Exploring the Perceptual Space of a Novel Slip-Stick Haptic Surface Display

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Abstract
Touch screens offer advantages for mobile interaction: large, rich graphical displays and powerful multi-touch input. However, they lack inherent haptic feedback to match this expressiveness. One recent approach to this problem has been to actuate glass plates at high frequency to controllably vary surface friction. This paper extends this work by describing *vibration beating*, a novel haptic actuation method that increases the range of cues that can be rendered via dynamic variations of surface friction. In order to understand how users perceive the cues it produces a set of 16 stimuli were chosen and two studies that generate and interpret a perceptual map are described. Three distinct clusters of tactile cues are identified, delimited and named. These groupings will form the basis of future work to develop interfaces and interaction techniques based on the vibration beating actuation method.

Keywords
Haptic; tactile; surface display; perceptual map

ACM Classification Keywords
H.5.2 [Information Interfaces And Presentation]: User Interfaces – Haptic I/O;

Introduction

The power of tablets and smart phones featuring large, rich graphical displays and expressive multi-touch input has popularized mobile computing for a range of sophisticated tasks including gaming, communication, social networking, navigation and office work. However, one long acknowledged limitation of the touch screen interaction paradigm is the lack of physical cues, of inherent haptic feedback [8]. On a touch screen, actions as diverse as tapping, scrolling, gesturing and drawing are not distinguished with a similarly diverse set of haptic responses; no matter what a user does, the screen feels the same.

In order to address this issue, mobile devices typically employ transducers or eccentric motors to create vibratory feedback in response to user actions [e.g. 2]. Although the buzzes and clicks produced by such systems are valuable, their use with touch screens is limited by the fact they are non-localized (e.g. cues propagate through the entire device) and by the limited range of feedback that can be generated (e.g. 5-9 discriminable cues [3]). Accordingly, researchers have begun to explore novel actuation paradigms that promise a more diverse set of sensations and better fit to the touch-screen form factor. One recent approach has been to provide haptic cues directly to the touch screen surface using phenomena such as electrostatic friction [1], a low latency technique which involves no moving parts, or the use of high frequency vibrations to produce a "squeeze-film" between a user's finger and the touch screen that results in sensations of variable surface friction [6].

The work described in this paper extends these efforts – its goal to increase the versatility, flexibility and scope of haptic surface displays. It achieves this through the introduction of *vibration beating*, a novel actuation approach for surface haptic displays that extends the capabilities of current squeeze-film devices to produce a wider variety of feedback. It then describes two studies to reveal how users perceive the cues this technique generates in terms of their similarity, distinctiveness and overall quality. This is achieved through a Multi-Dimensional Scaling (MDS) approach that captures and categorizes user perceptions of haptic sensations. The contributions of this work are the introduction of the novel vibration beating haptic actuation approach and the studies exploring perception of the cues it generates.

Related Work

A range of surface haptic displays to enrich mobile and touch-screen interaction paradigms have been proposed. Poupyrev et al.'s Ambient Touch [8], capable of producing a range of clicks and vibrations on a device screen, is perhaps the earliest example of such a system. In the decade since, researchers have created actuation techniques that support richer and more expressive forms of feedback. The T-PaD [9] is one example. This system uses a piezoelectric plate vibrating at imperceptible ultrasonic frequencies to minutely deform a glass sheet, generating a friction-reducing squeeze-film of air between its surface and a fingertip touching it. Varying vibration magnitude leads to different levels of this effect (and therefore of *slip-stick* or surface friction), a feedback modality that has been recently applied interaction with interface widgets [6]. The results include reports of improved user engagement and application realism. The slip-stick effect is a promising new paradigm for tactile display that this paper seeks to further explore.

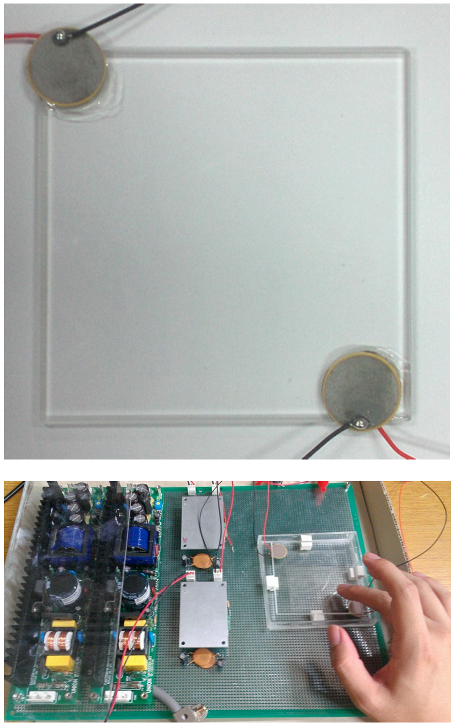

Figure 1. Haptic display hardware. Top image shows glass plate with circular piezoelectric elements mounted on two corners. Bottom image shows the complete hardware setup, including control electronics. The actuated plate is visible to the right of this image.

However, new forms of haptic cue, and the actuators that generate them, need be designed with close attention to human performance. Compared to visual and audio stimuli, relatively little is known about how haptic sensations are perceived (see Grunwald [4] for a recent review) and less still regarding how they can be appropriately designed and deployed to support users in interaction tasks. Indeed, many foundational studies of tactile cues, categorizing and defining how they can best be designed to support users, are relatively recent, even for established vibrotactile technologies [e.g. 3]. This paper argues that understanding how the feedback produced by novel actuators, and of the promising slip-stick effect in particular, is a timely research topic.

MDS, an established method for showing the relationships and commonalities in stimuli set, is an appropriate tool for achieving this objective. MDS is based on numerical ratings of the pair-wise subjective dissimilarity of a set of cues. This data is used to generate a perceptual map that optimally positions each cue with respect to all others. Interpretation of this map can yield clusters of spatially proximate cues, and provide insights into the dimensions along which they differ. The method has previously been applied to the sensation of real world haptic properties [5] and to the design of tactons, or virtual haptic icons, generated by vibrotactile motors [7]. We know of no work that has applied this method to cues generated by slip-stick surface displays.

Haptic Display Hardware

The haptic device studied in this paper is a novel variant of an ultrasonic friction-reducing display based on the squeeze-film effect. Its design is simple. Whereas existing displays [e.g. 6, 9] use one or more actuators exciting a glass plate at the same frequency, the system studied here uses a pair of identical actuators, situated on opposite corners of the plate and capable of operating at different frequencies. Specifically, the actuators are 16mm round, 0.5mm thick PI piezoelectric disks that are attached with epoxy glue to a 76.2mm square, 3.2mm thick Schott borofloat33 glass plate. The standard low-friction squeeze-film effect is produced by exciting the plate with vibrations from both actuators at a frequency of 39.5 kHz, empirically observed to be the system's resonant frequency. The device is pictured in Figure 1.

Varying the frequency of the two actuators enables more flexible and nuanced control of the slip-stick effect, increasing the amplitude and form of the sensations that can be rendered, an effect we have termed *vibration beating*. The frequency difference between the two actuators is the *beating frequency*. Specifically, in the current work, one actuator excites the plate at the optimal frequency (39.5 kHz), while the other operates in the range from 38.6 to 39.5 kHz, representing beating frequencies of 0-900Hz.

Informal subjective observations of the results of this procedure revealed that different beating frequencies led to a range of qualitatively different tactile sensations, from friction reduction through vibrations to apparent tangential forces. Empirical work to measure and physically quantify these effects is currently underway; this work in progress paper reports on parallel efforts to determine the subjective experience elicited in users by touching a surface subject to actuation with the vibration beating effect. It achieves this objective via two studies using multi-dimensional scaling analysis techniques.

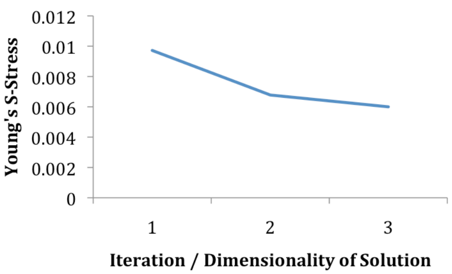

Figure 2. Results of stress tests on dimensionality of solution spaces in MDS study.

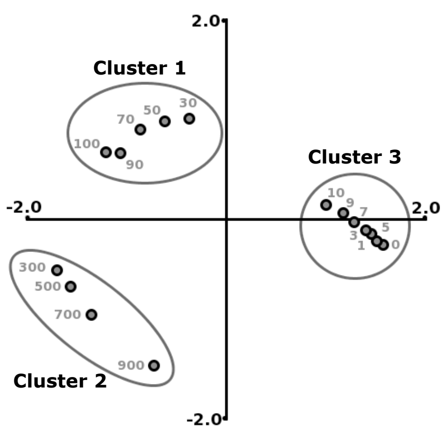

Figure 3. 2D perceptual map generated by ALSCAL MDS analysis. Data points are labeled with cue frequency. Three clusters (indicated by ellipses) have been manually added to the chart.

Multi-Dimensional Scaling Study

Participants, Materials, Procedures & Measures

Ten participants, with a mean age of 24, completed the study. Three were female and seven male. 16 haptic cues were used in the study, respectively displaying beating frequencies of 0, 1, 3, 5, 7, 9, 10, 30, 50, 70, 90, 100, 300, 500, 700 and 900Hz around the 39.5 kHz base frequency. This non-linear scale was selected as it maximizes the range of frequencies studied while also fitting expectations regarding human perception – specifically that Just Noticeable Differences (JND) are proportional to the magnitude of a stimulus rather than fixed and absolute values.

The experiment used a simple, reliable mechanism for capturing dissimilarity ratings. Each trial in the experiment involved the sequential presentation of a pair of cues on the same haptic device. Participants pressed a button to move between cues. After both had been explored, participants rated perceived dissimilarity on a 9-point Likert scale. Each participant compared each possible combination of cues once, leading to a total of 120 trials. The order of the two cues in each trial was randomized. In this way, the study generated a total of 1200 dissimilarity ratings.

Results and Discussion

Ratings from the participants were averaged to generate a mean dissimilarity rating. These data were analyzed in SPSS using the ALSCAL MDS procedure with a Euclidean distance algorithm for ordinal data. Young's S-stress, a measure of the degree to which a solution fails to account for the data, was calculated for solutions with one, two and three dimensions. The resultant scree plot (Figure 2) shows a modest "elbow", or point at which the decrease in stress slows markedly (and improvements drop below 0.001, a typical threshold), between the second and third dimensions. Consequently, a 2D perceptual map was selected for further analysis. This solution is shown in Figure 3. Three strongly delimited clusters of cues emerge around the frequency ranges of 0-10Hz, 30-100Hz and 300-900Hz. In order to identify, name and qualitatively distinguish between these three clusters and two dimensions a follow up study capturing attribute ratings relating to the 16 haptic cues was performed.

Attribute Ranking Study

Participants, Materials, Procedures & Measures

Eight graduate students (one female, seven male, mean age 26) participated in this study; six had also completed the previous experiment. The study was based on the 16 haptic cues and display device used in the previous experiment. However, rather than compare pairs of cues, participants rated each cue on the following three 11-item response scales: rough-smooth; slip-stick; and flat-bumpy. The choice of these terms is derived from attributes used in previous MDS studies of haptic perception [5]. The 16 cues were delivered in a random order to each participant.

Results and Discussion

Mean values for each of the cues on each of the scales were calculated; these data are shown in Figure 4. In order to explore how these figures relate to the perceptual map generated by the MDS analysis we adopted the approach described in Hollins *et al*. [5]. Regression analysis treating each of the three mean attribute ratings as dependant variables and the pairs of MDS coordinates as dependent variables were conducted. This generates a value, β (the standardized coefficient of regression), for each mean attribute

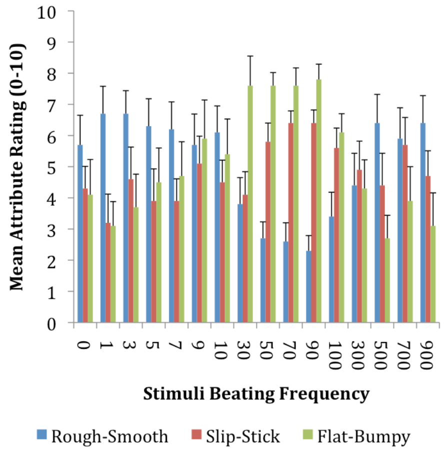

Figure 4. Mean ratings from attribute ranking study. Zero signifies a match the first attribute in each pair; ten to the second attribute. Bars show std error.

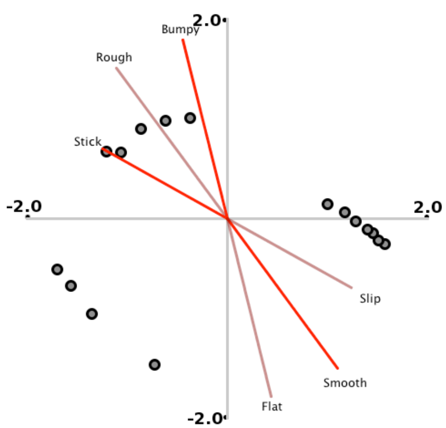

Figure 5. 2D perceptual map overlaid with β calculated in regression analysis. For ease of viewing β has been doubled and both positive (darker color) and negative (lighter) vectors are shown.

rating and value on each MDS dimension. Figure 5 visualizes these data as labeled vectors superimposed on the MDS perceptual map generated in the previous study. This technique provides an indication of how each of the attribute pairs relates to the cue clusters.

Perceptual maps generated by MDS are not aligned to meaningful axes; manual rotation of the plots is typically performed to facilitate data interpretation. Figure 5 suggests that the slip-stick attribute pair accounts for most variability in the x-axis, while the flat-bumpy pair accounts for that in the y-axis. Accordingly, the plot was rotated to align these dimensions with these respective axes; the plot in which slip-stick was aligned with the x-axis proved most explanatory and is shown in Figure 6.

This chart highlights the key aspects and limitations of the results. These include the suggestion that the original cluster 2 (see Figure 3) was too broad in scope. One of the cues (900Hz beating frequency) included in this grouping differs substantially from the others on the slip-stick axis; it was removed and the revised cluster in Figure 6 redrawn without it. It also appears that the three attribute pairs used in the second study were not sufficient to fully describe the perceptual space – some of the variability among the clusters (specifically in the y-axis) does not appear to be adequately expressed in the mean attribute ratings. Resolving this issue will require either a follow-up study that uses a broader range of attribute pairs, or a detailed analysis of the perceptual maps and attribute scales on a user-by-user basis (via an INDSCAL MDS analysis). It is not uncommon for individual differences to play a strong role in the interpretation of perceptual spaces [5] and exploring their impact on this study, and the vibration beating approach to haptic actuation of a glass plate, is a clear next step for this work.

Finally, figure 6 helps attach meaningful names and qualities to the cue clusters. Clusters 1 and 2 are both perceived to be sticky (high-friction) but to differ in their surface texture; cluster 1 is rated as relatively rough or bumpy, whereas cluster 2 is more flat or smooth. Cluster 3, on the other hand, is perceived to be slippery (low friction) and rough/bumpy. This description of cluster 3, which includes the standard low friction effect achieved with a beating frequency of zero, matches expectations from prior work [9]. Interpreting these results, we have labeled the clusters as follows:

- *Buzz* (cluster 1, 30-100Hz, a sticky vibration)
- *Electric* (cluster 2, 300-700Hz, a sticky plane)
- *Textured Ice* (cluster 3, 0-10Hz, slippery bumps)

These factors represent different classes of sensation users can discriminate (and recognize) without training. These results demonstrate that the vibration beating approach to variable friction display can enable a rich range of qualitatively different sensations, broadening the scope of this actuation technique. It also represents valuable progress towards quantifying how users perceive these sensations, showing there are three key clusters of cues. Follow-up studies will be required to validate the descriptions and understandability of these distinctions, and to explore the expressiveness of the device within each of these categories. In the meantime, they provide an actionable breakdown of the output capabilities that can be used in the design of haptics-enabled interfaces and applications.

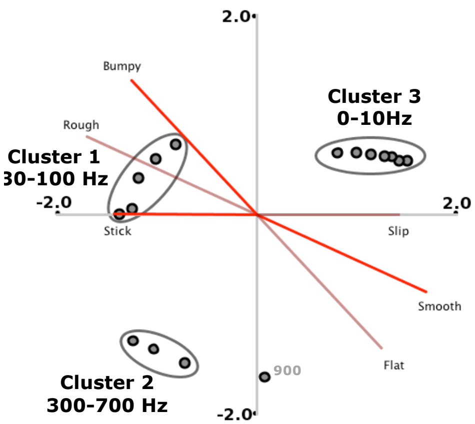

Figure 6. 2D perceptual map rotated to align with regression analysis of slip-stick attribute ratings. Revised clusters have been manually marked on the chart. One of the stimuli (900Hz) stands alone.

Conclusions and Future Work

This paper has briefly described a novel approach to haptic actuation of a glass plate based on dual piezoelectric actuators beating at different frequencies. It is capable of generating a wide variety of qualitatively different cues beyond simple variations in surface friction. Two studies were conducted to understand how users perceive and comprehend these sensations; three distinct clusters were quantified, identified and named. Future work will seek to improve on, develop and quantify the performance of the display hardware, to integrate it with touch screen components, to extend investigations of human perception and, ultimately, to explore how the device can be best used to support mobile interfaces and interactions. We believe the combination of variable friction with other tactile sensations (e.g. clicks, textures), as enabled by the vibration beating method described in this paper, represents a rich display modality well suited to supporting interaction tasks such as scrolling, dragging and gesturing.

In conclusion, advances in actuator design are enabling an entirely novel set of physical and haptic design attributes, such as variable friction, to be applied to interfaces on mobile devices. As these technologies develop and mature, studies of human perception, such as the one described in this paper, will be important to ensure that these new sensations are appropriately understood in terms of how they are perceived by user. This paper takes first steps towards achieving this goal for the vibration beating approach to haptic actuation.

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References

[1] Bau, O., Poupyrev, I., Israr, A., and Harrison, C. 2010. TeslaTouch: Electrovibration for Touch Surfaces. In Proceedings of UIST '10. ACM, New York, NY.

[2] Brewster, S., Chohan, F. and Brown, L. 2007. Tactile feedback for mobile interactions. In Proceedings of CHI '07. ACM, New York, NY, USA, 159-162.

[3] Brown, L.M., Brewster, S.A. and Purchase, H.C. 2005. A first investigation into the effectiveness of Tactons. In Procss of World Haptics 2005. Pisa, Italy.

[4] Grunwald M (Ed.), Human Haptic Perception, Birkhäuser Verlag, 2008.

[5] Hollins, M., Bensmaïa, S., Karlof, K. and Young, F. 2000. Individual differences in perceptual space for tactile textures: Evidence from multidimensional scaling. In *Attention, Perception & Psychophysics 62*, 8.

[6] Levesque, V., Oram, L., MacLean, K., Cockburn, A., Marchuk, N.D., Johnson, D., Colgate, J.E. and Peshkin, M.A. 2011. Enhancing physicality in touch interaction with programmable friction. In Proceedings of CHI '11.

[7] Pasquero, J., Luk, J., Little, S., MacLean, K. E. 2006. "Perceptual Analysis of Haptic Icons" in Proceedings of IEEE-VR'06, Alexandria, VA, USA.

[8] Poupyrev, I., Maruyama, S. and Rekimoto, J. 2002. Ambient touch: designing tactile interfaces for handheld devices. In Proceedings of UIST '02. ACM, NY, 51-60.

[9] Winfield, L., Glassmore, J., Colgate, J., and Peshkin, M. 2007. T-PaD: Tactile pattern display through variable friction reduction. In Proceedings of Worldhaptics 2007, IEEE, Tsukuba, Japan.