BubbleWrap: A Textile-Based Electromagnetic Haptic Display

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Abstract

We are investigating actuators that are able to provide different types of haptic sensations and that can be wrapped around a wide range of surfaces and objects. Our first prototype, BubbleWrap, consists of a matrix of electromagnetic actuators, enclosed in fabric, with individually controllable cells that expand and contract. It provides both *active haptic feedback*, using vibration, as well *passive haptic feedback*, using shape and firmness. An initial experiment demonstrated that users could reliably discriminate among the three firmness levels displayed on our prototype.

Keywords

Haptic display, Actuators, Shape changing display, Firmness control

ACM Classification Keywords

H5.2. User Interfaces : Haptic I/O.

Introduction

The haptic channel provides useful and rich information for interacting with our physical environment: it is fast, needs little conscious attention, allows for abstract information encoding, and produces strong emotional responses [2][3][4]. For example, Poupyrev et al. [11] and Hoggan et al. [6] added tactile feedback to graphical items on touch screens to improve input efficiency. However, we believe that actuators employed in previous research suffer from two drawbacks: lack of dynamic range of sensation and lack of adaptability.

Range of haptic sensations

Most haptic actuators generate only a limited range of haptic sensations. For example, a vibration-based system, such as [6], has difficulty simulating the changes in shape and firmness that result from a button press. We are interested in the potential of using a single technology that provides *both* active and passive feedback: We can obtain active feedback by using vibration and obtain passive feedback by gradually modifying firmness and shape. This type of actuator not only produces richer haptic sensations, but can also enhance expressiveness by using haptic feedback to create symbols, such as Tactons[1].

Adaptability

Systems such as SmartSkin[13] turn everyday objects into input surfaces. We are interested in the corollary, i.e. augmenting physical surfaces to provide haptic output. We need a lightweight, flexible material that can be wrapped around an object and placed next to the body, perhaps as a part of a bag, or laid onto the armrest of a chair or a desktop.

Our first prototype, called BubbleWrap (fig. 1), is a textile-based electromagnetic haptic display that can vibrate, for active feedback, as well as dynamically change its firmness and shape, for passive feedback. It consists of a matrix of electro-magnetic actuators, enclosed in fabric, with individually controllable cells that expand and contract. This textile layer can be wrapped around a wide range of surfaces or objects.

BubbleWrap could be used for a variety of applications, such as a flexible keyboard. Today's physical keyboards are clearly efficient for entering text, but take up space and are impractical for small mobile devices. On-screen keyboards are practical but not very efficient, especially for touch typists. We could create a BubbleWrap keyboard that takes little space when not in use, but would inflate when needed, using changes in shape and firmness to simulate the keys and provide proprioceptive feedback as the user presses each key. We could also use vibration to notify users of input errors.

Figure 1: BubbleWrap haptic display prototype

The next section presents related work, followed by a description of the design of the first BubbleWrap prototype. We then present the results of a preliminary evaluation and conclude with a discussion and directions for future research.

Related work

Several researchers have added haptic feedback to mobile devices by using vibrotactile actuators. For example, Hoggan et al. [6] studied the effect of vibrotactile feedback on text input efficiency on a mobile touch-screen. Brown et al. [1] created Tactons to map information such as calendar event notifications to vibration patterns.

Shape-changing interfaces encode information by modifying the shape of the device, using any of a number of different approaches. Pin-based displays use a matrix of elements that move up and down. Horev [7] describes how one might design a *TactoPhone,* in which the back of the phone is a morphing surface for displaying animated tactile icons. His video prototype shows how it might be used to provide location information. *Lumen* [12] is a 2D low-resolution pin-based display that controls the height and color of individual 'pixels'. Shape Memory Alloy provides noiseless, smooth and continuous actuation. Although notification through the haptic channel, SMA threads are fragile and are not very responsive.

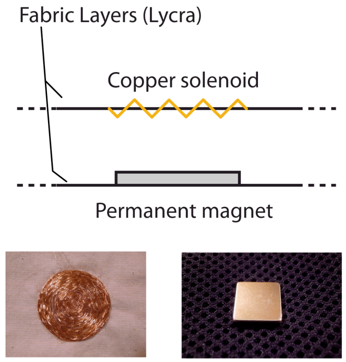

Figure 2: BubbleWrap actuators: permanent magnet + copper solenoid

Hemmert et al. [5] designed *Dynamic Knobs* for mobile phones, in which the knob acts as both an input and an output device. However, it would be difficult to create a generic, lightweight mobile display that consisted of multiple knobs, if one used servo-motor technology.

In another video prototype, Horev [7] proposed a morphing cube that inflates according to the amount of data on a hard drive. Although he uses the object's size as a visual information display, one could imagine using inflation to modify an object's hardness. In this vein, Kim et al. [8] designed the Inflatable Mouse to support pressure-based input for navigation. It produces simple movements by varying the inflation level and can be used to communicate an emotional state, e.g., a heartbeat, or to sound an alarm, e.g., by shrinking the mouse. This type of actuator is not very responsive and it seems difficult to control multiple independent elements.

Other domains, particularly virtual and augmented reality, use force feedback to simulate textures. For example, Minsky et al. [10] used a motor-driven two-degree-of-freedom joystick to simulate texture. Luk et al. [9] used a "lateral skin stretch" to simulate small-scale shapes and textures.

As stated earlier, our goal is to find a single technology that allows us to provide both active feedback, through vibration, and passive feedback, by controlling firmness and shape. We need a lightweight, flexible material that can be wrapped around an object or laid onto a wide range of surfaces. The above technologies are either too fragile, too big, or too difficult to manufacture in thin layers; we need to identify a different technology that meets our needs.

BubbleWrap Design

We created the first BubbleWrap prototype as a proof-of-concept of a textile-based haptic display, using a 4x4 matrix of extendable cells. We also created a single-cell version for test purposes, to evaluate whether users could easily identify changes in firmness with this technology. Each BubbleWrap actuator consists of a bottom layer of fabric on which a 1.5x7x7 mm thin permanent Neodymium (NdFeB) magnet is attached. A coil is sewn on the top layer (Fig. 2).

Solenoid-based actuators are interesting because, in addition to their commonly used ability to vibrate, they also allow us to maintain stable states. Such actuators are easy to build, cheap, responsive and allow a good ratio of thickness to power. When at rest, the overall height of the fabric layer is approximately 5 mm. At maximum expansion height is of 15mm.

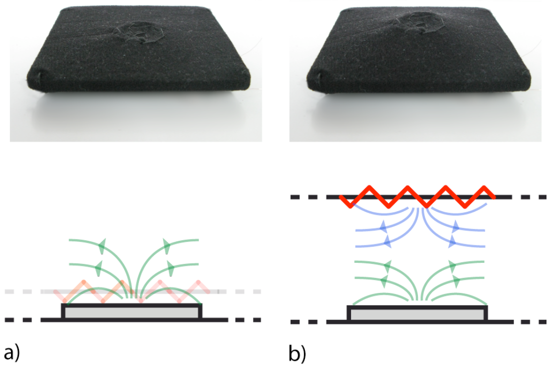

Figure 3: a) Magnetic field of a permanent magnet. b) Current flows through the coil, turning it into a magnet that is repulsed by the permanent magnet.

We simulate hardness by expanding and contracting the fabric cells using electromagnetic force (Fig.3). The neodymium magnet constantly generates a magnetic field (Fig. 3a). By controlling the amount of current flowing through the coil, we vary the force with which this electromagnet is repulsed by the permanent magnet (Fig. 3b).

Continuous current variations allow continuous control of height and firmness. Since electromagnetic force resists the user's pressure, the height of an extended cell gives an impression of firmness. When the height is zero, the direct resistance of BubbleWrap's backing gives the impression of hardness, relative to the expanded mode. The frequency of the inflation rate can be adjusted so as to provide either dynamic passive or active feedback.

To drive BubbleWrap's 4x4 matrix, we used an electronic board based on an Atmel atmega128 microcontroller. The prototype uses 12V at 1A. We used 16 digital outputs of the board to generate Pulse Width Modulations (PWM) signals that drive each actuator, via power transistors. This type of output allows us to easily control the state change of the actuators, enabling us to display animations and vibratory patterns.

Experiment

Changes in firmness play a role in how we interact with physical objects, such as when pressing a button. Since we were not aware of any studies of actuators that were specifically designed to control firmness, we decided to run a preliminary experiment. We measured the ability of users to distinguish among three different degrees of firmness, as produced by the BubbleWrap prototype. As a control condition, we also measured users' ability to distinguish among three different degrees of firmness, using three different thicknesses of physical foam.

Method

Twelve unpaid subjects (10 male, 2 female), between 22 and 35 years old, participated in the experiment. We used a MacBook Pro laptop to control BubbleWrap, using a java-based application to communicate with the BubbleWrap driver via a serial protocol. Our goal was to minimize the range of heights, for both BubbleWrap and the physical foam, to keep the display as thin as possible. At the same time, we wanted to maximize discriminability among the three firmness levels. We also attempted to ensure that the overall expansion range (15 mm) was similar between the physical foam and BubbleWrap. However, it should be noted that the density of the two materials is different. The force necessary for maximal compression of the thickest piece of foam is approximately 3 N, compared to approximately 1.5 N for the BubbleWrap actuator at its maximal expansion. Because it is difficult to obtain identical forces for both conditions, we chose to favor the control condition, since the difference between the three thicknesses is greater for physical foam than for BubbleWrap.

Procedure

We adopted a repeated measures within-subjects design with two factors: *material* (BubbleWrap or physical foam) and *firmness* (hard, medium, soft). Conditions were counter-balanced across participants using a latin square. We hid the material to be judged behind a panel and asked participants to pass their hands through a hole to touch the material. Participants had five minutes of training for each material. Each trial started with an auditory signal, after which participants were asked to decide as quickly as possible which of three levels of firmness they felt, 1 for the hardest and 3 for the softest. The trial ended as soon as the participant typed his or her choice. We recorded both reaction time and errors.

Results

We performed an ANOVA and accounted for repeated measures by treating subject (participant) as a random variable, using JMP 's REML function. We accounted for replicated measures by taking the mean of each condition. We also treated firmness as an ordinal data type. Participants were extremely accurate (97%) and quick (1.6 seconds) when distinguishing among the three levels of firmness of physical foam. They were also extremely accurate (98%) and quick (1.7 seconds) when distinguishing among the three levels of firmness for BubbleWrap. We found no significant differences between materials with respect to either accuracy or reaction time: $F(1,11) = 1.34$, $p = 0.27$ and $F(1,11) = 1.12$, $p = 0.31$, respectively.

Levels of firmness has a significant impact on error rate ($F(4,44) = 3.77$, $p = 0.03$). Participants had fewer than 1% error at the first level of firmness (hardest) with both materials. The softer levels had higher error rates (level 2 was 2% and level 3 was 3%). Firmness level also had a significant effect on reaction time ($F(4,44) = 10.65$, $p < 0.01$). This is due to the fact that level 1 (the hardest level for both materials) is at an absolute end of the range, whereas we could add additional levels of firmness, beyond level 3. However, the effect on reaction time and error rate of firmness crossed with material is not significant ($F(4,44) = 1.12$, $p = 0.33$ and $F(4,44) = 0.41$, $p = 0.66$, respectively). Thus, for each firmness value, material has no significant effect on error rate or reaction time.

Conclusion and Future Work

We designed, implemented and tested BubbleWrap, a first prototype of a haptic display that provides both dynamic passive feedback via firmness and shape control, and active feedback via vibrations. Copper solenoids coupled with permanent magnets as actuators are a simple and inexpensive solution for designing a fabric-based haptic display that could be wrapped around existing objects. Results of our preliminary study show that users can quickly and reliably discriminate among three levels of firmness generated by our prototype. These encouraging results suggest that texture properties like firmness can be controlled programmatically.

This technology has several drawbacks, such as potentially high energy consumption and weight. We plan to further study the technical properties of this actuator as a haptic device, including displacement, power consumption and frequency, with corresponding design implications. For example, we can reduce weight by replacing the permanent magnet with another solenoid but the resulting actuation will increase energy consumption.

We are also working on adding input capabilities to the textile layer. Hoggan et al. [6] showed that input on a touch screen can be improved by adding haptic feedback for typing tasks. We plan to adapt this technology to touch-screens, so as to improve text input performance.

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