# Sharp Tactile Line Presentation Array using Edge Stimulation Method

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**ABSTRACT**

We report on a tactile shape presentation display that has a rigid plane for a surface and can present highly localized tactile stimuli using small vibrotactile stimuli. We have proposed an edge stimulation (ES) method that can present sharp tactile sensation along the boundary edge of vibratory surfaces. The basic concept is to use the ES method for shape presentation. The ES method allows the tactile display surface to be a flat plane; it can be mounted on a flat surface of any devices and can project images on this surface. The ES method uses low-frequency and small-amplitude vibrations that achieves low power actuation. Previously, we have developed an edge stimulation device (ES device) with voice coil actuators in 2×2 array and examined the concept of the ES method for shape presentation, though it was low rigidity (display surface was easy to be bent) and not capable for various shape presentation. In this study, we developed 3×3 array shape presentation display with rigid piezo-vibrators taking advantage of ES method. Psychophysical experiment on detection thresholds for vibratory stimuli demonstrated the display can make 5 $\mu$m at 30 Hz vibration perceivable, even though they normally require a 30 $\mu$m amplitude for simple vibrations. In the shape recognition test results, users correctly scored of 96 % for 8 patterns discrimination tasks.

**Keywords:** Vibrotactile Stimulation, Haptic display

**Index Terms:** H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; H.1.2 [Models and Principles]: User/Machine Systems—Human factors

## 1 INTRODUCTION

Tactile shape presentation is currently the focus of attention for its applicability in mobile devices, which are seeing a wide proliferation of touch panels. The shapes of virtual buttons, letters, numbers, and symbols are presented for tactile feedback; the addition of such tactile information helps the user with faster and accurate handling. Achieving a sharp distinct tactile sensation is essential for better recognition of tactile shape information and facilitates intuitive handling in virtual interactions. There are several methods for presenting tactile stimuli; the main types are static and dynamic. Current tactile displays have employed the dynamic type for the easiness of fabrication and variety in generated stimulation pattern covering passive touch. The dynamic type generally uses vibrotactile stimulus to generate a tactile shape sensation; this is called the vibrotactile stimulation method.

Previous works used pin shaped thin vibrators as the vibrotactile stimulator; there were arranged in a matrix called a pin-array vibrator. The tactile shape is formed by several tactile dots of pin vibrators; the user perceives a tactile shape as a combination of these dots. The Optacon obtains 2-D image information using an image sensor and encodes it with spatially distributed pin vibrators as 2-D surface shape vibratory stimuli. Summers et al. developed a display using a tactile array comprising 100 contactors in a 1 cm×1 cm matrix [2]. Ikei et al. developed 10 pins of 0.5 mm×0.5 mm square cross-section arranged in a 5×2 matrix of 3-mm spacing to cover the center portion of a fingerpad eminence[3]. Stress2 is a haptic display that uses lateral vibrations of a piezoelectric vibrator to generate dot-shaped tactile information[4], while VITAL is an 8×8 matrix (2 mm spacing) vibrotactile display[5] and 3×3 matrix tactile display developed by Yang[6].

These tactile displays generally use high-frequency vibrations (200-300 Hz) due to the vibrotactile sensitivity of humans to frequency. However, mechanoreceptors that are sensitive to high frequencies (fast adopting type II unit: Pacinian corpuscle) have large receptive fields and are essentially unsuitable for obtaining the spatial distribution of vibrations. In contrast, low-frequency vibrations (5-30 Hz) are sensed by mechanoreceptors such as Merkel's disks (slowly adopting type I unit) and Meissner's corpuscles (fast adopting type I unit), which have a high spatial resolution for tactile stimuli. Thus, using low-frequency vibrations to present tactile shapes is a natural approach, although large amplitudes are required for those low frequencies to be perceptible (about 30 $\mu$m); thus, actuators are large.

We have proposed a vibrotactile stimulation method that uses low-frequency and small-amplitude vibrations while reducing the detection threshold to 5$\mu$m that is 1/6 of typical mechanical vibrators[7, 8]. We selectively stimulate high spatial resolution mechanoreceptors such as Merkel's disks and Meissner's corpuscles in the shallow layer by locating two surfaces in close proximity and vibrating them with in different phases while suppressing the spread of vibration on the skin. The tactile image emerges along the boundary edge of the surfaces, and the sensation is sharp, localized, and clear. We call this the edge stimulation ES method, which is found and reported in [8]. Fig. 1 shows a schematic of ES method. The ES method allows the tactile display surface to be fabricated as a flat plane in contrast to the previous pin-array displays discussed above; we can mount the ES tactile display on the flat surface of any device and project images on the display surface. Moreover, the low-frequency and small-amplitude vibrations of the ES method allows for low-power actuation. Previously, we have developed an edge stimulation device (ES device) with voice coil actuators in 2×2 array and examined the concept of the ES method for shape presentation, though it was low rigidity and not capable for various shape presentation[9]. We have been investigated the basic concept and the performance for human perception on the ES method with the previous device. In this study, we developed a 3×3 array shape presentation display with piezo-vibrators based on ES method and our goal is to demonstrate the effectiveness of the device for shape recognition. We can obtain sufficient vibration amplitude without bimorph structures or other displacement amplifying structures. We conducted a series of psychophysical experiments on detection thresholds for the validation to achieve the ES method on the developed device, and the line pattern recognition rate to validate the effectiveness of the ES method at tactile shape presentation.

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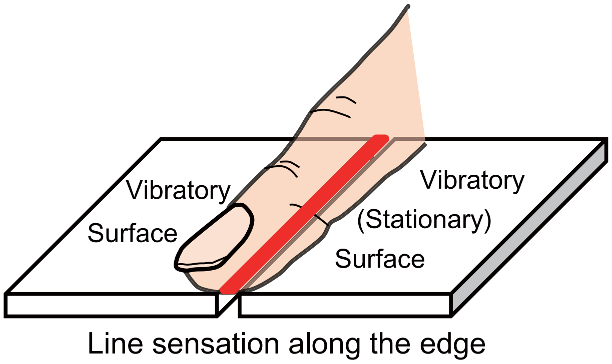


Figure 1: Schematic of edge stimulation (ES) method. Two plain flat surfaces of vibrators in close proximity vibrate in different phases. A line-shape tactile sensation emerges along the boundary edge between them.

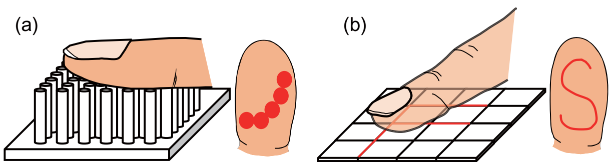


Figure 2: Concepts of shape presentation: (a) pin-array display, where tactile shape is formed by combinations of dots; (b) ES method, where tactile shape is formed by continuous lines.

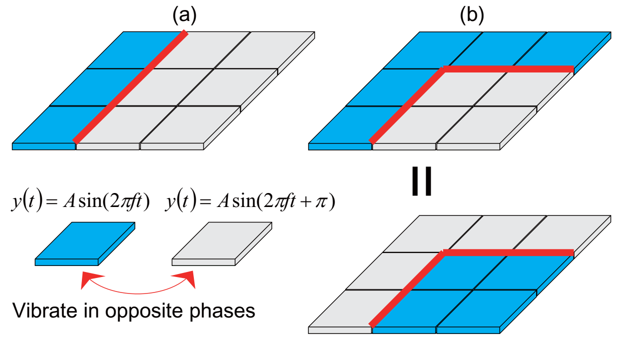


Figure 3: Tactile line presentation using ES method. Line sensations emerge between vibratory surfaces in opposite phases: (a) straight line; (b) bending line.

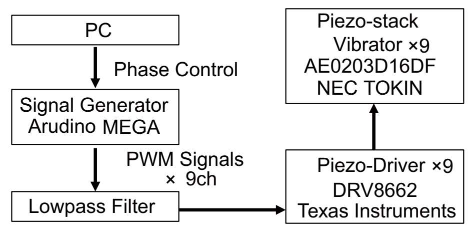


Figure 4: Overview of tactile line presentation device system.

## 2 Shape Presentation

### 2.1 Edge Stimulation Method

The ES method uses vibration amplitudes under the detection threshold; when a user touches a flat vibratory surface, the vibratory sensation is not obtained on the surfaces themselves but rather along the boundary edges of surfaces in different phases. The tactile sensation is more localized than simply touching a thin pin vibrator. Concretely, a 0.5 mm diameter pin vibrator with an amplitude at the detection threshold produces a 2.34 mm wide tactile image. In contrast, the vibration overlap method with a gap of 0.5 mm produces a 0.64 mm wide tactile image [7]. We have previously reported mechanical parameters that affect the detection threshold under the ES condition.

1. Gap distance between two vibratory surfaces

   The gap distance is positively correlated to the detection threshold. This means that the ES method is effective when the gap distance is small. The detection threshold rises suddenly for gap distances of more than 2.5 mm, while the curve of detection thresholds for gaps of less than 2.5 mm is almost linear[8].

2. Phase deviation between two vibratory surfaces

   The detection thresholds and phase deviation of two vibratory surfaces are negatively correlated. When the phase deviation increased from 0 to $\pi$, the detection threshold fell exponentially from about 30 $\mu$m to 5 $\mu$m[7]. This means that the vibrotactile intensity can be modified not only by changing the amplitude but also by changing the phase deviation of the two adjacent surfaces.

Fig. 2 shows the concept of presenting tactile shapes with the ES method. Instead of the dot combinations of a pin-array type display, we propose an element producing a continuous line sensation.

### 2.2 Line Presentation using Phase Shifting

We control the phases of vibrators and present line sensation only between the vibratory surfaces in opposite phases and we can switch the line shapes by changing their phases. Fig. 3 shows the tactile line presentation methods. We present tactile lines between the vibrators in opposite phases. A continuous straight line can be presented by setting the boundary lines of opposite phases to be straight, as shown in Fig. 3(a). A bending line can be presented by setting the phases as shown in Fig. 3(b).

The ES method can also present a line sensation between stationary and vibratory surfaces; we did not use this approach in this study because it produces a lower intensity and adjusting the intensity of vibratory surfaces in opposite phases is difficult so far.

## 3 Tactile Display

The developed ES device has nine vibrators in a $3\times3$ array. Fig. 4 shows the entire system of the device. A PC controls each phase of the vibrators. Arduino MEGA 2560 generates nine-channel pulse width modulated signals; an analog low-pass filter turns them into sinusoidal waves. Piezo drivers (Texas Instruments DRV8662) amplify the signals at a maximum of 40 db to 200 V. We used piezo-stack type actuators (NEC TOKIN AE0203D16DF; $2\times3\times20$ mm) owing to their rigidity against the indentation normal force. They show 17.4 $\mu$m displacement at a maximum voltage of 150 V and normal force of 200 N; these are sufficient for human touch(several newtons). The 5 mm square acrylic plates are attached on the top of the vibrators to make the display surface is a 15 mm square flat plane(see Fig. 5(a)). The entire display is less than the area of human index finger, as shown in Fig. 5(b). Gap distances of the surfaces are fabricated to be less than 0.1 mm. Vibratory surfaces vibrate in normal direction and they do not interfere with each other.

## 4 ES Device Evaluation Experiment

We evaluated the developed ES device through a psychophysical experiment to validate the feasibility of ES method for $3\times3$ arrays.

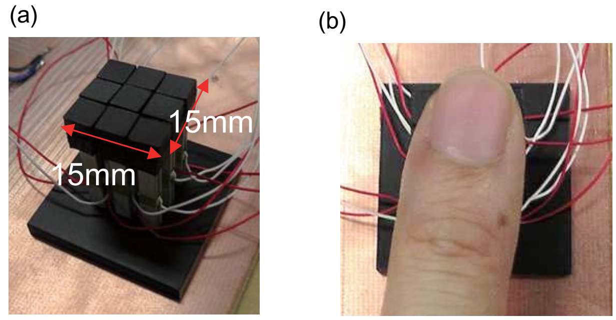


Figure 5: Overview of developed haptic display: (a) square-shaped vibrators in array vibrate in different phases; (b) entire display is smaller than fingertip of index finger.

Detection thresholds were investigated under several different conditions where nine vibrators were vibrated in the same and opposite phases. If the device achieves ES method properly, the detection threshold of the former will be larger than that of the latter.

### 4.1 Method

Fig. 6 shows the experimental overview. Participants touched the display shown in Fig. 5 with the tip of their index fingers and with an indentation force of 1 N. As the participants were touching the surfaces, the vibratory surfaces were vibrated according to the following equation:

$$A : f(t) = A\sin(2\pi f t) \quad (1)$$

$$B : g(t) = A\sin(2\pi f t + \phi) \quad (2)$$

where $f(t)$ and $g(t)$ are the displacement [$\mu$m], $A$ is the amplitude [$\mu$m], $f$ is the frequency [Hz] and $\phi$ is the phase deviation between two surfaces A and B. We used two phase deviation conditions: 0, $\pi$ and the frequency was set to 30 Hz. Three conditions were presented, (a)left, (b)up and (c)all were in the same phases, which were set as shown in Fig. 7.

As the participants were touching the vibrator contactor, we repeatedly changed the vibrators' input voltage by 2 V. After each increase, the participants were asked whether they perceived a vibratory stimulus. The input was increased from 0 V to 150 V, and the threshold amplitude was recorded. Next, the input was decreased in steps of 2 V from a well-defined input, and the threshold amplitude at which the participant could not perceive the vibratory stimulus was recorded. The method of limits was then used to calculate the detection threshold for vibration. For condition(c), 17.4 $\mu$m amplitude that is the maximal amplitude of the device, when the participants were not able to perceive a 17.4 $\mu$m amplitude, we instead used large displacement type piezoelectric actuator (TOKIN, AHB850C851FPOL-1F) with a 15 mm square acrylic plate on top and repeated the same task. This process was repeated three times at each condition for a total of nine times for each individual. Participants wore headphones playing white noise so that they would not perceive any environmental changes. The seven participants were all right-handed males, aged 21-32. None of the participants had any known medical conditions or disorders affecting their tactile senses.

### 4.2 Result

Fig. 8 shows the detection thresholds under each conditions. Under conditions (a) and (b), the average detection thresholds were about 5 $\mu$m, which did not contradict previous information on ES effects[7]. When all vibrators were vibrated in the same phase, only one participant reported that he felt no vibration under 17.4 $\mu$m

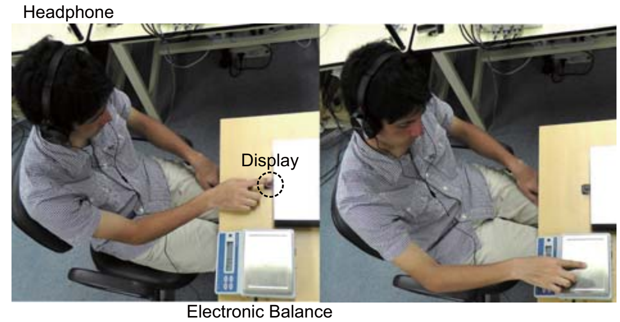


Figure 6: Experimental setup.

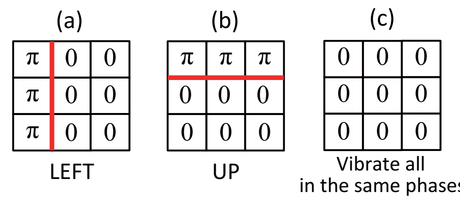


Figure 7: Pattern conditions: (a) left line, (b) up line, (c) vibrate all in same phase (no lines).

with the ES device. This may be due to the displacement difference of each vibrator to the input voltage; the difference may be felt as a vibratory sensation. After the vibrators were changed to large-displacement ones, the average detection threshold was 28 $\mu$m.

### 4.3 Discussion

In the detection threshold studies of Verrillo and others[10, 11, 12], it is about 10 $\mu$m for condition under touching both circular vibrator and rigid surroundings with hole and about 30 $\mu$m for vibrator only that is similar to the results of under conditions (a) and (b), condition (c), respectively. Based on the results, the developed ES device achieved the ES effects, and a line sensation could be generated; for example, at 10 $\mu$m, the lines between surfaces in the same phases could not be perceived, while those between surfaces in opposite phases could be selectively perceived. The vibratory sensation was sufficiently strong when the amplitude was 10 $\mu$m; the piezo-stack type vibrator can be made thinner and replaced for a 10 mm height.

## 5 Shape Recognition Experiment

We produced line sensations with the ES device to investigate the effectiveness of the ES method at tactile shape presentation. We conducted a shape recognition psychophysical experiment and examined the correct answer rate.

### 5.1 Method

Fig. 9 shows the experimental overview. Eight patterns of tactile images, including two conditions with no tactile sensations, were presented in random order. Fig. 10 shows the six line patterns–left, right, up, bottom, double vertical lines, and double horizontal lines– and two conditions with no line sensations–vibrate all and vibrate none. The stimuli were presented previously, and the participants knew the stimuli sets described above. The participants touched the display and made sure that their index finger covered the entire display with an indentation force of 1 N. Participants practiced touching with a force of 1 N by touching an electronic balance. The stimuli were presented for 2 s before the participants removed their fingers. After each trial, the participants were asked to sketch the perceived tactile image on the answer sheet by drawing lines. If the participants sensed no lines, they just skip the answer. Each condition of tactile lines was presented 10 times for a total of 10×8

Table 1: Correct recognition rates

| Participant | LEFT | RIGHT | UP | BOTTOM | Double VERTICAL | Double HORIZONTAL | LINE TOTAL | Vibrate ALL | Vibrate NONE | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|
| H | 10/10 | 10/10 | 10/10 | 10/10 | 9/10 | 10/10 | 59/60 | 10/10 | 10/10 | 79/80 |
| K | 10/10 | 10/10 | 10/10 | 10/10 | 10/10 | 10/10 | 60/60 | 10/10 | 10/10 | 80/80 |
| Ha | 10/10 | 6/10 | 8/10 | 10/10 | 8/10 | 9/10 | 51/60 | 10/10 | 10/10 | 71/80 |
| Y | 10/10 | 10/10 | 10/10 | 10/10 | 7/10 | 10/10 | 57/60 | 10/10 | 10/10 | 77/80 |
| RATE | 1.0 | 0.9 | 0.95 | 1.0 | 0.85 | 0.96 | **0.9** | 1.0 | 1.0 | **0.96** |

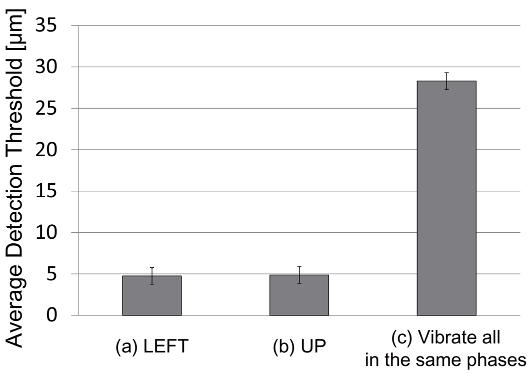


Figure 8: The result of the psychophysical experiment.

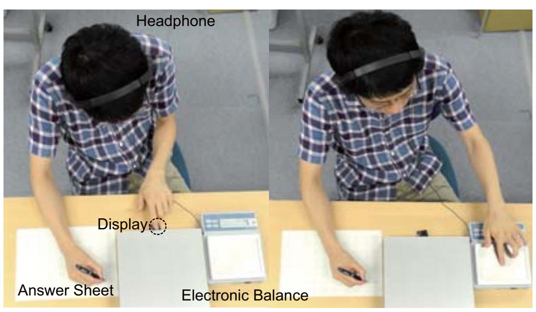


Figure 9: Experimental setup.

= 80 trials by each individual. In order to ensure that the participants would not perceive any environmental changes, they wore headphones that played white noise. The four participants were all right-handed males aged 20-30. Vibratory stimuli were generated according to the equation. (2) in the first test. We used two phase condition of 0 and $\pi$, an amplitude of 10 $\mu$m, and a frequency of 30 Hz.

### 5.2 Result and Discussion

Table. 1 shows the results of the recognition test. The participants were able to discriminate lines at a rate of 90%, and the total correct answer rate was 96%. There was no condition with a significant number of mistakes. The high score indicates the effectiveness of the ES method at presenting line shapes. When presented (g) or (f), all the participants skipped the answer sheet correctly. Reports of the participants after the tests showed they were not able to discriminate the (g) form (f) conditions. Most mistakes were under condition (f), where double vertical lines were mistaken for a vertical line to either the left or right.

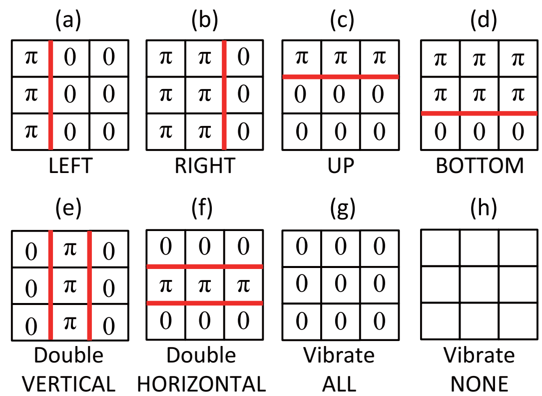


Figure 10: Eight tactile image patterns. Line sensations only arise above the edges between surfaces in different phases.

## 6 Conclusion

We developed a 3×3 array shape presentation display and succeeded in presenting tactile lines with minimum amplitudes of about 5 $\mu$m. The small amplitudes enabled the use of piezo-stack actuators that were thinner than 10 mm, which can help decrease the size of the display. Users demonstrated a high discrimination rate for eight tactile line patterns of 96%. Our future work will involve developing larger and thinner displays and spatio-temporal variations of tactile lines.

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