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Characterizing Tactile Rendering Parameters For Ultrasound Based Stimulation

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Abstract— **In this study we identify and measure the parameters that can perceptually drive a smooth and continuous vibrotactile sensation exerted by a focused ultrasound array at the palm of the dominant hand. We conducted a psychophysical experiment that measures (1) the minimum stimulation duration that is perceived by the participants as continuous, (2) the minimum stimulus onset asynchrony (SOA) duration that is perceived as continuous, and finally, (3) the minimum stimulation intensity that is perceived by the participants expressed in terms of the driving signal modulation frequency. The effect of the first two parameters was also examined spatially by repeating the experiment with an increased number of stimulation points. Results showed that a perceivable stimulation can occur for a stimulation duration between 5ms and 60 ms and an SOA of less than 50 ms. The study also showed that these parameters can be relaxed if the density of stimulation is increased (higher number of stimulation points for the same stimulation pattern). Finally, the study showed that the minimum perceivable modulation frequency is about 470Hz. In the conclusion, we summarize the study findings and provide perspectives for future work.**

I. Introduction

Among the different forms of haptic interaction, tactile stimulation is of high interest in the haptic research community, especially in the development of teleoperation feedback [1], in medical applications [2], in virtual reality [3] and entertainment [4].

Tactile stimulation can be achieved through contactful or contactless interaction of devices that transfer mechanical energy to the human skin. Such apparatuses can be vibration based (vibrotactile), focused ultrasound, surface acoustic wave tactile devices, electrorheological or magnetorheological devices, air jet, laser, or electrotactile stimulation devices [5] [6] [7].

Of the previously mentioned methods, focused ultrasound tactile stimulation is emerging as the most efficient contactless tactile stimulation method because of its high spatial and temporal resolution, which makes it ideal to render tactile stimulation, and mainly because of the ability to achieve stimulation in a contactless fashion [5].

Focused ultrasound stimulation is based on a phenomenon called acoustic radiation pressure. It is exerted at a surface that acts as an obstacle to the propagation of an acoustic wave, and it is defined as the pressure difference between the acoustic wave propagation pressure (Lagrangian pressure) and the static pressure that would have been existed in the absence of the obstacle [8]. Ultrasound phased arrays are emitting acoustic waves from multiple acoustic sources and when the signals driving the sources are properly phased, the emitted sound waves are superimposed at a precalculated location. At this location, the acoustic radiation pressure is the sum of all the pressures of the emitted waves.

Despite the intense research and development of ultrasound phased array-based tactile displays, stimulation patterns are mostly rendered empirically and there is not sufficient study on the rendering techniques used by the ultrasound arrays in order to efficiently stimulate users.

The aim of this study is to identify, investigate and determine the rendering parameters that can be used in order to effectively stimulate the users. The rest of this study is organized as follows: we present how other schemes of tactile stimulation are rendered in Section II; we describe the experimental method and the tactile display we used to conduct the experiment in Section III; the experimental results are presented and analyzed in Section IV; while the conclusions of this study and our future work are discussed in Section V.

II. Related work

Regarding the in-contact tactile stimulation there is a plethora of studies that investigated various stimulation patterns. Geldard was the first who studied the spatio-temporal discrimination perceived on the skin close to the eyes and ears in 1950 [9].

A tactile illusion called ”tactile saltation” was studied by Tan et al. who developed a vibrotactile display to investigate it [10]. Bonani et al. [11] succeeded in creating an illusory vibrotactile movement by using vibration motors in order to generate affective touch. Many other researchers investigated the spatio-temporal resolution of such vibrotactile stimuli in various parts of the human's body such as the back, the neck, and the arm through a series of psychophysical experiments [12][13][14][15].All these studies are based on contact-full vibration motors.

The illusions of funneling and saltation are very well studied illusory tactile feedback techniques. For the funneling illusion the skin is stimulated in two distinct points with different intensities of stimulation, resulting in a perceivable stimulation somewhere in between these points. For the saltation illusion the stimulation points are excited progressively with an overlapped stimulus onset asynchrony (hereafter SOA) which generates an illusion of a moving stimulation along the stimulation points [16].

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In our previous work we described the SOA thresholds between discrete/continuous and simultaneous/continuous stimulation for in-contact tactile actuators in order to generate a smooth continuous movement sensation by utilizing the saltation illusion [17]. Israr et al. developed the ”Tactile Brush”, an algorithm that renders tactile stimulation patterns on 2-D space by using a contact 2-D tactile display and utilizing the aforementioned illusions [18].

Regarding the contactless tactile displays, there has been recently an intense development of ultrasound based tactile displays. Dalecki et al. showed first that underwater ultrasound radiation could generate tactile sensation [19]. Shinoda et al extended the topic further by developing a 2-D utrasound display with 324 transducers capable of generating airborne tactile stimulation [20]. Gavrilov presented a method to display 2D tactile shapes by generating multiple focus ultrasonic focal points [21]. A research team called ”Ultrahaptics” developed a multi point ultrasound tactile feedback system capable of generating a 2-D tactile sensation in midair [22]. Long et al. aslo performed a usability study on their method of volumetric rendering of haptic shapes using focused ultrasound arrays which showed that the users were capable of identifying simple 3-D objects through the sense of touch [23].

It is clear that despite the extended development of such systems, there is little to no research on how the tactile stimulation that is generated by these systems can be perceptually rendered in order to produce the desired experience from the user’s perspective.

For all of these reasons, we conducted a psychophysical experiment in order to identify the parameters which would, perceptually, drive an ultrasound array to produce smooth and continuous midair tactile sensation based on user feedback at the palm of the dominant hand.

III. Experimental Method and Setup

A. Identification of Parameters

In order to conduct the experiment, the Haptogram ultrasound display (Figure 4) was utilized. The development of the Haptogram display was thoroughly discussed in our previous work [24] and its characteristics has been experimentally identified and measured [25].

Haptogram is a 2-D 10-by-10 ultrasound transducer array that, when properly phased, generates a focal point which can programmatically be moved very fast to create apparent tactile motion within the working space. The focal point can be perceived as a pressure point based on the phenomenon of acoustic radiation pressure. By successively changing the position of the focal point, a perceivable haptic shape can be created. Some very important questions arise, though. Firstly, what is the perceptually optimal duration of stimulation at each point. Secondly, what is the perceptually optimal time delay between two (or more) successive simulations (SOA) and how the duration of each parameter is affected when the number of stimulation points is increased. Finally, what is the range of stimulation intensity that a user can perceive.

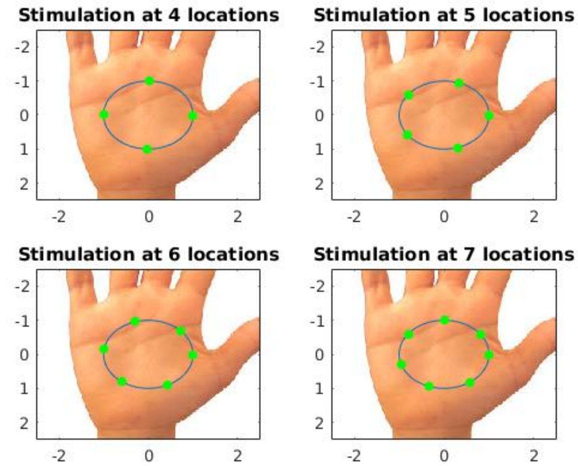

Fig. 1. The four different stimulation patterns.

B. Stimulation Duration

To answer the first question, users were stimulated at the anterior surface of their hand (palm) with the Haptogram array at four different points (top left of Figure 1). The array was focusing at each point for a short duration (1ms) with almost no delay in between the different position stimuli (<1ms). At each iteration, the user had to respond if they felt stimulation at the four different focal points as being simultaneous. If the answer was YES then the duration of the pulse was increased by an interval. After some iterations, and when the duration of the stimulation at each point was long enough, the user changed the answer from YES to NO since the stimulation no longer felt simultaneous. After this point the duration of the stimulation started decreasing at each iteration but with a smaller interval until the stimulation became again short enough for the user to change the answer again. The program recorded the duration of the stimulation after five answer changes. The same procedure was repeated for five, six, and seven focal points arranged on a circle of 6cm diameter (Figure 1) and 12cm above the array (as shown in Figure 4). Figure 2 shows the procedure that was followed for the first part of the experiment.

C. Delay Between Stimuli (SOA)

To answer the second question, a fixed duration stimulation was introduced to the participants with a long delay in between the four different locations of stimulation (>100ms). The participants had to answer if the stimulation felt discrete. After each iteration that the user was answering YES, the duration of the delay became shorter and after some time the user was no longer feeling the stimulation as discrete, and the answer changed to NO. Then, the delay started increasing again with a shorter interval until the user felt the stimulation discrete and changed the answer again. After five changes of the answer the delay was recorded. The same procedure was repeated for five, six, and seven focal points arranged on a circle of 6 cm diameter (Figure 1) and 12 cm above the array

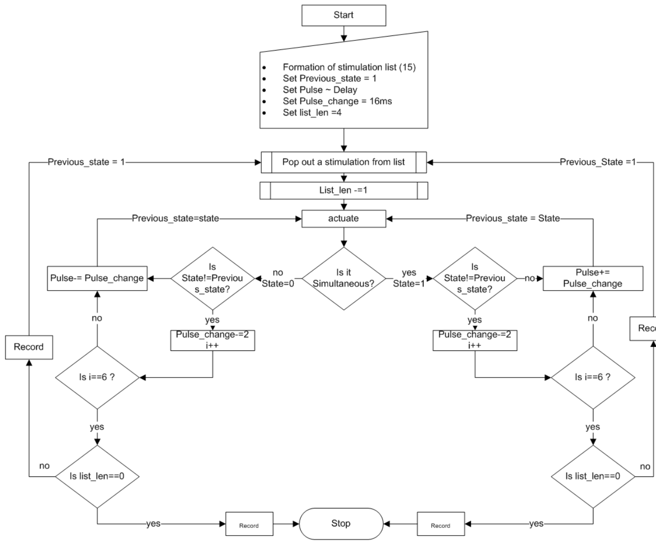

Fig. 2. Flowchart of the experimental procedure followed to determine the perceptually minimum pulse duration.

(as shown in Figure 4). Figure 3 shows the procedure that was followed for the second part of the experiment.

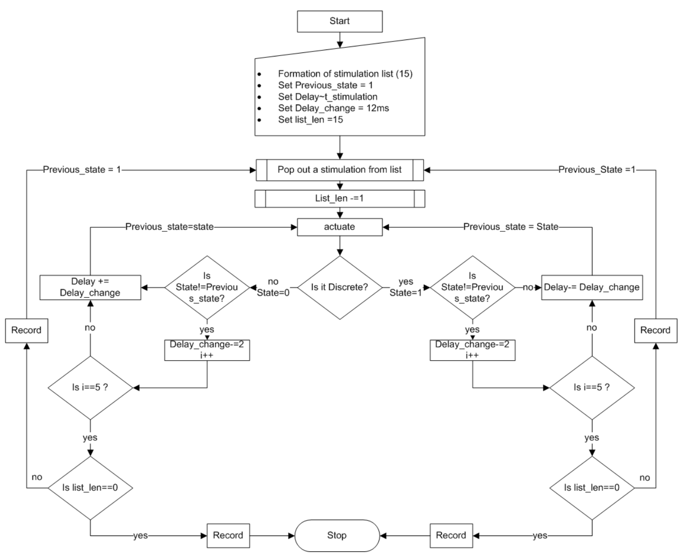

Fig. 3. Flowchart of the experimental procedure followed to determine the perceptually minimum delay duration.

D. Minimum Intensity

The Haptogram tactile display is also capable of providing a varying intensity of stimulation at each focal point by modulating the 40kHz signal that is driving the ultrasound transducers with a lower stimulation frequency signal, which caused an increase in the perceived intensity. Human skin can perceive tactile frequencies from 40Hz to 1000Hz. At lower frequencies the perceived intensity is higher and at higher frequencies the perceived intensity is lower.

A secondary objective of this study was to measure what is the modulating frequency that will produce the minimum perceivable intensity from the array. To answer this, a similar approach with the previous experiment was adopted. The user was stimulated at the center of their palm (single point of tactile stimulation) with a low modulation frequency. The user was asked to answer if the stimulation is perceivable at each iteration. While the user was answering YES, the modulation frequency was increasing until the user answered NO. Then the modulation frequency started decreasing again, with a smaller interval. After five changes of the answer, the modulation frequency was recorded. The same procedure was followed in order to determine the minimum perceivable intensity from the high modulation frequency side.

Fig. 4. The Haptogram device/Experimental setup.

E. Experimental Setup

Eighteen voluntary participants took part in the experiment (ages 19 to 42). All the participants had a normal sense of touch by their own report and had basic or no prior knowledge of the haptic technology that was used. The participants were initially introduced to the experiment and the technology behind it. The experimenter had minimal engagement during the experimental sessions, given that the experimental procedure was fully automated. Figure 4 shows a participant during the experimental session. The experiment was approved by New York University Abu Dhabi IRB committee.

IV. Results

The parameters that were considered in this study are three: Pulse duration, delay duration, and the minimum intensity of stimulation. The goal is to determine the perceptual values for these three parameters in order to achieve a smooth continuous tactile sensation at the palm of the dominant hand generated by an ultrasound tactile display. The minimum thresholds of each parameter are presented below for four to seven points of stimulation, as perceived by the participants.

A. Stimulation Duration

The first parameter under examination is the duration of the stimulation at each point. Figure 5 shows the average of the minimum stimulation duration needed to be perceived as continuous for 4 to 7 distinct points. It is clear that the average duration of stimulation becomes shorter as the number of stimulation points increase. The duration of stimulation deviates significantly though (from 50ms for 4 stimulation points to around 30ms for 7 points). Consequently, it is very difficult to determine the perceptually dominant stimulation duration for an arbitrary number of stimulation points from Figure 5.

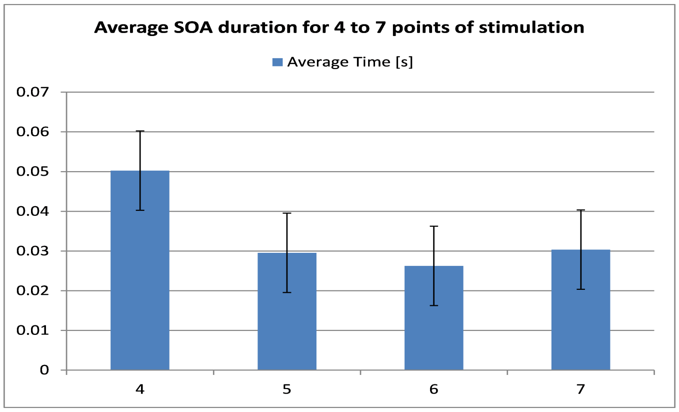

Fig. 5. Average time and standard deviation of the stimulation duration for 4 to 7 stimulation locations.

By examining how the participants are converging to the different temporal duration ranges, conclusive results can be extracted about the optimal pulse duration value.

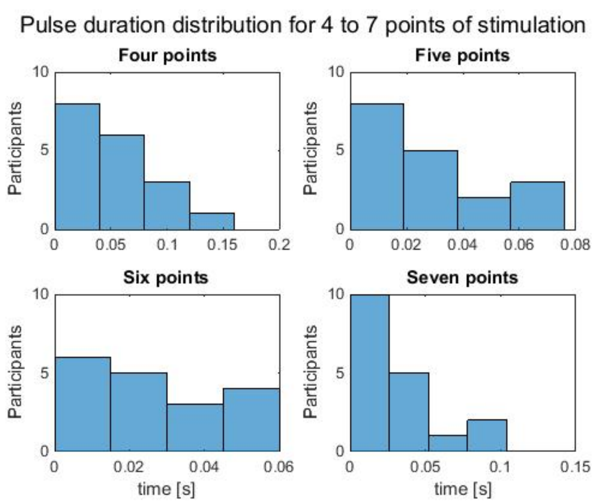

Fig. 6. Histograms of the stimulation duration distribution for 4 to 7 stimulation locations.

The histograms of Figure 6 show the distribution of the participants' convergence in four different time bins for the corresponding number of stimulation points. It is clear that most of the users converge to short duration stimuli, especially as the number of stimulation points increases. This becomes clearer in Figure 7 where the distribution of the duration convergence is examined regardless of the number of stimulation points. Almost 88% of the participants are converging to a minimum stimulation duration in the range of 5ms to 50ms and all the participants can perceive the stimulation as continuous when the duration is higher than 5ms (total minimum).

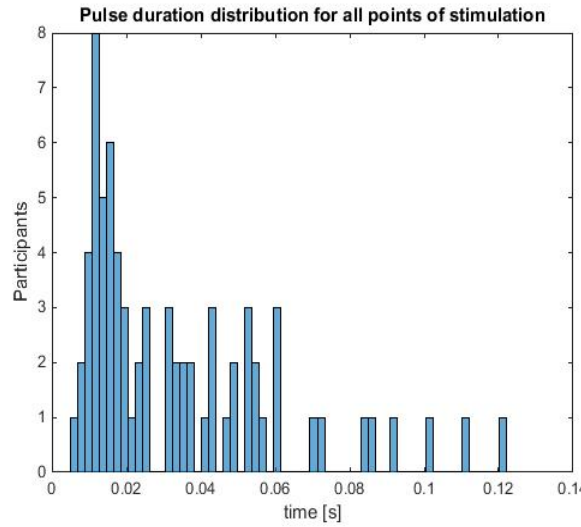

Fig. 7. Histogram of the stimulation duration distribution regardless the number of stimulation locations.

B. Delay Between Stimuli (SOA)

A similar analysis can be done for the second parameter. Figure 8 shows the converged average delay duration between the consecutive stimuli for the different number of stimulation points. It is clear that the minimum delay duration is increasing as the number of stimuli points is increasing, which is logical since as the number of stimulation points is growing, the spatial distribution becomes denser and thus a continuous stimulation can be perceived even with longer delays between stimuli. Still, the convergence delay duration for the different number of stimulation points is deviating significantly, and more useful results regarding the optimal SOA duration can be extracted from figure 9, which displays histograms for how participants convergence in four different duration ranges (bins). It can be seen that most

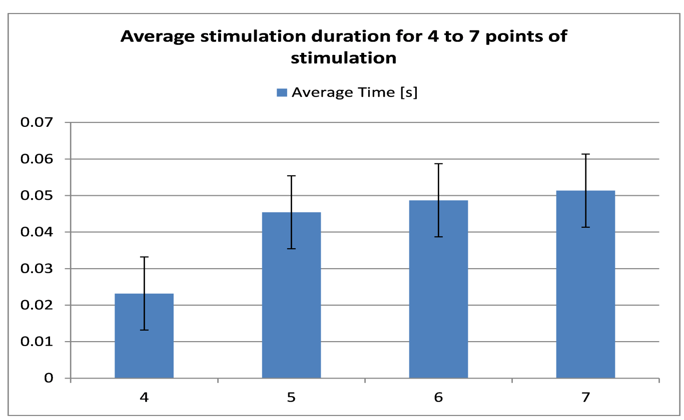

Fig. 8. Average time and standard deviation of the SOA duration for 4 to 7 stimulation locations.

of the users converge to a shorter delay duration between stimuli.

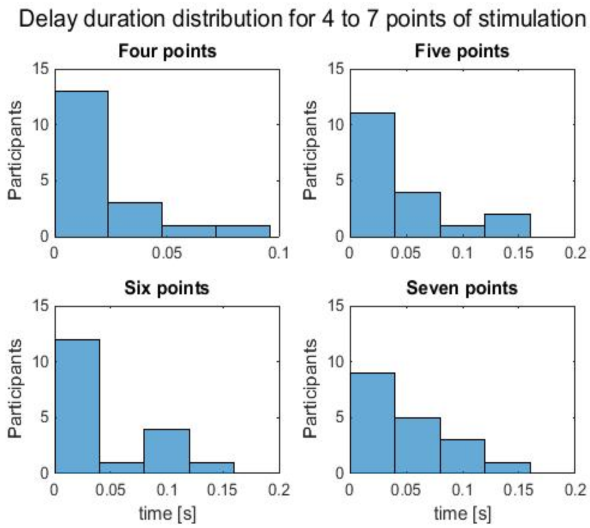

Fig. 9. Histograms of the SOA duration distribution for 4 to 7 stimulation points.

Figure 10 further highlights that more than 66% of the participants are converging to a SOA region between 0 and 40ms. Therefore, it is safe to assume that the users can perceive a smooth continuous stimulation with SOA of less than 40ms.

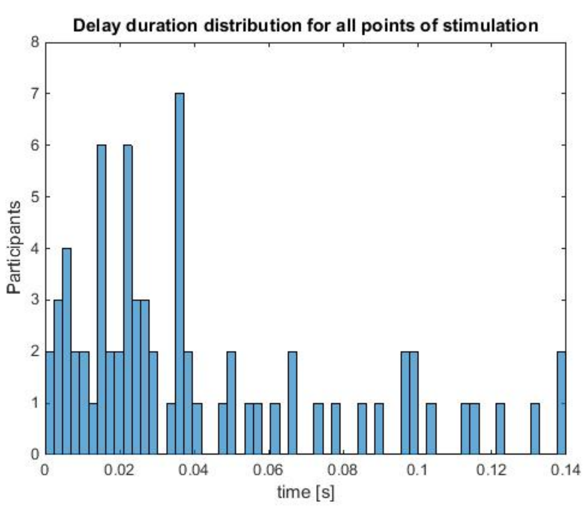

Fig. 10. Histogram of the SOA duration distribution regardless the number of stimulation locations.

C. Minimum Intensity

The final parameter under investigation is the frequency that is required to modulate the transducers driving the signals in order for the users to perceive the minimum intensity from the stimulation. This is the minimum intensity threshold that the users can perceive. Figure 11 shows the average of the modulation frequency that achieves this threshold. The low-to-high-frequency bar approaches the threshold from lower modulating frequencies (higher perceived intensity) to higher modulation frequencies (lower perceived intensity), whereas the high-to-low-frequency bar approaches the threshold form high to low modulation frequency.

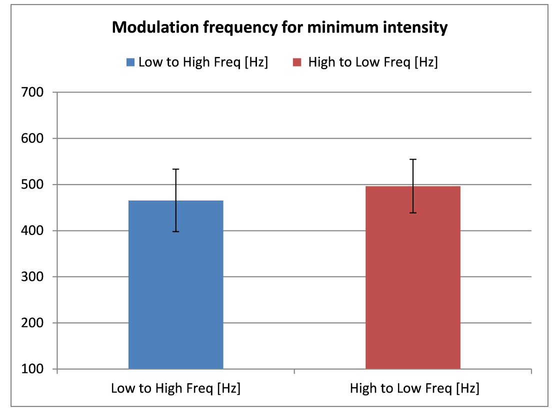

Fig. 11. Average and standard deviation of the modulation frequency driving signal.

It is clear that there no significant differences regarding the minimum threshold of the perceived intensity which is located at around 470Hz of frequency modulation.

By taking under consideration the aforementioned results, a perceptual stimulation signal that can render a smooth continuous sensation has the following properties: a stimulation duration from 5 to 50ms, an SOA less than 40ms, and a driving signal that is modulated by a frequency between 40Hz and 470Hz. Finally, as the density of the stimulation points increases, the first two parameters can be relaxed.

V. CONCLUSIONS

The motivation for this study is to identify and characterize the rendering parameters of tactile stimulation with focused ultrasound array at the palm of the dominant hand. Results from this study can be utilized to render various tactile stimulation (simultaneous, continuous, and discrete) for different applications. For instance, 2D and 3D tactile shapes can easily be created and customized to fit various application needs. As for future work, we plan to investigate the use of ultrasound-based tactile stimulation in immersive haptic applications. An interesting future work would be to examine the thresholds for different parts of the human body (the current study focused on the palm, therefore future work may consider upper arm, chest area, back, or neck).

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