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ORIGINAL RESEARCH

Frequency based tactile rendering method for pin-array tactile devices

Sang-Youn Kim[1] · Yu-Joon Kim[1] · Dong-Soo Choi[1] · Byeong-Seok Shin[2]

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Abstract
In interactive Internet of Things (IoT) environment, a solenoid-based tiny pin-array tactile device can become a key module to haptically simulate a surface of interconnected objects. The solenoid-based pin-array tactile device creates a large enough force and stroke to stimulate human skin and generates a wide frequency range. The solenoid-based tiny pin-array tactile device, however, brings a new issue of controlling the pin's stroke of the tactile device. To overcome the limitation of the solenoid-based device, a new tactile rendering method is needed. In the proposed tactile rendering method, we control the operating frequency of pins, instead of controlling their stroke, to haptically simulate the surface of interconnected objects. Our experiments demonstrate that our proposed method with a pin-array tactile device is suitable for simulating the surface of interconnected objects.

Keywords Solenoid-based pin-array tactile device · Haptic rendering · Internet of things · Tactile rendering

1 Introduction

Internet of Things (IoT) devices are designed to transfer their supermedia streams of data to users in order to increase the quality of their experience (Kwon and Shin 2017). An important segment of this data is haptic human sense, which plays a major role in the quality of the user's experience (Kokkonis et al. 2018).

The term "haptic" relates to kinesthetic or tactile sensation, which refers to sensory data obtained through the receptors of the joints, muscles, ligaments, etc. and through the receptors of the skin, respectively. Kinesthetic information plays a role in understanding the stiffness of an object obtained from an IoT device or a virtual object in the IoT device, while tactile information allows users to feel the texture of the virtual object. For small IoT devices, vibrotactile actuators have been widely used rather than kinesthetic actuators, because kinesthetic actuators are bulky (Galiana and Ferre 2013; 3D Systems Phantom Premium 2018; HaptX 2018; Virtual Reality Society 2018). The tactile information allows users to efficiently and intuitively manipulate various small sized devices including small interaction system or tiny IoT devices (McNaughton et al. 2017; Nanjappan et al. 2018; Chu and Zhu 2018). Even though a tactile actuator is useful for improving users' quality of experience, it can hardly create a detailed texture or small-scale shape of virtual objects. In order to overcome this limitation, several attempts have been made to develop pin-array-type tactile actuating systems that can selectively stimulate human mechanoreceptors. Xie et al. (2014) developed a tactile display that used piezoelectric extension actuators topped by scissor amplifiers to oscillate mechanical pins. Basciftci and Eldem (2016) introduced a refreshable braille device that consisted of 96 braille cells including eight-pin piezo actuators for the visually impaired. Jung et al. (2017) presented a fast and high-resolution tactile pad that included a 40×25 pin array using 100 commercialized braille modules. Ikei et al. (1997) suggested a tactile rendering method, where gray value in gray-scaled image was mapped to the stroke of a corresponding pin, for piezoelectric-based pin-array tactile displays. Since the piezoelectric-based pin-array tactile displays can control not only the stroke of the pin but also its operating frequency, it remains difficult to embed them into small IoT devices due to their size.

In order to reduce the size, a small pin-array tactile device based on ultrasonic motors was developed (Kyung et al. 2008). Moreover, Kim et al. (2008) proposed multi-fingered

✉ Byeong-Seok Shin
bsshin@inha.ac.kr

[1] Interaction Lab., Advanced Technology Research Center, Korea University of Technology and Education, Cheonan-si, Republic of Korea

[2] Media Lab., Inha University, Incheon, Republic of Korea

tactile displays consisting of a 4×4 ultrasonic actuator array. Hernandez et al. (2009) introduced a novel miniature ultrasonic motor and its characterization for a braille tactile display. Although an ultrasonic motor-based pin-array tactile device is small enough to be embedded into small devices, its operating frequency is insufficient to stimulate all mechanoreceptors in human skin. Another candidate for reducing the size of the tactile device is a solenoid actuator. Many research works have been done for fabricating pin-array tactile devices based on solenoids. Yang et al. (2009) demonstrated a miniature pin-array tactile module that used both elastic and electromagnetic force. Bolzmacher et al. (2014) presented a morphing tactile display based on 32 electromagnetic actuators for haptic interaction in vehicles. Kim et al. (2015) developed a tiny modular pin-array tactile device in which each pin was individually operated by tiny solenoids. Zarate and Shea (2017) introduced a 4×4 array tactile display based on electromagnet actuators and applied permanent magnets to make the tactile display stable. The solenoid actuator-based pin-array tactile device creates a high enough operating frequency, output force, and amplitude to stimulate all mechanoreceptors in human skin, and it is small enough to be inserted into tiny devices. However, it is difficult to control the stroke of each pin in a pin-array tactile device based on a solenoid actuator.

Since the pin's stroke in the pin-array tactile device is hard to control, it is difficult to haptically simulate various patterns of a target image or a virtual object with the solenoid-based tactile device. Therefore, in this study, we propose a tactile rendering method to make users sense various vibrational intensities without controlling the pin's stroke in a tactile device based on solenoid actuators. The vibrational intensity perceived by a human can be changed by simply adjusting the vibrational frequency. As the vibrational frequency increases, the vibrational intensity perceived from a human's mechanoreceptor also increases even though the strength of the vibration is the same (Verrillo 1968; Kyung et al. 2005). Therefore, in this paper, we control the operating frequency of each pin in a tactile device (not its stroke) to change the vibrational intensity perceived by a human. Furthermore, we introduce a tactile image concept to compute and extract the tactile information to be used in the proposed tactile rendering method. This tactile rendering method is applied to a pin-array tactile device based on solenoid actuators, and it can discriminate a variety of image patterns.

This paper is organized as follows: Sect. 2 introduces a tactile image and a method to construct the tactile image from a target image. Section 3 presents the tactile rendering method using the tactile image. Finally, Sect. 4 shows the experimental environment and the result of the proposed tactile rendering method.

2 Tactile image representation

In this section, we introduce the implementation of a tactile image. Commonly, the probe of a haptic device is modeled as a point, called the haptic interface point (HIP). Whenever a user explores a virtual environment with a pin-array tactile device, the contact portion between the pin-array device and the user's skin (usually a distal phalanx of a finger) is not a point but multiple points simultaneously (area). By integrating the stimulation forces from several points, a human perceives surface texture or surface properties. Thus, an interaction portion for the pin-array tactile device should be defined as an area [we call it the haptic interaction area (HIA)]. Figure 1 shows the basic idea of the proposed tactile rendering method. The HIA is modeled as a square shape, and it moves as the pin-array tactile module moves. The general concept of the proposed method is to extract feature points from an image portion in contact with the HIA and to operate corresponding pins based on the feature. In order to extract feature points from the target image, we firstly converted the target image into an image having the height variation of the target object surface's microshape.

To develop the proposed tactile rendering method, we convert a target image (Fig. 2a) into an image that contains the fine texture of the object's surface. We call this image the tactile image. The tactile image is represented by the gray level, which means is the height variation of the target object surface's microshape. Figure 2 shows the procedure for creating the tactile image. We firstly changed a target image (Fig. 3a) into a grayscale image (Fig. 3b) whose colors change from white to black. In this process, the intensity value (gray value) of an image pixel is concentrated

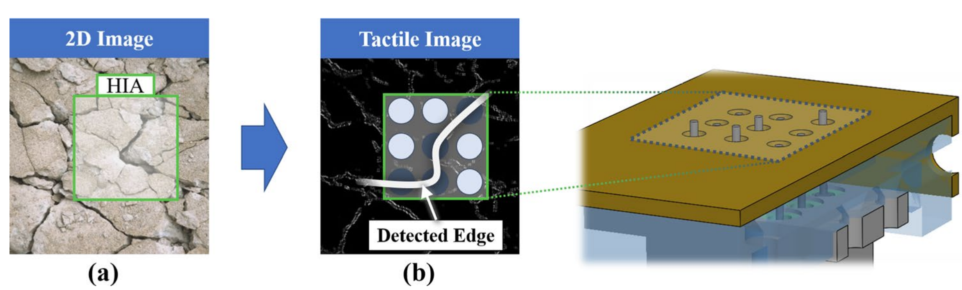


Fig. 1 Basic idea of the proposed method. **a** 2D image, **b** Tactile image with pins' operation

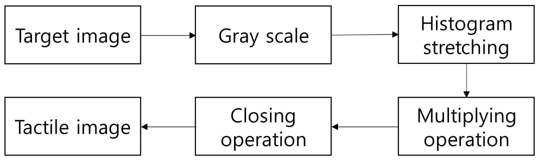


Fig. 2 Procedure for creating tactile image

in a specific range, not in the full range of pixel values. Therefore, we extended the concentrated range to the full range (from 0 to 255) using the histogram stretching method (Alparslan and Ince 1981; Du et al. 2018). Figure 3c is the image after applying the histogram stretching method to the grayscale image (Fig. 3b). Figure 4a, b show the histograms of the grayscale image and the image after applying the histogram stretching method, respectively. By applying the histogram stretching method to the grayscale image, we obtained an image with clearer boundaries. After that, we multiplied the image after applying the histogram stretching method by itself to maximize the boundary information in the image, as shown in Fig. 3d. During the multiplication, we could detect noisy pixels in the image. One of the morphology operations, the closing operation, was used to

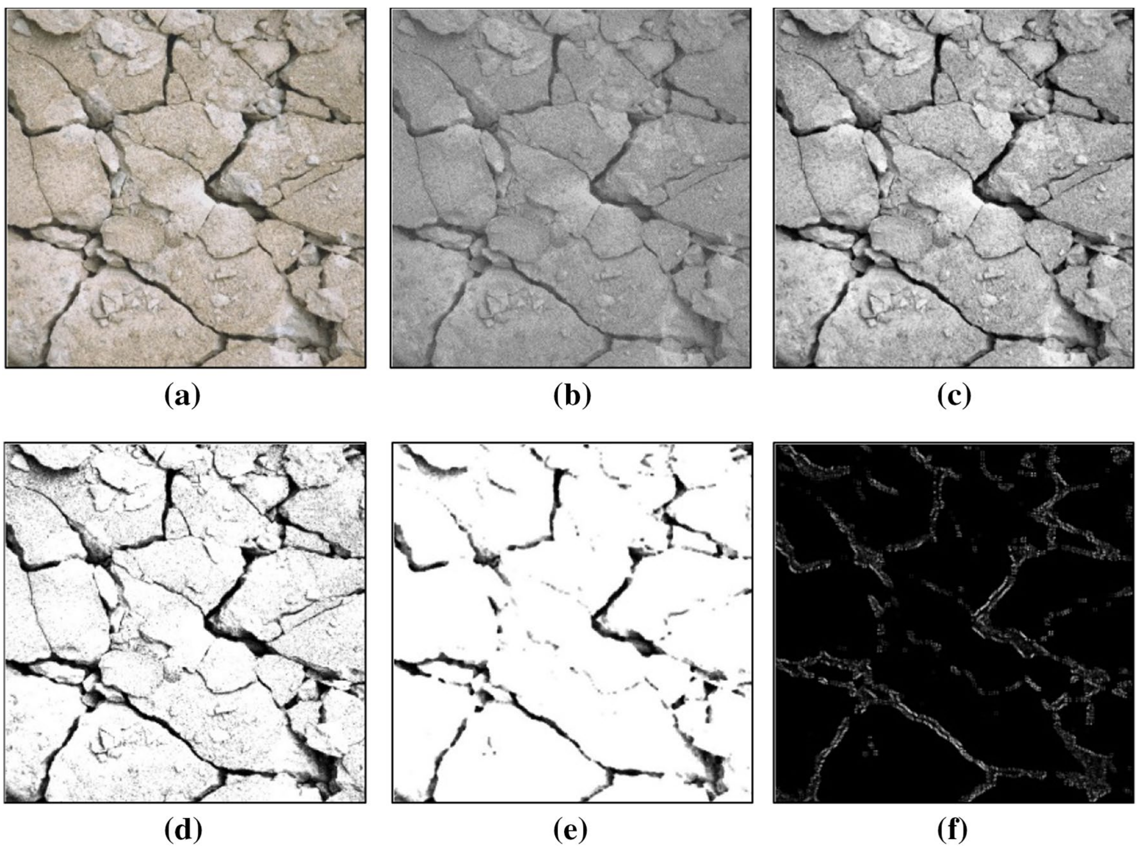
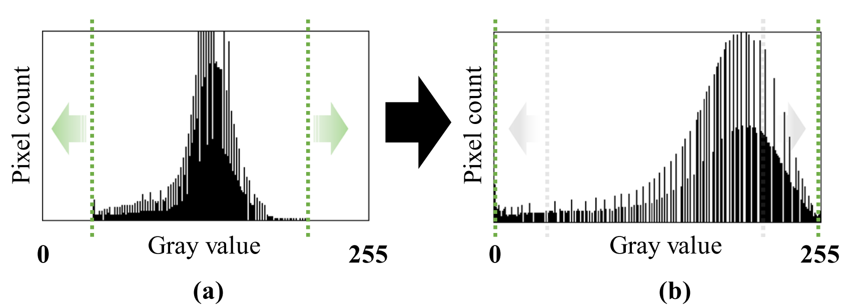


Fig. 3 Conversion of target image to tactile image. **a** Target image, **b** grayscale image, **c** image after applying histogram stretching method, **d** image after multiplication, **e** image after closing operation, **f** tactile image

Fig. 4 Histograms of two images. **a** A grayscale image, **b** an image after applying histogram stretching method



remove noise and sharpen the edges in the image. In this work, the closing operation was implemented by conducting the dilation operation and then the erosion operation.

Figure 5a shows the magnified image of a specific part of Fig. 3d. We can easily find many noises on the surface of the image after applying the multiplication (Fig. 5a). Figure 5b, c are images after applying the dilation operation and the erosion operation, respectively. Although the dilation operation reduces noises in the surface of the image, it can make the boundaries of the object's surface unclear (Fig. 5b). In order to recover the boundaries, morphological erosion was added to the image. From Figs. 5c and 3e, we could confirm that most of the boundaries are restored through morphological erosion.

The goal of this research is to develop a tactile rendering method using a small pin-array tactile device for haptically discriminating boundaries in the surface of a target object. Therefore, it is necessary to detect boundaries in the surface of the image after the closing operation. To find the boundaries in the surface, we applied the Sobel edge detection algorithm (Sobel and Feldman 1968), and Fig. 3f is the resulting image. We named the image in Fig. 3f the tactile image.

3 Frequency-based tactile rendering

The grayscale pixel value in the tactile image represents the height variation in the surface of a target object. The closer the gray value is to 0 (black), the smaller the change in height. The closer it is to 255 (white), the greater the change in height. Therefore, the tactile image contains the fine geometry of the object's surface. Figure 6 shows the relationship between the gray value in the tactile image and the height variation in the surface of a target object. If the grayscale pixel value in the tactile image is mapped to the stroke of each corresponding pin in a pin-array tactile device, the user can easily recognize the surface of the object with haptic information. However, since it is hard to control the stroke of a pin in the solenoid-based small tactile device, we decided to control the frequency of the pin.

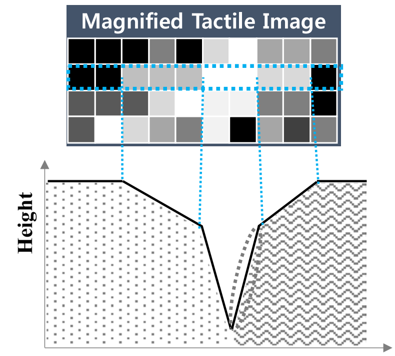


Fig. 6 Relationship between gray value in tactile image and height variation in surface of target object

If the strengths of the two vibratory stimuli are the same, users feel the high-frequency stimulus stronger than the low-frequency stimulus in the frequency range of 0–150 Hz (Kyung 2006). This frequency range may vary depending on the thickness of the contactor, but in the range of 0–150 Hz, users perceive that high-frequency stimuli are stronger than low-frequency stimuli. Therefore, solenoid-based tiny pin-array tactile devices can haptically render the surface of the target object by simply changing the vibration frequency only. The grayscale pixel value in a tactile image can be changed to the operating frequency of the corresponding pin in a pin-array tactile device using Eq. (1)

$$f_p = \frac{f_{pmax} \times g_g}{255} \quad (f_{pmax} < 150) \tag{1}$$

where f_p is the operating frequency of a corresponding pin, f_{pmax} is the maximum operating frequency of a

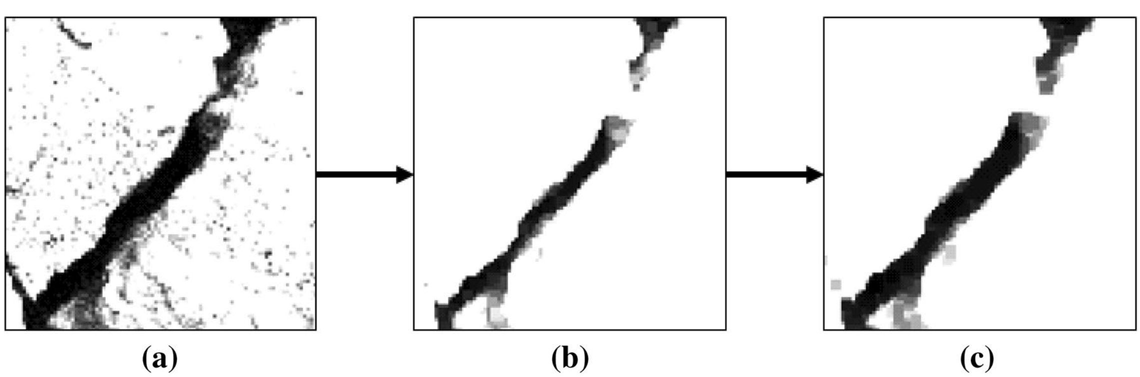


Fig. 5 Closing operation for removing noise and sharpening the boundaries in target image. **a** Image with noise, **b** resulting image of morphological dilation, and **c** resulting image of morphological erosion

corresponding pin, and g_g is the average grayscale value of the HIA. For haptically simulating the microshape of the target object's surface, the contact area between the tactile device and the user's finger should be mapped to the HIA, as shown in Fig. 7. In this work, the size of the HIA is defined as 33 × 33 pixels. In the case where a 3 × 3 pin-array tactile device is used for haptic interaction, one pin is responsible for 11 × 11 pixels. By setting the average of the gray values within 11 × 11 pixels to the operating frequency of the corresponding pin, a user can understand the microshape of a target object's surface.

4 Experiment and evaluation

4.1 Experiment I: perceiving patterns

In the previous section, we presented the tactile image and the tactile rendering method for solenoid-based pin-array tactile devices so that users can haptically sense the microshape of the target object's surface. In this section, we performed a performance evaluation test on how many surfaces are distinguished by the proposed method. Ten people with an average age of 26 years participated in this experiment. All of them were between 24 and 29 years old. Seven participants were male, and the rest of the participants were female. All participants conducted this experiment ten times. The HIA in this experiment was set as 33 × 33 pixels. We prepared ten images with different small bumps on a PC monitor, as shown in Fig. 8. After that, we printed the ten images on paper. Each sheet of paper contained one printer-printed image. The ten images were randomly displayed to the participants on the PC screen, and the printed images did not overlap. Furthermore, the solenoid-based 3 × 3 pin-array tactile device was installed on a mouse because participants had to personally explore the images displayed on the PC monitor. The total size of the tactile device is 15 mm × 15 mm × 8.5 mm and its working frequency range is 0–340 Hz. The contactor gap is 3.0 mm and its diameter is 0.5 mm. The maximum pin's stroke of the tactile device is 200 µm. Before the experiment, the participants learned how to use the prepared tactile mouse and felt the tactile sensation for 3 min. In the prepared images, the gap between bumps gradually decreased from 124 to 12 pixels. Table 1 summarizes the gaps between bumps in the prepared samples in pixel units.

After basic training, the prepared images were presented on the monitor in random order (only the experimenter could see this information), and the participants were asked to rub the image using the tactile mouse without visual information. The participants were asked to place their index finger on a surface where tactile contactors were protruding. After that, the participants viewed the printed images and selected the printed image that was the same as the haptically sensed image. During the

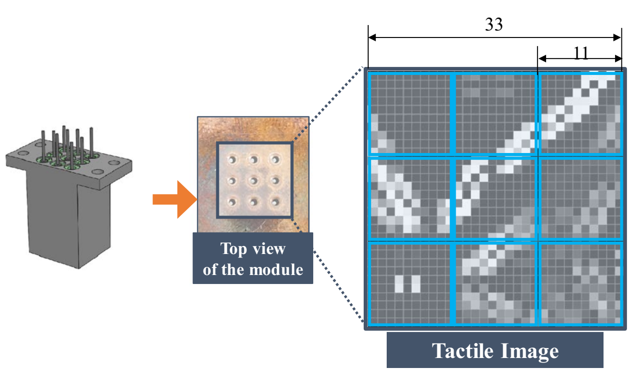


Fig. 7 Mapping pin-array module to tactile image

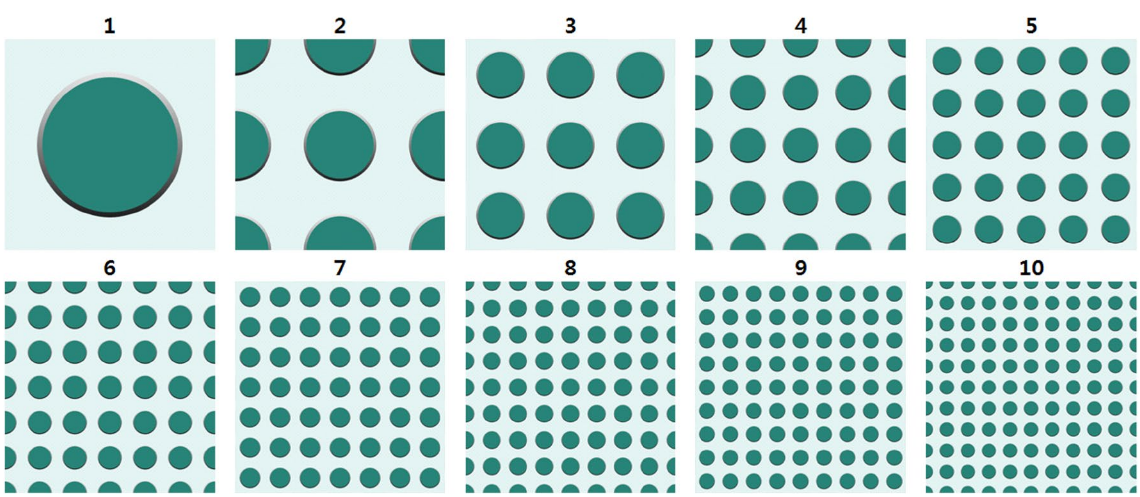


Fig. 8 Ten prepared images with small bumps and decreasing gaps between them

Table 1 Comparison of gaps between bumps

Sample no.	Gaps between bumps (pixels)
1	124
2	62
3	41
4	30
5	24
6	21
7	18
8	15
9	13
10	12

experiment, all images were shown to each participant, and white noise was played to prevent vibration sound from the tactile device. To enhance the reliability, this procedure was repeated ten times for each image. Because the number of participants was 10, the total number of trials was 100.

The results of all participants were used to form a confusion matrix (Table 2). The rows of the confusion matrix represent the images presented to the participants via tactile stimulation, and the columns represent the images selected by the participants. In the case of the two images (1 and 2), the accuracy was 100%. The correct answer percentage for sample 5 was 70%. For sample 5, there was a 30% chance of incorrectly responding to sample 8. The lowest correct answer percentage was 50%. According to the results of the experiment, the accuracy rate of the participants decreased as the gap between the bumps became narrower. The moment the gap between the bumps becomes smaller (30 pixels) than the HIA (33 pixels), the accuracy rate begins to decrease.

4.2 Experiment II: perceiving height variation on surface of prepared sample

In this section, we investigated whether users could perceive the height of microshapes on the surface with the proposed rendering method. A simple tactile image consisting of 11×110 pixels was prepared for this experiment, as shown in Fig. 9a. The same participants who participated in the previous experiment participated in this experiment. The participants explored this prepared object with the proposed rendering method. At this time, they could not see the gray value of the tactile image; they could only see a wide rectangle, as shown in Fig. 9b. After exploring the object's surface, the participants received a piece of paper consisting of five regions, as shown in Fig. 9c. They then wrote numbers on the paper according to their perceptions of degree of dents. All participants found the largest and second largest dents well. Thus, the proposed rendering method was able to haptically simulate the microshape of a target object without changing the pin's stroke of the tactile device.

4.3 Experiment III: perceiving various sample images

An experiment was performed to investigate whether participants could discriminate the various images with the proposed rendering method. The same participants who participated in the previous experiment participated in this experiment again. We prepared five sample images (330×330 pixels), as shown in Fig. 10, and printed them on paper. Each sheet of paper contained one printer-printed image. Figure 10a shows the five prepared samples, and Fig. 10b shows their computed tactile images. During the experiment, the participants could not see the image but could only see a borderline of the prepared sample on a monitor, and they rubbed on the image using the tactile mouse with the proposed rendering method. After rubbing it, they viewed the printed images and

Table 2 Confusion matrix of results

		Presented									
		1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	6 (%)	7 (%)	8 (%)	9 (%)	10 (%)
Response	1	100									
	2		100								
	3			80	10						
	4			20	60						
	5				30	70					
	6						80		20		
	7							60	10		
	8					30	20	10	60	20	20
	9							30	10	50	30
	10									30	50

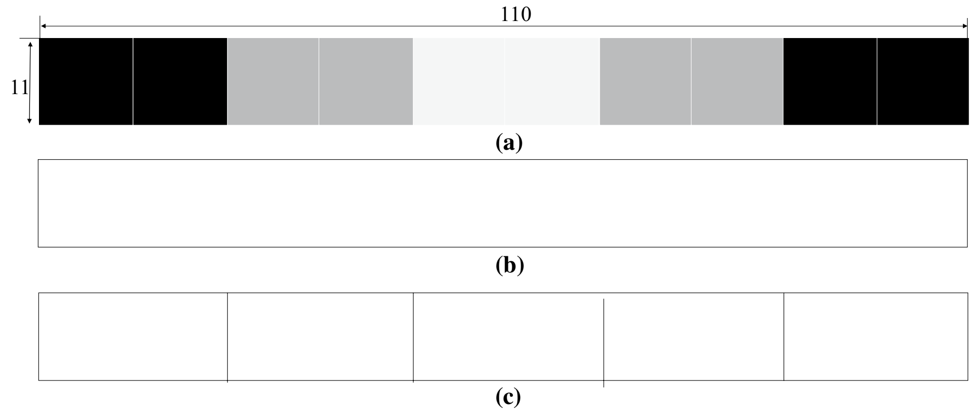


Fig. 9 Prepared tactile image (**a**) image shown on monitor during experiment (**b**), and image shown on paper (**c**)

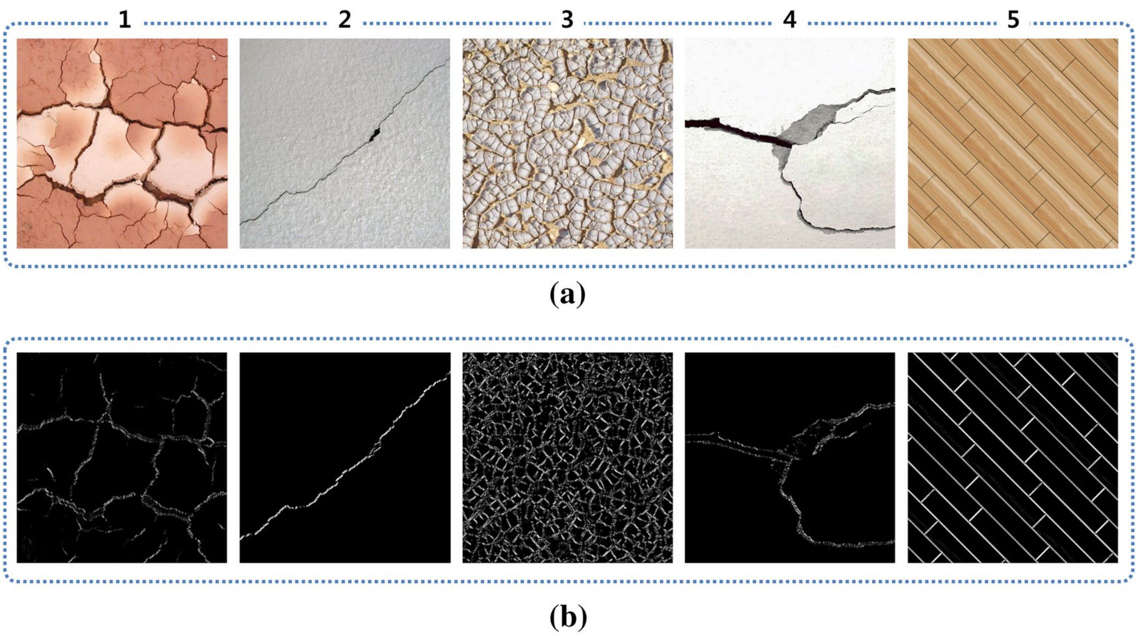


Fig. 10 Five prepared sample images (**a**) and their tactile images (**b**)

selected the one most similar to the haptically sensed image. During the experiment, each participant experienced all images. White noise was played to prevent participants from guessing based on the vibration sound.

Figure 11 shows the mean percentages of correct answers. The score for samples 1 and 2 was 90%, while it was 95% for sample 3. The score for samples 4 and 5 was the lowest (85%). When sample 1 was shown to the participants, 10% of the participants confused sample 1 and sample 5. For sample 4, 15% of the participants mistook sample 4 for sample 2. This result shows that the proposed method was able to discriminate the prepared stimuli reliably.

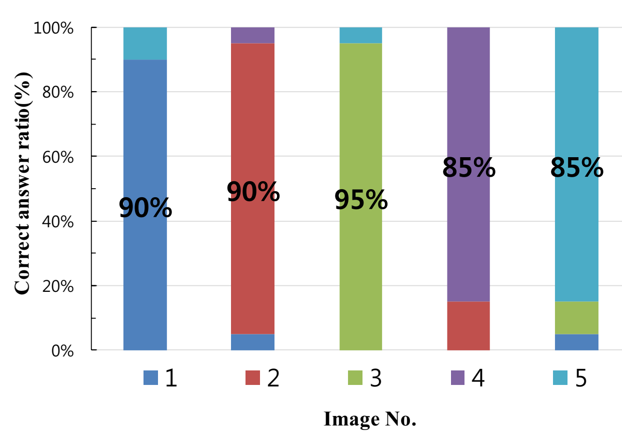


Fig. 11 Average percentages of correct answers

5 Conclusion

Because two energies are combined to maximize the vibrational force in solenoid-based pin-array tactile devices, it has a large enough force and sufficiently wide operating frequency to stimulate a human's mechanoreceptors. However, it is difficult to control the pin's stroke of a solenoid-based pin-array tactile device unlike piezo or SMA (shape memory alloy)-based tactile actuators. Therefore, in this paper, we identified the problem of the solenoid-based device and presented a tactile rendering method that can control the magnitude of the force that a user perceives without changing the pin's stroke of the solenoid-based device. We conducted experiments with images having various patterns and verified that humans can perceive not only various image patterns but also height variations of an image sample. We expect that the proposed method will contribute to increasing the quality of user' experience and will be the basis of haptic interaction with IoT devices.

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