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Absolute Detection Threshold of Vibrotactile Stimulation Pulse Width and Inter-Pulse Gap

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***Abstract*— Vibrotactile stimulation is often used in sensory substitution systems and brain-machine interfaces for presenting information to the skin. This paper identifies the temporal resolution required to achieve the absolute detection threshold of vibrotactile stimulation. A custom vibrotactile sleeve was designed to conduct two experiments with multiple trials on seven subjects. The results show that the absolute (50%) detection threshold for a single vibrotactile stimulus is 15ms pulse width with a proposed adequate (90%) detection threshold of at least 25ms pulse width for the average user. Furthermore, the absolute detection threshold for an inter-pulse gap between two vibrotactile stimuli is 15ms, with a proposed adequate detection threshold of at least 20ms inter-pulse gap. This work concludes that a single vibrotactile message should have a temporal resolution of at least 25ms pulse width in addition to 20ms inter-pulse gap. Hence, a single vibrotactile message requires a total of 45ms.**

I. INTRODUCTION

Sensation and perception are two separate processes that are very closely related. Sensation is input about the physical world obtained by the humans' sensory receptors, and perception is the process by which the brain selects, organizes, and interprets these sensations. Perception of the same senses may vary from one person to another because each person's brain interprets stimuli differently based on that individual's learning, memory, emotions, and expectations. The most common type of stimuli is tactile stimulation through the skin receptors. One modality that has been increasingly investigated to stimulate skin receptors is vibrotactile stimulation, which refers to the perception of vibration through touch. Vibrotactile stimulation is often used in sensory substitution systems [1] and brain-machine interfaces [2] for presenting information to the skin by mechanical stimulation using vibration motors. Such interfaces offer the potential to communicate large amount of information to the user. Understanding the temporal perception limits of vibrotactile stimulation would define the speed at which vibrotactile messages could be delivered, laying the foundation for rapid vibrotactile communication protocols.

Many studies have been conducted to determine the fundamentals of vibrotactile stimulation parameters such as the vibration frequency, amplitude, intensity, and location. Humans have four mechanoreceptor channels specifically dedicated to detecting vibrational tactile information [3]. The Pacinian (P) channel is the most relevant to vibrotactile application due to its capability of detecting a vibration frequency of 250-300Hz [4]. The vibrational amplitude, however, is dependent upon the vibrational resonance frequency of the device; and the vibrational intensity often refers to the combination of the vibrational frequency and amplitude. The intensity of vibration is dependent on the location of the human body, as each location has a different receptor density and therefore various detection threshold [5]. Several studies have targeted the forearm as a location for investigating the spatial acuity of vibrotactile stimulation and reported that a minimum distance of 2.5cm is required to discriminate between two vibrotactile stimulation on two different spots [6]. The forearm is a suitable location for an unobtrusive and private stimulation. Despite the increase in vibrotactile stimulation use, there has not been any extensive studies that exclusively aim to test and determine the temporal parameters of vibrotactile stimulation, thus highlighting the need for a comprehensive study to explore the temporal resolution of vibrotactile stimulation.

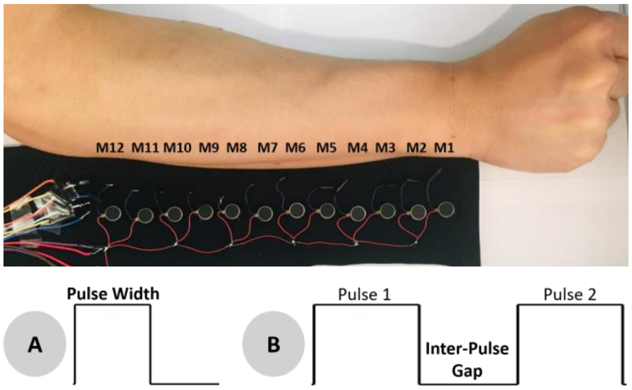

Fig. 1. (Top) a sleeve consisting of twelve vibrators for stimulating vibrotactile sensation on the user's forearm. (Bottom) The two tested temporal parameters: A) minimum pulse width and, B) inter-pulse gap.

The absolute detection threshold is defined as the degree of intensity of a stimulus necessary to correctly detect that stimulus 50% of the time [7]. This paper is the first study that identifies the temporal resolution required to achieve the absolute detection threshold of vibrotactile stimulation. Using the vibrotactile sleeve shown in Fig. 1, the goal of this study was to determine the minimum pulse width (i.e. pulse duration) for a single vibrotactile stimulus as shown in waveform A in Fig. 1, and the smallest perceivable inter-pulse gap (i.e. the smallest delay between two vibration stimuli) as shown in waveform B in Fig. 1. Section II covers the design and implementation of the custom vibrotactile sleeve designed and utilized for this work. Section III and IV describes the objective, methods, and results of both

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experiment 1 and experiment 2, respectively. Section V concludes this work and its results.

II. VIBROTACTILE APPARATUS DESIGN

The vibrotactile apparatus designed for this study consists of two main elements: a wearable vibrotactile arm sleeve and a smart circuit interface for driving the vibration motors. The design requirements of this system are I) capability to be wearable and portable to conduct ubiquitous experiments for characterizing vibrotactile stimulation parameters, and II) ability to perform realtime autonomous vibrotactile stimulation.

The vibrotactile sleeve shown in Fig. 1 consists of twelve vibration DC motors, which are also known as eccentric rotating mass (ERM) motors. ERM motors are extremely popular in smartphones and often used to offer vibration alert notifications to the users. These motors rely on the rotation of an unbalanced load (i.e. eccentric) to create vibration effects on the human skin [8]. The motors mounted on the sleeve are miniaturized coin-shaped vibration motors with a 10mm diameter, as shown in Fig. 2. The small form factor of these motors facilitates portability of the vibrotactile sleeve and lowers the overall power consumption. Moreover, the 10mm ERM motors were chosen for their relatively cheap cost and ease of control. The motors frequency and amplitude cannot be controlled independently from each other. However, for the purpose of vibrotactile stimulation, they can be controlled to have a vibration frequency between 200-250Hz and an intensity of 0.6-1.0Grms by simply varying the voltage between 3-5V. Such vibration frequency and intensity range are sufficient to stimulate a sense of touch on the human skin. Using different frequencies and amplitudes could vary the detection threshold and thereby the ERM motors frequency and amplitude used for this study are fixed to 250Hz and 1.0Grms, respectively. The twelve ERM motors mounted on the sleeve are made by Adafruit.

In order to conduct autonomous vibrotactile stimulation, a smart circuit interface was designed to drive the ERM motors on the sleeve in realtime. The circuit schematic shown in Fig. 3 illustrates the connection between the ERM motors and the microcontroller I/O pins. Each motor is connected between 5V power supply and the Collector pin of a bipolar junction transistor (BJT). The Collector current flowing through the motor is controlled by the voltage applied at the Base pin of the BJT. The Base pin of each BJT is then connected to an I/O pin of the microcontroller board, thus enabling the system to control the Collector current through software. The Collector current was measured at 80-100mA when applying an output voltage of 3-5V through an I/O pin. In other words, a Collector current range of 80-100mA corresponds to a vibrational frequency range of 200-250Hz and intensity of 0.6-1.0 Grms. This enables the users to experience a range of vibrational parameters and tune it to match their skin sensitivity (if needed) using software controlled vibrotactile sleeve. The twelve transistors are 2N2222 NPN BJTs, and the microcontroller used to interface with the circuit is an 8-bit architecture development board with the ATMEGA32U4 series as the core and twenty-two digital I/O pins.

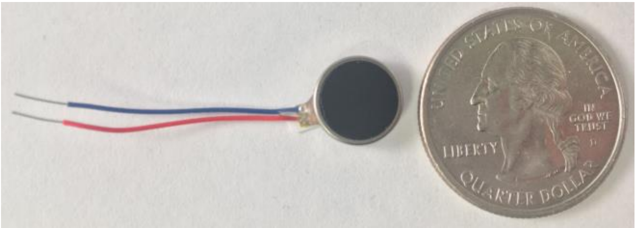

Fig. 2. Coin-shaped 10mm diameter eccentric rotating mass (ERM) motor used on the vibrotactile sleeve.

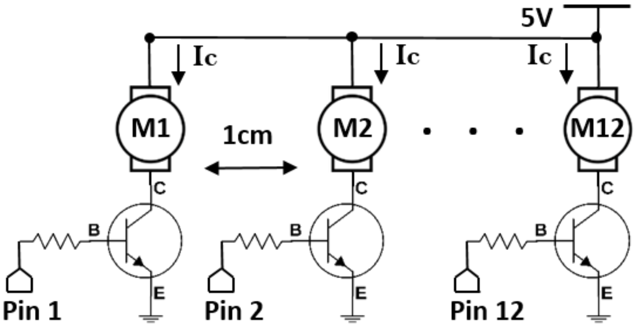

Fig. 3. A circuit schematic illustrating the connections between the ERM motors and microcontrollers I/O pins to conduct autonomous vibrotactile stimulation in realtime.

III. EXPERIMENT 1: ABSOLUTE DETECTION THRESHOLD OF A SINGLE VIBROTACTILE STIMULUS

The goal of this experiment is to determine the perceptibility of a single vibrotactile stimulus and its temporal parameters. Specifically, the experiment aims to answer the questions of whether the user can feel the vibrotactile cue being rendered and the minimum detectable pulse width of a single vibrational signal that can be stimulated as shown in waveform A in Fig. 1. Psychophysics researchers represent the sensitivity to physical stimuli via the absolute detection threshold, which is the weakest level of energy required by an external stimulus to be detectable by the human senses 50% of the time [7]. This experiment determines the absolute detection threshold of a single vibrotactile stimulus in terms of the stimulus pulse width. Moreover, this work propose the adequate detection threshold of a single vibrotactile stimulus, which we define as the degree of intensity of a stimulus necessary to correctly detect that stimulus at least 90% of the time. This threshold level is better suitable for critical application such as sensory substitution systems for navigation and assistive driving.

A. Methods

Seven subjects were tested to determine the absolute and adequate detection threshold for a single vibrotactile stimulus. The test setup requires the participant to place their dominant forearm on the vibrotactile sleeve as indicated in Fig. 1. The twelve ERM motors were ensured to make contact with the participant skin where M1 positioned at the wrist and M12 placed near the elbow. The participants were trained for approximately thirty minutes to become familiar with vibrotactile stimulation and how it feels on the skin. Each subject has performed ten trials and each trial renders thirty-six vibrotactile stimulations with a fixed pulse width as shown in Fig. 4. For instance, trial 1

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renders a 50ms pulse width thirty-six times evenly across M1 and M12. The pulse widths tested in this experiment are 15ms, 20ms, 25ms, 30ms, 35ms, 40ms, 45ms, 50ms, 55ms, and 60ms. During each trial, the subjects is asked to respond “yes” upon detecting or feeling a single vibrotactile stimulation whilst the test administrator is recording these responses. The possible outcome of each vibrotactile stimulus in this experiment is either 0 or 1, where 1 being detected by the participant and 0 being undetected. A random delay of one to three seconds is inserted as buffer between each pulse width for the subject to give their answer. This random delay is not the inter-pulse gap examined in the second experiment. The purpose of this delay is to give the participant time to respond, and eliminate any consistent pattern of stimulation that might affect the subject’s expectations. Essentially, the key variable across the ten trials is the pulse width of the vibrotactile stimulus and this experiment examines several vibrotactile pulse widths from 15-60ms for seven subjects.

B. *Results*

Fig. 5 shows the perceptibility per subject across a range of pulse widths. Each data point in the figure is the average of six stimulations rendered evenly on M1 and M3 (wrist area). The data for the rest of the M locations are part of a larger study and will not be investigated in this paper.

Fig. 5 shows that four out of seven subjects reach an absolute detection threshold at 15ms pulse width with perceptibility higher than 50%. However, two subjects had a 0% perceptibility at 15ms pulse width, meaning that they did not feel any vibration on their skin during that trial. This results in a substantial standard deviation of 41.94% and thereby a 15ms pulse width may not be suitable for crucial applications. Similarly, the 20ms pulse width had two subjects with a 16.67% and 66.67% perceptibility as shown in Fig. 5. The standard deviation for this trial was 31.1%, which indicates that a 20ms pulse width may not be easily detectable for everyone. The next trial with a 25ms pulse width scored a perceptibility range of 83.33-100% with a standard deviation of 6.3%, which is significantly lower than the previous two trials. Lastly, all seven subject were able to achieve 100% perceptibility for the subsequent seven trials with a pulse width range of 30-60ms.

The average perception of a vibrotactile stimulus as a function of pulse widths is shown in Fig. 6. Each data point on this figure is the average of seven points. Fig. 6 shows that a pulse width of 15ms had an average perceptibility of exactly 50%, thus making it the absolute detection threshold for the average user. The data also shows that a 20ms pulse width has an average perceptibility of 80.95% among seven subject, despite the large 31.1% standard deviation. Furthermore, Fig.6 shows that the 25ms pulse width trial had an average perceptibility of 97.62%. If the adequate detection threshold is defined as the intensity of perceptibility higher than 90%, then a pulse width of 25ms meets that standard. The rest of the 30-60ms pulse widths scores a 100% perceptibility as shown in Fig. 6. Based on the individual and average perceptibility results shown by Fig. 5 and Fig.6, we recommend using a pulse width range of 25ms or higher as basic unit for constructing vibrotactile messaging protocol.

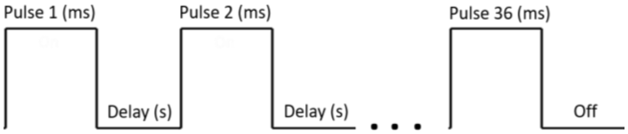

Fig. 4. Experiment 1 waveform used for testing the pulse width. Each trial renders thirty-six pulses with a fixed pulse width.

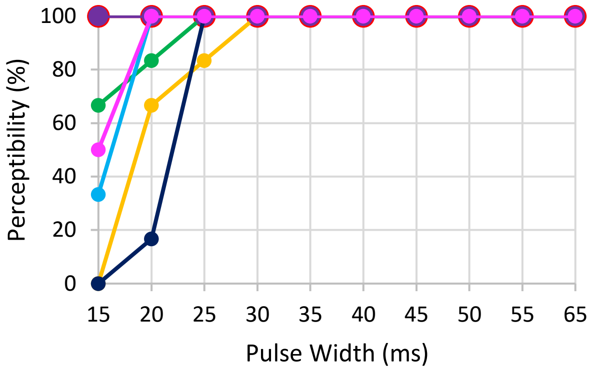

Fig. 5. Perceptibility per subject to a single vibrotactile stimulus as a function of pulse width.

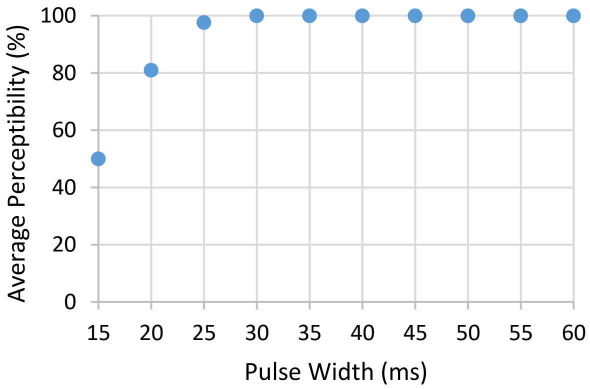

Fig. 6. Average perceptibility of seven subjects of a single vibrotactile stimulus as a function of pulse widths.

IV. EXPERIMENT 2: ABSOLUTE DETECTION THRESHOLD OF THE INTER-PULSE GAP BETWEEN TWO VIBROTACTILE STIMULI

The goal of the second experiment is to determine the perceptibility of two vibrotactile stimuli and their temporal parameters. Specifically, the experiment aims to answer the question whether the user can feel two vibrotactile cues being rendered and what is the minimum detectable inter-pulse gap (i.e. the smallest delay between two vibration stimuli) that can be used for the user to feel two distinct vibrotactile stimulations as shown in waveform B in Fig. 1. The pulse width used in this waveform is fixed at 50ms due to its 100% perceptibility achieved in the previous experiment.

A. *Methods*

The same seven subjects were tested to determine the absolute and adequate detection threshold for inter-pulse gap. The experiment setup is similar to the first experiment

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and shown in Fig. 1. Each subject has performed seven trials and each trial renders thirty-two vibrotactile stimulations of two types. Sixteen of these stimulation are of a one-pulse type (waveform 1) and the other sixteen are of a two-pulse type (waveform 2) as shown in Fig. 7. The idea is to test whether the participants feel a one-pulse or two-pulse waveform on their skin. For the two-pulse waveform, each trial has a fixed inter-pulse gap, and the gaps tested are 1ms, 3ms, 5ms, 10ms, 15ms, 20ms, and 25ms. For instance, trial 1 randomly renders sixteen 50ms one-pulse waveform and 50ms two-pulse waveform with an inter-pulse gap of 15ms. Test subjects are asked to say “one” upon detecting a single vibrotactile stimulus or “two” upon feeling two distinct vibrotactile stimuli. After each waveform, a random delay of two to three seconds is inserted to give participants time to respond. The expectation of this experiment is that if the inter-pulse gap is long enough, the subject should be able to distinguish between one-pulse stimulation versus two-pulse stimulation. Otherwise, the subject should only feel a one-pulse as the inter-pulse gap becomes shorter.

B. Results

The average perception of inter-pulse gap between two vibrotactile stimuli is shown in Fig. 8. The absolute detection threshold for the inter-pulse gap is shown to be 15ms with an average perceptibility of 80%. However, an inter-pulse gap of 20ms achieved an average perceptibility of 100% among all seven subjects, which is higher than the adequate detection threshold. Therefore, an inter-pulse gap of at least 20ms is recommended be used for constructing multi-pulse vibrotactile communication protocols. By combining the results from this experiment and experiment 1, this work concludes that the basic unit of constructing a single vibrotactile message should have a temporal resolution of at least 25ms pulse width in addition to 20ms gap, a total of 45ms per vibrotactile message.

Fig. 8 also shows an unexpected increasing trend in the average perception of inter-pulse gap below 15ms. Explicitly, the inter-pulse gaps of 10ms, 5ms, 3ms, and 1ms have an average accuracy of 30%, 40%, 40%, and 60%, respectively. The expectation of this experiment suggest that the perceptibility should decrease as the inter-pulse gap becomes shorter, which contradicts the results shown in Fig. 8. Many of the test subjects has expressed a general consensus that a two-pulse waveform with a 1ms inter-pulse gap felt longer than a one-pulse waveform, but did not necessarily feel as a two-pulse stimulus. This indicates that a 1ms inter-pulse gap did not improve the perceptibility of detection but rather led the subjects to correctly guess it because they learned to compare the length of one-pulse to two-pulse stimulus. One approach to mitigate this side effect is to increase the pulse width of the one-pulse waveform to a 100ms pulse in order to make it feel similar to the two-pulse waveform, thus making it more difficult for the subject to guess based on the length of vibrations.

V. CONCLUSION

This paper is the first study that identifies the temporal resolution required to achieve the absolute detection threshold of vibrotactile stimulation. Two experiments were conducted on seven subjects each with multiple trials. The results show that the absolute detection threshold for a single vibrotactile pulse width is 15ms with a proposed adequate detection threshold of 25ms pulse for the average user. The absolute detection threshold for the inter-pulse gap between two vibrotactile stimuli is 15ms, with an adequate detection threshold of at least 20ms inter-pulse gap. The results conclude that the basic unit of constructing a single vibrotactile message should have a temporal resolution of at least a 25ms stimulus duration with a 20ms inter-pulse gap, a total of 45ms per vibrotactile message.

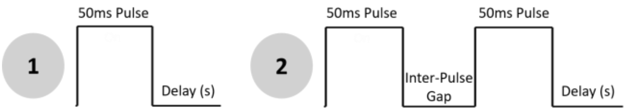

Fig. 7. Two types of waveforms randomly rendered followed by a delay.

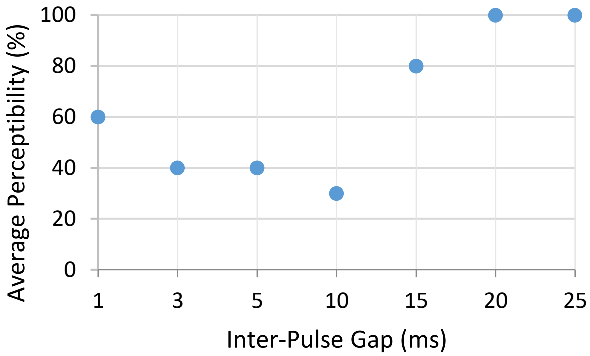

Fig. 8. Average perceptibility accuracy of inter-pulse gap between two vibrotactile stimuli.

ACKNOWLEDGMENT

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