The Haptic Tabletop Puck: Tactile Feedback for Interactive Tabletops

Nicolai Marquardt, Miguel A. Nacenta, James E. Young,
Sheelagh Carpendale, Saul Greenberg, Ehud Sharlin

Interactions Lab, University of Calgary, Canada
{nicolai.marquardt, miguel.nacenta, james.young, sheelagh.carpendale, saul.greenberg, ehud.sharlin}@ucalgary.ca

Abstract

In everyday life, our interactions with objects on real tables include how our fingertips feel those objects. In comparison, current digital interactive tables present a uniform touch surface that feels the same, regardless of what it presents visually. In this paper, we explore how tactile interaction can be used with digital tabletop surfaces. We present a simple and inexpensive device – the Haptic Tabletop Puck – that incorporates dynamic, interactive haptics into tabletop interaction. We created several applications that explore tactile feedback in the area of of haptic information visualization, haptic graphical interfaces, and computer supported collaboration. In particular, we focus on how a person may interact with the friction, height, texture and malleability of digital objects.

1. Introduction

Surfaces, and the objects we use on them, provide important tactile information that is useful for different tasks. For example, the texture of paper allows us to differentiate it from the table, the relief of objects such as rulers allow us to lay them out accurately (Figure 1.Left), and sometimes it is possible to interpret information that is encoded in the characteristics of the surface (Figure 1.Right). In contrast, when using digital objects in current interactive tabletops all tactile cues are sacrificed by most current devices, which are limited to the uniform, unchanging tactile feel of the table's surface.

Our overall research goal is to leverage dynamic and interactive tactile information for use with digital tabletops. In this paper, we specifically focus on the representation of three sources of tactile information: vertical relief, the malleability of materials, and horizontal friction with the surface (Figure 2). As we will explain, we not only use these variables to make the touch interface more realistic, but also explore interaction techniques and abstract mappings that extend the interface in new ways.

Ideally, we envision implementing future digital surfaces that provide rich and consistent tactile feedback across the entire interaction surface. However, as
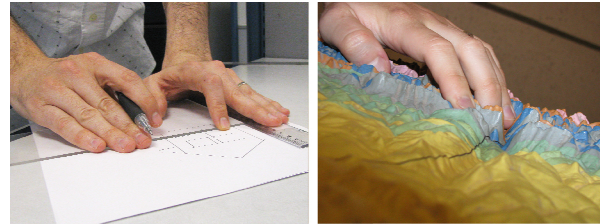

Figure 1. Using texture and relief for drawing (left). Exploring a geological map (right).
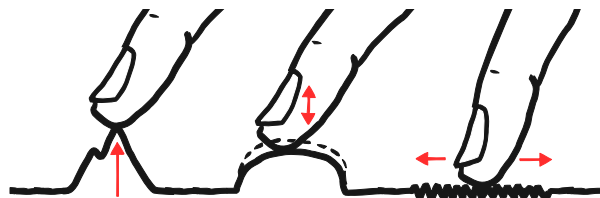

Figure 2. The three information sources (from left to right): height, malleability, and friction.

far as we know the technology for this is not available and such a solution will still require considerable research. For our explorations we devised the Haptic Tabletop Puck (HTP), a low-cost haptic device that can be used atop the table. This device allows us to explore the following dimensions of tactile feedback on the tabletop:

- *height and texture:* the relief and tactile feel that corresponds to elements displayed on the table. The HTP creates these through a servo motor that continually adjusts the height of a rod atop the device.

- *malleability:* how different materials respond to touch and pressure. The HTP can reproduce these through the haptic loop formed by the height of the rod and a pressure sensor.

- *friction:* resistance to movement in directions parallel to the table plane. A servo in the HTP pushes a rubber plate through its bottom against the surface.

- *location: different* positions of the table should provide appropriate haptic feedback. Fiduciary markers on the HTP base allows the surface to track the HTPs location and orientation.

- *multiplicity:* the ability to provide multi-user or multi-point haptic feedback simultaneously, for example for collaborative support. Several HTPs can be used simultaneously on the table.

The contribution of this paper is our exploration of how haptics can be brought to interactive tables. This encompasses the design of the HTP but, most importantly, the question of how it can be applied to real scenarios to enhance information exploration, interaction, and collaboration. In the remainder of this paper, we briefly summarize related work, present the design and implementation of the HTP, describe several scenarios and interaction techniques that use the HTP, and finish with a summary of our explorations and the lessons learned.

2. Background

Research about haptic force-feedback [1] and tactile interfaces [2] has a long history in the area of virtual reality [3,4], telepresence [1,5], and interfaces for visually-impaired people [6-8]. Physiological and psychological studies [9-11] lay the foundation of how to use this additional channel of haptic sensation.

Haptics have been explored by augmenting the traditional GUI mouse interaction. Zeleznik's pop through tactile buttons [12] provide two distinct click levels, Schneider's magnetically-actuated mouse [13] can apply frictional force during movement, and Chu's haptic mousewheel [14] enables pressure sensitive controls. This technique uses mouse input, making it impractical on interactive tabletops.

The SensAble PHANToM [15] is a 6 degree of freedom force feedback device, often used for haptics in virtual reality systems. Ikit's Visual Haptic Workbench [3] combines it with 3D projections to allow interaction in immersive environments. However, the PHANToM is a relatively expensive device, has a limited actuation radius, and the mechanics occupy a large space, which makes it less suitable for multi-user tabletop interaction.

The Actuated Workbench [16] and Pico [17] enable actuation of objects on a tabletop by applying magnetic forces. More recent work by Fukushima [18] controls friction of objects through vibration of the surface. These are powerful actuation mechanisms for tangible user interfaces, but they do not provide haptic vertical relief or malleability feedback. Shape displays, such as FEELEX [19] and Lumen [20], bring three-dimensionality to a table surface by using a matrix of movable rods (located under the tabletop surface) actuated by servos or shape memory alloys. While there is ongoing research to increase the number of haptic pixels in these systems [20], they currently only pro-

vide a small number of actuated points due to mechanical constraints (13x13 haptic pixels for Lumen, 6x6 haptic pixels for FEELEX, both in an area of around 25x25 cm).

The TouchEngine actuator [21,22] and the Active Click mechanism [23] provide tactile feedback for small touch screens. Due to the mechanical construction of these feedback mechanisms, the vibrotactile feedback is always applied to the complete screen surface, which makes this approach much less scalable to multi-user applications on larger surfaces. By using gloves with vibration actuators [24] or finger mounted actuators as in Rekimoto's SenseableRays [25], it is possible to provide this vibrotactile feedback independently of the actual screen size. Lee [26] created a similar effect by using a solenoid attached to a pen. While the vibrotactile feedback of these systems can create diverse tactile sensations by changing the intensity and frequency of the vibration, they do not allow variations in vertical relief, malleability, or friction.

These diverse haptic feedback devices have been applied to a wide variety of applications. One category is haptic visualization [27], where people can explore different kinds of information in addition to the graphical visualization. Examples are tactile exploration of geographical maps [28], images [6], graphs [8], or large scientific datasets [3]. Haptic feedback can also augment the interaction with traditional GUI elements. Examples are dynamic physical shapes as buttons (e.g., [29,20]), vibrotactile feedback to augment clicking (e.g., [25,26]), or tactile feedback of intervals on a slider [22].

3. The Haptic Tabletop Puck

The HTP was developed through a process of iterative exploratory design, in which brainstorming and prototyping were undertaken in parallel, mutually informing each other, to arrive at the current HTP design. We will start by giving a technical description of our prototype, followed by a more in-depth discussion of the expressiveness in relation to the use of our current prototype in applications.

3.1 Design and prototypes

The HTP concept is based on the combination of four main elements: a mechanically activated rod that moves vertically within a column to reach different heights above the table, a sensor on top of the rod that detects the amount of pressure being applied to its top, a standard fiducial marker (Microsoft Surface Bytetag) underneath the device that allows the interactive tabletop to locate the puck on the surface, and a brake pad on the bottom that can increase the friction against the table. The basic elements are displayed on the diagram
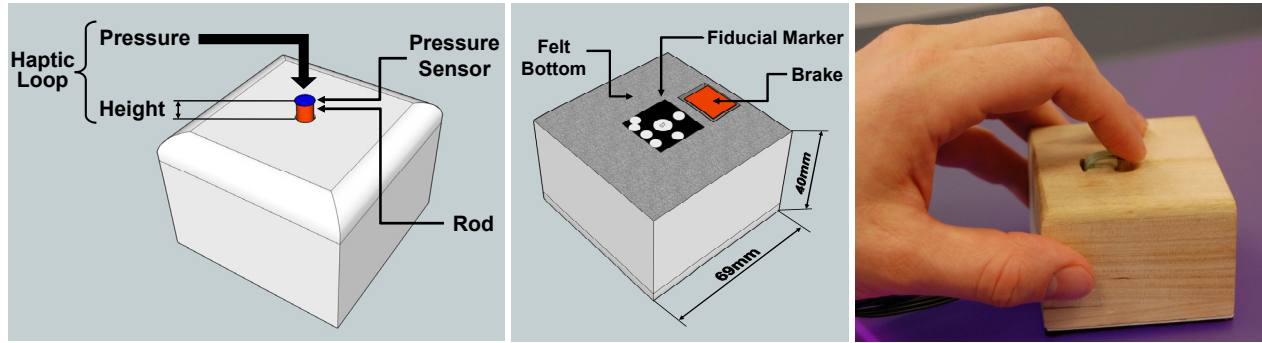
Figure 3. Diagram of the current prototype from the top (left) and from the bottom (center), and photograph of the current prototype (right).

of the current HTP prototype (Figure 3.Left and Center). A photograph of the current iteration is shown in Figure 3.Right.

Our current implementation is designed to work on top of a Microsoft Surface[1]. The device uses *Hitech HX-55* micro servomotors to control the vertical position of the rod and the brake, and an *Interlink Electronics Circular Force Sensing Resistor* as pressure sensor located on top of the rod, all encased into a wooden box with felt bottom. We chose a small rod as the moving part (as opposed to making the whole top of the device mobile) so that its vertical position with respect to the encasing could be felt through simultaneous touch of the finger on rod and encasing, or through the relationship between the sensing finger and the other fingers holding the device. The height range of the current prototypes is 9mm. We chose to align the output vertically, because this makes the device stable when pressing it from above, and allows for a good measure of pressure without compromising the position of the device on the table.

To provide friction, the device has a servo-activated rubber surface that comes out of the bottom of the device through a rectangular opening on the base. This mechanism increases the friction of the bottom of the device against the table, making it more difficult to drag around. Currently, this mechanism supports only being either on or off.

3.2 Limitations of the prototype

The size of our version of the device is dictated by the size and technology of the components. Currently the device is a 69x69x40mm box (see Figure 3 and 4). However, we believe that by applying different technologies and a more compact design it will be possible to build a much smaller device that could be dragged with a single finger.

The servos that we use are inexpensive and small, and therefore high-resolution haptic feedback is not possible. The servo motor and the sensor of current prototypes are controlled through Phidgets boards, and are therefore tethered. This current implementation of HTP, however, has allowed us to explore a multitude of applications.

It is possible that additional properties may arise from a smaller footprint and a higher haptic resolution. However, while we are already developing new, smaller, and wireless versions of the HTP, the focus of our work is on the concept and its applications, not on the particulars of the hardware. As a consequence the rest of the paper will focus on these factors.

3.3. Expressiveness

HTP provides a variety of different channels capable of measuring and representing different types of information. The most obvious output channel is the height of the rod along the vertical axis. Using the position of the HTP to determine a height value gives a simple way to represent relief in maps (see Section 4.1. and [28]). However, height can also be used to represent more abstract information; for example, dy-
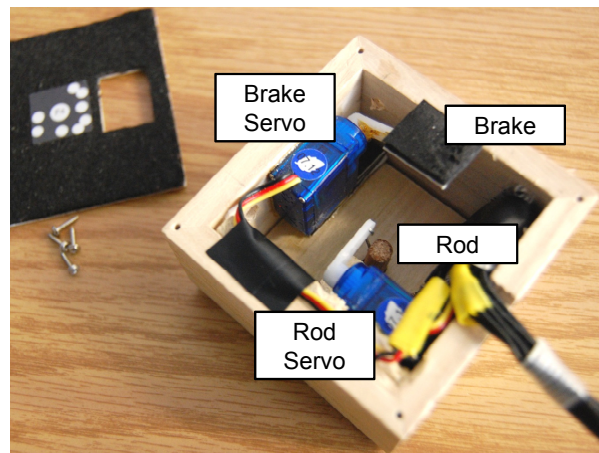

Figure 4. Inside view of the prototype.

namic sinusoidal vibration with varying frequency or amplitude can convey information [27].

By measuring the contact pressure between the finger and the rod we get a continuous source of input that is more expressive than the more common binary mouse button [30]. The combination of pressure and height can enable dynamic force feedback, through which we simulate the malleability of different materials, or mechanical devices (e.g. buttons).The brake in the bottom of the device provides extra friction along the directions parallel to the surface plane. The friction can also be dependent on the location of the device.

The variables described so far can be controlled independently and can be associated to the position of the device on the table, dramatically increasing the versatility of the otherwise single-point haptic feedback. Moreover, since the table is massively multi-touch (MMT), many HTPs can be used concurrently on the table, limited only by the size of our prototype. Thus the haptic feedback can react to other elements on the table (e.g., other pucks and finger touches).

4. Applications

Prototyping has allowed us to explore many tactile interaction techniques for tabletops. In this section we showcase some of the new avenues that a haptic device like HTP can open for interaction on tabletops. The techniques are introduced through example scenarios loosely organized into three groups: tactile exploration, tactile-enhanced interaction, and collaboration. Please, note that the techniques presented here are not restricted to the particular scenario that we use to introduce them.

4.1. Tactile Exploration

Besides using texture and height information to represent relief, the tactile channel can also be used in other ways to explore data. Tactile information can be particularly effective when other channels, such as visual and aural, are already crowded.

We have implemented a map application for the exploration of geographical features (Figure 5.a). We map the relief of the terrain to the height of the rod (Figure 5.b represents the height map), use different tactile material responses to represent different types of terrain (e.g., vegetation is soft, mountains are "breaky"– Figure 5.c shows the varying materials), and map ocean temperature to different vibration frequencies (from 0Hz for cold areas to 5Hz for warm water– Figure 5.d). As these multiple properties influence the height of the single rod, we combine them together in different ratios depending on the application. For instance, an equal ratio would assign one third of the
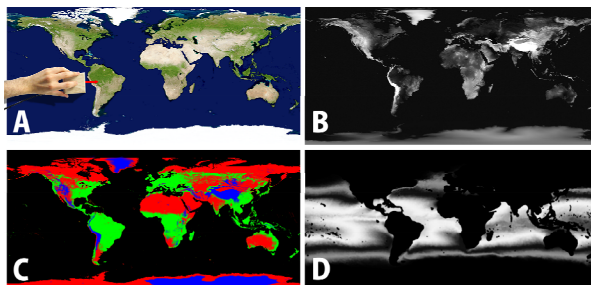

Figure 5. Map (A), and layers of tactile information (B,C,D). Images courtesy of NASA.

height to relief information, one to represent the oscillation, and one to represent the material response.

We have also observed that the large puck often made it difficult to understand which map position was being represented. Therefore, we attached a virtual arrow to the puck to enable fine-grained selection. This arrow points to a location a few centimeters in front of the HTP (Figure 5.a).

The haptic channel can be used to offload information from the visual channel. We developed a painting exploration application where we map rod height to areas of interest, in this case the difference between a painting and its infrared (or x-ray) image. This allows the observer to explore, for example, *pentimenti* (previous versions of a region of the painting that have been painted over by the artist) in place without multiple views or visual artifacts. The person exploring the painting is able to directly *feel* the hidden areas of the painting, and can visually reveal them in-place by pressing on the rod to activate a circular lens that shows the alternative layer (see Figure 6 and video figure).

Figure 6. The puck reveals hidden content in a particular area of the painting by raising the rod (left). By pressing on it the x-ray layer can be revealed (right)

4.2. Tactually-Enhanced Interaction

Haptics can be useful beyond exploration of data; for example, tactile cues can help the creation of new data (e.g., new pictures) as well as the interaction with GUI elements [26]. We have created a painting application that uses height feedback and pressure sensitivity to enhance control. Different layers of the picture are signaled to the user through different height levels. A
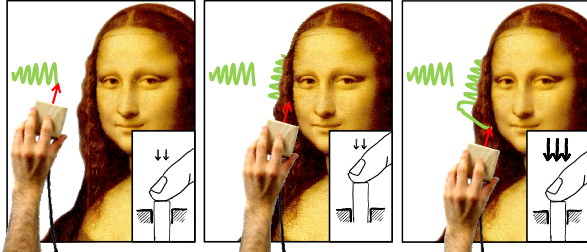
Figure 8. Light pressure activates the brush (left). When the puck enters a new layer, the height changes, and the brush is only active on the lower layer (center). By pressing hard, the brush becomes active in both layers (right).
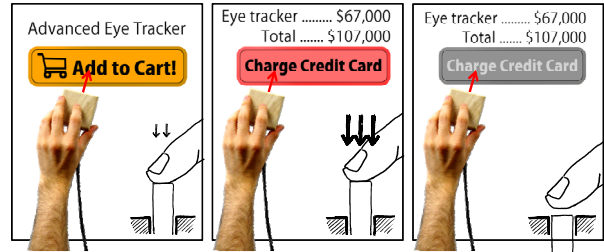

Figure 9. Adding an item to the cart takes little pressure (left), but actually making the purchase needs a strong click (center). Once the purchase is done the button stays down and cannot be pressed (right).

slight pressure on the rod will activate the brush; however, if the brush moves across layers, it will not paint over the new layer unless the pressure is increased (Figure 7 and video figure). This allows effective control of the effects of the brush without obscuring the drawing itself.

Height and malleability can also be used to enhance GUIs [25,26]. For example, we implemented a sample webpage-style button, where the state can be signaled by its elevation. If the button is pressed slightly, it can have a tactile response similar to that of real buttons, and if it is pushed down with a certain pressure, the button (and the rod) can stay down to both communicate state to the user and to prevent it from being pushed again (see Figure 8). The level of pressure required to push the button can also signal the importance of the action (as suggested by Chu and colleagues [14] for mouse interaction).

Using height and pressure combined can also help with object layout and manipulation. For example, in our office layout application, furniture tends to stay in a particular room unless the pressure applied is enough to bring the object across the wall. To signal that the object cannot move beyond a certain point, we apply Wigdor's *No touch left behind* approach [31], where the arrow stretches to keep the connection between the puck and the object while the object stays behind. Moreover, we provide feedback through the puck's brake, which makes the puck harder to drag, immediately warning the user that their actions are not having an effect (see sequence in Figure 9).

The same approach can be used to enhance existing layout interaction techniques such as alignment tools (e.g., guides), which often contribute to the visual clutter in applications. Giving feedback through differences in height seems particularly appropriate in these cases, as it simulates the edges and grooves of real world tools.

4.3. Haptics for collaboration

Tabletops are often used by groups, where in particular haptics can be leveraged for floor control and interaction awareness. To explore this, we have extended the office layout application to enable several people to work on it at the same time.

We created a mode in which objects can only be manipulated by one user at a time. Our tactile negotiation mechanism creates the constraint that only one HTP at a time can be pressed down on any given object (the one that has control). When another person wants to take control, they can push the rod down, which will push the rod of the other (controlling) HTP upward, indicating a desire to take the floor (see Figure 10.Left). This mechanism is subtle, but difficult to ignore, and does not require any visual symbols. Moreover, this technique can be used to negotiate control in a richer manner; for example, a collaborator can try to request control by subtly pushing on the rod, and the current controller can easily deny it by keeping a strong pressure on it.

We also used the office layout application to implement a tactile awareness technique. In our prototype, any clicks or dragging actions executed through a puck generate "tactile ripples" that propagate across
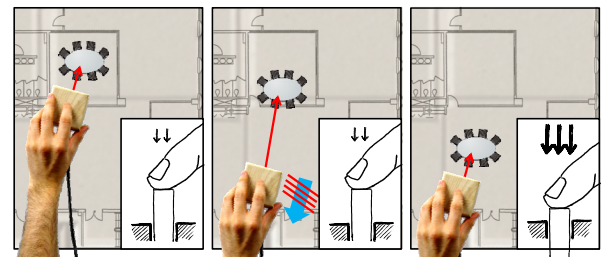

Figure 7. Light pressure grabs the object (left), but when trying to move it beyond the room's boundaries, horizontal friction is applied, the object will not move, and the red arrow stretches (center). If enough pressure is applied, the object goes to the intended place.
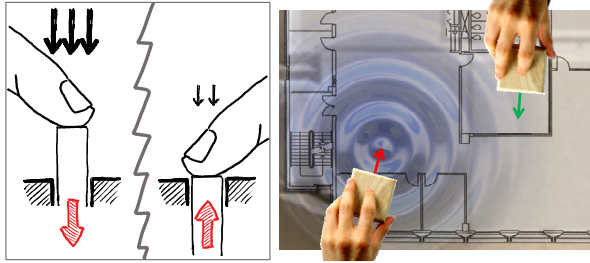
Figure 10. The floor control mechanism links two or more HTPs so that all collaborators can know if they are in control or when control is being requested from them (left). Actions in one part of the screen generate *tactile ripples* that can be perceived by other pucks on the table (right). The ripples on the figure are only visible for illustration purposes.

the table, making other HTPs oscillate (Figure 10.Right). The oscillation parameters (shape of the signal, amplitude and frequency) can also transmit useful information to collaborators; for example the identity and distance of a user generating an event. During development we have noticed that small amplitude signals of moderate frequency can be easily noticed and do not generate significant interference with the ongoing activity.

These haptic techniques can be useful to transmit awareness information without requiring a shift in visual attention. We believe that these techniques would be most useful when other forms of awareness information (e.g., peripheral vision, sound, the arms and bodies of collaborators) is harder to gather; for example, when people work on very large tables [32], or if they work collaboratively with a shared tabletop workspace from distant locations [33].

5. Early Observations

Although we have not yet conducted extensive formal evaluation of the prototypes, we have had the opportunity to informally observe many visitors of the lab and colleagues (not directly involved in the project) using the HTP. These informal and early observations have provided valuable insights regarding how people approach such a device and opened directions for future exploration.

We observed that people begin haptic exploration on the tabletop in different ways. Most people began immediately to move the device around the surface and actively explored the haptic content. While vertical relief and friction feedback were immediately evident, it took more time to notice the malleability of objects (as it requires people to apply actual pressure to the rod). However, after people initially experienced the diversity of malleability, they often continued to explore this dimension over the tabletop surface and

across applications. People reported that the haptic feedback through touching was a very active and engaging experience.

We also noticed people holding and grasping the device in different ways. Most commonly, they placed the tip of their index finger on the top of the rod. However, sometimes they placed their entire finger or even the palm of their hand across the rod. Usually when the rod moved, people followed the up and down movements with their finger. In a few situations, however, people left their finger statically in the space above the rod, resulting in a mere tapping of the rod against the finger. One person even preferred to just visually observe the vertical height changes of the rod, for instance the slow wave oscillations associated to the water-ripples video, or the up and down movement when exploring a visualized stone relief. People also sometimes closed their eyes to explore the content solely through the haptic sensation.

We noticed certain limits on how much information can be perceived through the haptic feedback (as noted in earlier research, e.g., in [22]). Complex combinations of information can make it difficult to differentiate changes; for example, simultaneous oscillation with high-amplitude height changes can made it challenging to distinguish materials through malleability.

6. Discussion

The HTP has been a valuable device for our research in the haptic tabletop space. During the design and different iterations of the device we have come to appreciate how a simple and inexpensive device can open up new areas of exploration. By choosing small size, low cost components and mobility over high fidelity feedback and many degrees of freedom, we have been able to quickly build many interaction techniques and prototype multiple applications.

We have learned that the flexibility and possibilities of the device come from the specific combination of variables. By themselves, height, pressure and friction are already powerful, but the combination amounts to more than the sum of the parts; this is exemplified by the drawing and layout examples, where height, pressure and malleability form meaningful interaction styles.

What makes our approach powerful, however, is that these haptic variables can vary with the position of the puck on the table, effectively multiplying the interaction bandwidth of the device. We find that the combination of tabletops and haptics is particularly synergistic for several reasons. First, people already make use of tactile information naturally by touching and feeling surfaces on tables (e.g. Figure 1); second, tab-

letops afford placing objects on top of them, and pressing against the surface, which makes for a stable haptic loop; and third, the tracking capabilities of the table allow the device to be lightweight, simple, and easy to program.

One of the first impulses when building haptic tabletops is to be able to reproduce the tactile characteristics of objects on the tabletop; however, we soon discovered that beyond reproducing realistic tactile textures and mountain reliefs, abstract haptic mappings can be powerful and compelling, such as in the floor control example or the drawing and layout applications.

By building the prototype applications we also found some unexpected new possibilities and constraints. For example, we found that mapping the haptic feedback to the location right underneath the rod might feel like the most "physically accurate" (it simulates an actual rod in contact with a carved surface); however, in our applications the haptic channel acts in conjunction with the visual channel, and hiding the most relevant visual information under the puck does not make sense. Instead, we draw an arrow that connects the device with the sensed pixel. Since the arrow maintains its connection with the puck, interaction still feels direct, but there is almost no obstruction. Moreover, since the arrow is dynamically drawn on the screen, it can be used in new and creative ways to provide feedback. The exploration of the space between direct and indirect input devices is an interesting field of enquiry in itself.

Although the interaction techniques that we built for our prototype applications were found very compelling to the people that informally tested our system, it is difficult to know if people will want to use the haptic channel in real use situations. In general, there are few applications for which we cannot find a visual-only alternative; however, the haptic channel can be valuable for scenarios in which visual clutter is an issue, or where the more compelling tactile sensations are an asset.

Nevertheless, we believe that now is an appropriate time to explore haptics for interactive tabletops; the interface of the tabletop is still maturing and there is an opportunity to make haptics one of the available modalities.

7. Conclusion and Future Work

With the Haptic Tabletop Puck we introduced an inexpensive hardware design for a device that allows us to explore haptic feedback on tabletops. We have explored applications that use three dimensions of haptic feedback: vertical relief, malleability of materials, and horizontal friction on the surface. Our prototype applications showcase how adding a haptic layer to the interactive surface experience can augment the existing visual and touch modalities.

In the future, we intend to improve our understanding of the value of haptics in the tabletop experience through more formal evaluations. We are also in the process of improving the hardware design of our device and we plan to explore how different form factors can affect the user experience. We already received useful comments that suggest that smaller and untethered HTPs could support an even wider spectrum of new haptic tabletop applications; for example, smaller pucks could be put under several or all of the fingers of a person and support massively multi-touch haptic interaction. General improvements in the resolution of the haptic feedback (such as a faster haptic loop, and multiple levels of friction) can also be valuable. At the application level we are also considering other collaborative scenarios that can make use of a variety of haptic interaction techniques.

7. References

[1]   R.J. Stone, "Haptic Feedback: A Potted History, From Telepresence to Virtual Reality," *Proc. of First Int. Workshop on Haptic-Computer Interaction*, 2000.

[2]   M. Benali-Khoudja, M. Hafez, J. Alex, and A. Kheddar, "Tactile Interfaces: a State-of-the-Art Survey," *Intl. Symposium on Robotics*, 2004, pp. 721--726.

[3]   M. Ikits and D. Brederson, "The Visual Haptic Workbench," *The Visualization Handbook*, Elsevier Academic Press, 2005, pp. 431-449.

[4]   L. Dominjon, J. Perret, and A. Lecuyer, "Novel devices and interaction techniques for human-scale haptics," *The Visual Computer*, vol. 23, 2007, pp. 257-266.

[5]   K.A. Li, P. Baudisch, W.G. Griswold, and J.D. Hollan, "Tapping and rubbing: exploring new dimensions of tactile feedback with voice coil motors," *Proc. of UIST '08.* ACM, 2008. pp. 181-190.

[6]   M. Kurze, "TGuide: a guidance system for tactile image exploration," *Proc. of the 3rd Intl. Conference on Assistive technologies.* ACM, 1998, pp. 85-91.

[7]   L. Biagiotti, G. Borghesan, and C. Melchiorri, "A Multimodal Haptic Mouse for Visually Impaired People," *Proc. of 2nd Intl. Conference on Enactive Interfaces*, 2005.

[8]   W. Yu, R. Ramloll, and S.A. Brewster, "Haptic Graphs for Blind Computer Users," *Proceedings of the 1st Intl. Workshop on Haptic Human-Computer Interaction*, Springer-Verlag, 2001, pp. 41-51.

[9]   K. Hale and K. Stanney, "Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations," *Computer Graphics and Applications, IEEE*, vol. 24, 2004, pp. 33-39.

[10]   J. Gibson, "Observations on active touch.," *Psychological Review*, vol. 69, 1962, pp. 477-491.

[11] A. Parkes, I. Poupyrev, and H. Ishii, "Designing kinetic interactions for organic user interfaces," *Commun. ACM*, vol. 51, 2008, pp. 58-65.

[12] R. Zeleznik, T. Miller, and A. Forsberg, "Pop through mouse button interactions," *Proc. of UIST '01*. ACM, 2001. pp. 195-196.

[13] C. Schneider, T. Mustufa, and A.M. Okamura, "A magnetically-actuated friction feedback mouse," *Proc. of EuroHaptics 2004,* pp. 330–337.

[14] G. Chu, T. Moscovich, and R. Balakrishnan, "Haptic Conviction Widgets," *Proc. of GI '09. ACM, 2009.*

[15] T.H. Massie and J.K. Salisbury, "The phantom haptic interface: A device for probing virtual objects," *Proc. of the ASME Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 1994, pp. 295-300.

[16] G. Pangaro, D. Maynes-Aminzade, and H. Ishii, "The actuated workbench: computer-controlled actuation in tabletop tangible interfaces," *Proc. of UIST '02*. ACM, 2002. pp. 181-190.

[17] J. Patten and H. Ishii, "Mechanical constraints as computational constraints in tabletop tangible interfaces," *Proc. of CHI '07*. ACM, 2007. pp. 809-818.

[18] S. Fukushima, Y. Hashimoto, and H. Kajimoto, "Tabletop interface using a table's circular vibration and controllable friction," *CHI '08 extended abstracts.* ACM, 2008, pp. 3801-3806.

[19] H. Iwata, H. Yano, F. Nakaizumi, and R. Kawamura, "Project FEELEX: adding haptic surface to graphics," *Proc. of SIGGRAPH 2001*. ACM, 2001, pp. 469-476.

[20] I. Poupyrev, T. Nashida, S. Maruyama, J. Rekimoto, and Y. Yamaji, "Lumen: interactive visual and shape display for calm computing," *SIGGRAPH '04 Emerging technologies*. ACM, 2004, p. 17.

[21] I. Poupyrev, S. Maruyama, and J. Rekimoto, "Ambient touch: designing tactile interfaces for handheld devices," *Proc. of UIST '01*. ACM, 2002, pp. 51-60.

[22] I. Poupyrev, M. Okabe, and S. Maruyama, "Haptic feedback for pen computing: directions and strategies," *CHI '04 extended abstracts.* ACM, 2004, pp. 1309-1312.

[23] M. Fukumoto and T. Sugimura, "Active click: tactile feedback for touch panels," *CHI '01 extended abstracts.* ACM, 2001, pp. 121-122.

[24] Chou Wusheng, Wang Tianmiao, and Hu Lei, "Design of data glove and arm type haptic interface," *Proc. HAPTICS '03*, 2003, pp. 422-427.

[25] J. Rekimoto, "SenseableRays: opto-haptic substitution for touch-enhanced interactive spaces," *CHI '09 extended abstracts.* ACM, 2009, pp. 2519-2528.

[26] J.C. Lee, P.H. Dietz, D. Leigh, W.S. Yerazunis, and S.E. Hudson, "Haptic pen: a tactile feedback stylus for touch screens," *Proc. of UIST '04*. ACM, 2004, pp. 291-294.

[27] J.C. Roberts and S. Paneels, "Where are we with Haptic Visualization?," Proc. of *EuroHaptics '07*, 2007, pp. 316-323.

[28] A. Chang, J. Gouldstone, J. Zigelbaum, and H. Ishii, "Pragmatic haptics," *Proc. of TEI '08*. ACM, 2008, pp. 251-254.

[29] C. Harrison and S.E. Hudson, "Providing dynamically changeable physical buttons on a visual display," *Proc. of CHI '09*. ACM, 2009, pp. 299-308.

[30] J. Cechanowicz, P. Irani, and S. Subramanian, "Augmenting the mouse with pressure sensitive input," *Proc. of CHI '07*. ACM, 2007, pp. 1385-1394.

[31] D. Wigdor, "No touch left behind," *Microsoft Expression Video, http://www.microsoft.com/china/expression/newsletter/2009-01/default.aspx*, 2009.

[32] M.A. Nacenta, D. Pinelle, D. Stuckel, and C. Gutwin, "The effects of interaction technique on coordination in tabletop groupware," *Proc. of GI '07*. ACM, 2007, pp. 191-198.

[33] P. Tuddenham and P. Robinson, "Territorial coordination and workspace awareness in remote tabletop collaboration," *Proc. of CHI '09*. ACM, 2009, pp. 2139-2148.