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T-Mobile: Vibrotactile Display Pad with Spatial and Directional Information for Hand-held Device

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Abstract— **In this paper, we have applied phantom sensation and sensory saltation to generate spatial and directional information using a vibrotactile display pad providing vibrotactile cues, T-mobile. A grooved and slim design is applied to the contact side of the T-mobile for comfortable gripping, and the contact part consists of 12 vibrotactile panels which can operate independently and separately. To maintain isolation among vibrotactile actuators, the surface of the cover is divided into several pieces. Each vibrating module consists of a linear resonant vibrational motor, a section of covering surface, and a vibration isolator. As an evaluation of the developed device, two experiments were conducted to test whether directional information and spatial information can be successfully displayed by the device. As a result, spatial and directional information is useful for displaying intuitive information for hand-held navigation with vibrotactile feedback.**

I. Introduction

ADOPTING vibrotactile cues is one of simple ways to apply haptic technology to a mobile device like PDAs, cellphones, hand-held appliances for providing discrete haptic sensation, especially, tactile information. Many kinds of vibrotactile display have been developed for various purposes utilizing the haptic sensation including visual and aural information. As an instance, recent fully touch-based cellphones usually use vibrotactile feedback for its ringtone of several kinds of vibrotactile stimulus, dial keypad to indicate whether the key is pushed or not. However, the cellphone still uses only one actuator for transmitting their vibrotactile stimulus to the user. As an information provider, an array type vibrotactile displays have been investigated since they have several degrees of freedom using multi actuators. The forearm, including the wrist, is one of the preferred parts of the body to stimulate the vibrotactile cues using an array-type vibrotactile display. Oakley et al. [3] applied their multi-element, forearm-mounted vibrotactile display to the forearm and investigated the feasibility of the device. However, Piateski and Jones [1] had compared the performance of the arm and torso mounted vibrotactile display by testing the ability of subjects to identify patterns of vibrotactile stimulation, their results indicated that the torso was superior as compared to the forearm in identification of vibrotactile patterns.

The haptic back display was developed by Tan et al. [2] using a 3-by-3 tactor array. They investigated the use of the device for delivering attention- and direction-related information through a well-known illusion - *cutaneous rabbit*, essentially based on sensory saltation. In their study, a haptic attentional cueing system can be beneficial to a user by speeding up the reaction time to detect a change in a visual scene. The directional cue can be used as a haptic navigation guidance system informing the driver which direction to turn at the next intersection with saltatory lines. Yanagida et al. [9] examined the possibility of distinguishing alphanumeric letters by using only 3-by-3 array of vibrating motors on the back of a chair. Piateski and Jones [1] also applied their 4-by-4 array vibrotactile display on the back and they showed the display was effective in displaying navigational information and vibrotactile patterns could be interpreted as directional or instructional cues with almost perfect accuracy.

As long as using a simple motor, vibrotactile display is difficult to transmit clear vector information compared with a kinesthetic display, because vibration is typically not uni-directional but omni-directional and consists of various frequencies and amplitudes. Much more, vibrational isolation among the actuators is also considered in design stage, (i.e. location of actuator, the way to implementation, and how to display vector information using the display).

To overcome this limitation, researchers have been trying to use multi-actuators by utilizing an illusory effect of tactile sensation. Somatosensory saltation (or cutaneous rabbit) is a classic somatosensory illusion, whereby repetitive and rapid sequences of stimulation at two or more skin locations can, under certain conditions, lead to illusions that intermediate space between the actual stimulation sites was stimulated on the body, as if a rabbit hopped along successive locations. As one of the possible ground for displaying continuous spatial location (because continuous spatial information is important in vector property), *phantom sensation* could be applied to the vibrotactile rendering method. Phantom sensation is also called *funneling illusion* and related to *apparent movement* phenomenon [5], which is time varying effect of phantom sensation. Under some conditions, the two stimuli are experienced as a single point somewhere

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between the exact location depending upon the relative intensity of the stimulation, the relative timing of onsets, and the sensitivity of the skin. Phantom sensation is also associated with the cutaneous rabbit. As several pulses are delivered in rapid succession, illusory sensations are felt at discrete and evenly spaced locations between two stimulators.

By utilizing above sensory illusions, we can display both spatial and directional information together through the vibrotactile display while interacting with mobile applications like walking navigation or information transmission or several functions related mobile form factors. In the rest of the paper, we introduce the overall characteristics of the device, the display method utilizing vibrotactile cues, and experiments. An overview of the vibrotactile display pad is described in section II; the use of the vibrotactile cue is explained based on sensory illusions and a strategy of the display method in section III; two experiments relating directional information and spatial information were conducted and results are analyzed in section IV; in section V, we describe the feasibility of the developed vibrotactile display and the appropriateness of the proposed rendering method based on sensory illusions for the vibrotactile cue.

II. T-MOBILE: VIBROTACTILE PAD DEVICE

In this section, an overview of the developed vibrotactile input device named as T-Mobile (since it is designed for hand-held mobile devices) is described. The device can provide isolated vibrotactile cues from twelve pieces of vibration surface.

We have considered on the following design issues mentioned in Ryu et.al's work [15] while developing the T-mobile.

- Ergonomic design for convenient grip
- Easy to discriminate the vibrating area
- Protection from shape deformation of contact surface
- Fine sensation with minimum actuators

Based on the criteria mentioned above, we designed a prototype, the T-mobile. The tactile surface, composed of 12 panels, is applied only on the backside of the contact surface. We allocate three panels to the row because minimum number of locations to raise sensory saltation is three. Furthermore LCD screen size is typically 16:9 or 4:3 ratio, four panels are assigned to the column, so total 3 by 4 arrayed structures was applied in the T-mobile backside. A resonant linear vibration motor is installed in each panel as a tactor for generating vibratory stimulus up to 175Hz. Although the actuator can vibrate up over 1kHz, it can generate its maximum amplitude at 175Hz, resonant frequency of the linear actuator. A total of 12 vibro panels can independently stimulate the fingers or the palm when the user contacts the backside of the T-mobile. The layout of the panels is as shown in Fig. 1, and the intervals between tactors are maintained at about 18mm (longitudinally 24mm). The actual implementation is shown in Fig. 1.

The controller of the T-mobile is composed of a micro-controller, and a motor driver. The main role of the micro-controller is to determine the vibrating power of each panel to represent the desirable spatial and directional vibrotactile cues. The desired spatial- and directional-information are converted into the vibrating powers of each panel, and the details of the tactile pattern generating algorithm are explained in the next section. The calculated power is encoded by a Pulse Width Modulation (PWM) command, and the digital input/output (DIO) channel of the micro-controller converts the PWM command to driving voltage. Finally, the motor driver precisely supplies the amount of time and voltage to each tactor with respect to the PWM signal. In this process, we define 8 levels of PWM power to provide 8 different vibratory stimuli. The micro-controller updates the PWM commands with 1msec sampling time. The process in which to calculate the power of each tactor for continuous spatial information is described in our previous work [15].

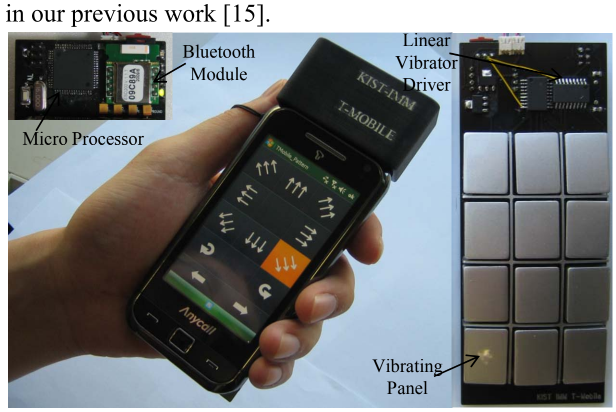

Fig. 1. Vibrotactile pad device, the T-Mobile

III. VIBROTACTILE CUES BASED ON SENSORY ILLUSIONS

Although we cannot really feel the midpoint between the fingertips, we can perceive our illusory sensations as if the stimulus exists there. In this section, two illusory effects, somatosensory saltation and phantom sensation, are explained. Many researchers have reported on the optimal inter-stimulus duration and the optimal number of pulses for the forearm or the back to induce the cutaneous rabbit (sensory saltation). Therefore, we need to determine the optimal value of parameters concentrating on the "hand". Moreover, we discuss the model for the vibrotactile cues for displaying spatial and directional information through the developed device.

3.1 Sensory saltation

The somatosensory saltation(also called as 'cutaneous rabbit') is a classic somatosensory illusion, whereby repetitive and rapid sequences of stimulation at two or more skin locations can, under certain conditions, lead to illusions that intervening space between the actual stimulation sites is stimulated on the body, as if a rabbit hopped along successive locations [8][13][14]. When several pulses are delivered in rapid succession first to one stimulator and then to a second, illusory sensations are felt at discrete and evenly spaced locations between two stimulators. Tan et al. [2] utilized this phenomenon to their haptic back display for directional cueing. In their study, a near optimal value of 50ms interstimulus duration was chosen among a variation from about 20 to 300ms. And, the optimal number of pulses for the back was selected as 3 chosen from between 3 and 6. As mentioned in their work, intensity and duration of the saltation pulses were of secondary importance [8][11]. In the cutaneous rabbit, there are two kinds of stimulation modes, one which is veridical and the other is saltatory. In previous researches, both modes did not show the significant differences in the results. Therefore, we have chosen a veridical mode as a stimulation method.

Since there were few attempts to find an optimal value of stimulation for specific vibrotactile display in the palm and the finger, we should conduct an empirical test of our developed device to find the appropriate interstimulus duration and the optimal number of pulses to display directional information as we already did in our previous work [15]. The distance between tactors in our proposed design is 18mm (24mm) from center to center. The important factor is the temporal resolution of the cutaneous sensation because the resolution limits tactile pattern perception by placing absolute upper bounds on the rate at which two or more consecutive patterns can be perceived. In utilizing the saltation effect, judging temporal order is one of key factors for generating vibrotactile directional cues. As Hirsh and Sherrick had reported [12], it requires at least 18msec time interval that a human judges which of two stimuli came first. Moreover, Hill and Bliss [16] ascertained that when the task also requires identifying the spatial locations of the tactile stimuli not known in advance, the additional processing demand raises the threshold for discriminating temporal order up to 26ms. Thus we have fixed the interstimulus duration at 24ms for same locations and 30ms for other locations. The stimulus duration was 18ms. We had empirically found the parameters for directional vibrotactile cues by saltation. Among 3, 4, and 5 taps, subjects reported 4 taps was best to perceive the target direction intuitively. If the total stimulation time exceeds 500ms, subjects reported the stimulus was not a single pattern but rather a combination of two or three discrete stimulus or patterns. Based on this empirical test, we have generated eight directional vibrotactile cues and two rotational vibrotactile cues not exceeding a total stimulation time of 500ms. As shown in Fig. 2, the conceptual diagram describes how to generate vibrotactile directional cues for the T-Mobile.

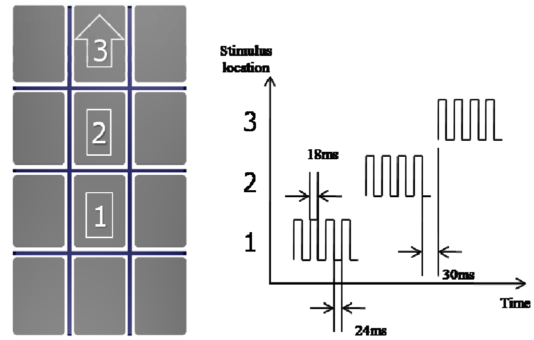

Fig. 2. Generation of vibrotactile stimulus for displaying directional information

3.2 Phantom Sensation

If two stimuli with equal loudness are presented simultaneously to adjacent locations on the skin, it is not felt separately but rather combined to form a sensation midway between the two stimulators [4]. This perceptual phenomenon is called Phantom sensation. Phantom sensation is associated with the phenomenon known as the sensory saltation as mentioned in the previous section. Phantom sensation poses a concern to those wishing to use the skin as a substitute for the retina or chochlea, for they may cause considerable spatial distortion of the input pattern as it is represented neutrally. In order to display continuous or more locations than actual sensational locations, the phantom sensation phenomenon should be chosen for displaying spatial locations through the developed vibrotactile device. Time-varying phantom sensation is one of methods to display continuous movement. It is also called apparent movement phenomenon [10]. This sensation is affected by the separation of the stimuli, their relative amplitudes, and their temporal order.

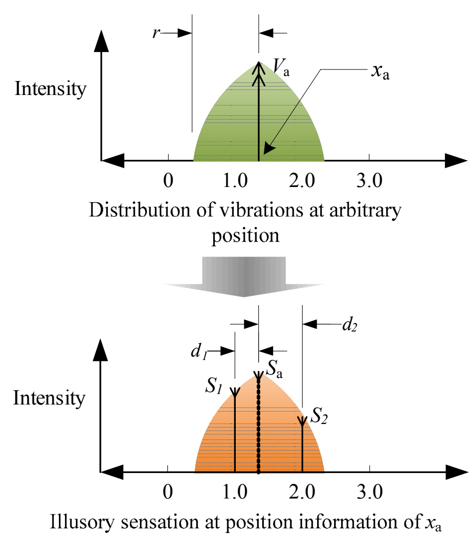

Fig. 3. Representation of an arbitrary location with adjacent tactors

As Alles mentioned in his work [4], the phantom sensation could be generated by amplitude variation and time delay. However, amplitude variation method is much more distinct than that produced by a time delay alone. An increase in the interstimulus interval can cause the location of the sensation to move to the earlier stimulus. The maximum time delay is 8~10ms as the phantom sensation is lost when the delay increases to more than 10ms. In order to maintain the equal loudness of the phantom sensation according to the position, the amplitude of the two stimuli should have logarithmic variation [4]. Based on these features, we have rendered vibrotactile stimulus for displaying spatial location with continuous for the entire grooved surface. A detailed implementation of vibrotactile rendering is similar to our previous work [15]. But, as a simple explanation based on this phenomenon, we can express an arbitrary point by discretely located actuators. For the desired represented position, x_d, the original sensation, S_a, is mimicked by vibrations from the adjacent tactors instead of the tactor at the desired position as shown in Fig. 3. The original vibration, V_a, is divided into vibrations, S_1 and S_2, at adjacent tactors in the range. When the vibrations, S_1, S_2 are reproduced by the adjacent tactors, the user perceives an illusory sensation. Finally, the user can associate the sensation with the arbitrary position.

IV. Experimental Evaluation of the T-Mobile

4.1. Directional Information

4.1.1 Procedure

Ten normal, healthy subjects in KIST (seven men and three women) aged 25 to 35 years participated in the evaluation of directional information. They had no known abnormalities of their tactile sensory systems and had no history of peripheral vascular disease. The tactile display 'T-Mobile' was used as a stimulating device for displaying vibrotactile directional information.

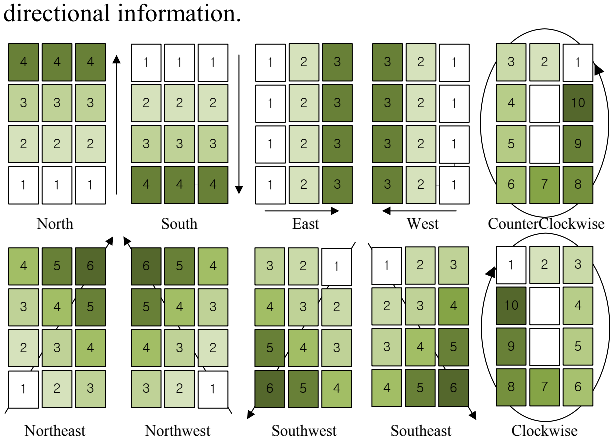

Fig. 4. Representation of directional informations

Directional information was generated based on the previous tactile parameters discussed in section 3. For masking the sound of the vibrotactile actuators, pink noise was applied to subjects using headphones during the transmitting of vibrotactile stimulus. As shown in Fig. 4., ten directional cues consisting of the four cardinal points and its four midpoints, and two rotational information represents turn round were randomly displayed eight times. Therefore, a total of 80 trials were applied to each subject. Using a ten alternative forced choice method (10AFC), subjects were instructed to indentify one of the listed directions to represent the intuitive navigational direction based on their feelings from the fingers and the palm. Before starting the experiment, a test trial was applied to subjects to determine a reference for ten directional vibrotactile stimuli. During the test trial, the subject was permitted to ask that any directional stimuli be repeated by a computer program. After perceiving each vibrotactile directional cues, the subject choose which direction had been detected, and the computer program recorded the response on the data file. Subjects were given unlimited time to respond after each stimulus, but most answered within 10 sec. After the end of each block of experiments, which consisted of 10 trials, a three minutes' break was applied.

TABLE I
Experimental Results of Identification of Direction Information

		Subject Response									
		1	2	3	4	5	6	7	8	9	10
Presented directional pattern	1	97.6	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	3.8	92.5	1.3	0.0	2.4	0.0	0.0	0.0	0.0	0.0
	3	7.5	5.0	87.5	0.0	0.0	1.2	0.0	0.0	0.0	0.0
	4	3.8	3.8	0.0	82.5	2.5	5.0	1.3	0.0	1.3	0.0
	5	0.0	5.0	0.0	0.0	88.8	0.0	2.4	3.8	0.0	0.0
	6	0.0	0.0	0.0	0.0	0.0	90.0	6.3	2.4	0.0	1.3
	7	0.0	0.0	0.0	0.0	1.3	1.3	95.0	2.4	0.0	0.0
	8	0.0	1.2	0.0	0.0	0.0	1.2	2.6	93.8	0.0	1.2
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	96.3	3.7
	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.2	97.6

4.1.2 Results

Table 1 shows a summary of the experimental results. The data are averaged over all subjects and diagonal terms of the confusion matrix indicate percentage of correct responses of the subjects. Mean percentage of the correct answers was 92.1% for directional information of the T-mobile. There was no significant difference in the recognition rates for the different directional vibrotactile cues presented ($F(9,81)=1.686$, $p=0.106$). That means subjects were easily able to identify all vibrotactile directional cues. The finger and the palm were not a preferred site of the body in transmitting directional information because the posture might be changed frequently and steady contact is not guaranteed compared to a relatively flat skin surface of the forearm or the torso (back). As Piateski and Jones mentioned, the back is one of a good possible and good alternatives for the forearm. The percentage of the correct answer for the back was 99-100% for their result, however even the fingers and the palm shows 92% so the hand-held vibrotactile display could be a good alternative for the forearm or even the torso. Compared to the 8 area display for the wrist, elbow, and upper arm from Schatzle et al. [7], these results were relatively remarkable for correct recognition. Since manipulability or sensitivity is better than the torso in the fidelity point of view, vibrotactile display for hand-held device has several advantages. By splitting the vibrating surface, we have achieved a higher percentage than other previous developments for a similar task, and its potential as a novel add-on type vibrotactile display was examined.

4.2 Spatial Location Display

4.2.1 Procedure

In order to evaluate the location display performance of the T-Mobile, an experiment for presenting spatial information was carried out. The goal of the experiments were to measure whether the user can properly perceive the spatial information on different parts of the hand using the T-Mobile, furthermore, to compare the effectiveness of information transmission on the fingertip and palm by using the T-Mobile. Ten students at KIST participated in this experiment. They were 6 males and 4 females between the ages of 25 and 32. None of subjects reported any sensory difficulties or troubles on the hands. In this experiment, only 3 tactors located on the equator of the T-mobile were used for presenting 9 spatial locations, as shown in Fig. 5.

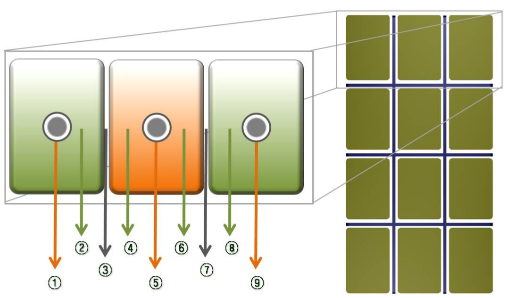

Fig. 5. Schematic diagram of presenting 9-directions using 3 tactors

The subject sat in front of the T-Mobile and griped the backside of the T-mobile, and she/he listened to instructions before testing. A computer program presented 9 types of vibration signals that implied the related locations, and the experimenter notified the subject of the spatial meaning of the signal. When the experiment was started, the computer program presented vibration signals in random order. A nine alternative forced-choice (9AFC) method was applied, and the subject had 9 trials to detect each spatial location, a total of 81 trials for all locations. In each trial, the computer program allowed another three chances to sense the vibrotactile stimuli when requested by the subject. To mask the sound of the vibrotactile actuators, pink noise was applied to subjects using headphones during the transmission of vibrotactile stimulus. After each stimulus, the participant answered as to which location had been detected, and the answer was recorded automatically by the program. After an experimental block, which consisted of 9 trials, a three minutes' break was applied in order to prevent the adaptation effect of tactile sensation.

4.2.2 Results

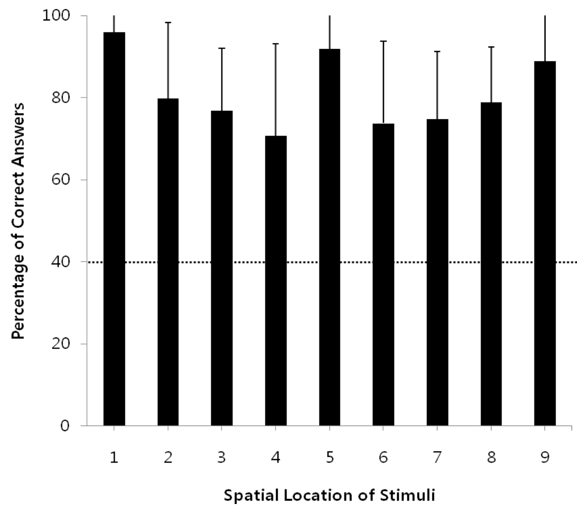

Fig. 6. Experimental results of spatial location identification

Figure 6 shows a summary of the results of this experiment. The mean percentage of correct answers was 81.2%. Locations 1, 5, and 9, where the tactors were directly attached, were highly distinctive, and even the lowest rate of recognition was over 71%. There was no significant difference in the recognition rate among locations 1, 5, and 9 ($F(2,18)=1.713$, $p=0.206$). Though the experimental procedure was based on the 9AFC, the spatial location modulated by only one vibrotactile actuator shows over 92.2% accuracy. This implies that the difficulty of the experiment was same as that of a 5AFC. In a 5AFC, the chance rate is 20% and the percentage of correct answers for 6 spatial locations, except locations numbered 1, 5, and 9, were all above 71%, and the mean value was 75.8%. Therefore, it was reasonable to conclude that a reliable discrimination of spatial locations was achieved by utilizing the combination of two stimuli from different locations based on the phantom sensation. The results proved that the proposed display method can represent 3 more directions between tactors. This means we can achieve 4 times higher resolution than the actual number of tactors by the proposed method.

4.3 Discussion on Experimental Results

The main objective of the experiment was to examine whether or not the vibrotactile stimuli based on sensory illusion could provide appropriate spatial and directional vibrotactile cues. As a novel vibrotactile display device for displaying vector information, the T-mobile performs almost perfectly in displaying the directional information and the proposed method based on perceptual characteristics of the spatial information is reliable. The main contribution of this work is that the feasibility of displaying spatial and directional information together was examined in a vibrotactile display system. Furthermore, spatial locations exceeding the number of actuators were realized utilizing one of the perceptual illusions, the phantom sensation. As a result, a resolution four times higher than the actual number of tactors was achieved. As Loomis [6] mentioned in his study, sequential presentations of vibrotactile stimulus is superior over simultaneous presentations. That is why sensory saltation is the most popular method in presenting vibrotactile patterns since saltation is originally based on the sequential display of discretely located stimulus. For a grooved surface, saltation is well applied when isolation of the vibrotactile piece of the surface is maintained. If a force based identification test is conducted in the same procedure with a spatial location test, we should be able to determine an optimal number of vibrotactile actuators to display continuous or reliably discernable spatial locations. By utilizing the device, hand-held navigation or several controls by cellphones will be intuitively achieved according to the vibrotactile information cues.

V. Conclusion

We have developed an add-on type vibrotactile display pad system that can provide spatial and directional information. The developed device consists of 12 pieces of vibrotactile pad, each of which components consists of a vibration isolator, a resonant linear vibrator, and a cover part. Spatial and directional information was generated applying sensory saltation and phantom sensation phenomenon for the developed device. The possibility of combining vibrotactile cues for transmitting vector information consisting of directional information and spatial location was examined with the device.

Intuitive directional information consisted of eight directions and two rotations and was displayed through the developed device. Performance evaluation of the suggested vibrotactile cues for spatial locations based on human perceptual characteristics was conducted through two experiments for ten and eight subjects. The experimental results indicate that directional information can be interpreted by a novice user as reliable and intuitive, since a 92% correct response rate was achieved using the vibrotactile display. Moreover, inter-stimulus locations can be displayed reliably to the hand with the proposed vibrotactile cues based on phantom sensation, though the number of actuators is limited for displaying continuous spatial locations.

For a future work, vibrotactile acuity and spatial summation would also be tested for the groove-shaped and piecewise-isolated structure of the developed vibrotactile display pad. Also, apparent movement, which is time varying phantom sensation, should be applied to the developed device to generate continuous movement over the surface.

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