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Haptic Edge Display for Mobile Tactile Interaction

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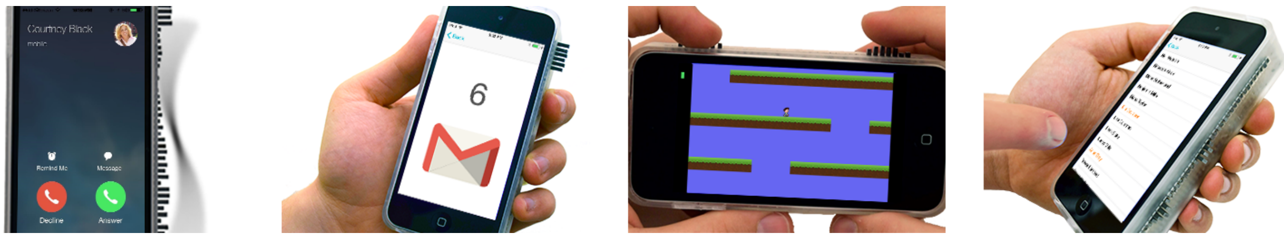

Figure 1: Haptic Edge Displays enable novel input and output techniques for mobile devices. Left to right: Dynamic affordances to easily answer incoming call; Haptic notifications for unread messages; Gaming; Interaction techniques

ABSTRACT

Current mobile devices do not leverage the rich haptic channel of information that our hands can sense, and instead focus primarily on touch based graphical interfaces. Our goal is to enrich the user experience of these devices through bi-directional haptic and tactile interactions (display and control) around the edge of hand-held devices. We propose a novel type of haptic interface, a Haptic Edge Display, consisting of actuated pins on the side of a display, to form a linear array of tactile pixels (taxels). These taxels are implemented using small piezoelectric actuators, which can be made cheaply and have ideal characteristics for mobile devices. We developed two prototype Haptic Edge Displays, one with 24 actuated pins (3.75mm in pitch) and a second with 40 pins (2.5mm in pitch). This paper describes several novel haptic interactions for the Haptic Edge Display including dynamic physical affordances, shape display, non-dominant hand interactions, and also in-pocket "pull" style haptic notifications. In a laboratory experiment we investigated the limits of human perception for Haptic Edge Displays, measuring the just-noticeable difference for pin width and height changes for both in-hand and simulated in-pocket conditions.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous; Interaction Using Specific Capabilities or Modalities

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Author Keywords

Mobile Haptics; Tactile Display; Dynamic Affordance

INTRODUCTION

Current mobile devices allow users to choose from millions of different applications. However, all of these different applications have the same limited means of interaction: touch on a graphical interface. The haptic channel and complex dexterity of the human hand are ignored by these devices, which have severely limited interaction bandwidth. In addition while the dominant hand is used for touch, the non-dominant hand remains under utilized.

Commercial haptic interfaces for mobile devices have been introduced to address some of these issues. These systems provide haptic feedback primarily through global or localized vibro-tactile means [31, 30]. We believe that there is a richer set of mobile haptic interfaces than the current state of the art that enable new interactions and experiences that leverage the rich tactile sensing and output capabilities of the human hand.

We propose a new approach to mobile haptics: Haptic Edge Display, a miniature tactile shape display [21] around the edge of a traditional mobile device, which allows for both haptic feedback as well as expressive input utilizing the dominant or non-dominant hand. Recent research in Shape Displays has explored rendering 3D geometry and user interface elements [11], which can maintain their shape without constant actuation. This allows for passive haptic exploration on the part of the user, in addition to active haptic output found in many current haptic interfaces. The Haptic Edge Display can work alone as a display for haptic notification or with a graphical user interface to augment interaction and provide haptic feedback.

We explore the design space of Haptic Edge Displays through a prototyping process, as well as the implementation of two functional mobile devices with different resolutions and speeds. Our first mobile prototype consisted of 24 actuators spaced 3.5 mm apart with a travel of 15 mm. In our testing and exploration of this device we found the need for a higher resolution display. The high-resolution prototyped Haptic Edge Display has a linear array of 40 actuators, with a pitch of 2.5 mm and travel of 0-7 mm. We leverage off-the-shelf miniature piezo linear actuators, similar to those made by New Scale Technologies and Piezo Motor. Piezo actuators have many advantages that make them an ideal choice for use as tactile display in mobile interfaces: low energy consumption, long life, low cost, back-driveability, and high refresh rates. Integrated capacitive touch sensors allow for expressive input.

The Haptic Edge Display can be used for a variety of application scenarios to provide: Dynamic Affordances (buttons and controls), “push" and “pull" haptic notifications both in-hand and in-pocket, interpersonal communication, and expressive haptic output for gaming. In order to further explore the design space of Haptic Edge Displays, we chose to investigate the ideal resolution for such a display. To do so, we conducted two psychophyscial experiments to find the maximum lateral and depth finger perception for both in-pocket and out-of-pocket scenarios.

This paper offers four core contributions:

- A novel type of haptic interface for mobile devices utilizing an array of linear actuators protruding from the bezel of the display.
- Two prototype implementations of Haptic Edge Displays.
- Software applications which demonstrate possible applications for UI control, tactile display, and notifications.
- A psychophysical study to measure ideal resolutions for Haptic Edge Displays.

RELATED WORK

As previously mentioned, current mobile interaction is mostly limited to touch on a graphical interface. This requires the dominant hand to be touching the screen, blocking a significant portion of the screen. Different approaches have been used to address this issue. Baudisch’s work uses the back of device as an input [3], while Sidesight and Unifone place sensors on the sides of mobile devices [7, 20]. On the other hand, Blasko’s work places a pressure-sensitive strip on the finger to be used as an input [5]. Similar to Sidesight and Unifone, Haptic Edge Display also utilize the mostly vacant sides of the mobile devices as the primary location for haptic mobile interaction.

Commercial mobile haptic interfaces have primarily relied on vibro-tactile feedback, for notification, touch confirmation, and gaming [25, 6]. Prior work has combined touch interaction on a graphical touch screen interfaces with haptic feedback to simulate different button presses, using small piezo actuators [31, 32]. In addition, pneumatic actuation has been explored as a means to directly create dynamic buttons directly on a touch screen [16]. Commercially, Tactus systems create touch screens from which physical buttons emerge, using hydraulically filled transparent wells [9]. More recently, researchers have used electrostatic vibration to render different friction forces on a finger when interacting with a mobile touch screen for haptic exploration of interface elements as well as gaming [2, 27]. In contrast, our research looks to utilize haptic display through shape change and displacement.

Tactile Arrays display dense tactile information through mechanical or electrical means, e.g. stimulating different parts of a finger tip [4, 37]. Particularly relevant is the Exeter touch array, which uses piezo actuators to move 100 small pins in a 1.5cm square area, to simulate different haptic sensations [35]. Our approach applies tactile array technology to mobile devices, tightly coupled with their graphical interfaces, to develop new interactions and haptic display capabilities.

Researchers have explored the application of haptic interfaces to more traditional user interface applications, such as media control [34]. Hemmert applied this work in the context of mobile devices, creating a haptic button on the side of a mobile device that can display different information to the user when navigating menus [18]. Hoggan investigated the use of multi-actuators for haptic communication [19]. The THMB device created by Pasquero also provides unique cutaneous haptic feedback to the user through multiple cantilevers mounted on a slider on the side of a device [29, 28]. ComTouch investigated the role of haptics in interpersonal communication [8].

Shape-changing mobile devices can also provide haptic feedback that is more salient than traditional vibrotactile means. Even when the device is inside the user’s pocket, it can convey various types of information by changing its physical shape [10]. In normal out-of-pocket situations, it can display internal, yet off-screen content through changes in thickness[17] or by angular actuation of either the entire device or just parts of the device [14, 33, 1].

Haptic Edge Displays build on this prior mobile haptic and shape-changing interface research to allow for novel interactions with haptic and tactile feedback that are intuitive and versatile in different scenarios such as in-pocket or out-of-pocket, or in the dominant or non-dominant hand.

HAPTIC EDGE DISPLAYS

This paper introduces the Haptic Edge Display, a novel approach to haptic interfaces for mobile interaction. A Haptic Edge Display consists of small linear actuators arranged in a linear array around the bezel of a mobile device. (see Figure 1) This allows a user to receive rich haptic information while holding a device in their non-dominant hand, by changing the height of each individual tactile pixel (taxel) independently. Patterns and shapes, as well as temporal animations, can be created and felt by the user’s hand. The haptic display can easily be combined with graphical interfaces.

Interaction

Haptic Edge Displays provide a wide variety of rich new haptic experiences that can augment traditional mobile interaction.

Haptic Display

Haptic Edge displays can render a physical 1.5D profile shape emerging on the edge of the display.

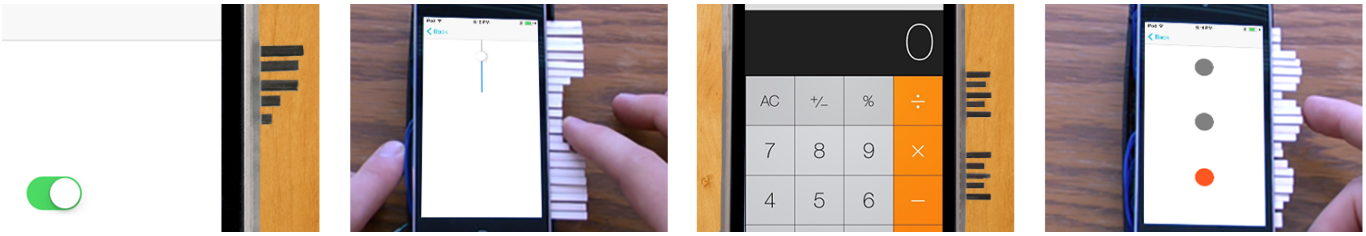


Figure 2: Dynamic Physical Affordances rendered on the Haptic Edge Display *Left to right:* Toggle; Slider; Tabs; Radio Buttons.

Haptic Edge Displays can display the following classes of information: Surface Texture, Geometric properties (ie Shape, local curvature), Motion (texture and geometric properties changing over time), Force output and Compliance (Variable stiffness). Haptic Edge Displays primarily rely on slow-adapting type I (SA I) Merkel cells in the fingers and palm, that sense coarse texture and are used for pattern/form detection as well as the proprioceptive ability to measure displacements in joint angles in each finger [22]. Sensations can be perceived both passively (i.e. statically holding device) and through haptic exploration (i.e. moving hand or finger over device). This is an advantage of the Haptic Edge Display over techniques for haptic rendering, such as electrostatic methods [2] which require movement to generate changes in tactile sensation.

Tactile Input
In addition to the output capabilities of Haptic Edge Displays, they can be used as an input device. Each taxel has an integrated capacitive touch sensor. This allows for a group of taxels to act as an input element. In addition, taxels are compliant and back-drivable, allowing for deformation based input. This can allow users to create custom shapes by pushing or pulling or allow for rich tactile input.

Dynamic Physical Affordances
Currently, mobile devices have fixed physical affordances, such as buttons for controlling the volume of sound output or returning to the home screen. We envision a future for mobile devices where buttons and other interface elements can change their size, shape and location to fit the different needs of interaction for varying applications. We call these Dynamic Physical Affordances.

Buttons and sliders can be rendered on the edge of the display to map to different functions and dynamically reconfigure to meet the changing needs of applications. Bi-stable buttons, such as radio buttons, can be emulated with the Haptic Edge Display. Buttons can also have haptic feedback through vibration and detents.

These Dynamic Physical Affordances can be used to change the physical affordances for different applications. For example, when a user opens a game, shoulder buttons can be rendered on the Edge Display, allowing for more expressive control. (see Figure 1) However, when the user quits the game the buttons disappear. similarly, when a user is in camera mode a physical button could be rendered in the top right corner regardless of the orientation of the device. This button could also have dynamic resistance making it easy to press the button halfway down which could focus the camera and then pushing the full way down to take a picture.

These affordances can be tied to graphical content. For example, a list of contacts can be displayed on the graphical display, and the frequency of their use can be mapped to the Haptic Edge Display, see Figure 1. Thus a contact that is frequently called is easy to find, and pressing in on that taxel would call the contact.

Figure 3: The Haptic Edge Display being used in-pocket for "pull" style haptic notifications.

Haptic Notification
Vibration is currently the most common medium for haptic notification. Although vibration is very useful for drawing people's attention, it is less useful for ambient or glance-able types of notification. We envision passive haptic notifications that allow users to easily retrieve information when they seek it, not necessarily when it first arrives. For example, imagine a user with their mobile device in their pocket, see Figure 10. The Haptic Edge Display could be used to display the number of unread messages the user received, each message represented by one taxel sticking out. By touching the side of the device the user could easily determine how many unread messages she received. If notifications are time sensitive, more expressive notifications can be created by outputting a dynamic shape such as a sinusoidal wave.

IMPLEMENTATION

Hardware

Initial Low-Fidelity Prototype
To begin our exploration, we created a low-fidelity mobile prototype using commercially available linear servo motors,

(a) **(b)**

Figure 4: The internal configuration of two Haptic Edge Displays are shown: (a) original low-fidelity prototype and (b) high-resolution prototype.

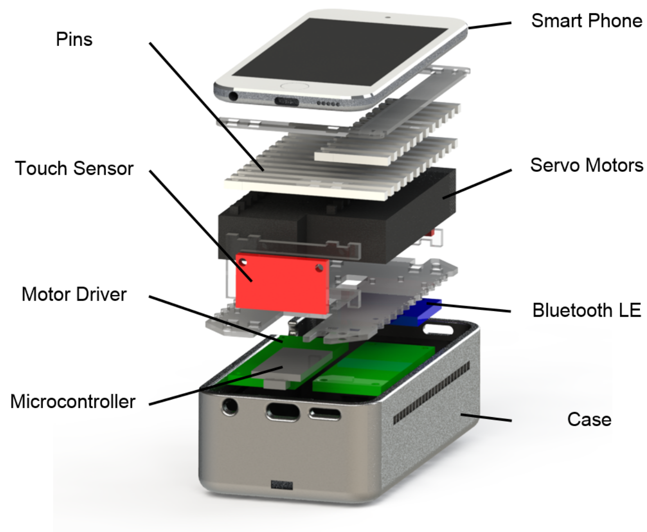


Figure 5: Exploded view of the low-fidelity Haptic Edge Display

VS-19 Pico Linear servos. (see Figure 4a) The system consists of a Bluetooth LE module, 24 linear servo motor actuators, 24 pins with copper tape for capacitive touch sensing, 2 touch sensor boards, 2 servo motor drivers, a microcontroller, and a smartphone.(see Figure 5)

The device communicates with the smart phone via Bluetooth LE and commands desired pin positions via PWM signals. Each pin is connected to a capacitive touch sensor board, made by Adafruit, by running copper tape on one side of the pins. By stacking two rows of servo motors with 7.5mm width, the closest pitch we were able to achieve was 3.75mm (refer to Figure 6 for terminology). In addition, due to the bulky packaging of the servo motors, the minimum thickness we could achieve for the first prototype was 36.5mm, which is five times thicker than many available mobile devices such as the iPhone 6 (7.1mm). Due to the friction in the gears of the motors, the first prototype is not back-drivable. It also has maximum speed of just 12mm/s and was fairly noisy during actuation. All 24 servo motors require maximum of 2A at 3.7V for a maximum total power consumption of 7.4W.

From some initial informal testing, we found that users were very interested in interacting with the haptic edge display, but wanted a system that provided higher fidelity interactions. Thus, we realized the need for a higher resolution prototype that was thinner, quieter, faster and back-drivable.

High Resolution Prototype

The second prototype utilized piezoelectric actuators in place of the linear servo motors, enabling us to drastically reduce not only the pitch of the device but also the overall size of Haptic Edge Display. (see Figure 7) In addition, these particular piezo actuators are back-drivable which enabled a larger range of interaction possibilities. Other major differences are listed in Table 1.

The piezoeletric actuator, TULA35 from Piezo Electric Technology, Inc, consists of two components as shown in Figure

	Initial Prototype	High Resolution Prototype
Dimension (mm)	$67.5 \times 130 \times 36.5$	$62 \times 127 \times 24.2$
# of Pins	24	40
Pin Width/Pitch (mm)	3.5 / 3.75	1.6 / 2.5
Pin Thickness (mm)	3	3.125
Travel (mm)	17	7
Max Speed (mm/s)	12	30
Actuation	Servo Motor	Piezoelectric
Travel Resolution (μm/step)	6.25	0.25
Output Force (gf)	3.7	3-5
Total Power Usage* (W)	7.4 (@ 12mm/s)	10 (@ 20mm/s)
Single Power Usage (mW)	300	250
Back-drivability	N/A	Yes
Noise	Loud	Low

* When all of the pins move at the given constant speed.

Table 1: Specification comparison between prototypes

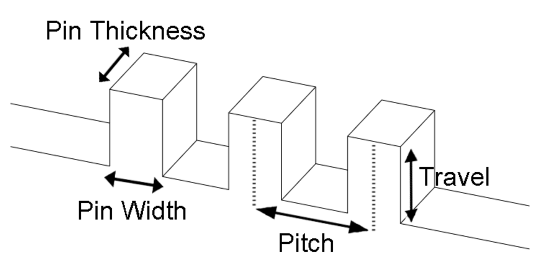


Figure 6: Terminology for the Haptic Edge Display

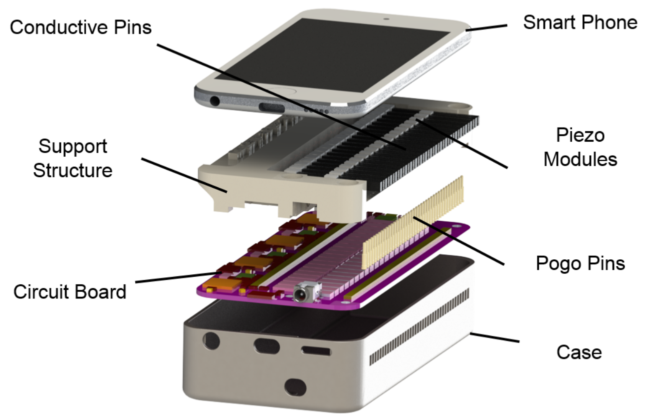


Figure 7: Exploded view of the high resolution Haptic Edge Display

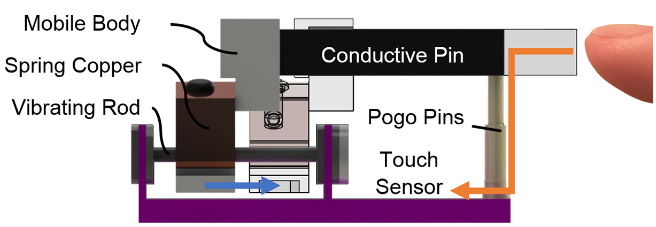


Figure 8: Diagram of the piezoelectric actuator and touch sensing

8: a custom mobile body and a vibrating plate/rod. It operates in a particular frequency range of 65-85 kHz which normal PWM LED drivers are not capable of. By varying the duty cycle the mobile body can move forward or backward relative to the vibrating rod. Empirically, a 25% duty cycle has been shown to provide the best performance moving forward while a 75% duty cycle is best for reverse direction.

A custom four-layer PCB board was designed as shown in Figure 9. The circuit can be broken down into four modules: microcontrollers (MK20DX256VLH7), Bluetooth LE communication, piezoelectric actuator drivers (LT3572), and capacitive touch sensing (MPR121). Position sensing with linear potentiometers has also been demonstrated for a single pin in this design. Four microcontrollers are used for the final prototype with each delivering ten PWM output signals and are connected via an I2C communication bus.

Similar to the first prototype, capacitive touch sensing was used as an input method. However, rather than using copper tape to connect the path, the pin itself is steel, thus conductive, and a pogo pin was used to deliver the signal from the steel pin to the PCB Board as shown in Figure 8.

Each pair of piezoelectric actuators is driven by one piezoelectric controller chip, which can consume a maximum of 150 mA at 10 V. Thus, for 40 piezo actuators, a total maximum of 3 A at 10 V, or a maximum power consumption of 30 W, is needed. However, we currently only run 10 actuators concurrently giving a max total power consumption closer to

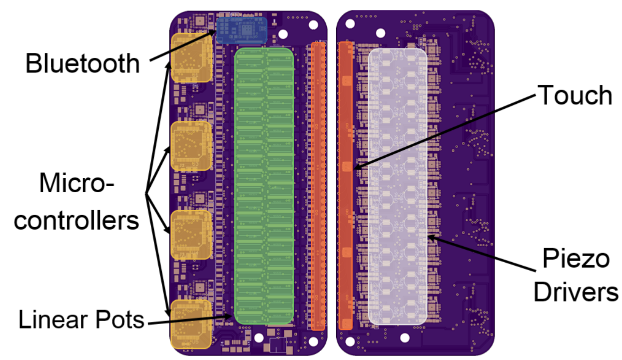


Figure 9: Layout of the circuitry on the custom four-layer PCB board

7.5W. Currently, two power sources are used: 10 V for piezo actuators and 3.7 for the digital circuits.

Software

We separated the software into three different subsystems. Two subsystems were written for the microcontrollers: one for the microcontroller designated as master and the other for the rest of the controllers designated as slaves. The third subsystem was written for the mobile device.

Communication between the master controller and the mobile device occurs over Bluetooth LE using the code provided by the Adafruit Bluefruit LE Connect repository. The master and slave controllers communicate over I2C. User input to the Haptic Edge Display is detected by the master controller and forwarded on to the mobile device, while input on the mobile device display is handled locally.

For some applications, a large number of taxels are needed to move simultaneously, but due to power constraints, our system could only power 10 moving taxels. To circumvent this issue, the master controller determines how many taxels need to be moved and if the number exceeded a safe threshold (8 taxels for this prototype), the controller will break the taxels into smaller groups, cycling very quickly between groups to move that set of taxels. Because the cycle time is quick enough, all taxels can appear to moving at the same time, although at a somewhat slower pace.

Applications on the mobile device are able to interact with the Haptic Edge Display by issuing commands to the master controller, specifying a pin and a desired position. The master controller internally handled the details of moving the taxel to this position.

DEMONSTRATION APPLICATIONS

Gaming

Falling Frenzy

Falling Frenzy is started in landscape mode and the Haptic Edge Display creates shoulder buttons, one on each side of the screen. On the screen, the user is presented with a small character standing on the ground. When the user presses one of the shoulder buttons, the character moves either left or right. A third physical button appears when the character reaches certain contextual areas in the game, where a virtual button appears at the same time.

This game illustrates the benefit of dynamic physical buttons to enhance a mobile game's experience. First, it allows for buttons to be allocated in places that intuitively make sense to control the character's movements. Second, the character's interaction with the red virtual button demonstrates how the physical and the graphical worlds can be combined to create intuitive gameplay that would not be possible with the graphical display alone.

Snake

Snake is a variant of the 1976 arcade game Blockade which has appeared on many mobile phones. This game is played in portrait mode and the user controls a snake that moves around the screen eating apples and growing larger. The player controls the snake by swiping in the direction of the desired movement. Whenever the snake body approaches the side of the display, taxels on the edge display move outwards to represent the movement of the snake. These physical expressions of the digital world are common in gaming, such as rumble packs found in game controllers, and the Haptic Edge Display provides a more intuitive alternative to simple vibration.

Heartbeat

Haptic Edge Displays can be also used in the context of communication. Touch is an essential part of our communication in person, such as greeting people with a handshake. However current mobile interfaces used for communication rely mostly on audio and video media, ignoring the haptic channel. The Heartbeat application works by showing a beating heart on the screen, while simultaneously creating a dynamic pulsing action on the Haptic Edge Display. This allows the user to both see and feel the heartbeat of another person.

We think there are great possibilities in this type of interaction. The Heartbeat application is a translation of a physical heartbeat to a digital reading and back to a physical output via the device. This interaction could also take the form of two users virtually linking their Haptic Edge Displays. One user's actions on her edge display could be sent to the second user's edge display essentially transferring the physical touch to the second user.

Figure 10: Drawing application

Phone Call & Contacts

The phone call application demonstrates how Haptic Edge Displaycan be used to augment the normal mobile interaction experience. Instead of traditional vibrotactile feedback, it outputs a dynamic sinusoidal shape display to alert the user in a more subtle, gracious manner. By varying parameters of the wave such as frequency and amplitude, different scenarios such as emergency or call from favorites can be expressed.

The Contacts application resembles a generic contacts list commonly found on phones. Many contacts lists have a portion of the interface set aside for favorite contacts (or at least a way to easily access them). Instead of dedicating a portion of the screen for this purpose, when important contacts show up on the screen, a button is rendered by the Haptic Edge Display next to them. This button can easily be tapped by the user to open up that contact.

Reading

One benefit of physical books over their digital counterparts is their ability to provide an indicator of progress ambiently through their physical form. Our Reading application provides this benefit by adding a physical indication of progress. As a user scrolls through a passage, the Haptic Edge Display renders a small bump that travels from the top of the display to the bottom. As it passes through the user's fingers it provides awareness to her overall position in the passage.

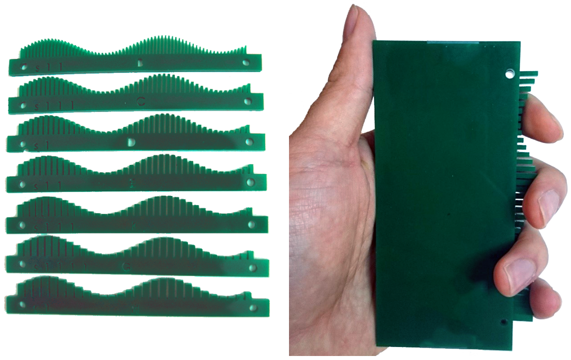
EVALUATION

To inform the design of an ideal Haptic Edge Display, we performed two psychophysical experiments to find the lateral and depth haptic resolution of humans' fingers, a compound effect from the tactile spatial acuity and joint proprioception. We investigated how well such a device could function both in-hand and in-pocket, the latter of which is especially relevant for haptic notifications. To examine at the worst case scenario we compared an in-hand condition with a simulated in-pocket condition with stiff denim fabric. The in-pocket condition was simulated to find the Just Noticeable Difference (JND) of lateral and depth finger pad perception (which corresponds to the pitch and travel resolution, respectively) as compared to the normal in-hand control condition.

We initially hypothesized that both the lateral and depth haptic resolution would be lower for in-pocket situation. However, we also hypothesized that the in-pocket haptic resolution would still be high enough to be able to perceive meaningful shapes and/or expressive tactile notifications through fabric.

Background

Though there has been much research in psychology and neuroscience to measure the limits of human haptic perception, these studies tend to focus on a single transducer, i.e. the tactile spatial acuity of the finger tips or the resolution of proprioception in the hand. We are interested in understanding how these work together to perceive complex shapes, such as those displayed by the Haptic Edge Display.



(a) (b)

Figure 11: Test pieces with different pin widths are demonstrated in (a).

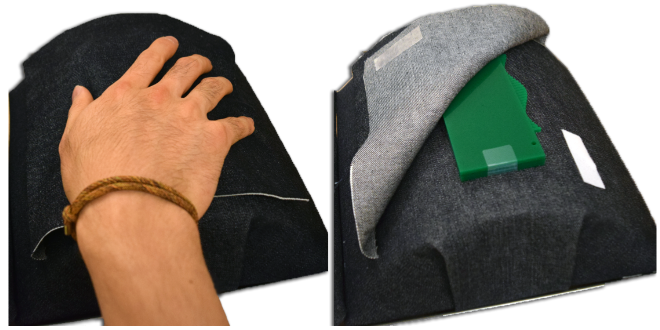


Figure 12: For the denim condition, participants felt the test piece that was placed inside two players of denim held together by a velcro strip.

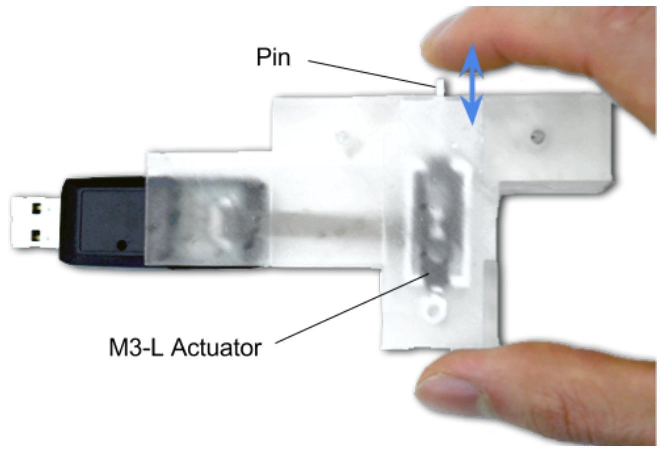


Figure 13: The apparatus used for depth perception experiment

The measure of the tactile spatial acuity is often measured through a two point test to determine the minimum distance needed to discern the two points. The tactile spatial acuity of the fingertip is roughly 0.6mm, whereas the base of the finger and the palm are 5mm and 9mm respectively [23, 36]. This sense of touch and localization relies on slowly adapting afferents nerves known as Merkel receptors.

The proprioceptive acuity of finger joints is the measure of accuracy in determining the orientation and angle that a finger joint is moved into. This influences the ability to sense the overall shape of an enclosed object in the hand. Researchers have shown that subjects can detect with 70% accuracy changes around approximately 6° in finger joint rotation [12, 15].

Psychophysical Methods

Finger Pad Lateral Perception

Ten healthy subjects were recruited to measure the lateral perception on the finger pad in both in-hand and in-pocket (through-fabric) conditions. The subjects consisted of 8 males and 2 females; 9 were right handed, and their ages ranged from 23 to 31. Subjects had various previous haptic experiences ranging from none to extensive. None of the subjects had neurological disorder, injury to the hand/arm, or any other conditions that may have affected their performance in this experiment. They were compensated for their time and the experiment was approved by the University's Institutional Review Board, and subjects gave informed consent.

The setup consisted of two arcs that are covered with two layers of denim connected by a velcro strip to simulate the in-pocket situation. Each subject faced the apparatus wearing noise-cancelling headphones for audio isolation. For the in-pocket condition, the test pieces with different pin widths, as shown in Figure 11a, were placed inside the pocket as in Figure 12. For the out-of-pocket condition, the test pieces were placed on top of the pocket. This setup was surrounded by a curtained box to allow subjects to touch the devices without visual feedback.

The two-alternative forced-choice experiment followed the method of constant stimuli [13]. For three seconds, subjects freely explored each test pieces either through the fabric or above it with non-thumb fingers of their dominant hand as shown in Figure 12. After exploring two test pieces with a three second break in between, subjects were asked to report the stimuli with higher resolution. Before the actual experiment, three practice trials with feedback were given to help subjects familiarize themselves with the process.

For each trial, one setup contained the reference test piece with pin width of 2 mm, while the other contained a comparison test piece. The reference pin width was chosen such that it was close to the pin width of the Haptic Edge Display. Each subject performed six repetitions of fully randomized trials that included seven values for the pin with w = {1, 1.5, 1.75, 2, 2.25, 2.5, 3 mm} and two conditions of either denim or no fabric covering the test piece, summing up to a total of 84 trials for experiment 1. All test pieces had a sinusoidal shape with amplitude of 8.5 mm, wavelength of 50 mm, and pin spacing of 0.5 mm. During the experiment, subjects were given an optional five-minute break after every forty-two trials.

Finger Pad Depth Perception

A different set of ten healthy subjects was recruited to measure depth perception on the finger pad. The subjects consisted of 8 males and 2 females; 9 were right handed, and their ages ranged from 23 to 31. Again Subjects had various previous haptic experiences ranging from none to extensive. None of the subjects had neurological disorder, injury to the hand/arm, or any other conditions that may affect their performance in this experiment. They were compensated for their time and the experiment was approved by the University's Institutional Review Board, and subjects gave informed consent.

Instead of the pin width, the subjects were asked to report the pin height that was greater following the same procedures as Experiment 1. The apparatus differed slightly as only one device was used to provide two pin heights to the subject. A piece of fabric was added over the device for the simulated in-pocket condition. As shown in the close up view of Fig.13, M3-L linear actuator module from New Scale Technology, Inc with a position resolution of 0.5 µm was used to provide the desired pin height. The pin attached to M3-L had the same width and thickness as the one used in the Haptic Edge Display. Similar to Experiment 1, participants performed a total of 84 trials consisting of six repetitions with two fabric conditions (denim/no fabric) and seven pin heights h = {1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3 mm}. Reference pin height was chosen to be 2 mm, roughly the middle of the actuator's position range.

Psychophysical Results

For the finger pad lateral and depth psychophysical experiments, the proportion of times each participant responded that the comparison value was greater than the reference was plotted against the comparison values. Using the psignifit MATLAB toolbox, three relevant values were computed (http://bootstrap-software.org/psignifit/): point of subjective equality (PSE), stimulus value corresponding to a proportion of 0.25 (J_{25}), and stimulus value corresponding to a proportion of 0.75 (J_{75}). The JND is defined as follows:

$$JND = \frac{J_{75} - J_{25}}{2}$$

The Weber Fraction (WF) is calculated as follows:

$$WF = \frac{JND}{PSE}$$

The results from the psychophysical experiments are summarized in Table 2. The average JNDs for lateral perception under denim and no fabric conditions are 0.59mm and 0.32mm, respectively with standard deviation of 0.41 and 0.13. The average JNDs for depth perception under denim and no fabric conditions are 0.27mm and 0.15mm, respectively with standard deviation of 0.15 and 0.09. Fig. 14 shows two bar graphs for both lateral and depth perception with error bars. Welch's two sample one-tailed t-test showed a statistically significantly difference between the JNDs under different fabric conditions for both lateral and depth perceptions with p-values of 0.035 and 0.021 respectively.

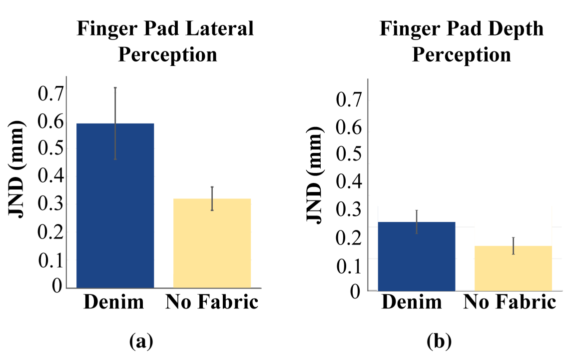


Figure 14: Mean JNDs above demonstrate that there are statistically significantly difference between the two fabric conditions (denim/no fabric) for both (a) lateral and (b) depth finger pad perception.

DISCUSSION AND FUTURE WORK

The psychophysical experiments provided results that suggest a need for different control approaches for in-pocket and in-hand scenarios. Due to the intervention of the fabric, a person's haptic perception capability decreases, thus requiring greater stimuli for differential detection. Thus, we will have to take into consideration this reduced sensitivity when designing an application for in-pocket scenario.

From our psychophysical experiments and informal testing with the device we found that for in-hand haptic feedback very little travel was required to create a compelling sensation with the exception of the dynamic affordances. This suggests that future versions of the Haptic Edge Display could be built with substantially less travel, and potentially faster and thinner with less power consumption, such as dielectric elastomer actuators [26], polymeric actuators [24], or hydraulic wells [9].

One of the criticisms expressed by users of the first prototype was that while the buttons looked like they could be pressed, they didn't actually feel like press-able buttons. We tried to address this in our second prototype by moving to the piezoelectric actuators which are back-drivable. We also plan on closing the control loop for the pins using a carbon mask linear potentiometer. This will enable us to not only control the pins more accurately but also enable us to sense the force applied by the user. Knowing whether the user is lightly tapping or aggressively pushing on the pin can help in understanding the intent of the user.

While the piezoelectric actuators enabled us to solve many of the shortcomings of our first prototype, they have not come without their own problems. Since driver for each pair of piezo actuators consumes approximately 0.15A at 10V, about 3A at 10V is needed to run 40 piezo actuators. This is equivalent to 30W of power and is more than what can be supplied with a typical battery. The boost converter embedded in the piezo driver board is inefficient increasing the power consumption. While we currently run the actuators using 30V (the ideal voltage for max speed), they can also work with 15V, increasing the efficiency of the boost converter. In addition, we do not believe that in daily usage all actuators will be used continuously. Currently at 30V, the system can move one button (consisting of 4 pins) out/in 2500 times with a 500mAh 3.7V battery. When using the reading application, the same battery can handle a scroll moving up/down 450 times across the side of the device.

There are a number of limitations in overall dimensions of the Haptic Edge Display constrained by the size of the piezo actuators as well as the mechanical linkages for the pins and position feedback. While the height of the actuator is only

	Lateral Perception						Depth Perception					
	Denim			No Fabric			Denim			No Fabric		
Subject	JND (mm)	PSE (mm)	WF (%)	JND (mm)	PSE (mm)	WF (%)	JND (mm)	PSE (mm)	WF (%)	JND (mm)	PSE (mm)	WF (%)
1	0.51	2.00	25.4	0.50	2.06	24.4	0.15	1.92	7.7	0.05	2.01	2.3
2	0.27	2.17	12.7	0.31	0.94	15.8	0.24	2.05	11.8	0.05	2.03	2.7
3	1.37	2.26	60.7	0.26	1.95	13.3	0.60	1.94	30.7	0.24	2.02	11.9
4	0.82	2.26	36.5	0.17	2.04	8.5	0.13	2.00	6.4	0.03	2.05	1.6
5	0.33	2.07	15.7	0.33	1.95	17.1	0.24	2.02	11.9	0.16	2.03	8.0
6	0.36	2.01	18.1	0.54	2.00	27.1	0.21	1.98	10.6	0.18	2.03	8.6
7	0.69	2.15	32.1	0.33	1.99	16.4	0.27	1.97	13.5	0.16	2.02	7.9
8	1.12	2.08	53.9	0.30	2.07	14.4	0.18	2.04	8.6	0.20	2.14	9.4
9	0.15	1.99	7.5	0.34	2.04	16.4	0.46	1.92	23.9	0.11	2.05	5.2
10	0.27	1.86	14.5	0.10	2.02	4.8	0.23	1.97	11.5	0.30	2.00	15.2
Mean	0.59	2.08	27.7	0.32	2.01	15.8	0.27	1.98	13.6	0.15	2.04	7.3
Std.Dev.	0.41	0.13	18.0	0.13	0.05	6.6	0.15	0.05	7.7	0.09	0.04	4.4

Table 2: Finger Pad Lateral and Depth Perception

3.5mm, a total height of 7mm is required. This could be improved with different techniques for position sensing and using the actuator's rod as the pin. For instance, if we use the upcoming actuator from the same company which has a 2.5mm diameter, the actuators do not need to be stacked in two rows, and all the parts of a mobile body could be made out of single copper pin. Then, considering a 0.8mm PCB board and a case with a thickness of 1mm, we expect that the overall thickness can be reduced down to 13.3mm.

Although the Haptic Edge Display is currently set up primarily for right-handed users, users can easily flip the device to be used for left-handed users. This flip can be detected using the phone's accelerometer. In the future, we plan to add Haptic Edge Display to all sides of the mobile device. This will enable us to detect the handedness of the user by detecting the fingers with touch sensing, and provide haptic feedback accordingly. The addition of these locations could increase the range of applications feasible with the device. We would also like to explore moving the pins to the back of the device.

CONCLUSION

Given the lack of sufficient haptic feedback in current mobile systems, the Haptic Edge Display is designed to augment the experience in current mobile tactile interaction. While some mobile devices attempt to utilize the rich haptic sensation with vibrating motors, it is not up to the high standard of the intricate human hand as demonstrated in the psyhophysical experiments described here. Although not completely up to the finger pad resolution, the Haptic Edge Display attempts to bridge the gap between the current mobile tactile interaction and the ideal haptic interaction. We have demonstrated through two prototype systems and a number of applications, how Haptic Edge Displays can be utilized for providing Dynamic Physical Affordances, in-pocket “pull" notifications, and rich haptic display. Psychophysical experiments on lateral and depth finger perceptions were performed for both in-pocket and out-of-pocket scenarios. The results informed us of the necessary parameters, pin width and height of an ideal Haptic Edge Display in order to match the resolution of human fingers for both scenarios. The high resolution prototype was able to reduce the pin width from 3.5mm to 1.6mm, approaching the lateral resolution of 0.32mm.

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