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A PIN-ARRAY TACTILE DISPLAY USING SHAPE-MEMORY ALLOY WIRES FOR THE PRESENTATION OF VARIOUS TACTILE SENSATION

Yusuke Baba[1], Haruo Igarashi[1], Renke Liu[1] and Hideyuki Sawada[2]

[1]Department of Pure and Applied Physics
School of Advanced Science and Engineering
[2]Department of Applied Physics
Faculty of Science and Engineering
Waseda University
3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
yusuke.baba@toki.waseda.jp; h.igarashi@akane.waseda.jp; askar_liu@fuji.waseda.jp; sawada@waseda.jp

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Abstract. *A pin-array tactile display is developed as a method of presenting tactile sensations that we experience when we stroke our fingers on the surface of objects. Important requirements for pin-array tactile displays include the frequency response up to 300 Hz, the high pin density, the independent controllability of each pin, the compact size, and the light weight. While it is essential for wearable devices, especially from the viewpoint of portability and usability, to be small and lightweight, the high-frequency response and high pin density often result in a larger size of a device. In this paper, we propose a pin-array tactile display using Shape-Memory Alloy (SMA) actuators arranged in high density, which is characterized by the high-frequency response, the independent controllability of pins, and the compactness. The performance of the device is evaluated by user experiments to examine the relationship between the control parameters and the presented tactile sensations.*

Keywords: Tactile display, Shape-memory alloy wire, Controlling frequency, Reproduction of tactile sensation

1. Introduction.

Various types of tactile displays have been developed and introduced so far since the presentation of tactile sensations gathers great attention to Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) applications [1]. The examples are one that presents a tactile sensation of the softness of an object [2], and the other that presents a tactile sensation of the unevenness of an object's surface. For the latter sensation, pin-array tactile displays consisting of vibration pins arranged in a matrix have been widely studied and developed.

Killebrew et al. proposed a tactile display using linear motors as actuators [3]. It had a wide-range frequency response and a comparatively higher density of arranged pins. However, the whole device was huge and expected to be situated on a wall. For these reasons, users could not move their fingers with the device. Ujitoko et al. proposed a tactile display using pneumatic actuators featured with its high density [4]. On the other hand, the size of the system was large since the actuators required an air pomp. Kajimoto and Jones developed a display using nichrome wire as an actuator [5], which had a wide frequency response and a high density of arranged pins, but required a fan for the heat radiation because the nichrome wire of the actuator was heated up to 1000 K. In addition, securing the length of the nichrome wire made the device larger. The challenges for developing

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tactile displays are to extend the response range of the actuation frequency and to place actuators in high density, which leads to huge device sizes.

A Shape-Memory Alloy (SMA) is an alloy that can remember its original shape, and has been widely applied for thermally reactive actuators [6,7]. We have been studying tactile displays using SMA wires as micro-vibration actuators [8-11]. The developed SMA actuators are characterized by their frequency response of up to 300 Hz, compact size and lightweight, simple mechanism, and easy parallel controllability using a simple electric circuit with low energy consumption. Each pin is independently controlled by different vibration frequencies and different timings of its activation for presenting various tactile sensations. Tactile displays using SMA actuators are expected to meet the requirements of wide frequency response and compact body. On the other hand, due to the requirement of the bridge-like structure, there was difficulty in arranging the actuators in a high density on the surface of display devices.

In this paper, a novel tactile display with high-density SMA actuators is introduced by a newly introduced diagonal arrangement and two-layered structure. Through the three user experiments, the characteristics of the tactile sensations presented by the proposed display, under the control of the driving parameters such as frequencies and amplitudes given to each pin, are validated. The presented tactile sensations are discussed in comparison with real materials at various types of vibratory frequencies.

The paper is organized as follows. In Section 2, by the discussions of the human sense of touch and the requirements for tactile displays, a novel tactile display using SMA actuators is introduced. In Section 3, a preliminary experiment is presented for determining the driving parameters of the tactile display by referring to actual textures. In Section 4, two user experiments are introduced for the validation of the tactile presentation. Finally in Section 5, the conclusion and future works are described.

2. **Novel Tactile Display Using SMA Actuators.**

2.1. **Tactile display.**

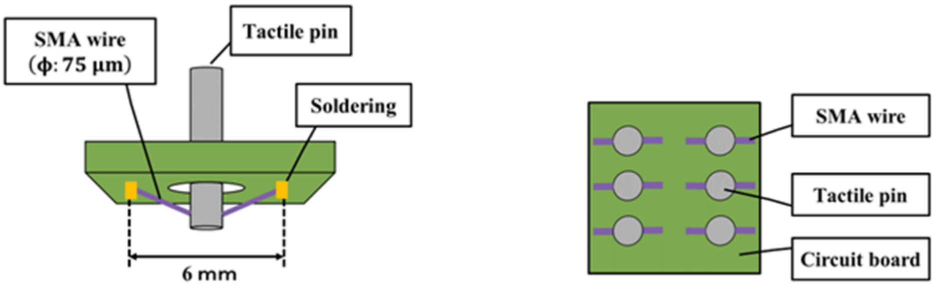
Tactile displays have been widely introduced for presenting tactile information to users together with visual and auditory information to provide realistic interaction in virtual space based on VR and AR technologies. Typically, a tactile device is attached to the user's hands or fingers to present different tactile sensations in response to the user's actions. When a user strokes the hand on the surface of an object in the virtual space, the corresponding tactile sensation given by simple vibratory stimuli is presented through the device.

2.2. **Human tactile sensation and required conditions of tactile display.**

Four different tactile receptors that underlie the skin respond to physical stimuli given to the skin. Meissner corpuscles and Pacinian corpuscles react to vibratory stimuli with different frequency ranges. Meissner corpuscles react to the frequency from 10 to 100 Hz, and Pacinian corpuscles, on the other hand, have a frequency range response of 40-500 Hz [12]. Furthermore, the two-point discrimination threshold of a human fingertip is reported as 2 mm [13], and it is considered that the resolution of the presented tactile sensation can be increased by the pin pitch of less than 2 mm. In addition, the small size and light weight of the display is an important factor from the viewpoint of usability and portability, since the device is typically used for interaction with virtual objects in a VR environment. For these requirements, we proposed a novel pin-array tactile display based on SMA actuators.

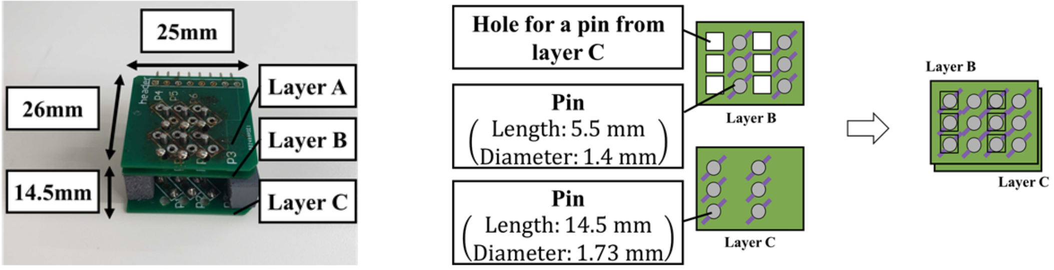
2.3. **SMA wire actuators.** An SMA wire composed of Ti-Ni-Cu with a diameter of 75 μm (Toki Corporation, BMF75) is used in this study. When heated to a specific temperature, an SMA wire shrinks up to 5% of its original length in the length direction due to the shape-memory effect, and returns to its initial length by radiating heat to the air. The SMA wire has an electrical resistance of 0.23 Ω per millimeter, and by applying electric current, the temperature instantly rises due to the internal Joule heat. Since the wire has a sufficient surface area, the temperature drops by radiating heat, when the current stops. Owing to the thermally efficient characteristics of the SMA wire, the shrinkage and the return to the initial length are controlled by applying a pulsed current. In our previous study, we confirmed that the behavior of an SMA wire perfectly synchronizes with a pulse current up to 300 Hz [11].

2.4. **Structure of the pin-array tactile display.** To convert longitudinal vibration into vertical vibration, we have developed a novel structure by setting a tactile pin to be connected with an SMA wire as shown in Figure 1(a). Since one SMA actuator has a



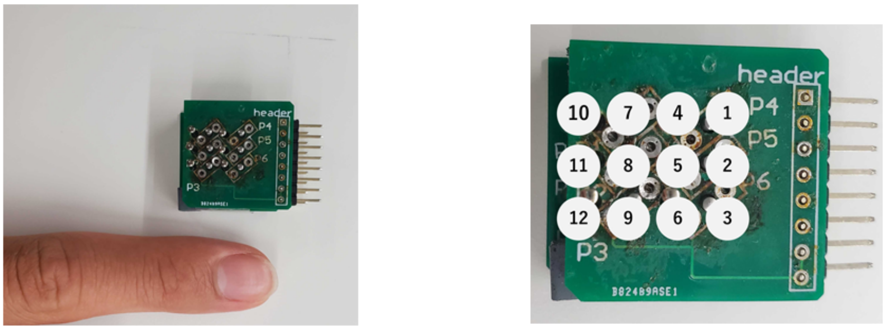
(a) Structure of a tactile actuator using an SMA wire and a tactile pin

(b) Arrangement of SMA actuators



(c) Outlook of the developed display

(d) Two-layered structure for high-density pin arrangement



(e) Constructed display having 12 tactile pins

(f) Pin numbers

FIGURE 1. Constructed tactile display

bridge-like structure, it requires sufficient space between adjacent pins. In our previous studies, we had difficulties in arranging the actuators in a high density in a surface as shown in Figure 1(b). In this study, to solve this problem, each SMA actuator is placed diagonally, and a two-layered structure is newly introduced to achieve the pin arrangement with high density in the lateral direction. Figure 1(c) shows the novel structure of a tactile display: layer A is a cover plate to fix pins to reduce the pin instability; layers B and C are the boards with the six SMA actuators, in which each actuator is mounted diagonally as shown in Figure 1(d). To align the height of tactile pins in the layer A, the pins with the length of 5.5 mm and the diameter of 1.45 mm are attached to the layer B, and pins with the length of 14.5 mm and the diameter of 1.73 mm are used in the layer C. On the surface of the display, 12 pins are placed with a center-to-center distance of 4 mm. The weight of the display is 6.4 g, which is lightweight enough for wearable use. The constructed display having 12 tactile pins is shown in Figures 1(e) and 1(f).

2.5. **Tactile display control.** The driving circuit of an SMA actuator is shown in Figure 2. The PWM signal is output from a microcomputer (Raspberry Pi 4), which is amplified by a specially-designed current amplifier using two transistors (2SD880) [14]. Twelve SMA actuators and amplifiers for each pin are connected to the driving circuit in parallel so that each pin can be controlled independently, and an electric current of up to several hundred milliamperes is provided for driving each actuator. The activating timing, frequency, and duty ratio of the driving signals given to each pin can be independently controlled to present various tactile sensations. Some examples are described in the experimental sections. Figure 3 shows the overall system, together with a scene of tactile

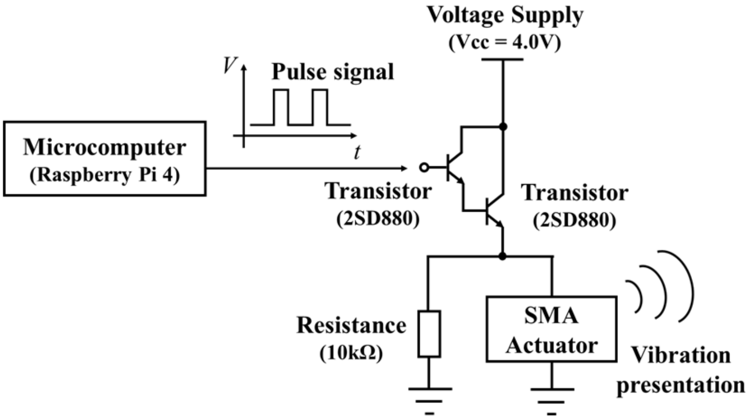
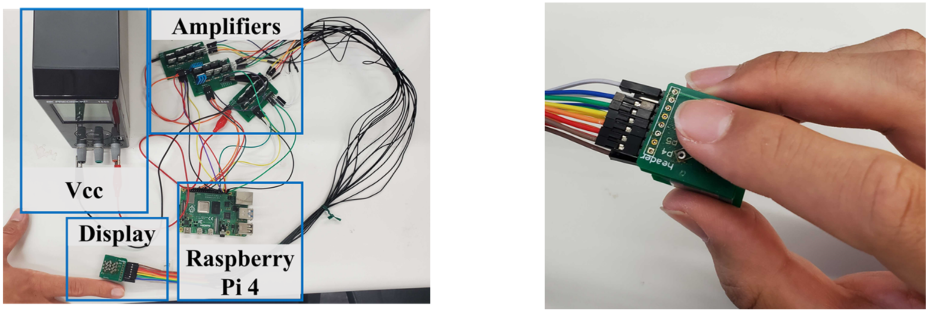


FIGURE 2. Current amplifier circuit for an SMA actuator



(a) System overview
(b) Tactile presentation to a fingertip

FIGURE 3. Tactile display system and a scene of tactile presentation to a fingertip

presentation to a user's fingertip. A user is able to feel various tactile sensations by softly touching the surface of the display with the fingertip.

3. Preliminary Experiment.

A preliminary experiment was firstly conducted by employing one subject to determine activating parameters for driving the tactile display, and to find perceived tactile factors for evaluating presented tactile sensation.

3.1. Methods.

Since the proposed device is characterized by the densely-arranged pins and their wide frequency response range, a user is able to recognize rich tactile sensations by freely moving the device held in hands. Furthermore, the driving parameters such as vibration frequencies, activating timing of pins, and duty ratio, can be freely and variously controlled by the specially-designed driving circuit. In this experiment, we considered a situation that a user stroked the index finger on the surface of an object to feel the texture. The control parameters examined here were the vibration frequencies and the activating time differences among pins.

In order to clarify the characteristics of the sensations presented by the display in response to the different driving parameters, especially frequency, we prepared eight vibration patterns as shown in Table 1. The duty ratio was fixed at 5.0% since the vibratory stimuli were compared under the same condition by giving equal energy. The vibration frequencies were set from 1 Hz up to 80 Hz, which was the range perceived by Meissner corpuscles. A time difference of 1 msec up to 83 msec was given to pins to activate them with random timing, since we hypothesized that by vibrating each pin at random timing, the display would be able to present different tactile sensations of touching an object's surface having random unevenness. For example, in the case of the 0 msec time difference, all the pins start vibration at the same time. On the other hand, in the case of 83 msec, the first pin starts vibration, and then in 83 msec, the next pin, which is randomly selected, starts vibration. Figure 4 shows an example of the driving time chart in the case of Pattern 1. Each pin vibrates at 1 Hz, and the duty ratio of the driving pulse is set with 5.0%, where the ON time is 50 msec and the OFF time is 950 msec for each pin. The time difference for activating pins is set at 83 msec. In this case, pin #9 is firstly selected for driving, and then 83 msec later, pin #11 starts vibrating. In 83 msec, pin #4 follows. The pin numbers are shown in the picture in Figure 1(f).

Table 1. Frequencies, duty ratios, and time differences for 8 driving patterns

Pattern name	Vibration frequency [Hz]	Duty ratio [%]	Driving time difference $\Delta\tau$ [ms]
Pattern 1	1	5.0	83
Pattern 2	4	5.0	20
Pattern 3	7	5.0	12
Pattern 4	10	5.0	8
Pattern 5	20	5.0	4
Pattern 6	30	5.0	2
Pattern 7	50	5.0	1
Pattern 8	80	5.0	1

For each tactile presentation, the subject held the display as shown in Figure 3(b), then moved the hand from left to right, and then moved back to left repeatedly, while the sensations were presented. After the presentation, the subject answered how he felt and what kind of sensation he recognized.

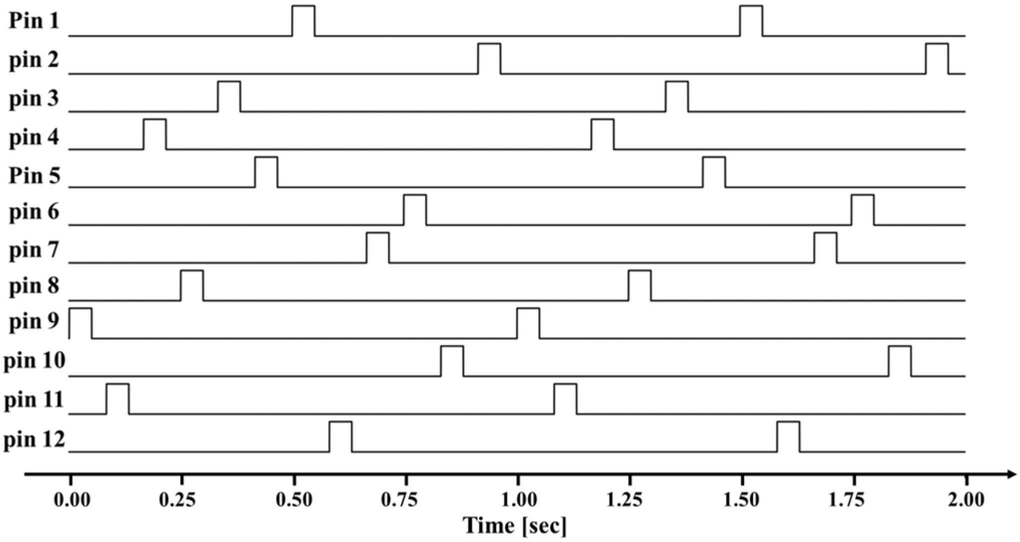


Figure 4. Example of a timing chart for Pattern 1

3.2. **Results.** When the vibration frequency was low, the difference in driving timing of the pins was clearly recognized, and the sensation of stroking on large bumps was recognized. When the vibration frequency increased and the driving time difference among pins became shorter, the bump-like sensation changed to small bumps, and then became a flat rough surface like a plastic sheet. Specifically, at 1 Hz vibration, smooth large bumpy sensation was obtained, and at 4 Hz a feeling of bubbles bursting sensation was obtained. The vibration of 20 Hz presented rough and numb sensation, and at 80 Hz, a feeling like touching the fine surface of a plastic and a feeling like touching charged plastic were obtained.

3.3. **Definition of different texture patterns.** From the results above, we discovered that the constructed display successfully presented different sensations that we could experience when we stroked the finger on a sheet and a fabric having random bumps and rough textures. Here, we define two factors for the evaluation of displayed tactile presentation, which are smooth/rough and bumpy/flat, by referring to the characteristics of the tactile sensation presented by the display found in the preliminary experiment.

Figure 5 illustrates the relations among the four surface patterns. Texture 1 presents smooth and flat surface without particular patterns related with bumps and roughness.

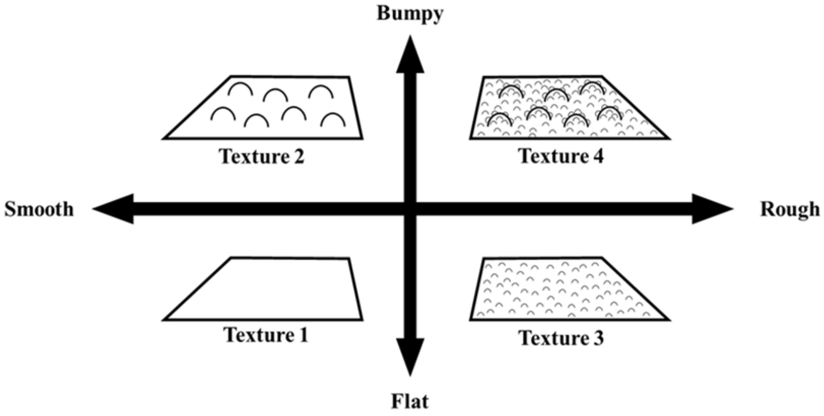


Figure 5. Textures defined to make discussion easier

The recognized sensation given by Pattern 1 at 1 Hz corresponds to Texture 2. When the frequency gets higher, the type of texture sensation gradually changes from Texture 2 to Texture 3. The recognized sensation at 80 Hz corresponds to Texture 3. Texture 4 shows a rough and bumpy surface, which consists of the mixture of large bumps and fine bumps. In Experiment 1, however, any of the prepared patterns were not recognized as the bumpy and rough texture like Texture 4. In order to present the sensation of Texture 4, the two vibration frequencies should be mixed, one frequency to be related to greater bumps, and the other to present smaller bumpy sensation. Through preliminary experiments, we determined the triple frequencies empirically with 4 Hz and 7 Hz for lower frequencies and 30 Hz for higher frequency. We name this as Pattern 9 in this experiment, and the employed parameter values are shown in Table 2. Figure 6 describes the driving time chart of Pattern 9.

Table 2. Given frequencies, duty ratios, and time differences to Pattern 9

Pin number	Vibration frequency [Hz]	Duty ratio [%]	Driving time difference $\Delta\tau$ [ms]
#1	30	5.0	0
#2	4	5.0	55
#3	30	5.0	7
#4	7	5.0	83
#5	30	5.0	28
#6	7	5.0	131
#7	4	5.0	179
#8	7	5.0	35
#9	4	5.0	242
#10	30	5.0	14
#11	4	5.0	110
#12	30	5.0	21

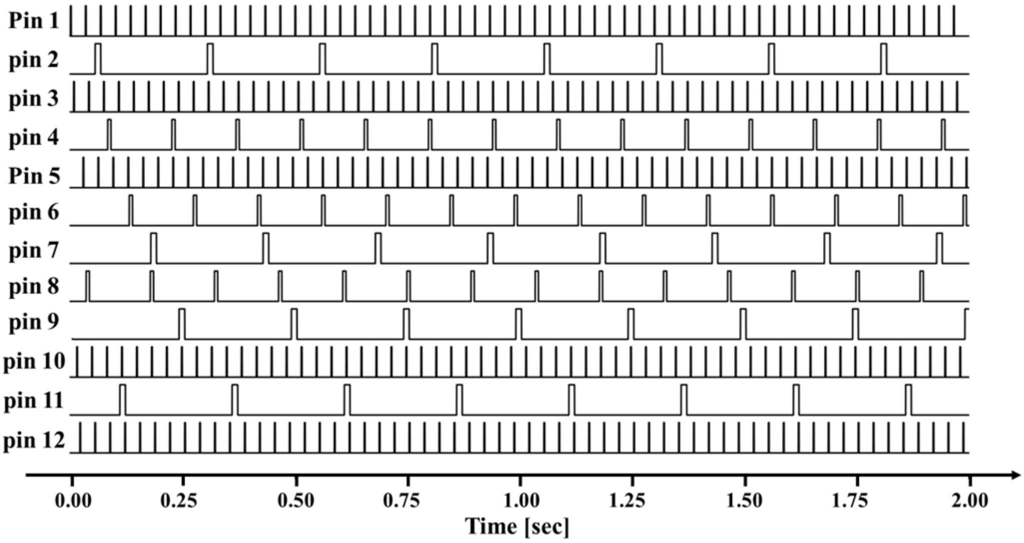


Figure 6. Example of a timing chart for Pattern 9

4. User Experiments for the Evaluation of the Display.

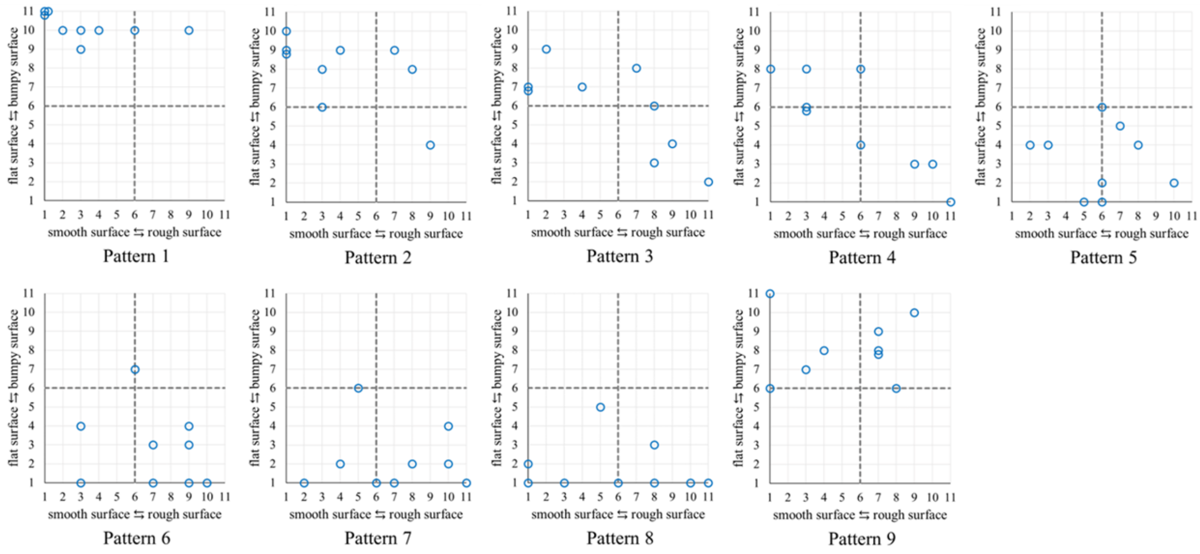
4.1. The participants. For the evaluation of the tactile display, two experiments were conducted by employing 9 subjects having standard tactile sensitivity (average age: 23.2 years, 6 males, 3 females, 8 right-handed, and 1 left-handed).

4.2. Experiment 1: Evaluation of presented tactile sensation driven by different frequencies.

4.2.1. *Methods.* Experiment 1 was conducted to evaluate the presented sensation by changing the vibration frequencies. We prepared 9 patterns with different driving parameters shown in Tables 1 and 2, and each sensation was presented in numerical order from Patterns 1 to 9. In patterns from 1 to 8, different frequencies were given to generate different tactile stimuli, and all the pins in the display were vibrated with the same frequency in each pattern. On the other hand, in Pattern 9, different frequencies were given to each pin as shown in Table 2. Before starting the experiment, all subjects were provided with the definitions of 4 textures presented in Figure 5.

Each subject placed the tip of the index finger of the dominant hand on the tactile display, and Pattern 1 was firstly displayed. While the tactile stimuli were displayed, the subject reciprocally moved the hand from left to right, and then back to the left, at 5 mm/s, for 30 seconds. After the presentation, the subject was instructed to answer how he felt the sensation in the scale of smooth/rough and flat/bumpy. The ratings were provided on eleven-level evaluations, with the rating of “6” as the neutral level, by the rating of “1” indicating a sensation like touching a smooth or flat surface, and the rating of “11” indicating a sensation like touching a rough or bumpy surface. Each subject repeated this procedure for the 9 patterns in the order.

4.2.2. *Results and discussion.* Figure 7 shows the summary of the results presented by the scatter plots that visualize the relationship between the evaluation values of smooth/rough and flat/bumpy for each pattern. Two axes correspond to the two evaluation factors defined by Figure 5. When the vibration frequency increased (from Patterns 1 to 9), the evaluation value of flat/bumpy decreased. From Patterns 1 to 6, the evaluation value of



Pattern 1 Pattern 2 Pattern 3 Pattern 4 Pattern 5

Pattern 6 Pattern 7 Pattern 8 Pattern 9

FIGURE 7. Scatter plots of smooth/rough and flat/bumpy evaluation for each pattern

smooth/rough increased. For Patterns 1 to 6, most participants selected Textures 2 and 3. On the other hand, by mixing different frequencies (Pattern 9), Texture 4 was chosen.

4.3. **Experiment 2: Verification of tactile sensation when pins are driven with the same frequency and time difference.**

4.3.1. *Methods.* Experiment 2 was conducted to compare the displayed tactile sensations with actual materials in order to analyze the relationships between the controlled frequencies and displayed tactile sensations. By referring to the results from the preliminary experiment and experiment 1, we selected 5 patterns, 1, 2, 5, 7, 8, and tried to compare them with actual materials. As shown in Figure 8, ten different materials were prepared, which were a rough metal mesh, a wool blanket, a sponge, a fine metal mesh, a woven plastic luncheon mat, sparkling water, and coated metal board, a fastener, a balsa wood, and a synthetic leather. The experiment was carried out by the following procedures.

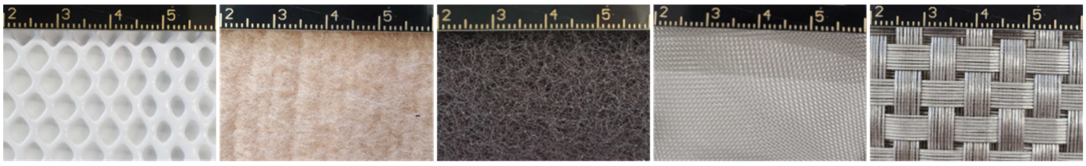
Step 1. Each subject lightly stroked the index finger of the dominant hand on the 10 materials at a speed of 50 mm/s except material 6. For material 6, a subject put the index finger of the dominant hand in sparkling water to feel a bubble-bursting sensation.

Step 2. Each subject experienced the presented tactile sensation of Pattern 1, holding the display as shown in Figure 3(b), then moving the hand from left to right, and then moved back to left repeatedly at 50 mm/s.

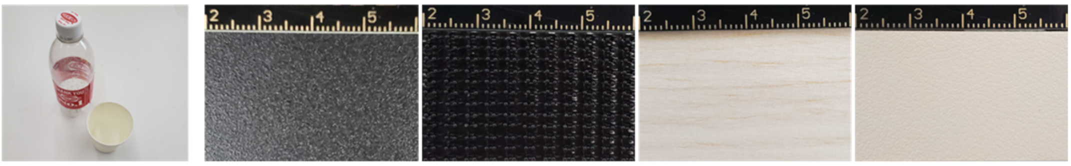
Step 3. Each subject experienced the presented tactile sensation of Pattern 1, holding the display as shown in Figure 3(b), then NOT moving the hand in order to compare the sensation with Material 6.

Step 4. Each subject touched the materials once more and selected the most appropriate material out of ten.

Step 5. Each subject repeated Step 2 to Step 4, with Patterns 2, 5, 7, 8, in the order.



Material 1 Rough metal mesh | Material 2 Wool blanket | Material 3 Sponge | Material 4 Fine metal mesh | Material 5 Woven plastic luncheon mat



Material 6 Sparkling water | Material 7 Coated metal board | Material 8 Fastener | Material 9 Balsa wood | Material 10 Synthetic leather

Figure 8. Real materials

4.3.2. *Results and discussion.* Figure 9 summarized the selected materials for each displayed tactile pattern. Most subjects chose Material 1 (Rough metal mesh) for Pattern 1, which had a smooth-bumpy surface. For Pattern 2, Material 6 (Sparkling water) was mostly chosen, which meant the provided sensation was recognized as a feeling of bursting bubbles in sparkling water. The subjects' choices from Patterns 5, 7, and 8 varied across the materials. More than half of the subjects selected Materials 5 and 10 from Patterns 5, 7 and 9 from Pattern 7, and 2 and 9 from Pattern 8. Materials 5 and 10 had fine-textured

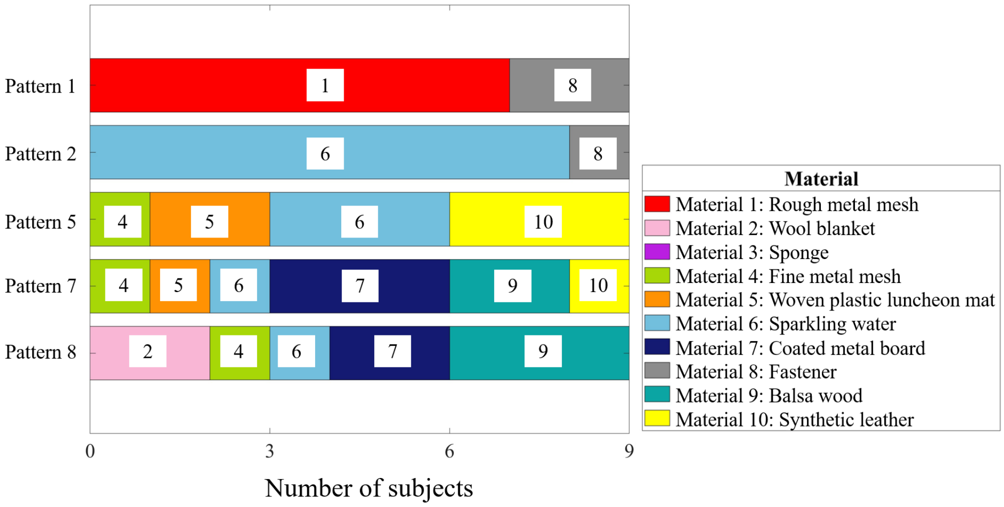


Figure 9. Result of a number of selected materials for each pattern

surfaces, and the surfaces of Materials 7 and 9 were rough. We can summarize that when the presented frequencies are low, the display presents the sensation of a smooth-textured surface with large bumps. As the frequency increases, the presented sensation becomes a flat and rough surface. Furthermore, based on the display ability to provide tactile sensations similar to those of actual materials, the device will be employed not only to enhance the virtual reality experience, but also for tactile transmissions remotely for online shopping and tele-communication.

5. **Conclusion.** A compact pin-array tactile display was developed using shape-memory alloy wires. The advantages of the developed display are the high pin density, the high-frequency response, the independent controllability of each pin, and the compactness. In this study, we conducted experiments to verify the characteristics of the sensations presented by the display in response to the different controlling frequencies. The experimental results indicate that as frequencies gradually increased across all display pins, the tactile sensation changed from a smooth bumpy surface to a rough flat surface. Furthermore, a combination of different vibration frequencies could present rough and bumpy surface sensation. From the comparison with real objects, the display was capable of presenting tactile sensations of real material surfaces. In future work, we will need to examine mixed-frequency vibration patterns in order to examine complicated tactile sensations. Additionally, by simultaneously displaying 3-dimensional visual information and realistic auditory information, the device will provide much realistic interaction in virtual reality environments by providing tactile feedback.

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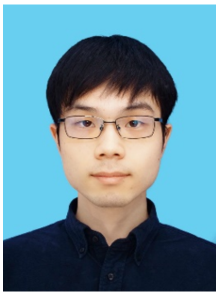
Author Biography

Yusuke Baba received a B.S. degree at the Department of Physics, Waseda University, Japan, in 2022. He is currently a master student at the Department of Pure and Applied Physics, Waseda University, Japan. His research interests include human interaction and tactile displays.



Haruo Igarashi received the B.Sc. degree in Mathematics from the University of Tokyo, Japan in 2020, and the M.Eng. degree in Physics-Based Engineering from the Waseda University, Japan in 2022. He is currently a Ph.D. student and research assistant at the Department of Pure and Applied Physics, Waseda University, Japan. His research interests include four-dimensional interactions and human interfaces.

Renke Liu received the B.S. degree from Beijing Institute of Petrochemical Technology, Beijing, China, in 2019, and the M.S. degree from Waseda University, Japan, in 2022 in the Department of Pure and Applied Physics. He is currently a Ph.D. student and research assistant at the Department of Pure and Applied Physics, Waseda University, Japan. His research interests include soft robotics, control systems, and deep reinforcement learning.

Hideyuki Sawada is a Professor in the Department of Applied Physics, Faculty of Science and Engineering, Waseda University. He received the B.E., M.E. and Ph.D. degrees in Applied Physics from Waseda University in 1990, 1992 and 1999, respectively. In 1999, he joined the Department of Intelligent Mechanical Systems Engineering, Faculty of Engineering, Kagawa University, as an Associate Professor, and became a Professor in 2010. His current research interests include robotics, sound and image processing, machine learning, human interfaces, and tactile sensing and display.