Use of High-Frequency Pulses to Generate Unique Electrotactile Sensations for Real-Time Feedback in Wearable Sensory Systems

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***Abstract*— Wearable real-time systems such as health monitors exhibit a need for user feedback capable of communicating a wide range of messages. This paper describes how high-frequency (100 - 2k Hz) electrotactile stimulation pulses can be utilized for producing multiple unique message sensations within a limited time period of 0.5s. Two experiments were conducted on willing participants using a custom electrotactile stimulator. Experiment 1 investigated the effectiveness of producing unique sensations by varying electrotactile pulse frequency above 100Hz. Results indicate that even though pulse frequencies above 100Hz produce detectable sensations, discrimination by frequency higher than 100Hz is not feasible. Experiment 2 investigated the effectiveness of discriminating electrotactile pulse frequencies higher than 100Hz when the signal was modulated at a fixed low frequency (6Hz) "bundle". Results show that variations in low-frequency Bundle duty-cycle produced at least three distinct sensations that may be utilized to expand the available set of uniquely perceived electrotactile sensations.**

Keywords—electrotactile feedback; point-of-care; wearable sensing

I. INTRODUCTION

Advancements in processing capabilities, either in commercially available smartphones or embedded processors such as compute modules and microprocessors have ushered in new possibilities for on-the-go computing and sensing. The lives of billions of individuals globally are heavily influenced by information acquired by and communicated through such "devices". One of the most common implementations of such devices is through wearable real-time health monitoring systems [1]–[3].

In a wearable real-time health monitoring system, the sensing agent often works in parallel with its human user, observing factors that the human cannot naturally perceive, for instance bio-markers, skin conductance, social interaction dynamics, and environmental parameters such as air pollution. These measurements are then processed and fed back to the user. In a real-time monitoring system such as a psychological health monitor [1], [3] or an air pollution sensor [2], the observation results must be communicated back to the user in real-time. Depending on circumstances, the communication may have to be discrete, unobtrusive, or capable of complex message content. For example, in case of a wearable behavioral therapy system for posture balance in patients with degenerative cerebellar disease, the wearable balance control system must be in constant communication with the user to issue balance-correction commands [4]. As such, the communication between a wearable health monitoring system and the user will have a great impact on the effectiveness of the overall system.

From a neuroscience perspective, communication with a human subject is only possible through primary human senses, especially visual, audio, and tactile. Currently the predominant method of communication is through visual and audio cues, e.g. displaying messages on a smartphone screen or playing notification sounds, because these methods permit conveying complex information to the user. However visual and audio are not suitable for real-time feedback due to their obtrusive nature and their toll on human attention span. Multiple studies have shown that audio and visual inputs require a substantial amount of human attention [5],[6], and over-reliance on these inputs may create attention deficiency and anxiety [7]. Brain-machine interface literature supports an alternative communication path through artificial tactile stimulation called electrotactile feedback [8]–[10]. This style of feedback can provide information to the user through the largest sensory organ in human body -the skin- in an unobtrusive and discreet manner. Furthermore, studies have shown that tactile input is one of the least attention-demanding inputs to the human brain and can even improve focus and attention span in task related cases [11]. Currently, electrotactile stimulation is reliant on emulating vibration frequencies in the range of 10Hz to 100Hz to generate uniquely perceivable tactile sensations, with only a few distinct sensations in that range [12]. As a result, a limited number of unique messages can be effectively communicated to the user.

Utilizing a previously reported setup [10], this paper explores the potential for using electrotactile pulse frequencies greater than 100Hz to generate unique sensations. This work demonstrates that, while pulse frequency alone yields limited discrimination, modulation of high-frequency pulses at a fixed low frequency (6Hz) bundles enables at least three new distinct sensations through changing bundle duty-cycle. This approach

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could be utilized to produce a wider range of uniquely perceived electrotactile stimulations, which in turn enables more complex messaging for electrotactile feedback in wearable real-time health monitoring systems.

II. Electrotactile stimulation and experiment setup

The term electrotactile refers to evoking a tactile sensation on skin surface by injecting a current into the dermis layer that increases the voltage around myelinated afferent axons and causes them to fire action potentials [13]–[15]. These currents are in the form of bi-phasic or mono-phasic pulses [10]. The somatosensory section of brain that processes tactile signals cannot differentiate electrotactile signals from signals generated by mechanoreceptors. Hence, electrotactile signals will be inferred as tactile sensations. Electrotactile feedback can convey information to the user discreetly, with no onset delay or sound profile [16]. Due to its nature of direct nerve stimulation, it consumes less attention resources compared with audio/visual methods [16]. It has been used for a variety of purposes such as prosthetic limb feedback [17]–[19] and sensory substitution [20]–[23], rehabilitation [4], [24], haptic surfaces [25]–[27], and a variety of other applications including VR/AR [28], [29]. Commercialization efforts of electrotactile technology include a device for sensory substitution of visual periphery for the blind called BrainPort [30] and a bionic arm feedback mechanism called MaxSense [19].

Despite the benefits of using electrotactile for real-time wearable health monitoring systems, in order for these systems to realize their full potential they must be able to provide complex information to the user in a concise manner. The literature currently states that the only two distinguishable elements of an electrotactile signal are the stimulation pulse frequency and amplitude [12], [19], [31]; in other words, users can differentiate electrotactile inputs based on their perceived frequency (pitch) and amplitude. However, amplitude is not a reliable stimulation variable [9]. The electrotactile current amplitude must be above a minimum detectable threshold called the 'sensation threshold' and below a certain level of unpleasant sensations called the 'discomfort threshold'. Amplitude variations are limited to the field between the sensation and discomfort levels [12]. However, the threshold currents may vary based on the stimulation site, duration, frequency, and amplitude levels [32]. As such, stimulation amplitude is not a reliable source of drawing distinction among electrotactile signals. The perceived pitch is usually studied in the frequency range of 10-100Hz wherein 3-4 distinct pitches have been reliably distinguished in the literature [31], [33]. These frequencies correspond to the natural response of tactile receptors to vibration, and frequencies higher than 100Hz have been largely ignored for the purpose of producing significant differences in perceived pitch. As a result, electrotactile feedback has traditionally shown a very limited number of signals that users can clearly and consistently discriminate.

The instrumentation circuitry used for electrotactile experiments is composed of a classical voltage to current converter and a current mirror stage to steer the current into the electrodes as shown in Fig. 1. The op-amp displays signal generator bi-phasic waveforms on a 1kΩ resistor, creating a biphasic current that is replicated and reflected into the electrotactile electrodes by the current mirror transistors. The electrodes are isolated from the current mirror through a 0.1μF capacitance as part of safety procedures to minimize the risk of electrical shock and painful sensations in case of catastrophic system failure [23]. The isolation capacitance limits electrotactile currents in case of transistor and fuse failures. A supply voltage of ±100 V is necessary to ensure that the current mirrors can deliver the desired current without saturating to the high impedance load (typically 10-100kΩ [9]) that is the epidermis layer. The voltage waveforms are created by an ATmega32U4 DAC and filtered through a Sallen-Key low-pass filter. To ensure the electrotactile current is independent of the electrode voltage, a cascode current mirror architecture was used, which also reduces current mirror errors. This electrotactile system is created in a multi-channel capacity. The electrotactile signals created by the current mirror are passed through an 8-channel analog multiplexer and distributed among 8 electrotactile electrodes. All of the described hardware along with an electrode array form the experiment setup shown on Fig. 2.

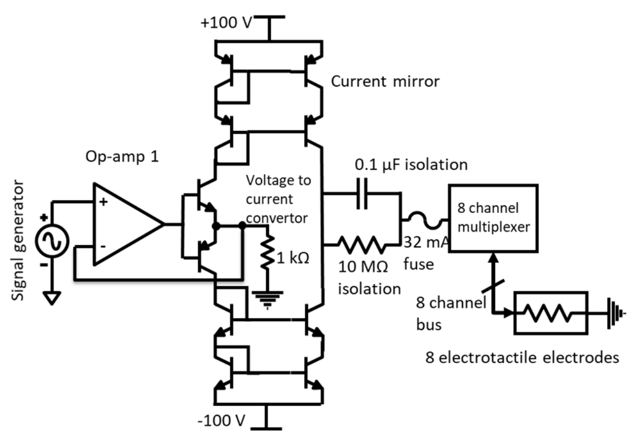

Fig. 1. Current control circuitry used for realizing biphasic electrotactile currents.

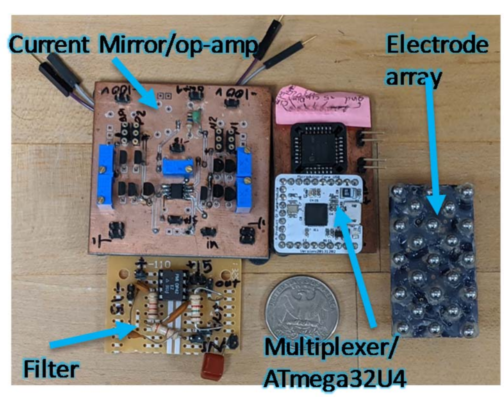

Fig. 2. Electrotactile hardware used in reported experiments.

Two experiments were designed and executed to understand the effects of high-frequency electrotactile stimulation for producing a wide range of uniquely perceived electrotactile stimulations. A total stimulation window of 0.5s has been selected to provide a messaging speed similar to the typical reading speed of humans (1 word per 0.3 s).

III. Experiment 1: Exploring the Ability of Humans to Differentiate High-Frequency Pulses

This experiment was conducted to evaluate the reaction of human subjects to an electrotactile stimulation with pulse signal repetition rate (SRR) above 100Hz . The goal is to confirm the assertion made by literature [12], [19], [23] that this frequency range does not yield a difference in terms of perceived sensation. Three participants (2 males, 1 female) within the age-group of 18-30 were selected for this experiment. In this setup, biphasic stimulation pulses with a total length of 480μs were selected as base pulses. Hence the maximum SRR achievable with this setup is ~2100Hz.

A. Procedure

For this experiment, SRR was swept from 100Hz to 2.1kHz and each stimulation was presented for 0.5s. Fig. 3 depicts three example waveforms with different SRR values. SRR was increased linearly with 100Hz steps, constituting a total of 20 steps. Each SRR waveform step was presented to the user as a comparison in which the target waveform was compared to a reference waveform with SRR of 100Hz. The reference and target waveforms were stimulated on the participant with a 1s delay between them. The sequencing of waveform comparisons was random from the pool of 100Hz to 2.1kHz to prevent bias. Immediately after each comparison was presented, participants were asked to rate the distinction between the two comparison waveforms as similar or different (0 or 1, respectively).

B. Results and discussion

The average comparative discrimination response of participants is presented in Fig. 4, where a 1 indicates that all participants unanimously marked the SRR value as different from the reference and a 0 means they unanimously could not tell them apart. These results indicate that, even though some high frequency waveforms demonstrate some distinction in sensation, the uncertainty in these responses suggest that high-frequency stimulation alone cannot consistently produce noticeable differences. This conclusion corroborates the general assumption in literature that high-frequency pulses fail to provide distinct vibration sensations. However, it also demonstrates that pulse frequencies up to 2100Hz can be reliably detected, which motivated experiment 2.

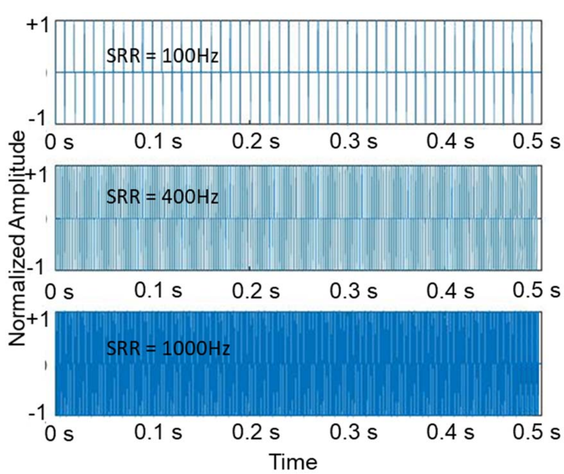

Fig. 3. Example waveforms for 3 of the 20 SRR (pulse repetition rate) frequencies used in experiment 1. Amplitude is normalized to ±1.

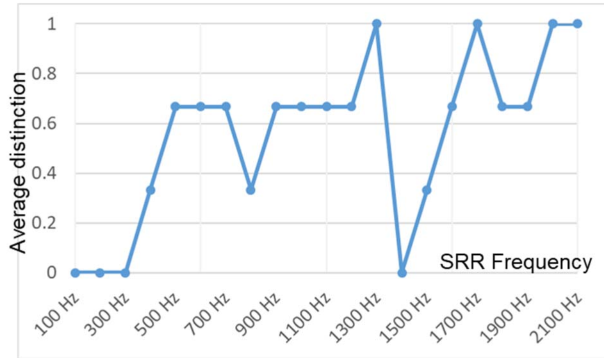

Fig. 4. Average comparative discrimination response of participants and the variation across all participants SRR frequencies spanning from 100Hz to 2.1kHz.

IV. Experiment 2: Discriminating High-Frequency Pulse Trains

This experiment explored the impact on signal discrimination caused by modulating high-frequency pulses by a lower "bundle" frequency as shown in Fig. 5. Here, a base electrotactile waveform composed of high-frequency Pulses is modulated at a lower Bundle frequency. The controllable parameters of this frequency modulation scheme and their ranges are listed in Table 1. The goal of this modulation scheme is to determine if applying multiple frequency components could permit generation of diverse electrotactile sensations using high frequency (>100Hz) pulses, especially in contrast to current literature that relies on a single linear variation of pulse frequency, around 10Hz to 100Hz [12], [19].

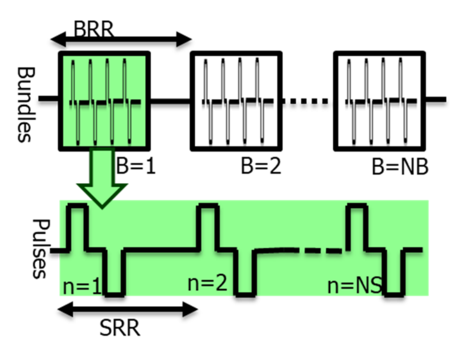

Fig. 5. Frequency modulation scheme for generation of unique sensations.

TABLE 1. PARAMETERS USED IN FREQUENCY MODULATION SCHEME DESCRIBED BY FIG. 5.

Parameter	Symbol	Range
Number of bundles	NB	1-20
Bundle repetition rate	BRR	2Hz to 100Hz
Number of pulses per bundle	NS	1-20
Pulse signal repetition rate	SRR	100Hz to 2kHz

A. Procedure

Four participants (3 males, 1 female) within the age-group of 18-30 were selected for this experiment. SRR was set to 400Hz, well above the maximum pulse frequency of 100Hz typical in the literature. BRR was set to 6Hz, making the maximum possible NS = 66. Notice that varying NS effectively varies the duty cycle of the Bundle modulation. For this experiment, NS was swept from 1 to 66 in steps of 2 pulses, with a total waveform length of 0.5s. Fig. 6 depicts modulated waveforms for four example NS values. Similar to experiment 1, each value of NS was presented as a comparison of waveforms separated by a 1s delay against the baseline (initially, NS=1). Each participant was asked immediately after each comparison stimulation to rate the distinction between the two waveforms as similar or different (0 or 1, respectively). The target NS value was randomized to prevent bias from the baseline value to the baseline plus 20. Once an NS value was found that produced consistent distinction, the comparison baseline was reset to the distinction NS plus one and the experiment was continued, randomly varying NS between the new baseline and the new baseline plus 20.

B. Results and discussion

Fig.7 depicts the experimental results for one participant who achieved distinction baselines at NS=6 and NS=42. The distinction baselines for each of four participants are depicted in Fig. 8, and the top graph shows the average of distinction baselines of all participants. The participants identified at least three distinction points for sub NS=66 with average levels at NS= 1, 7 and 33. Each of these baselines corresponds to a duty-cycle of the modulating 6Hz Bundle. These results demonstrate that high frequency electrotactile pulses can be utilized to produce distinct sensations by modulating them at lower frequency and varying the modulation duty cycle.

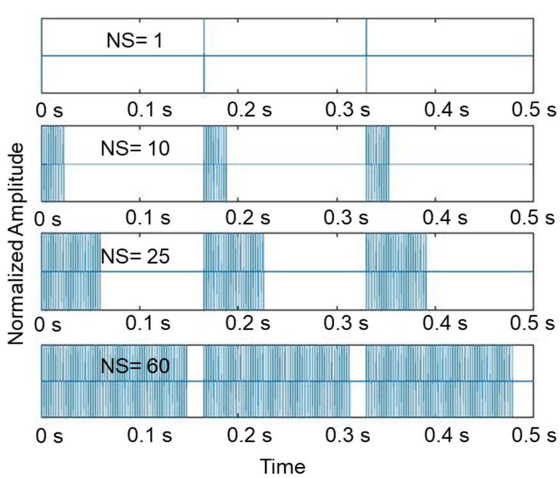

Fig. 6. Example waveforms for different NS (number of Pulses per Bundle) that were used in experiment 2.

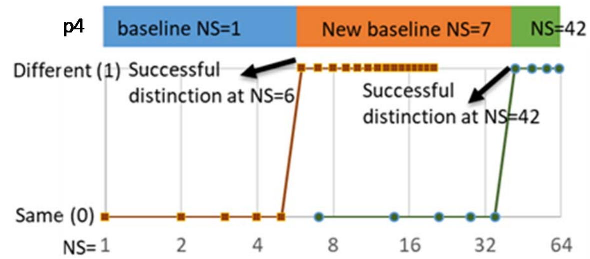

Fig. 7. Comparative distinction reaction of one participant to the increasing NS (number of Pulses per Bundle) and the extracted comparison distinction baselines.

V. CONCLUSION

Two experiments were conducted using a custom electrotactile stimulation setup. The possibility of generating unique sensations with electrotactile pulse frequencies higher than 100Hz was explored. Two experiments were conducted. Experiment 1 evaluated the ability of participants to sense and differentiate electrotactile signals with SRR higher than 100Hz up to 2.1kHz. Experiment 2 explored utilizing high-frequency pulses (SRR = 400Hz) to modify a low frequency bundle of electrotactile pulses and create unique sensations. The experiments concluded that even though pulse frequencies higher than 100Hz cannot generate noticeable differences in terms of perceived frequency, modulating these high-frequency signals by low-frequency Bundles will enable generation of unique sensations through changing the duty-cycle of Bundles. As a result, this distinction will allow investigators to replace current amplitude as a parameter of distinction [12] with alternative variables such as bundle duty, cycle as presented in this work. Doing so would incentivize the use of electrotactile stimulation as a method of feedback in wearable real-time health monitoring systems.

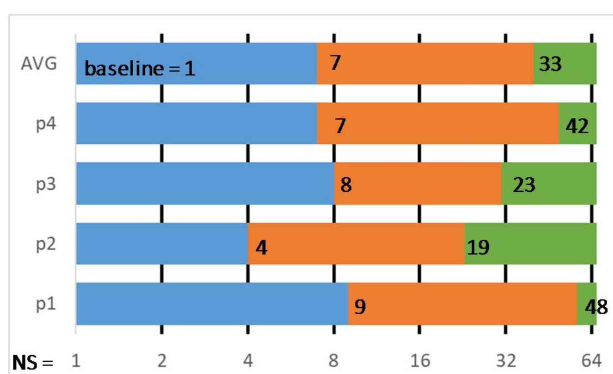

Fig. 8. Extracted stimulation baselines for NS (number of Pulses per Bundle) for all participants and their average.

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