Frequency burst modulation outperforms spatial encoding in multi-level vibrotactile stimulation

Nikolina Maravić, Jelena Bulatović, Filip Gašparić, Strahinja Došen, Nikola Jorgovanović

***Abstract*—Haptic or tactile communication refers to communication through touch. Multichannel vibrotactile stimulation is a commonly used interface to provide tactile feedback. The feedback information is delivered to the subject by modulating stimulation parameters. The present manuscript investigates two approaches for encoding of the feedback information. To this aim, two experiments were performed in 20 healthy able-bodied subjects, whose task was to learn to distinguish eight levels of feedback variable using either burst frequency modulation or spatial locations of vibromotor activation. Vibrotactile feedback was delivered through vibration motors placed on the subject's forearm. The experiments consisted of three phases: a familiarization phase, a reinforced learning phase and a validation phase. The main outcome measure was the success rate in discriminating the levels of the feedback variable. The results have shown that burst frequency modulation (72% success rate) outperformed the spatial coding (64%). Therefore, the frequency encoding is the preferred approach in transmitting multilevel feedback information in vibrotactile feedback systems.**

***Index Terms*—vibrations; stimulation; vibromotors; haptic interface; frequency burst modulation; spatial encoding.**

I. Introduction

The sense of touch is one of the most informative senses, and it is instrumental for daily life activities, haptic exploration and social interaction [1]. There are situations in which a person cannot receive tactile information from the environment, for example, in the case of teleoperation or prosthesis use. In these cases, the missing information can be provided through artificially designed haptic feedback [2]. Generally speaking, the term "haptics" refers to the two types of feedback: feeling of touch on the skin and kinesthetic feedback [3]. Kinesthetic sensations are generated by the sensors located within the muscles and tendons and they allow person to gain a sense of the position of the limbs in space [4].

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The haptic interface consists of a real-time display of a virtual or remote environment and a manipulator that represents an interface between the human operator and the simulation (VR) and/or remotely controlled system. The user makes movements within a virtual or remote environment by moving the robotic device and those movements are translated to the simulation and/or remote system. Haptic feedback, which is basically force or touch feedback in a human-machine interface, allows computer simulations of various tasks to convey real, tangible sensations to the user, and objects that are typically visually simulated to assume real physical properties, such as weight, hardness and texture. By incorporating haptic feedback into a virtual or remote environment, users have the ability to interact with objects, rather than just see their representation on a monitor [5].

There are two possible ways to reestablish sensory feedback: invasive, by direct stimulation of the physiologically appropriate neural structures in the peripheral or central nervous system, and noninvasive, by stimulating the skin electrically or mechanically [6]. In both cases, the user needs to learn how to associate the delivered stimuli with events and state of the system (e.g., prosthetic hand, gripper of a tele-manipulated robot).

Sensory feedback systems can be divided into three categories: feedback systems based on sensory substitution, feedback systems based on modality-matched stimulus, and somatotopic feedback systems [7].

Sensory substitution is a method that allows information from the environment to reach the user's body through sensory channels that are not intended for that particular stimulus (for example, replacing the sense of touch with the sense of hearing) or through the same sensory channels but when the stimulus arrives in another form (for example, pressure replaced with vibration) [8]. Most feedback systems use this idea, since it is simple to implement. The leading techniques are vibrotactile and electrotactile substitution, which delivers either mechanical vibrations or electric current to the skin to encode informations from the environment [9].

Vibrotactile feedback is one of the most commonly used solutions. In prosthetics, for instance, vibromotor is often used to produce continuous or discrete vibrations when the prosthesis contacts the object [10–12]. The feedback information (e.g., grasping force) can be conveyed by modulating the stimulus frequency [11–13], amplitude [12] or location [13].

In [14], four questions related to vibrotactile feedback for prosthetic hand control were investigated: optimal location for vibromotors, type of signal that activates them, period after which the feeling of irritation decreases after constant stimulation exposure as well as the effect of feedback on grip force control. This study confirmed the improvement in grip force control with the help of vibrotactile feedback.

In the experiment described in [15], 18 healthy subjects operated a virtual object using visual and/or vibrotactile feedback. They received informations via vibration on a finger, hand, neck or foot. All subjects had improved performance when vibrotactile feedback was provided.

The performance of 10 amputees during virtual grasping of objects with feedback on hand aperture and force was investigated in [16]. Their task was to capture the object displayed on the computer monitor with a virtual hand, adjusting the aperture of the hand and the force of the grip using computer mouse. The percentage of correctly applied levels of hand aperture and grip force showed that the use of vibrotactile feedback led to an improvement in hand control compared to the control without feedback.

In [17], two experiments were described: the first referred to the spatial discrimination of stimuli, and the second to the observation of different stimulation intensities. By combining three intensities and three durations of vibrotactile stimulation, nine different stimuli were obtained, which were tested using six vibromotors arranged in four different ways. In the first experiment, circularly placed vibromotors around the upper arm with a proportional distance gave the best results with the accuracy of 75%. Another experiment showed that the perception of vibration intensity was affected by both intensity and duration of vibromotor activation. Seven amputees achieved the accuracy of up to 92% with a circular-proportional vibromotor arrangement.

Despite many studies have used vibrotactile stimulation, no comparison of frequency and spatial coding shemes has been introduced so far. In this study, two vibrotactile coding schemes were presented and compared. Both schemes have the same resolution, they encode 8 levels of vibrations. The difference between two methods is that one implies a variable stimulus burst frequency and other implies variable location of stimulus. The novelty is in comparing frequency and spatial coding schemes which have not been presented so far. The quality of the coding schemes was evaluated using an average success rate achieved by 10 subjects in each experiment in distinguishing levels of vibromotor activation.

II. Methods

The aim of the research described in this paper is to find an adequate way for conveying information using vibrotactile feedback. The idea is to use vibromotors which will be activated according to different spatial and frequency coding schemes so that the user can interpret transmitted feedback information as good as possible. To this aim, we have investigated how well able-bodied subjects could distinguish eight levels of vibrotactile feedback when they are conveyed using different locations versus burst frequency of vibromotor activation.

A. Experimental environment

Eight coin type vibration motors (10mm diameter) were installed in the bracelet and placed circumferentially around the subject’s forearm, 2 cm below the elbow (Fig. 1). Vibromotors were marked with numbers 1 – 8. Vibromotor marked with the number "1" was placed in the middle of the lateral forearm, while the others were placed equidistantly, in a clockwise direction. The number of used vibromotors varied depending on the experiment that was performed. In the Experiment 1, four vibromotors were used (marked with numbers 1, 3, 5 and 7), while in the Experiment 2 all eight vibromotors were used. They were connected to the custom made driver board developed at the Faculty of Technical Sciences, University of Novi Sad, which was connected to a PC using a USB cable. The MATLAB software package (version R2018a, MathWorks, USA) was used for creating custom scripts to control the board and collect the data.

Figure 1 shows subject during the experiment. The bracelet with built-in vibromotors was placed around the his/her left forearm, while the subject used his/her right hand to control the mouse when getting acquainted with the levels of vibromotor activation, and then to select the assumed patterns of vibromotor activation.

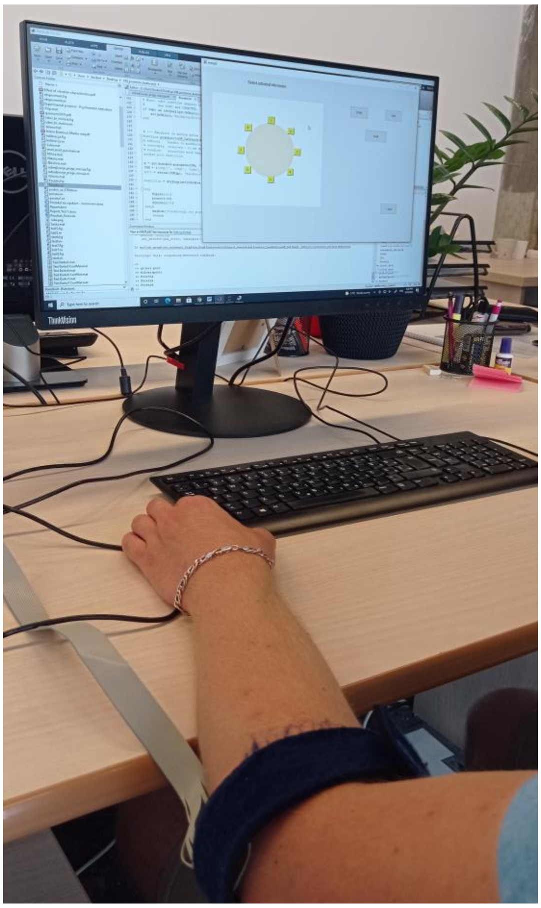

Fig. 1. Subject during the experiment.

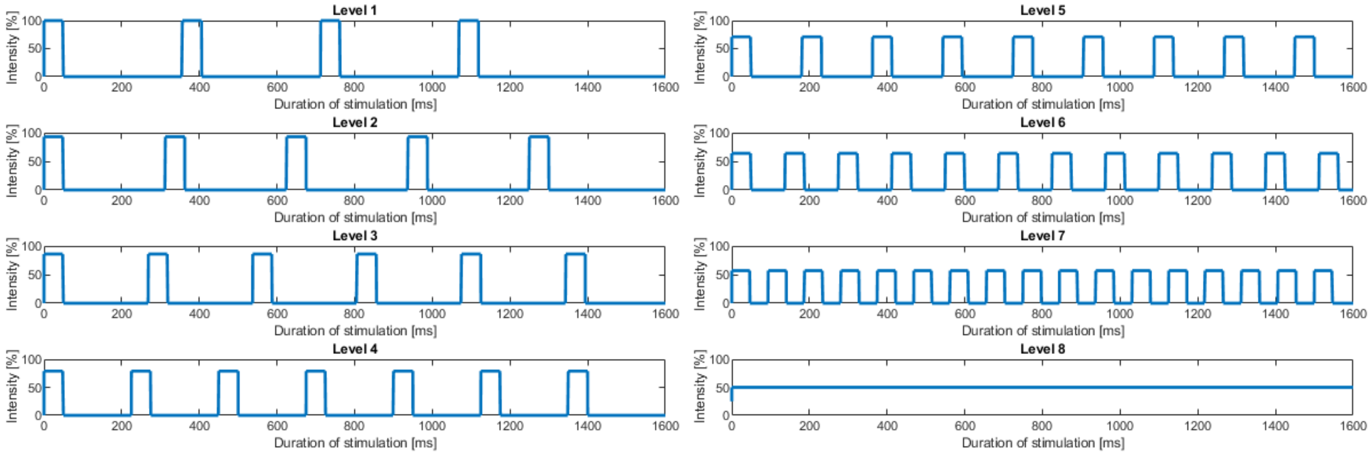

Fig. 2. Control signals for activating vibration motors at eight levels in the Experiment 1.

B. *Stimulation calibration*

Before the beginning of the experiments, it was necessary to determine the parameters of vibrotactile stimulation to create coding schemes that can be clearly perceived by the subjects. For each subject, firstly, the sensation threshold was determined for all vibrators. Each vibromotor was switched on individually, with the vibration intensity gradually increasing from 0 to 100%, in steps of 5%. The intensity at which the subject started feeling vibrations was recorded (sensation threshold).

For the most people the sensation threshold was approx. 30%. Therefore, in the Experiment 1 the intensity of vibrations was obtained by dividing the range between 50% and 100% to eight equidistant values. Remaining stimulation parameters for Experiment 1 were determined after a series of pilot tests. The total duration of stimulation was set to be 1600 ms during which the vibromotors were activated periodically, with an active stimulation ("ON") period of 50 ms. The length of the "OFF" period depended on the level of stimulation and was obtained by dividing the range from 50 to 400 ms by eight equidistant values (Fig. 2). The perceived intensity of vibromotor activation also depends on the length of the stimulation period. By reducing the period of stimulation, i.e. by increasing the frequency with which the stimulus appears, perceived intensity is increasing. However, by adjusting the intensity so that it gradually decreases with increasing burst frequency, the perceived intensity of vibrations can be made approximately equal at each level. When the frequency of stimulus occurrence is the lowest, the stimulation intensity is set to be the highest, i.e. 100% of the maximum value of the simulation, and this pattern was associated to the first level of hypothetical feedback variable. By testing different intensities, it was determined that, when burst frequency is the highest, the activation intensity should be reduced to 50% of the maximum - this corresponded to the eighth level of feedback variable. Figure 2 illustrates the control signals which activate vibromotors. As explained above, the designed patterns produce sensations that modulate in frequency while maintaining approx. the same intensity. Within the pilot tests, the configurations with 1 and 4 equidistantly arranged vibromotors were tested. Subjects reported that the different frequency levels can be distinguished better in the case of using 4 vibromotors. According to that, during the Experiment 1 at a time all four vibration motors were activated simultaneously.

In the Experiment 2, vibrotactile stimulation was delivered through 8 vibration motors equidistantly arranged around the forearm as shown in Figure 3. The vibration intensity was constant and set to 35% to assure that the sensations can be clearly perceived by the subject and yet limit the spread of sensations between adjacent vibrators Only one vibration motor was active at a time. In each trial, the vibromotor was activated for 1000 ms.

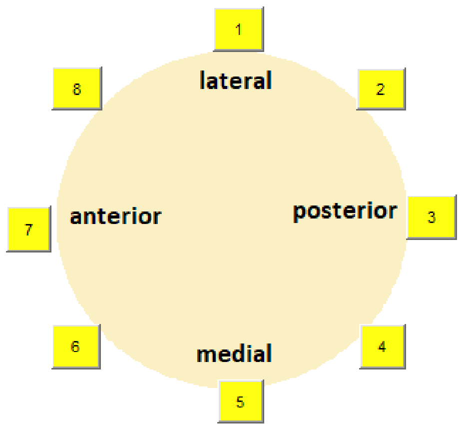

Fig. 3. Locations od vibromotors in the Experiment 2.

C. *Experimental protocol*

The procedure for both experiments was the same and the only difference is that patterns in one case are burst frequency modulations and in the other individual vibrations at different locations. Experimental procedure comprising three phases: the familiarization phase, the reinforced learning phase and the validation phase. Experiments are organized as follows:

1) *Familiarization phase*

During the familiarization phase, the subject was introduced to the experimental environment and to the sensations elicited by different patterns of vibromotor activations. The familiarization phase was finished when the subject was able to distinguish eight patterns of vibromotor activation.

2) Reinforced learning phase

In the learning phase, the vibromotors were activated at different patterns in random order. The subject guessed the value of the activation level after stimulation, and after selecting the answer, the actual value of the level was shown on a computer screen. Each pattern was activated three times in case of frequency coding and ten times in case of spatial coding.

3) Validation phase

The validation phase followed the same protocol as the learning phase, but without feedback information about the correct answer. Validation phase during the Experiment 1 consisted of 25 trials, which means each level appears at least three times (7 levels appears 3 times and 1 level appears 4 times as a task). Experiment 2 consisted of 80 trials, so each location of vibromotor appears 10 times. After 25 (Experiment 1) or 80 (Experiment 2) stimulations, the test phase was completed.

D. Subjects

The subjects in the experiments were professors, assistants and students from the Department of Automation and Computer Science at the Faculty of Technical Sciences, University of Novi Sad. The Experiment 1 was performed in 10 healthy subjects, seven women and three men; aged 29 ± 11 years (mean ± standard deviation), and the Experiment 2 was performed in 10 healthy subjects, six women and four men; aged 31 ± 12 years (mean ± standard deviation). All subjects signed a written consent form to participate in the experiment.

E. Data analysis

During the validation phase, data containing true and predicted values of the location and level of activated vibromotors were collected. The subject had the role of a classifier who had the task to classify each sample, i.e. stimulus into one of the eight possible classes. Here the classes represent the levels of activation of the vibromotor in the first experiment, i.e. locations of activated vibromotors in the second experiment. From the collected data, confusion matrices were formed for each subject. Each row of the matrices represents an actual class, while each column represents a predicted class. All correct predictions are located in the diagonal of the confusion matrices. Based on these matrices, subject's success rates were calculated as percentage of correct answers among a number of all attempts.

The Kolmogorov-Smirnov test was used to check if data came from a normal distribution. Because of data are not normally distributed, the Mann-Whitney U-test was performed in order to compare two coding approaches. The Mann-Whitney U-test tested the null hypothesis that success rates obtained in two independent experiments are samples from continuous distributions with equal medians. Considering the p-value is 0.2716 we cannot conclude that there is enough evidence to reject the null hypothesis and can conclude that a positive shift in the medians of observed data exists.

III. Results

From the collected data, confusion matrices were formed for each subject. Overall confusion matrices for both experiments were calculated as sum of confusion matrices for all subjects. The performance in recognizing vibration patterns is summarized in Fig. 4 in the form of overall confusion matrices with normalized success rates for all levels.

In Experiment 1, the subjects had the highest success rate in recognizing levels one, two, three and eight, while they were less successful in recognizing other levels. They made the most mistakes in recognizing the fifth level and in distinguishing between levels six and seven. It was easiest for them to recognize level eight, which was expected, considering that in this case the vibromotors were activated continuously for 1600 ms. Also, subjects report that the first, second and third level could be most easily distinguished by simply counting the pulses, since the pulses occur with a frequency low enough to count them.

In Experiment 2, most of the mistakes were confined to adjacent vibromotors. The highest success rate in localizing vibrotactile stimulation was achieved on the lateral side of forearm (vibromotors marked with numbers "1", "2" and "8" in Figure 3). The lowest success rate in localizing vibrations was achieved on the posterior side of forearm - vibromotor marked with number "3".

Average success rate for all levels in Experiment 1 is 72%, while in Experiment 2 it is 63%. Therefore, it can be concluded that better results were achieved when feedback variable in vibrotactile systems is stimulus burst frequency than spatial location of the stimulus.

IV. Discussion

A comparison of frequency burst modulation and spatial encoding of vibrotactile stimulation was presented. Twenty healthy subjects participated in two experiments. Effectiveness of each coding scheme was evaluated using success rate achieved in distinguishing eight different levels. Depending on the experiment, stimulus frequency or location was modulated. In the Experiment 1 four vibration motors were activated simultaneously with variable stimulus frequency, while in the Experiment 2 at a time one of eight vibration motor was activated and subject's task was to localize it. Better results in distinguishing eight different patterns were achieved in case of using frequency coding scheme.

The obtained results make a contribution to the field of haptic interfaces. Vibrotactile stimulation is simple to implement and it allows informations from the environment to reach the user's body through mechanical vibrations. In hand prosthetics, for instance, vibration pattern can be used for identifying the prosthesis contact with the object, or level of grip force.

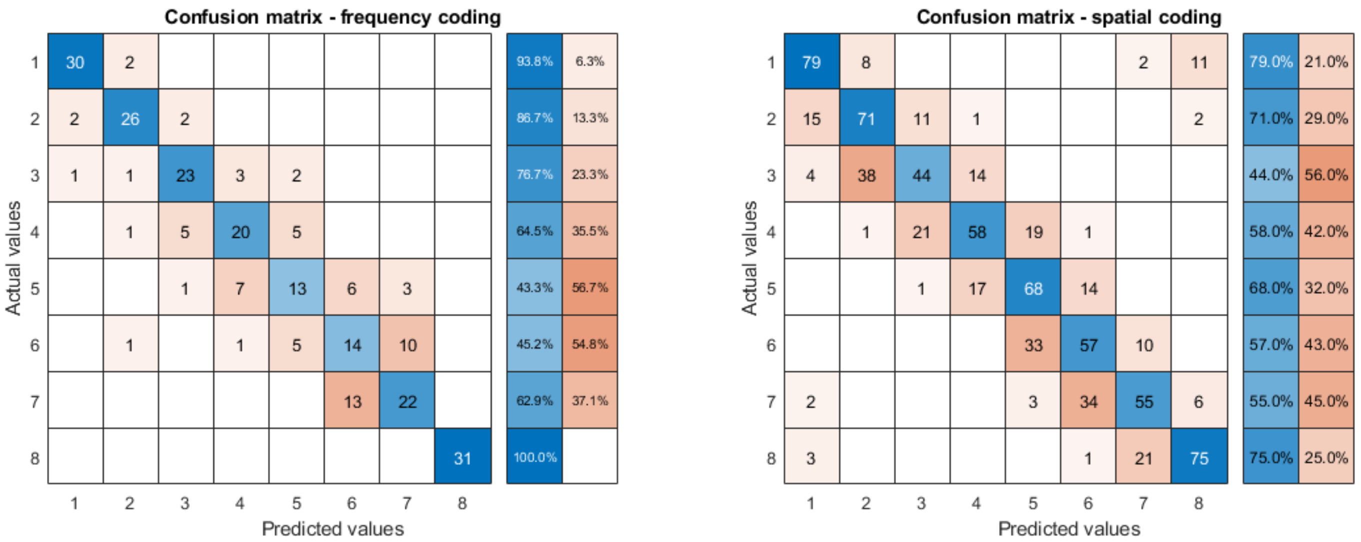

Fig. 4. Overall confusion matrices for both experiments.

V. Conclusion

High performance achieved in described experiments indicate that the frequency and spatial coding schemes of the vibromotor activation are intuitive to use, and they could be applied for providing vibrotactile feedback about 8 levels of feedback variable. However, the frequency burst approach outperformed the spatial encoding. Most of the mistakes made by the subjects involve adjacent levels.

Several female subjects characterized the feeling of vibration on the skin as unpleasant, especially when activating vibromotors at higher frequency levels (6, 7 and 8) during the Experiment 1. The reason for this may be that women's skin is thinner, more moist and covered with less hair, as well as the smaller volume of a woman's forearm compared to a man's, and the intensity of vibration felt in this case is higher. This problem can be solved by adjusting the vibration intensity before starting the experiment for each subject separately.

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