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Determining the Haptic Feedback Position for Optimizing the Targeting Performance on Ultrasonic Tactile Displays

Farzan Kalantari[1], Edward Lank[2], Yosra Rekik[1], Laurent Grisoni[1], and Frédéric Giraud [3]

Abstract— **Alongside questions of how to create haptic effects on displays via alternative hardware, recent work has explored rendering options with respect to haptic effects, i.e. when and where to provide haptic feedback. In particular, recent work by Zhang and Harrison for electrostatic haptic feedback noted that the optimal technique for haptic feedback during interaction is the Fill technique, where haptic effects are rendered at all times when a user's finger is within the bounds of the target. In this paper, we explore whether this result generalizes to an alternative haptic rendering technology that uses ultrasonic vibrations to create haptic sensations, a technique called the "Squeeze Film Effect". In contrast to prior work, our results indicate that positioning the haptic feedback as a discrete linear stimulus centred on the target provides an optimal trade-off between speed, accuracy, and user preference. We highlight the implications of this work to the generalizability of haptic feedback: Haptic feedback can improve time, errors, and user satisfaction during interaction, but *only if* the correct form of feedback is used for the specific haptic effect generated by the hardware.**

I. INTRODUCTION

Modern devices such as smartphones, tablets, and ultra portable computers frequently leverage touch as a primary input modality. Touch is an attractive input modality because the dexterity and sensitivity of our fingers makes possible a wide range of fine-grained manipulations and subtle variations of force. While touchscreen devices originally sensed touch as a binary state – touching or not-touching – recently we see ever-finer capture of characteristics of touch. For example, Android devices sometimes examine touch contact area to provide an estimate of pressure and recent Apple touch sensors have incorporated force sensors to accurately capture force applied during input. On the other hand, while consumer devices have begun to use additional information for touch input, these devices still rarely provide fine-grained haptic output despite established research that demonstrates the need for haptic output, i.e. haptic feedback, to enhance efficiency and realism during common interaction tasks [1].

Researchers exploring fine-grained haptic output typically explore various forms of dynamic haptic feedback to enhance input on touchscreen devices. Within this space of dynamic haptic feedback, four main technologies are used. First, vibrotactile actuators such as solenoids, vibrotactile coils, and ERM motors can be utilized for tactile rendering on touchscreens [2]. These actuators are used presently on smartwatches, mobile phones and tablets, but typically provide for a device, on-or-off sensation. Alongside vibrotactile actuation, two techniques, "electrostatic-vibration" [3], [4] and "electroadhesion" [5] use electrostatic force generated, respectively, by applying a voltage to the screen surface or by applying DC excitation of the tactile display. Both of these techniques increase the friction between the finger and the interaction surface when activated, thus varying the perceived stickiness of the surface. Finally, a fourth type of haptic feedback uses ultrasonic vibrations to generate an air-gap between a user's finger and the display to reduce friction when activated, a phenomenon called the *"squeeze film effect"*.

In 2015, Zhang and Harrison [6] examined how different haptic rendering techniques (shown in Fig. 3) affect target acquisition times and error rates for one type of haptic effect, electrostatic haptic feedback. However, given the significant differences between haptic effects, it seems reasonable to assume that different types of haptic effects might have different optimal renderings.

In this paper, we study haptic rendering techniques for an alternative haptic effect, the squeeze film effect. We describe a study replicating the experimental design of Zhang and Harrison [6]. We show that, for haptic feedback displays based on the squeeze film effect, the optimal rendering technique of Zhang and Harrison, haptic Fill, is not optimal for both time and error rate. We find instead that, balancing time and error, an alternative strategy called *line centre*, i.e., applying a haptic effect when the user's finger's contact point is at the centre of the target, best balances time and error rate.

II. RELATED WORK

A. The Squeeze Film Effect

While explaining all dynamic tactile rendering techniques is beyond the scope of this note, our specific hardware system utilizes a specific tactile rendering technique called the "squeeze-film effect" (Figure 1). The squeeze-film effect is an over-pressure phenomenon while generates an ultra-thin air film between two surfaces, similar to the way an air hockey table allows the puck to float with low friction. To create this air gap, an ultrasonic vibration of a few micrometers is applied to the surface. This pushes the surfaces slightly apart, allowing one surface to slide more easily across the other. In haptic rendering, the surfaces are the display screen which vibrates and the user's finger which is pushed slightly

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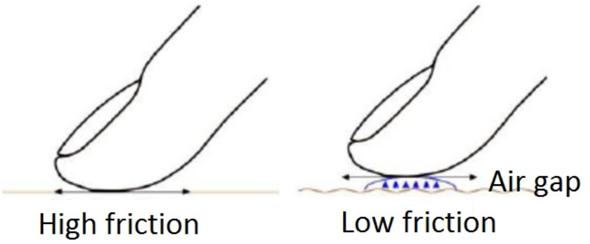

Fig. 1. The principle of squeeze film effect. Ultrasonic vibration creates an air gap which reduce the friction.

away from the surface by the vibration as described in [7]–[11]. An implication of squeeze film effect rendering is that, unlike electrostatic techniques which increase friction, squeeze film haptic rendering reduces friction when active.

B. Interaction Techniques with Tactile Feedback on Touchscreens

It has been shown in [12], [13] that haptic feedback based on friction reduction using the squeeze film effect is able to improve the performance of interaction techniques. Liu et al. [14] have recently investigated the effect of electrostatic vibration for evaluating the accuracy and efficiency of pan gestures on haptic touch screens. In literature we can also find several studies using haptic pens for improving the performances of different interaction techniques as explained in [15], [16].

In recent work, Zhang and Harrison [6] presented the first study on how best to use electrostatic vibration to enhance targeting. Specifically, they showed that, both from the perspective of time and errors, providing a tactile sensation across the entire target – electrostatic Fill – was the best strategy for designing dynamic haptic feedback as opposed to providing more localized haptic feedback (e.g. along one edge, in the centre, or in the background). In our research, we work with a dynamic haptic feedback system that leverages the squeeze film effect to provide dynamic haptic feedback. Furthermore, because the squeeze film effect works differently than electrostatic vibration – reducing rather than increasing friction – it was unclear to us whether, given the different sensations, electrostatic Fill would remain the optimal technique to enhance targeting. Therefore, in this paper we have applied the same comparative approach and procedure as in [6] to determine the positioning of haptic feedback for improving the user's targeting performance on ultrasonic based touchscreens using the squeeze film effect.

III. EXPERIMENT

With the exception of our haptic display technology, to preserve experimental validity we use the same experimental design of Zhang and Harrison [6]. We use an identical number of participants and an identical set of haptic feedback techniques while substituting squeeze film effect haptic output. For completeness, this section describes our apparatus, participants, and method.

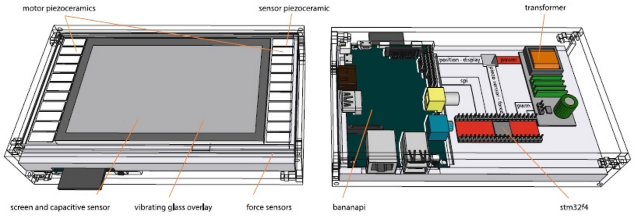

Fig. 2. The structure of E-ViTa haptic feedback display [17]

A. Apparatus

We used *E-ViTa* (Enhanced Visual-Tactile Actuator), a tactile feedback tablet based on ultrasonic vibrations to create the squeeze-film effect for haptic rendering [17]. A sine-wave grating with a spatial period of 1000 μm and an amplitude of 1.25 μm was applied to generate haptic feedback sensation to a user's fingertip. E-ViTa is developed on a Banana Pi, a single-board computer (Shenzhen LeMaker Technology Co. Ltd, China) with a 1 GHz ARM Cortex-A7, dual-core CPU and 1 GB of RAM working in parallel with STM32f4 microcontroller (STMicroelectronics, France). The communication between the microcontroller and the single board computer is provided via the Serial Peripheral Interface (SPI) bus at 10 kHz. This single-board computer is connected to a 12.5cm capacitive touchscreen (Banana-LCD 5"-TS, MAREL, China) for detecting the user's finger position on the display with a sampling frequency of 62 Hz.

Ten $14 \times 6 \times 0.5$ mm piezoelectric cells actuate a $154 \times 81 \times 1.6$ mm fixed glass plate, resonating at 60750 Hz with a half wavelength of 8 mm. A power electronic circuit converts a 12V DC voltage source into an AC voltage, controlled in amplitude and frequency and supplied to the piezoelectric cells. The microcontroller synthesizes a pulse-width modulation (PWM) signal to drive a voltage inverter that actuates the piezoceramics. The detailed structure of the E-ViTa haptic display is illustrated in Figure 2.

B. Participants

Twenty healthy volunteers (9 females) from the age of 24 to 37 and the mean age of 29.4 participated in our experiment. All participants were right-handed. They were all naive to the aim of the study and had no previous experience with haptic feedback displays. Participants were wearing active noise-cancelling headphones (Panasonic RP-DJS200, Japan) during the experiment, while Gaussian white noise was played at a comfortable listening level in order to prevent potential interference from auditory cues. The experiment took on average approximately 40 minutes.

C. Experimental Design and Variables

The experiment was a $5 \times 3 \times 5$ repeated measures within-subjects design. To determine significant main effects, repeated measures analysis of variance was applied for the following independent variables: *feedback* (*No Feedback*, *Line Leading Edge*, *Line Background*, *Line Center* and *Fill*), *target width* (Small: 30 pixels = 4.125mm, Medium:

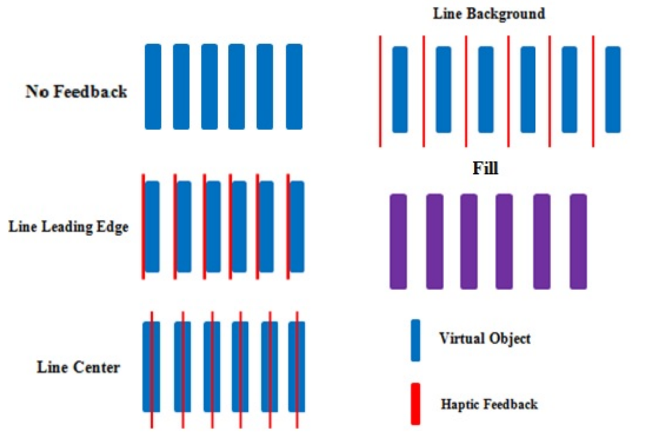

Fig. 3. Four haptic feedback and *No Feedback* designs in our experiment (adapted from [6])

50 pixels = 6.85mm and LARGE: 80 pixels = 11mm and *distance* (*shortest*: 114 pixels = 15.675mm, *short*: 228 pixels = 31.35mm, *medium*: 342 pixels = 47.025mm, *long*: 456 pixels = 62.7mm, *longest*: 570 pixels = 78.375mm where *distance* corresponds to the distance between the center of the control area and the center of the target area. The four haptic feedback designs as well as the *No Feedback* condition are illustrated in Figure 3.

The order of *feedback* conditions was counterbalanced among the participants. Under each *feedback* condition and for each *target width* × *distance* combination, participants completed five trials. *Target width* × *distance* combinations were presented in a random order. Overall, we have a total of 5 *feedback* × 3 *target width* × 5 *distance* × 5 repetitions $=$ 375 trials performed by each participant.

D. Procedure and Task

The experiment proceeded as follows. First, a brief description of our task as well as all the necessary instructions for interacting with our haptic feedback display were given to each participant. Participants were given about 10 minutes of training and familiarization before beginning the main task. We used a drag and drop task identical to past experiments contrasting haptic rendering techniques [6]. As illustrated in Figure 4, for each trial, the participant was required to correctly select the blue rectangular virtual object. Then the selected object had to be dragged and successfully dropped on a specified target, a red virtual object (Figure 3). The black objects were considered distractors. The red target became green to confirm that the trial had been successfully completed and the participant proceeded to the next trial. The trials in which participants were not able to perform the task correctly were marked as errors. The trials were repeated for each of the five haptic feedback options (No Feedback, Line Leading, Line Background, Line Center, and Fill) with the different target widths and distances as noted in the section on Experimental Design.

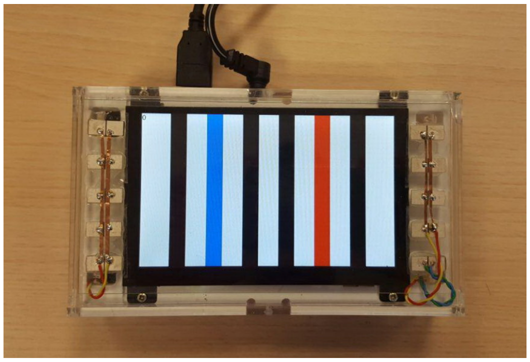

Fig. 4. An example setup of the trials in our experiment

IV. RESULTS

To understand the effect of different haptic rendering techniques, we analyze the effect of independent parameters on *error rate*, *number of failed attemps*, *number of overshoots* and *trial time* (our dependent measures). We also analyzed the subjective responses of participants vis a vis the five haptic feedback options. While our primary interest is in determining the effect that haptic feedback options have on these dependent measures, to further determine potential interaction effects between indepdent variables, all analyses were multi-way ANOVA. Tukey tests were used post-hoc when significant effects were found. In the following, we report the results for each of the dependent variables.

A. Error Rate

Targets that were not selected on first attempt were marked as errors. There were significant main effects of *target width* ($F_{2,28}$=54.76, p< 0.0001) on *error rate* but there was also a significant effect of *target width* × *distance* ($F_{8,112} = 2.63$, p $=$ 0.01) and *distance* × *feedback* ($F_{16,224} = 2.28$, p<0.005) interactions. Post-hoc tests revealed that for SMALL *target width*, performance deteriorated more significantly among decreasing *distance* (p< 0.05). Similarly, we found that for all *distance* conditions, performance deteriorated more significantly among decreasing *target width* (p< 0.05). Importantly, we found that for the *Fill* condition, *error rate* was significantly higher for LONGEST *distance* (mean 10.22 %, S.D 4.24%) than for SHORTEST *distance* (mean 23.11 %, S.D 7.77%) (p< 0.05).

The most compelling *haptic feedback* position, with respect to *error rate* was *Line Background* (mean 13.06%, S.D

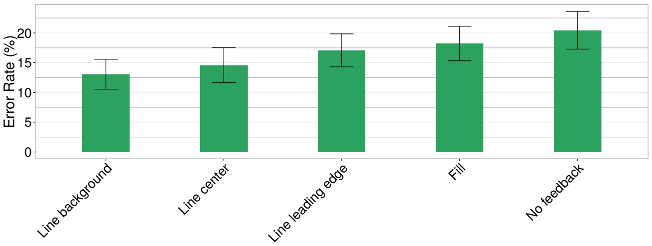

Fig. 5. Average error rate cross feedback conditions. Error bars are standard error across participants (95% CI).

2.51%) followed by *Line Center* (mean 14.57%, S.D 2.94%), *Line Leading Edge* (mean 17.06%, S.D 2.77%), *Fill* (mean 18.22%, S.D 2.90%) and *No Feedback* (mean 20.44%, S.D 3.16%) condition (see Figure 5). These results are in contrast to the findings of [6] when using electro-static based haptic display in which the *Fill* condition was found to provide the best performance. However and similar to [6], post-hoc tests showed no significant differences between different *line haptic feedback* types.

B. Number of Failed Attempts

We found that there was a significant main effect of *target width* ($F_{2,28}$= 5.88, $p< 0.001$) on *number of failed attempts*. Post-hoc tests revealed that the *number of failed attempts* is significantly higher with SMALL *target width* than with MEDIUM or LARGE *target width*s ($p< 0.05$). We correlated these results with comments from participants who felt that selecting and dragging virtual objects with small size was difficult. The major reason for these difficulties (as explained in [18]) is due to the limitation of the object size which can be accurately perceived by the user's finger on ultrasonic (squeeze-film effect) haptic displays.

C. Number of Overshoots

Number of overshoots were measured as the number of times when the participants enter and leave the target without selecting it. There was a significant main effect of *target width* ($F_{2,28}$= 10.63, $p< 0.05$) on *overshoots*. Post-hoc tests revealed that the *number of overshoots* is significantly larger with SMALL *target width* than with MEDIUM or LARGE *target widths* ($p< 0.05$).

D. Trial Time

Trial time was measured from the first control area movement, to target successfully selected. There were significant main effects of *target width* ($F_{2,28}$= 120.04, $p< 0.0001$) and *distance* ($F_{4,56} = 99.78$, $p< 0.0001$) on *trial time*, but there was also a significant main effect of *target width* × *distance* ($F_{8,112} = 2.79$, $p < 0.001$) interaction. Post-hoc tests revealed that the *trial time* increased more significantly for the SMALL *target width* among decreasing *distance* ($p< 0.05$). Similarly, the *trial time* increased more significantly for the *shortest*, *short* and the *medium distance* respectively among decreasing *target width* ($p< 0.05$).

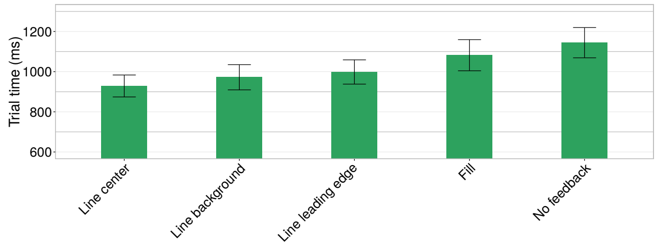

Fig. 6. Average trial time cross feedback conditions. Error bars are standard error across participants (95% CI).

The best *feedback* position, with respect to *trial time* was *Line Center* followed by *Line Background*, *Line Leading Edge* and *Fill* which lowered the trial time by respectively 18.84%, 15.04%, 12.75% and 5.45% compared to *No Feedback* condition (see Figure 6). For *error rate*, these results are in contrast to the findings of [6] in the case of electrostatic haptic displays in which the *Fill* condition has been found to provide the shortest *trial time*. We have also found a significant main effect of *Line Center*, *Line Background* and *Line Leading Edge* feedback conditions compared to *No Feedback* ($p< 0.05$) on *trial time*.

E. Qualitative Ranking

Participants were also asked to rank the five haptic feedback positions after completing the experiment. *Line Center* was the most preferred feedback with an average score of 4.2 (SD = 0.94), followed by *Line Background* with an average score of 3.8 (SD = 1.14), *Line Leading Edge* with an average score of 3 (SD = 0.96), and *Fill* feedback with an average score of 2.4 (SD = 0.73). The *No Feedback* condition received the lowest average score of 1.53 (SD = 1.40). These results present an interesting contrast with Zhang and Harrison [6], where *Fill* was most preferred and *Line Center* and *Line Background* least preferred.

We correlate these results with the comments of participants who felt that the three line haptic feedback conditions had better performance, required less concentration, and were less frustrating for accomplishing the experimental task. In particular one participant noted that he or she was *"comfortable with the line haptic feedback particularly in order to select and drag the small size of objects and ... to select the target"*. Another found advantages in precision, i.e. that *"when the tactile feedback is a line, I think that I can select the target even if my eyes are closed... those tactile feedback conditions tell me that there is either a distractor or the target, so I just need to count to know whether I'm on the target or not!"*. In contrast, for the *Fill* condition, the participants felt that it was cumbersome and required more concentration and time. One participant noted that the *"high amount of vibrations under my finger is not very pleasant and I'd prefer the other haptic feedback designs"*. Several participants also found a delay in notification for the Fill technique, with one claiming that he or she *"preferred the [line-based forms] of haptic feedback [because they] warned me before arriving at the target"*, thus increasing accuracy. Finally one participant noted that he or she was *"frustrated with [Fill] feedback... [because] it disturbs me and [requires] more concentration"*.

Despite the relative advantages of Line Centre/Background over the Fill condition, all participants found that haptic feedback of any form was an advantage. In the case of *No Feedback*, the participants declared that, *"Without any haptic feedback [it] is definitely harder to select and drag the objects, specially for the small sizes... I need lots of concentration in order not to pass the target and finish each trial successfully"* and that, *"If I wanted to do the task with a high velocity of touching the object with no haptic feedback,* *it was kinda impossible to finish each trial without several attempts and repetitions! Therefore it became a bit boring after several attempts."*

V. DISCUSSION

While all haptic feedback techniques clearly perform better than the No Feedback condition, analyzing our haptic feedback techniques using both qualitative ranking and quantitative effects, the main take-away from this work is that *Line Center* seems an optimal feedback technique balancing user preference (most preferred), speed (fastest selection time) and error rate (second lowest error rate) when using squeeze film effect haptic rendering techniques. *Line Background* and *Line Leading Edge* might also be possible rendering options for haptic effects. Finally, for squeeze file effects, *Fill* seems a poor choice both from the perspective of user preference (least preferred), time (slowest), and errors (highest).

As we noted before, for a competing haptic feedback technology, electrostatic vibration, Zhang and Harrison found that *Fill* was the best technique and that *Line Center* and *Line Background* were typically poor performers in time, error, and user preference when compared to *Fill*.

Alongside haptic rendering techniques, we note that our experiment results in a higher error rate than Zhang and Harrison [6]. In their work, they obtained an error rate of approximately 8%, compared to our error rate of 16.67%. While it is possible that haptic rendering differences may result in higher or lower error rates, we believe that other potential confounds may explain this discrepancy. These include factors such as touchscreen performance (Zhang and Harrison used 3M Microtouch capacitive panels over a standard LCD screen whereas we used the E-Vita, a standalone portable device) and participants (Zhang and Harrison's participants were significantly younger than ours – adults average age 24 versus adults average age 29 in our experiments). This is particularly true because of the discrepancy in the No Feedback condition. If haptic effects were responsible for increased error rate, one would expect that the No Feedback conditions would remain similar.

While we were surprised by these results, it may be the case that post-hoc rationale exists for the contradictory effects. After all, the squeeze film effect serves to reduce friction when active, whereas electrostatic techniques then to increase friction when active. It may be the case that participants can effectively sense increase in friction, thus arguing for the advantage of background based feedback techniques. However, the overall advantage of *Line Center* are not fully explained by this rationale. We believe that the overall message of this work is simply that different haptic technologies produce different physical sensations for the end user. These differences in physical sensation limit the overall generalizability of rendering options between competing technologies. As new techniques are developed, additional work will be required to explore how best to perform haptic feedback such that speed and accuracy are maximized.

One additional data point that both Zhang and Harrison [6] and our work presented here demonstrates is that effective haptic feedback continues to show advantages over no haptic feedback. Optimal haptic rendering techniques exhibit a 15 - 25% improvement in both speed and error rate. However, poor haptic rendering choices significantly effect these performance improvements. For the Squeeze Film Effect (our technique), choosing *Fill* haptic feedback results in less than 10% improvement, and, for electrostatic vibration (Zhang and Harrison's technique), choosing *Line Center* haptic feedback results in almost no improvement in time or error. As a result, the argument for haptic feedback is nuanced: Haptic feedback appears to improve time, errors, and user satisfaction, but *only if* the correct form of feedback is used for the specific haptic feedback technology generated by the hardware.

VI. CONCLUSION

We conducted an experiment to determine the best tactile feedback position on ultrasonic (squeeze-film effect) haptic displays for targeting tasks. Our results demonstrate that the *Line Center* condition provides the best balance of improved speed, accuracy, and user satisfaction compared to other techniques. We also note that the contrast between these results and past research on haptic feedback techniques [6] advocates for a need for caution when attempting to generalize results across different hardware configurations.

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