eisenberg, M., (2000). The Rototack: Designing a Computationally-Enhanced Craft Item, DARE 2000, April 2000, Elsinore, Denmark, pp. 93-101.