Tactile Feedback without a Big Fuss: Simple Actuators for High-Resolution Phantom Sensations

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ABSTRACT

Multi-touch screens and surfaces for manipulating digital content play a crucial role in mobile and ubiquitous computing. Augmenting these interactive surfaces with tactile feedback has been found to increase interaction speed, reduce operating errors and minimize visual and cognitive load. Communicating detailed tactile characteristics of virtual elements, however, requires complex electromechanical or electrostatic actuator setups. This increase in complexity makes tactile interfaces intricate, costly or poorly scalable.

In order to provide sophisticated tactile sensations with simple actuator technology, we exploit a haptic psychophysical phenomenon called Phantom Sensation. We present a comparison of three standard tactile actuator technologies to see which one can recreate the Phantom Sensation with maximum effect. Our results show the way to a simple and scalable implementation of illusion-based tactile feedback for interactive surfaces. We explore the notion of the Phantom Sensation and its possible applications within a ubicomp scenario.

Author Keywords
interactive surfaces, tactile feedback, actuator technology

ACM Classification Keywords
H5.2: User Interfaces. - *Haptic I/O.*

General Terms
Experimentation, Human Factors.

INTRODUCTION

Research in mobile interaction, pervasive and physical computing shows that users substantially benefit from tactile feedback on interactive surfaces [6, 9]. This holds true for both objective measures and emotional aspects of the interaction [4].

Figure 1: We used a prototypical tactile interface to compare three different actuator technologies.

In order to create tactile feedback, developers tend to reduce the size of tactile technology and increase the number of individual actuator elements to improve resolution and richness of tactile communication [5]. This approach, however, entails high mechanical complexity, often resulting in poor scalability and costly hardware.

Using so-called tactile illusions promises to reduce this complexity of actuators. Kato et al. [8], for example, first hinted at utilizing the Phantom Sensation, where a tactile stimulus can be produced and continuously moved between only two adjacent actuators. This tactile illusion has been thoroughly analyzed and reproduced in psychology and perceptual research since the 1950s [3]. But while research on psychophysical and perceptual aspects is widely available, the discussion of actual technical aspects is slim, even though prototypical implementations exist [11]. Information for practitioners on how to integrate such tactile feedback for interactive surfaces with readily available hardware is needed.

We present the results of a user study in which we identified the most effective commonly used actuator technology to recreate the effect (see Figure 1). Our findings allow the simple and cheap implementation of tactile stimulators to reproduce the Phantom Sensation. In addition, we discuss how our findings can be used in the context of interactive surfaces.

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Figure 2: We compared three actuator technologies in a user study: (a) Eccentric vibrational motors (integrated in an elastic arm sleeve) (b) solenoids (c) voice coil actuators

RELATED WORK

Electromechanical actuators are commonly used to communicate tactile information to the user of an interactive surface. A variety of technical solutions have been investigated, e.g., the vibration of the entire device or screen [7], the segmentation of a touch surface into individually movable 'tactile' pixels [12] or the use of TUIs atop the interactive surface [10]. The tactile characteristics that are communicated by these systems either simulate physical attributes (form, malleability) or encode abstract states (progress bar, zoom level) of an interactive element. Increasing the tactile resolution requires complex hardware setups with large numbers of actuators. We propose the use of tactile illusions to improve these limitations.

PHANTOM SENSATION

Phantom Sensations stem from the effect that "*two equally loud stimuli presented simultaneously to adjacent locations on the skin are not felt separately but rather combine to form a sensation midway between the two stimulators*" [1]. A Phantom Sensation is affected by two parameters, the *amplitude inhibition* and the *temporal inhibition*. Amplitude inhibition happens when two stimuli are applied simultaneously to the skin and both have equal sensation magnitudes. The Phantom Sensation appears midway between the two actuators. By varying the relative amplitudes of both stimuli, the apparent sensation can be moved towards the louder actuator. Two equally loud stimuli occurring in close succession cause temporal inhibition. A single Phantom Sensation is created between the two actuators. The position of this apparent stimulus can be adjusted by modifying the interstimulus time interval. The illusionary stimulus is shifted towards the earlier stimulus for interstimulus intervals up to 8-10 ms [1].

TEST SETUP

In order to compare different technologies for their ability to create a stable Phantom Sensation, we built a low-cost test setup (see Figure 1 and 2). Békésy [3] suggests the use of the glabrous skin on the user's forearm to apply the tactile sensations, because the mechanoreceptors in that area of the skin are very evenly distributed. In order to make our results comparable to existing studies, we decided to use the same stimulus area. Other properties of the system, such as the distance between actuators (80mm / 3.1in), interstimulus intervals (0-8ms) or stimulus length (333ms), were designed in accordance with related work in psychology and perception [1,3].

Our prototype comprises three common types of tactile electromechanical actuators (see Figure 2): eccentric vibrational motors, linear magnetic solenoids and voice coil speakers. We chose these three types for three reasons: (1) they are commonly used in the field (for an overview see [5]), (2) they are readily commercially available, (3) they differ in the characteristics of the stimuli they create. With the goal to produce the illusion in the most distinct and comparable way, we modified the contact pressure of every actuator by adjusting countersink on the components.

Vibrational Motors

A flat or cylindrical motor is spinning an eccentric mass causing the housing to vibrate. We used the Lily Pad Vibe Boards[1].With different driving voltage amplitudes, different velocity plateaus can be reached. Vibratory frequency and amplitude are linked and cannot be addressed individually. The stimulation is diffuse and affects a larger area of the skin than the other two actuator types. We attached these tactile actuators to the forearm with a fixed distance of 80mm / 3.1in using an adaptable arm-sleeve.

Solenoids

A solenoid consists of a magnetic coil that applies forces to a ferrous plunger. A solenoid can solely by switched up or down by applying voltage. It is not possible to control the amplitude independently. The top of the plunger provides a punctual stimulation with a high steady-state force. Although the movement is not linear, it only takes 2-8 ms to reach full amplitude.

Voice Coils

The third type of actuator can be described as a hybrid between the two aforementioned. A cone is moved by the reaction of copper coil in a magnetic field to a current passing through. We used Visaton SL 87 XA Speakers[2]. Dedicated voice coil actuators exist, but did not fit our needs in terms of amplitude, size and pricing. With our actuators, we are able to generate vibrations on a spatially limited area of the skin and amplitude and frequency of the stimuli can be varied independently.

STUDY

In the user study, we evaluated which technology created the most distinct and clearly perceivable tactile illusion. We used 3 technologies, each in time inhibition mode and amplitude inhibition mode, except the solenoids, with which amplitude inhibition is not possible. Accordingly, we compare 5 combinations of actuator-funneling-modes (AFM-combinations).

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[1] arduino.cc/en/Main/ArduinoBoardLilyPad

[2] visaton.de

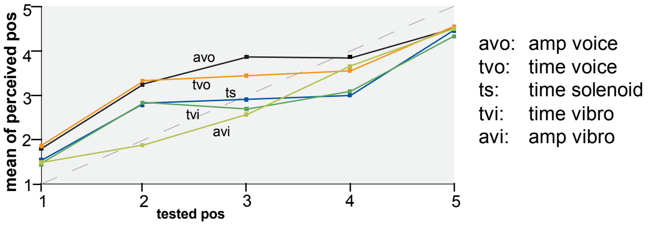

Figure 3: Perceived positions of Phantom Sensation for every triggered position (discrete values connected for readability)

Subjects

Fifteen computer literate persons (5 male, 10 female) served as paid subjects, all of them were right-handed. Ten persons stated that they had used tactile interfaces such as game-controllers before.

Apparatus

All participants were sitting at a table with their left forearm resting on the device. Based on existing research [2] we decided on discrete positions and depicted a scale from 1 to 5 next to the user's arm. Position 1 represents the distal actuator near the wrist, position 5 the proximal actuator near the elbow (compare Figure 2).

Procedure

After a short period of training, in which the participants could familiarize themselves with the tactile stimuli, the testing procedure began. The order of AFM-combinations was counterbalanced using a non-balanced Latin Square. A stimulus was given and the participant was asked to indicate the perceived position on the depicted scale. If more than one stimulus was perceived, the participant was requested to indicate the stronger one. Within an AFM-combination, every position was tested 3 times; the order within a set of 5 positions each was randomized. The tactile stimuli were communicated using the actuators mounted near the participant's wrist. The prototype was turned around when changing actuator technology (cf. Figure 1).

After each of the 5 AFM-combination trials, the participants were asked to fill in a questionnaire with 9 questions on prototype, stimulus and stimulus effect. Every participant was asked to mark his opinion on 7-point Likert scales (1=totally disagree, 7=totally agree). We think that these emotional aspects are very important for the acceptance of a tactile technology.

RESULTS

Each position was tested 225 times (15 participants, 5 AFM-combinations, 3 repetitions). For a start, we measured the frequencies of occurrence for each perceived position for all participants and techniques. The mean of perceived positions is 3.09. This result shows that a stable Phantom Sensation was produced with every one of the 5 AFM-combinations.

Figure 3 shows the mean perceived positions for each AFM-combination. Especially the AFM-combination vibrotactile amplitude inhibition (avi*)* shows a stable Phantom Sensation with spatial deviations less than 1 for each position.

We aggregated the data by creating a *mean input deviation (MID)* index. For each AFM-combination we had 15 data sets per participant (5 positions, 3 iterations each). The mean of spatial deviation was calculated for each position over all trials. The MID index was created by calculating the mean of the resulting 5 values and Figure 4 shows the results. The lower the MID index value, the more distinct the perception of the Phantom Sensation.

Based on Kolmogorv-Smirnov and Shapiro-Wilk, we used one-way repeated-measure ANOVA. It was found that the type of AFM-combination had a significant effect on the MID index ($F_{(4,56)}=8.45$, $p<0.001$). The Post-Hoc-Test with Bonferroni corrections showed significant differences between Time Vibro (MID=0.9) and Amplitude Vibro (MID=0.68) ($p<0.001$). The same holds true for Amplitude Voice Coil (MID=0.92) and Amplitude Vibro (MID=0.68) ($p<0.014$). All other comparisons showed no significant differences ($p>0.05$).

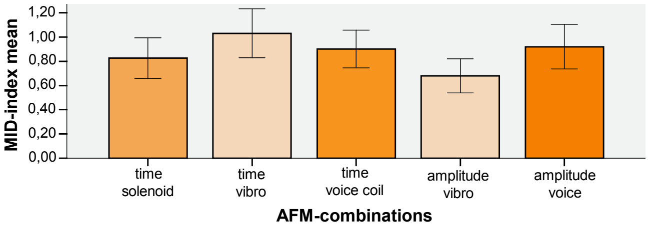

Figure 4: Mean Input Deviation (MID) for each AFM-combination.

Based on these findings, we excluded Time Vibro and Amplitude Voice Coil. Due to the high deviations in the distal position of illusions created by the voice coils (see Figure 3), we also excluded the AFM combination Time Voice Coil.

For the remaining AFM combinations (Time Solenoid and Amplitude Vibro), we consulted the results of the questionnaire. With Amplitude Vibro, the question "Do you think the generated stimulus is comfortable?" was answered with a mean of 4.47 (1=totally disagree, 7=totally agree). Accordingly, the question "Did you feel intimidated by the stimulus?" was answered with a mean of 1.00. In comparison, the results for Time Solenoid – 3.27 and 2.73, respectively – show a clear preference of the participants for the vibrotactile actuators using amplitude inhibition.

In summary, we can state that based on quantitative and qualitative results, the vibrotactile actuators using amplitude inhibition created the most distinct and stable Phantom Sensations. Additionally, this AFM combination was stated as creating stimuli being least disturbing and intimidating, but most comfortable.

DISCUSSION

The small, cheap and simple to control vibrational actuators turned out to be the appropriate means for creating stable tactile illusions. Despite their technological simplicity, they allow the creation and utilization of the Phantom Sensation. In general, we used prototypical and inexpensive technology to build our system. This has an influence on size and noise of the device. Currently, the user has to put his forearm atop the device, thus preventing bimanual input. To collect data comparable to existing studies we only tested 5 discrete positions. The Phantom Sensation, however, can be applied with a higher resolution [8] which is preferable in actual usage scenarios.

APPLICATION SCENARIOS

Vibrational motors are small and simple to control, thus making it easy to integrate them into wearable interfaces or implement them in the direct environment to guarantee reliable contact with the user's skin.

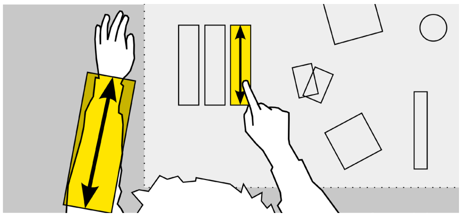

Figure 5: The Phantom Sensation may be used to convey the position of a virtual fader's knob to the user's forearm.

Figure 5 shows a potential scenario of use for the stimuli generated using the Phantom Sensation: The user is touching a fader widget on the interactive surface with the dominant hand. In reaction, the vibrotactile interface implemented in the table's border provides a tactile signal to the user's non-dominant forearm using a pair of actuators. The fader area is enlarged and mapped to the user's forearm to reduce visual load. Using the Phantom Sensation, only two actuators are needed even for high-resolution feedback.

Synchronized tactile illusions during touch interactions could convey the orientation, size and shape of interactive elements that are manually explored by the user. For example, the Phantom Sensation could be used to depict the position of a fader (see above) or the state of a pressure sensitive widget. One could also think of communicating abstract information, semantics or additional parameters not visually depicted in the interface. Examples may be the conveyance of a zooming level or a progress bar.

CONCLUSION AND FUTURE WORK

We have compared three actuator technologies to create a stable and repeatable Phantom Sensation. The vibrotactile actuator with amplitude inhibition mode turned out to be the most effective in terms of both quantitative and qualitative measures. Based on these findings, we presented scenarios for the utilization of vibrotactile Phantom Sensations.

Future evaluations should cover perceptual and conceptual aspects such as the role of the orientation of the interface in relation to the widget and the drawbacks of wearable actuator technology. Real life scenarios incorporating cognitive and visual load could identify drawbacks and opportunities.

In summary, the remote application of Phantom Sensations can help in creating interactions with rich tactile feedback. Complexity and effort for building these interfaces can be greatly reduced. Novel forms of tactile interfaces based on tactile illusions may help us in enhancing and enriching the interaction with ubiquitous environments.

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