Actuation and Tangible User Interfaces: the Vaucanson Duck, Robots, and Shape Displays

Ivan Poupyrev
Interaction Lab, Sony CSL,
3-14-13 Higashigotanda,
Shinagawa,
Tokyo, 141-0022 Japan
poup@csl.sony.co.jp

Tatsushi Nashida
SET Design Studio,
Sony Creative Center,
1-15-5 Jingumae, Shibuya,
Tokyo, 150-0001 Japan
nashida@dc.sony.co.jp

Makoto Okabe
Department of Computer
Science, University of Tokyo,
7-3-1 Hongo, Bunkyo,
Tokyo 113-8654 Japan
makoto21@ui.is.s.u-tokyo.ac.jp

ABSTRACT

In the last decade, the vision of future interfaces has shifted from virtual reality to augmented and tangible user interfaces (UI) where virtual and physical (or "bits and atoms") co-exist in harmony. Recently, a growing number of designers and researchers have been taking the next logical step: creating interfaces where physical, tangible elements are not merely dynamically coupled to the digital attributes and information, but are themselves dynamic, self-reconfigurable devices that can change their physical properties depending on the state of the interfaces, the user, or the environment.

A combination of the actuation, self-configuration, and tangibility can expand and enhance the design of tangible interfaces. In this paper, we present an overview of the use of actuation in user interfaces and discuss the rationality of building actuated interfaces. We then discuss actuated interfaces in detail based on our experience designing Lumen shape displays. Work on actuated interfaces is still in its infancy, projects are few and far between, so we consider this paper an invitation to discussion and hope it can help stimulate further research in this area.

Author Keywords

haptics, shape displays, interaction, collaboration

ACM Classification Keywords

HH.5.1: Multimedia Information Systems—Artificial, augmented and virtual realities; H.5.2 [Information Interface]: User Interface—Haptic I/O

INTRODUCTION

Until relatively recently self-motion and actuation had not been widely explored or exploited in tangible UI (a notable exception is Pangaro et al.'s work [19]). The coupling between tangible and digital has usually been in one direction; we can change digital information through physical handles, but the digital world has no effect on tangible interface elements. The use of physical motion, however, strongly relates to tangible UI philosophy and exploration of self-actuation seems to be a natural direction for tangible user interfaces research to take.

TEI'07, February 15-17, 2007, Baton Rouge, Louisiana, USA.

Indeed, one of the most attractive properties of the digital world is *malleability*: digital objects are easy to create, modify, replicate, and distribute. Physical objects on the other hand are rigid and static, which limits their utility in tangible UIs [19]. If we could dynamically change physical properties of tangible UI elements: their shape, texture, position, speed of motion, and so on, the design vocabulary of tangible user interfaces would expand tremendously.

Recently, with the development of new actuator technologies, microprocessors, and smart materials, adding actuation to tangible interface has become easier then ever. And there is a growing body of work that creatively explores self-actuation in art, design, and human-computer interfaces. Unfortunately, much of this work is scattered across different domains and there is little mutual awareness about the related work. That is why in the first half of this paper we survey the use of actuation in user interaction. We take a broad view, looking across various disciplines, hoping that projects in other domains will inform and stimulate design of actuated tangible user interfaces. We finish our survey with a categorization of actuated interfaces.

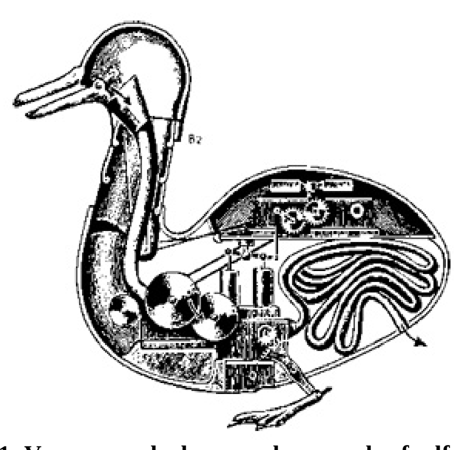

Figure 1: Vaucanson duck: an early example of self-actuated display used purely for decorative purposes [29].

In the second half of the paper, we discuss a class of actuated interfaces that we call *shape displays*, in significant detail. We focus on them because it's impossible to discuss all actuated interfaces in one paper. We feel, however, that it is important to illustrate the design issues involved in developing actuated interfaces using real and concrete examples. We choose shape displays because of our significant experience in designing interaction scenarios and applications for a prototype shape display that we designed and developed called Lumen [32]. Although some of these observations are specific to Lumen devices, others can be generalized and perhaps applied to any actuated displays. Hence, we would like to share these observations with the tangible UI research community.

ACTUATION AND INTERACTION

Actuation means, "*to put in action, move*"; therefore, we define actuated interfaces as *interfaces in which physical components move in a way that can be detected by the user*. There are many types of actuation, for example:

- *Change in spatial position of objects or their parts* e.g. their position, orientation;
- *Change in speed of motion of objects or their parts* e.g. speed of rotation, speed of linear motion, direction of motion;
- *Change in surface texture of objects or their parts,* e.g. visible or perceived by touch;
- *Change in force applied to the user* e.g. change in force amplitude, direction, or torque.

On a historical side-note, humans have been developing mechanisms that produced mechanical motion for centuries, such as catapults in ancient Greece or windmills in medieval Europe. What makes today's actuation different is that we can produce motion that is *sustainable* over an extended period of time, and, unlike windmills, we have a high *degree of control* over the actuation. We look over some actuated interactive devices below.

Automata and robots

People have always been fascinated with automata, or "self-moving machines". *Vaucanson duck* (Figure 1) is one of the earliest documented examples of such fascination: this famous model of a duck made by French engineer Jacques de Vaucanson in the mid 1730s consisted of more than a thousand parts; it could move, flap its wings, "eat", "digest", and excrete food like a "real duck". It also used rubber hose for the digestive tract: the first known use of the *cauchuck* discovered by Europeans just a few decades ago, in 1931.

Interestingly, the duck itself *did not serve any utilitarian purpose*, its was made entirely for enjoyment and to be observed as a highly technological decoration [25, 29].

Recent development of robotics overshadows early work on automata. However, until recently, robot design always had a clear purpose: to develop autonomous machines that can perform difficult or dangerous tasks. For most such tasks,

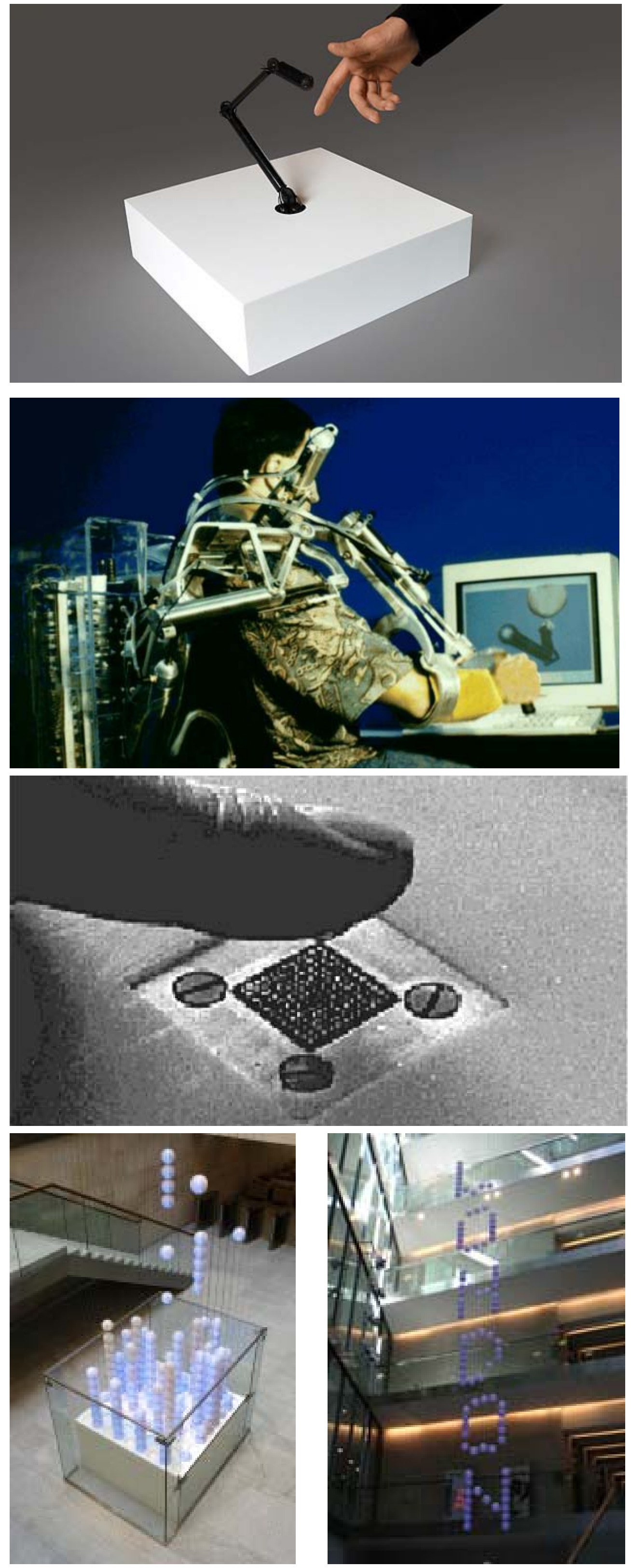

Figure 2: Actuated interfaces (from top): Outerspace, Pneumatic Haptic Interface, Tactile Array, Source.

neither human nor animal-like designs are necessary and usually there is no need for real-time interaction with them. In fact, most industrial robots are not developed to deal with people at all. The goal of such robots is to do *mechanical work*, and in this respect they are like any other type of machinery, e.g. cars or industrial equipment.

Recently, however, history took a curious turn: The most recent wave of robots, such as the Sony robotic dog Aibo, the humanoid RoboVie [13] and the "curious" robot Outerspace [17] (Figure 2, top) is designed mainly for *entertainment*: to surprise, delight and maybe educate people a little. In a sense, today's robotic research has made a full turn back to the Vaucanson duck, albeit a significantly more complicated.

A significant difference between today's robots and early automata is that the new generation of robots are *interactive*, designed to understand and respond to people.

Haptic interfaces

Not all interactive devices that can move on their own can be considered robots or automata. One important category is *haptic and tactile displays*: interactive devices that simulate the tactile and haptic sensation of virtual objects and textures. They have been extensively investigated in virtual reality and telepresence applications (e.g. [6, 12]); recently they have been finding their way to desktop and mobile interfaces to enhance user experience or productivity [e.g. 2, 20, 6, 12, review in 3, 5] or to use in person-to-person communication [7, 31].

The motion of haptic devices is "negative": they restrict motion of human hands, and hence the motion of the device is not visible. With tactile devices the same is true: since human skin is extremely sensitive[1] their motion is nearly invisible. One example of tactile devices is 2D pin displays [8, 26]. These usually consist of a small (~1 cm^2) array of pins that move up and down rapidly, creating vibration patterns felt by the fingers (i.e. [26], see Figure 2). The pins are very tightly packed and their movements are small – with a vertical displacement of less than 1 mm.

Ambient interfaces

Ambient interfaces use actuation to communicate information to users. For example in Pinwheels and Water Lamp installations [30] the flow of network traffic was mapped onto the speed of pinwheel rotation or frequency of drops of water.

Using actuation to communicate dynamically changing information naturally fits into a tangible interface philosophy. Indeed, in classical tangible interfaces the static elements of the user interface, such as icons and scroll bars, are mapped onto static physical objects–phycons [28]. It's natural to couple dynamic, constantly changing user interface elements with the *motion* of physical objects, rather than the objects themselves.

Actuated tangibles

Another example of actuated interactive devices is *self-rearranging* displays: devices that consist of multiple parts that can dynamically re-arrange themselves in space. For example, an Actuated Workbench [19] is a 2D array of electrical magnets built into the surface of a table. By controlling the strength and shape of the magnetic field the device can move one or more magnetic packs on the surface of the workbench, arranging them in any 2D pattern.

Actuation was used in tangible interfaces to preserve consistency between digital and tangible representations. The inconsistency occurs when there is more than one way to change digital information. For example, in collaborative applications a remote participant may change the position of a shared virtual object. With actuated interfaces, such as Actuated Workbench, the tangible interface element would move to reflect changes that are made remotely.

The problem of consistency is an old one and has already been addressed using actuation. For example, some high-end studio sound mixers change the position of their sliders when controlled sound parameters are changed from outside using MIDI.

Shape displays

A relatively recent addition to the corpus of interactive and actuated devices is *shape displays*, devices that can *directly create 3D physical shapes*. The idea of such devices can be traced back to Ivan Sutherland and his vision of the Ultimate Display [27]. Consider, for example, *Source* installation that allows direct creation of low-resolution 3D objects hanging in space. It consists of 729 balls suspended on metal cables forming a 9×9×9 spatial grid, where each ball is a "pixel" (Figure 2, [11]). By moving on the cables, the balls can form letters and images floating in space.

Another example of shape display is the art installation *Protrude, Flow* by Kodama and Takeno [15]. In that installation ferromagnetic liquid was actuated by an array of magnets to dynamically create a variety of beautiful, organic-looking shapes (Figure 3). Similarly, the Snoil device by Martin Frey (Figure 3, [9]), uses an array of magnets located under the magnetic fluid to create arbitrary low-resolution bitmap images. Although both devices are very interesting and impressive, direct interaction with them is difficult: we cannot expect people to touch the magnetic fluid with their hands.

On a significantly larger scale *Aegis Hyposurface* [1] is a wall-sized structure constructed out of interconnected metallic plates actuated by an array of pneumatic pistons (Figure 3). The surface of the wall can dynamically change its shape, either autonomously or in response to external events such as human movement captured by a camera. Images can be projected onto the surface. The Aegis Hyposurface is an example of an actuated device on the scale of a building. Direct haptic interaction with such devices is not possible and they are difficult to use at home.

[1] We can distinguish surface irregularities as small as 1-3 microns [16].

Figure 3: Shape displays (from top): Protrude, Flow, Snoil, Aegis Hyposurface, Glowbits

There have been a number of shape displays based on pin architecture. The FEELEX project [14] was one of the early attempts to design combined shapes and computer graphics displays that can be explored by touch. FEELEX consisted of several mechanical pistons actuated by motors and covered by a soft silicon surface. The images were projected onto its surface and synchronized with the movement of the pistons, creating simple shapes.

Lumen [32] is a low resolution, 13 by 13-pixel, bit-map display where each pixel can also physically move up and down (Figure 4). The resulting display can present both 2D graphic images and moving physical shapes that can be observed, touched, and felt with the hands. The 2D position sensor built into the surface of Lumen allows users to input commands and manipulate shapes with their hands.

Other related project are PopUp and Glowbits devices [18, 33]. PopUp consists of an array of rods that can be moved up and down using shape memory alloy actuators. The PopUp, however, does not have a visual and interactive component. Glowbits by Daniel Hirschmann (Figure 3) is a 2D array of rods with attached LEDs; the motorized rods can move up and down and LEDs can change their colors.

Discussion

We have overviews a number of reasons why actuation can be used in user interfaces. We summarize them in Table 1.

Applications	*Examples*
Aesthetics	Automata, ambient displays, shape displays
Information communication	Ambient displays, haptic displays, shape displays
Mechanical work	Robots
Controls—data consistency	Actuated tangibles
People-to-people communication	Haptic displays

Table 1: Applications of actuation in user interfaces

Most of the actual devices potentially span more then one application area and it seems that there is a lot of room for innovation and using some of the actuated interfaces in new application areas. For examples, robots could be used for information communication and ambient displays could be used for people-to-people communication.

Future research in actuated interfaces might attempt to systematically investigate applications of actuated devices for various applications, some if which are perhaps not listed above. In the next section we provide analysis of shape displays and there possible applications.

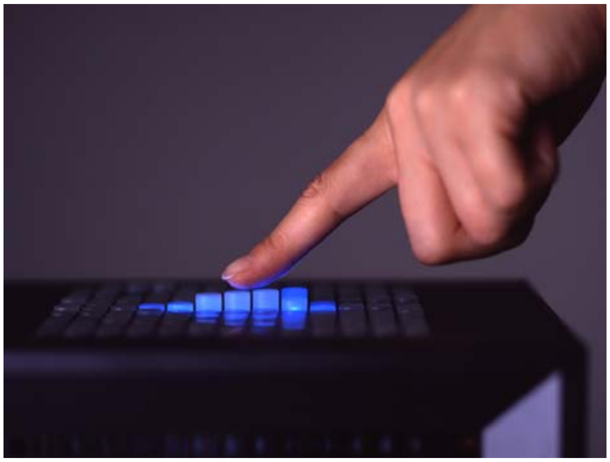

Figure 4: Lumen is an interactive shape and image display (photograps by Makoto Fujii, courtesy of AXIS Magazine)

INTERACTION WITH SHAPE DISPLAYS

In this section we investigate designing interaction scenarios for shape displays. It is based on our experience of designing and developing an interactive shape display device, called Lumen [32], that we briefly described above. Some of our observations are very specific to Lumen-type of devices, while other are quite general and reflect the basic challenges in designing any physically actuated interfaces.

We are also interested in shape displays because, while the current devices are still very primitive, we can imagine using them in the future for creating on-the-fly tangible UIs, where handles and controls are not physical objects but shapes created dynamically by shape displays.

Shape display: a general view

Shape displays attempt to create 3D physical shapes directly and some of *the shape displays* share following common properties:

1) They display *relief-like shapes* by physically displacing a surface of the device. This is done either by changing the properties of the materials, e.g. Protrude, Flow or Snoil, or by using mechanically actuation, such as in case Aegis Surface, FEELEX and etc.

2) They *combine dynamic shapes with images*, e.g. Aegis Surface, Lumen or Feelex. Combining shape with image is important. For example, if our goal is to display a 3D shape its natural to assume that shape's surface would have color and patterns, as in the case of real objects. That would require image producing capabilities.

Based on these observations, we suggest that the shape displays can be generalized as an extension of traditional bitmapped displays where each pixel has an additional attribute: *height*. The actual mechanism of displacement, the shape and arrangement of the pixels depends on implementation. We call this design approach *an RGBH graphics*, where RGB is a color components and *H* is a height of a pixel. It can be viewed as the next step in the evolution of a pixel (Figure 5). RGBH model is a very simple conceptual model but it captures the main properties of shape displays, allows us to compare them against each other, could be helpful in directing further development of shape displays.

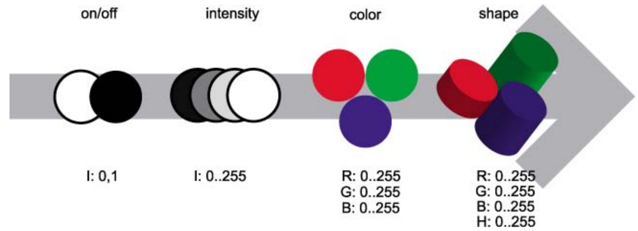

Figure 5: The evolution of the pixel: RGBH display

Synchronous/asynchronous modes in RGBH displays

Our observation and experimentation suggest that one of the main design properties in shape displays is the contrast between spatially synchronous and asynchronous modes of displaying information:

In the *asynchronous mode* the shape and image are spatially separated: some of the information is presented with the shape while other information is presented with graphics. For example, the left of Figure 6 shows a schematic image of game Pong, here only shape is used for the paddle and only image for the ball. Hence, the *shape and image are independent* from each other and serve different purposes.

In *synchronous display mode* the shape and the graphics are spatially overlaid over each other. Here the shape extends the graphics, it *adds a third dimension* to flat images. On Figure 6, right paddle and ball are presented using both shapes and images, the ball physically "deforms" when it hits the boundary of display. Most of the previous work on shape displays (such as [14]) are examples of synchronous displays.

Synchronous and asynchronous modes of information presentation are fundamental for any shape displays, that fall into the RGBH model we presented above. Consideration of these modes may also extend to other types of actuated interfaces. In our experimentation we found that it is the interplay between these synchronous and asynchronous modes that leads to many unique properties of shape displays.

Aesthetics of dynamic shapes

Adding physical actuation can be done purely for *aesthetic* and *decorative* purposes, similarly to Vaucanson duck. It allows increasing realism of images and creating new visual aesthetics, that is different from traditional 2D graphics or static 3D objects.

Indeed, an important property of any shape display is that the same physical shape will be perceived differently from different angles (Figure 7) giving shape displays architectural and environmental qualities. Hence, applications of the dynamic shape displays should assume and may take advantage of user mobility: large wall displays, stand-alone home electronic devices, architectural and design installations can change their shape depending on the position of the user. This can be done purely for aesthetic reasons, where the shape changes depending on the time of the day, available lighting, weather and so on. Alternatively, the shape can change to make it easier for the user to perceive it from different locations.

Increasing realism

Increased *realism*, is another important application. Indeed, related projects often suggest that creating highly realistic 3D shapes is the ultimate goal of such displays (e.g. [18]).

From our experience, however, we believe increasing realism is possible but only on a very limited scale since the current structure of the display limits us in the choice of shapes that we can display. For example, creating concave shapes would be difficult with current technology.

One approach that we investigated was adding partial 3D details to flat 2D objects. For example, virtual characters can manifest themselves both through visual images and shape, i.e. a 2D image of a fish swimming across the display can be combined with a 3D physical shape of its fins "sticking up" from the water (Figure 4, Figure 7).

In another example we used 3D shape to present deformations of the moving 2D objects: a bouncing ball physically deforms when it hits the boundaries of a display area (Figure 6). Note that these are all examples of *synchronous display*, where 3D shapes are used to enhance 2D image.

We can also increase realism by displaying *3D textures and material details through shape*. As a simple example we created an image of water floating from a water tap. The tap was drawn as a 2D image, while the water was creates using only a shape display (Figure 8). Using the same technique we also developed a range of other material animations, such as smoke, clouds and water ripples. Note that this is an example of *asynchronous display*, where shape and image present different elements. In informal evaluations, the floating water was immediately recognized and a many people commented on its realism, even though the images were quite abstract.

The major challenge with all shape displays is their low resolution. We estimate that to create realistic textures and effects the pixel size must shrink at the very least to 1 mm. If that becomes possible, communicating information through shape and images would be possible, where some parts are rendered using graphics and others – shapes. For example drops of water on a soft drink bottle can be rendered as physical shapes slipping down the bottle; motion of the grass and leafs on a tree can be rendered as tiny shape particles dynamically rising from the screen.

Tactile and haptic displays

All shape displays are essentially *haptic*: all the shapes can be felt and recognized by touch (Figure 9, left). The key difference between from other haptic devices is that shape displays are *direct*. Indeed, most of the haptic and tactile displays are indirect: they require users to wear or manipu-

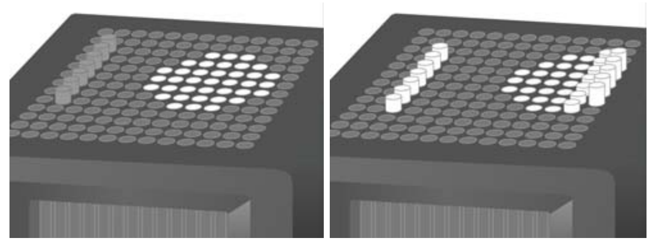

Figure 6: Asynchronous and synchronous display modes in shape displays

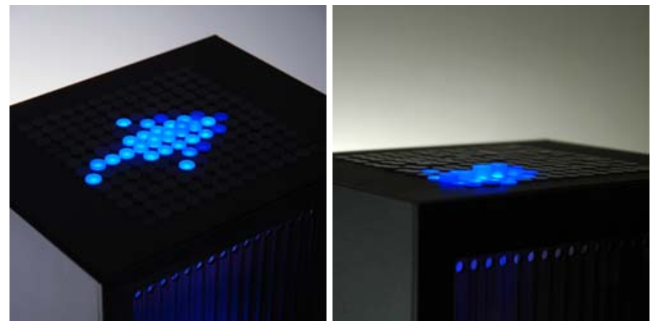

Figure 7: The same image of the fish is visible from extreme angles but is perceived differently

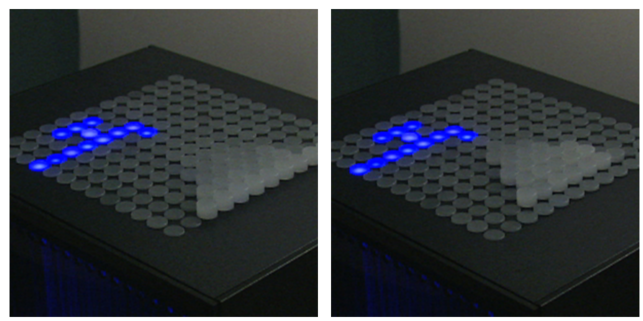

Figure 8: Drawing water with shape: water flowing from tap.

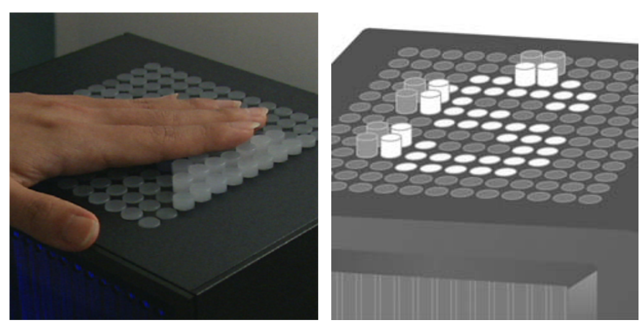

Figure 9: Left: all images are touchable and can be explored by touch; Right: Brail can be integrated with visual displays.

late tactile mouse, haptic stylus or manipulator glove. In case of shape displays the shape can be felt directly by user hand without any intermediate devices.

Therefore, it promotes *active touch* where a moving user's hand actively explores shape and tactile properties of virtual objects. Gibson in 1960s [10] demonstrated that giving the users freedom to actively and repeatedly move their hands and fingers while exploring the shape of objects increases the amount of information received through haptic sense. Note that such free exploratory movements are difficult to create with indirect haptic devices since they usually allow for only one point of contact.

Combined with input capabilities this allows to create interesting haptic scenarios where the *device* communicates with the user by “touching” her hand. In one scenario, when the user puts her hand on top of the shape display, the virtual character, a fish, would “swim” to the user and tap her hand with its “nose”. This interaction had a very strong effect because not only the user could touch virtual character, but conversely the virtual character can also “touch” the user. In another scenario the bouncing ball would bounce from the user hand and the user would feel the impact of the ball.

Dynamic tangible controls

One of the motivations in our work on shape displays was to dynamically create tangible 3D controls, such as buttons, sliders, handles and etc. We implemented several buttons, some of them pressable, using our shape display (Figure 10). The interface is tangible but its also provides dynamic, *on-demand* control that are displayed only when they are needed. Furthermore, the shape of tangible controls can change depending on their state and functionality.

Certainly, the development of practical on-demand shape-based tangible controls would require significantly higher resolutions as well as lighter and thinner shape displays which are impossible with current technology.

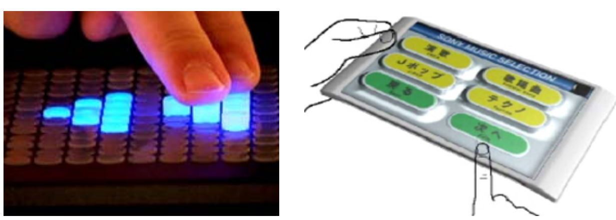

Figure 10: Left: Dynamic controls prototype; Right: Concept drawing of the on-demand physical user interface.

Shape as an additional information layer

Shape can also be used as an additional *information communication layer*. A 2D visual image can be overlaid with different physical shapes altering or enhancing the meaning of the display information. For example, on a traditional media player, different symbols must be used to encode different operations: pause, fast forward, rewind and etc. Using shape displays we can communicate the state of the player by using only single graphics symbol (e.g. “play” triangle) combined with different shape animation: e.g. a slow wave through the this symbol would mean playback, fast wave would mean fast forward, and the wave in the opposite direction – rewinding.

Applications for blind are another possible application: the shape displays can present both Brail and visual information in the same display space. For example on Figure 9, right we display letter “s” both as a alphabetic and as brail symbols in the same display surface.

Remote haptic communication

The human-to-human *communication* is a natural application of shape displays: by connecting devices over the network, we can establish haptic link between remote participants. The remote haptic communication has been explored before such as in InTouch project [4]. However, shape displays potentially allow for much richer communication since both 2D images, and 3D shapes can be transmitted over the network.

In one of the application scenarios that we designed the users can touch and draw simple traces on each other hand using shape display (Figure 12): the goal was to preserve the immediacy of direct touch (Figure 11). Note also that asynchronous property of shape displays allows to effectively separate displays for local and remote participants: i.e. graphics is used to provide the feedback on the user’s own input, while the actions from the remote participant are displayed through the shape.

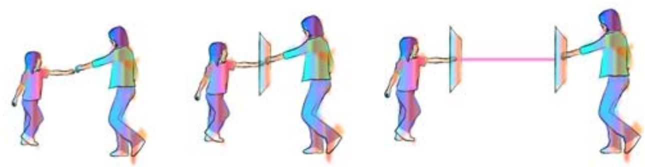

Figure 11: The goal of remote haptic communication is to preserve the immediacy of direct touch

Figure 12: Remote haptic communication in Lumen

Discussion

Earlier we outlined a range of applications and possible uses of actuation in user interfaces (Table 1). In this section we illustrated how an instance of shape displays can be used to prototype some of these uses. While some of the applications and design observations are limited to Lumen device, we believe some of the concepts have general applicability, in particular the idea of *synchronous versus asynchronous* information presentation, using actuation as a *additional information layer* in parallel to visual display, the *architectural qualities of shape displays*, use of actuation for *haptic communication* and others.

CONCLUSIONS

Is actuation the next frontier in tangible user interfaces? It might be so. In our exploration of shape displays we observed that a rather simple property: combination of image and dynamic shape, can lead to a large verity of new interaction scenarios.

There is a lot of space for further development. New emerging technologies, such as piezzo motors and shape memory polymers, will potentially allow creating efficient, thin and inexpensive actuated tangible interfaces in the future that can be used in decorative, communication, information presentation and other applications. Developing such application would perhaps require stepping outside of the boundaries of classic tangible UI domain and combining expertise from robotics, haptic interfaces, design and architecture. The work in actuated interfaces is still in its infancy, and therefore, we consider this paper is an invitation to discussion of the future of actuation in tangible interfaces and hope it can help to stimulate further research in this area.

REFERENCES

1. *Aegis Hyposurface*, in http://www.sial.rmit.edu.au/Projects/Aegis_Hyposurface.php.
2. Akamatsu, M. and S. Sato, *A multi-modal mouse with tactile and force feedback.* International Journal of Human-Computer Studies, 1994. **40**(3): p. 443-453.
3. Bowman, D., E. Kruijff, J. LaViola, and I. Poupyrev, *3D user interfaces: Theory and practice*. 2004: Addison-Wesley. 512.
4. Brave, S., H. Ishii, and A. Dahley. *Tangible Interfaces for Remote Collaboration and Communication*. *Proceedings of CSCW'98*. 1998: ACM.
5. Burdea, G., *Force and touch feedback for virtual reality*. 1996: John Wiley and Sons. 339.
6. Buttolo, P. and B. Hannaford. *Pen-based force display for precision manipulation in virtual environments*. *Proceedings of VRAIS*. 1995: IEEE: pp. 217-224.
7. Chang, A., S. O'Modhrain, R. Jacob, and H. Ishii. *ComTouch: Design of a vibrotactile communication device*. *Proceedings of DIS'2002*. 2002: ACM: pp. 312-320.
8. Cholewiak, R. and C. Sherrick, *A computer-controlled matrix system for presentation to skin of complex spatiotemporal pattern.* Behavior Research Methods and Instrumentation, 1981. **13**(5): p. 667-673.
9. Frey, M., 2005 *Snoil, http://www.freymartin.de/blog/archives/02_sensitive_skins/*.
10. Gibson, J., *Observations on active touch.* Psychological review, 1962. **69**: p. 477-491.
11. Greyworld, *Source*, http://www.greyworld.org/artwork/source/. 2004.
12. Hurmuzlu, Y., A. Ephanov, and D. Stoianovici, *Effect of a Pneumatically Driven Haptic Interface on the Perceptional Capabilities of Human Operators.* Presence, 1998. **7**(3): p. 290-307.
13. Ishiguro, H. *Toward interactive humanoid robots: a constructive approach to developing intelligent robots*. *Proceedings of First International Joint Conference on Autonomous agents and Multiagent Systems*. 2002: ACM: pp. 621-622.
14. Iwata, H., H. Yano, F. Naakaizumi, and R. Kawamura. *Project Feelex: Adding Haptic Surfaces to Graphics*. *Proceedings of SIGGRAPH 2001*. 2001: ACM: pp. 469-475.
15. Kodama, S. and M. Takeno. *Protrude, Flow*. *Proceedings of SIGGRAPH'2001 Electronic Arts and Animation Catalogue*. 2001: ACM: pp. 138.
16. LaMotte, R. and J. Whitehouse, *Tactile detection of a dot on a smooth surface: Peripherial neural events.* Journal of Neurophysiology, 1986(56): p. 1109-1128.
17. Lerner, M., *Outerspace: Reactive robotic creature*. 2005 http://www.andrestubbe.com/outerspace/.
18. Nakatani, M., H. Kajimoto, D. Sekiguchi, N. Kawakami, and S. Tachi. *3D Form Display with Shape Memory Alloy*. *Proceedings of ICAT'2003*. 2003: pp. 179-184.
19. Pangaro, G., D. Maynes-Aminzade, and H. Ishii. *The Actuated Workbench: Computer-Controlled Actuation in Tabletop Tangible Displays*. *Proceedings of UIST2002*. 2002: ACM: pp. 181-190.
20. Poupyrev, I. and S. Maruyama. *Tactile interfaces for small touch screens*. *Proceedings of UIST*. 2003: ACM: pp. 217-220.
21. Poupyrev, I., S. Maruyama, and J. Rekimoto. *Ambient Touch: Designing tactile interfaces for handheld devices*. *Proceedings of UIST'2002*. 2002: ACM: pp. 51-60.
22. Poupyrev, I., S. Maruyama, and J. Rekimoto. *TouchEngine: A tactile display for handheld devices*. *Proceedings of CHI 2002*. 2002: ACM: pp. 644-645.
23. Poupyrev, I., M. Okabe, and S. Maruyama. *Haptic Feedback for Pen Computing: Directions and Strategies*. *Proceedings of CHI'2004*. 2004: ACM: pp. 1309-1310.
24. Rekimoto, J. *SmartSkin: An Infrastructure for Freehand Manipulation onInteractive Surfaces*. *Proceedings of CHI2002*. 2002: ACM: pp. 113-120.
25. Riskin, J., *The defecating duck, or, the ambiguous origins of artificial life.* Critical Inquiry, 2003. **20**(4): p. 599-633.
26. Summers, I., C. Chanter, A. Southall, and A. Brady. *Results from a Tactile Array on the Fingertip*. *Proceedings of Eurohaptics'2001*. 2001.
27. Sutherland, I. *The ultimate display*. *Proceedings of International Federation of Information Processing*. 1965: pp. 506-508.
28. Ishii, H. and Ullmer, B., Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms, in *Proceedings of Conference on Human Factors in Computing Systems CHI '97)*, (Atlanta, March 1997), ACM Press, pp. 234-241.
29. Strandh, S.: *The history of the Machine*, Dorset Press, New York, 1979.
30. Dahley, A., Wisneski, C., Ishii, H. Water Lamp and Pinwheels: Ambient Projection of Digital Information into Architectural Space. *Proceedings of CHI 98*
31. Brave, S.., Ishii, H.,and Dahley, A. *Tangible Interfaces for Remote Collaboration and Communication* CSCW '98
32. Poupyrev, I., T. Nashida, S. Maruyama, et al. Lumen: Interactive visual and shape display for calm computing**.** SIGGRAPH Conference Abstracts and Applications, Emerging Technologies, 2004: ACM.
33. Hirschmann, D. Glowbits http://www.glowbits.com/