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Inside Touch: Presentation of Tactile Feeling Inside Virtual Object Using Finger-Mounted Pin-Array Display

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ABSTRACT Previously, tactile displays focused on the tactile presentation of the surface of a virtual object. In contrast, this study attempts to provide a tactile feeling on the space inside a virtual object when fingers penetrate it. Our previous study developed a finger-mounted pin-array display with the smallest pin pitch, representing the highest spatial resolution. Using the display, we attempt to present the tactile impression of "Rough," "Grainy," and "Sparse" which correspond to Japanese onomatopoeia of "Zara-Zara," "Tsubu-Tsubu," or "Chiri-Chiri" with simple patterned stimuli arranged in 3D space. A series of experiments were conducted in this study to determine the following: (1) the stimuli that can provide users with different tactile impressions inside objects and (2) the effect of tactile display spatial resolution on the recognition of tactile impressions inside objects. The results clarified that we could provide three different tactile impressions in space with certain stimuli configurations. Besides, the results demonstrated that participants recognized the tactile impression better with a larger spatial resolution configuration of the device. This study reveals a new field of tactile presentation, that is, tactile presentation inside an object.

INDEX TERMS Haptics, Tactile Presentation, Pin-arrays

I. INTRODUCTION

When objects are touched in the real world, we can sense various tactile information [1], [2]. We can recognize the properties of an object's surface by touching the object surface [3]. For example, the "Enclosure" or the "Contour following" can be used as one of the exploratory procedures to sense the global or local shape of objects [4]. Also, we can recognize the surface tactile roughness by "Lateral motion" [5].

Similarly, by touching the surface of a real object, we can indirectly recognize the internal properties. "Pressure" can be used as one of the exploratory procedures that provide the compliance or hardness cues of objects [6]. Because fingers cannot penetrate objects in the real world, the internal properties can only be indirectly inferred based on the interaction between the fingers and the object surface.

On the other hand, virtual tactile rendering technologies make it possible to allow users to experience a tactile impression that cannot be experienced in the real world. If users utilize wearable haptic displays, such as [7] or [8], the virtual objects can be penetrated by the fingers, and the user can directly experience touching the three-dimensional (3D) space inside a virtual object. As an application of wearable displays, this study proposes a tactile impression presentation

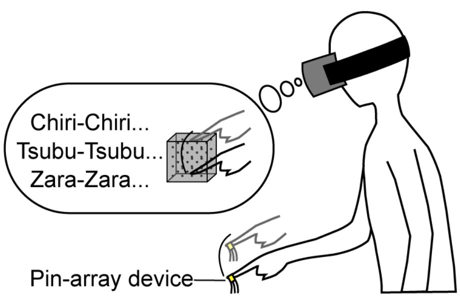


FIGURE 1: Users touch 3D space inside the object and feel tactile impression.

while touching the 3D space inside a virtual object. We provide different tactile impressions such as "grainy" or "rough" for the 3D homogeneous space inside a solid virtual object (shown in Fig. 1). Presenting various tactile impressions when touching inside the object can be used to use cases such as educational material for understanding the structure inside an object by touching it that is untouchable in the real world. An example of the use cases is the anatomical materials for medical training. Conventionally, the utilization of computer graphics that resort to a vision for the understanding of the human body has been developed [9]. Here, in addition to vision, if educational materials that use tactile sensation are developed, there is a possibility that it may lead to further promotion of understanding. In this use case, users penetrate the virtual body and touch the various body parts inside the body which gives users different tactile feelings. To realize this, it is better that we can freely control the tactile impression inside objects. However, studies regarding the tactile presentation inside objects have not been conducted, which may be partially due to the requirement of a display that provides distributed haptic feedback with a high spatial resolution to express the tactile impression of 3D space inside objects.

Previously, we developed a finger-mounted pin-array display that has the smallest pin pitches, representing the highest spatial resolution ever [10]; using this device, we have empirically known that we can present the tactile impression of dusty ("Chiri-Chiri" in Japanese onomatopoeia), grainy ("Tsubu-Tsubu"), or rough ("Zara-Zara") surfaces for 3D space inside objects when users receive specific patterned stimuli that are spatially arranged in space. We conducted experiments on the three tactile impressions we empirically knew by chance to clarify the following items:

- The stimuli that can provide users with different tactile impressions inside objects.
- The effect of tactile display spatial resolution on the recognition of tactile impressions inside objects.

II. RELATED WORK

A. TACTILE DISPLAY FOR 2D SURFACE

According to Okamoto et al. [3], the following five principle tactile dimensions are used for the human tactile perception of surface textures: fine/macro roughness, friction, warmness, and hardness. For example, regarding roughness, vibrotactile feedback while scanning virtual textured surfaces is commonly used for rendering the surface roughness [11]. Vibrotactile actuators are now embedded in smartphones or vibrotactile pens and are highly accessible (e.g., Apple Watch [12]). Regarding friction, researchers have developed friction displays that present tangential forces over the user's fingers. Force displays such as PHANToM represent the actual frictional force in the tangential direction of a contact surface [13]. Considering another approach, the frictional characteristics of a contact surface have been changed by using a squeeze film generated by ultrasonic vibration [14], a SAW [15], or a thin film slider operated by electrostatic force [16].

While these displays present users with surface tactile sensation, this study focuses on the tactile sensation for 3D spaces inside virtual objects.

B. HAPTIC FEEDBACK FOR 3D SPACE

For presenting the haptic feedback of 3D spaces, there are various approaches including the use of grounded-type device [17], [18], wearable devices [19], or mid-air haptics [20], [21].

Recently, there has been an increasing interest in exploring mid-air haptics. Focused ultrasound beams can be used to create a localized sense of pressure on the fingertip in mid-air. An array of ultrasound transducers generates a focal point by individually controlling each transducer's phase and intensity in a phenomenon known as acoustic radiation pressure. The pressure was used for presenting touchable icons [22], multipoint haptic feedback [23], and three-dimensional shapes [24]. Although recent studies have attempted to simulate multi-point [23], it is difficult to control the pressure distribution on the skin at the millimeter scale. Our hypothesis states that devices that can present distributed forces with a high spatial resolution are suitable for presenting tactile sensations in 3D space inside objects. Thus, we focused on the pin-array display.

C. PIN-ARRAY DISPLAY

There are two types of pin-array displays: grounded and wearable. Mechanically grounded pin-array displays can present robust haptic cues using grounded forces with users [25]–[27]. However, when users move their hand or finger to any position in the space around, these devices cannot display the shapes. Namely, the workspace and portability are constrained. A large interactive mobile workspace may be useful for the exploration of virtual spaces.

Recently, more haptic system designs considering wearability have started to appear; thus, wearable pin-array displays were developed [28], [29]. To provide users richer haptic information, the high contact point density is essential [30]. A few studies have attempted to increase the contact point density [29], [31]. The development of a high-density pin-array is complex since the pins were integrated with the actuators, such as motors, and the size of the actuator was a constraint. Due to its difficulty in developing a high-density pin-array display, no study focuses on presenting the tactile presentation inside virtual objects, which requires distributed haptic feedback with a high spatial resolution.

In our previous study [10], we adopted a pneumatic drive because a pneumatic actuator, or air cylinder, can be a simple and slim structure; This realized the pin-array displays that have the highest density. Details regarding the previously developed display are presented in the next section. As one of the applications of the high-density pin-array displays, we focus on the presentation of the tactile presentation inside the virtual objects. With our high-density display, the present study attempted to present the tactile presentation inside virtual objects for the first time.

III. APPARATUS

A. SYSTEM OVERVIEW

In the user studies, we used the finger-mounted pin-array display system, which consisted of a finger-mounted pin-array display, head-mounted display (HMD), sensor, simulator, and air pressure controller (shown in Fig. 2).

B. SYSTEM COMPONENTS

1) Sensor and HMD

Users wore HMD (HTC Vive) on their faces to watch a virtual scene (shown in Fig. 3) and were seated comfortably in a chair. The index finger of their dominant hand was placed in a pin-array display. In order to reduce the burden on the participants due to the weight of the device, the device was supported from above with stretchable elastic string from the ceiling. The position and orientation information of the fingertip were obtained by the magnetic sensor (POLHEMUS 3SPACE FASTRACK) attached to the user's dominant hand's index fingertip. The fingertip position and orientation information were updated at 120 Hz and sent to a PC via serial communication from the sensing system.

In addition, users wore noise-canceling headphones to hear white noise to muffle the external sounds. Users wore an HTC Vive Controller on the non-dominant hand to answer the questions in the experiment.

2) Simulator

A simulator (Unity3D) received the position and orientation of the finger from the sensor system. It moved and rotated the virtual finger surface according to the sensor value. The virtual finger had the nodes on the finger surface, which corresponds to the 128 pins of the pin-array display. If the collision of the nodes was detected, the control values were sent to the air pressure controller via serial communication.

3) Pin-array display

The finger-mounted pin-array display (shown in Fig. 4) was the same as presented in [10]. The update rate and response time of the system were 50 Hz and 75 ms. In an informal study conducted by authors before user studies, we did not feel the incongruency between the vision and haptics due to the devices' refresh rate and response time. The pin's grouping condition and the presented stimuli were newly configured in this study, which is described in the next sections.

C. GROUPING CONDITION TO SIMULATE SPATIAL RESOLUTION

To investigate the effect of the device's spatial resolution on the recognition of the tactile impression inside objects, the density of the pin-array device must be controlled in the experiment. One of the methods to control the density of pin-arrays can be to create three wearable pin-array devices with different spatial resolutions and then experiment with them. However, that would be problematic because participants would have to replace the devices during the experiment, which would make the participant aware of the spatial resolution of the display in use. We need to control the spatial resolution of the pin-arrays without replacing them.

Thus, this study simulated the spatial resolution of pin-arrays by grouping multiple pins into one virtual pin. Three grouping conditions were used. Grouping 0 used all pins individually (pin pitch is 1.4 mm, as shown in Fig. 5 (a)). Grouping 1 grouped three pins into one and enabled/disabled the three pins together (pin-to-pin distance 2.1 mm, as shown in Fig. 5 (b)). Grouping 2 used four pins as one group (distance between pins 2.8 mm, as shown in Fig. 5 (c)). Pins that cannot be grouped were not used. The output pressure of each pin was calibrated in advance. If the pin of the Grouping 0 condition was enabled, it was configured to output 0.08 MPa. If the pin of the Grouping 1 condition was enabled, each pin was configured to output 1/3 of 0.08 MPa to make the output of the representative point equal to Grouping 0. Each pin in the Grouping 2 condition was configured to output 1/4 of 0.08 MPa based on the same concept previously indicated. This adjustment of output depending on the grouping conditions was required to make the output at each representative point the same. This could make the density variable the only target of the comparison variable.

D. STIMULI PATTERN

As a first attempt at presenting tactile sensation inside the object, this study presented distributed stimuli that can be represented by spatially periodic stimuli whose control parameters are simple. As spatially periodic stimuli to represent stimuli inside the virtual objects, we used stimuli patterns that can be expressed by arranging spheres in a 3D grid pattern (Fig. 6). The tactile sensation may change depending on the direction in which the finger is moved, but in the experiments in this study, the finger movement was restricted to one direction.

When the nodes (which corresponded to pins) in the simulator overlapped the stimuli, the pin was pushed against the finger skin at a constant pressure. When there was no overlap with the stimuli, the pin did not push the skin. Under Grouping 1 and Grouping 2 conditions, the pins in a certain group pushed or did not depend on whether the representative point of the group overlapped the stimuli.

The control parameters of the stimuli patterns could be the sphere radius and spacing between spheres. However, in this study, we present the stimulus by configuring the sphere radius while fixing the spacing between the spheres at 2 mm because it is not efficient to explore the entire configuration of the stimuli patterns.

In advance, it was found in our informal study that a "grainy (Tsubu-Tsubu)," "sparse (Chiri-Chiri)," or "rough (Zara-Zara)," feeling can be felt with the specific sphere radius and spacing of the spheres. This study focused on these three specific feelings.

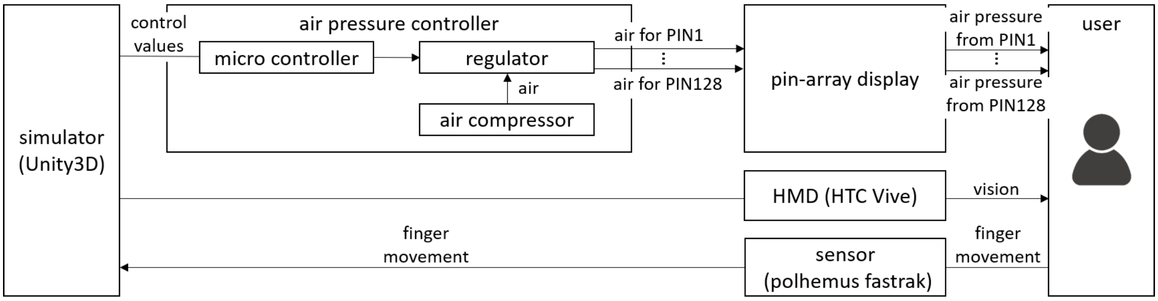


FIGURE 2: Data flow through components of the system and a user.

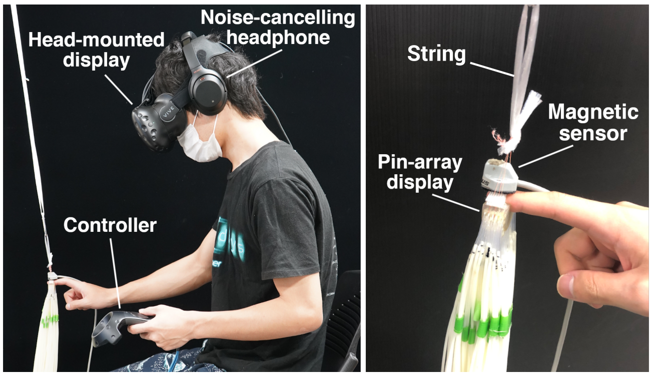


FIGURE 3: Apparatus

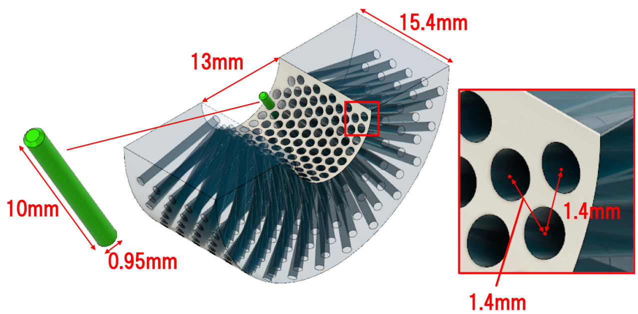
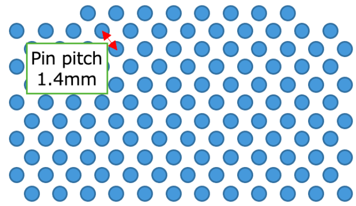
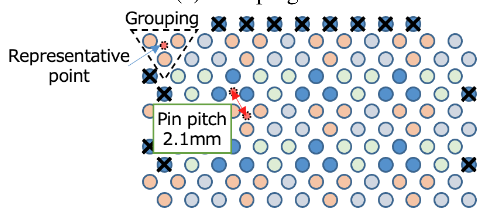


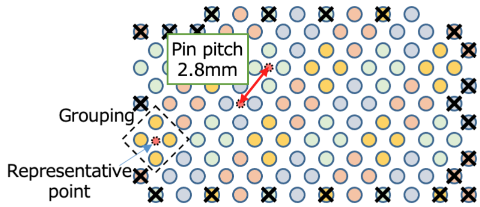
FIGURE 4: Specification of pin-array haptic device [10]. The number of pins is 128 and the pin pitch is 1.4 mm



(a) Grouping0



(b) Grouping1



(c) Grouping2

FIGURE 5: Pin-array devices's grouping conditions to simulate spatial resolution. (a) Grouping0: all pins move independently and the pin pitch is 1.4 mm. (b) Grouping1: three pins are grouped and the pins move together. The pin pitch is 2.1 mm. (c) Grouping2: four pins are grouped and the pin pitch is 2.8 mm.

IV. USER STUDIES

The purpose of a series of experiments in this study is to clarify the configuration of stimuli patterns and the spatial resolution of the device, with which we can present three types of tactile impressions inside the object. Therefore, we conducted two experiments (stimuli configuration experiment and stimuli discrimination experiment). The stimuli configuration experiment was conducted to prepare the stimuli patterns that was used in the discrimination experiment. In the stimuli discrimination experiment, we answered the research questions stated in the Introduction section.

The apparatus described in the previous section was used in the user studies. This study was approved by the ethics committee of the University of Electro-Communications (approved number: 19005).

A. USER STUDY 1: STIMULI CONFIGURATION

In this experiment, we investigated the optimized stimuli patterns for each grouping condition where participants could feel the three specific tactile sensations. There were ten participants with ages ranging from 22 to 26. The participants were all right-handed. All participants had normal or corrected-to-normal vision and no history of neurological

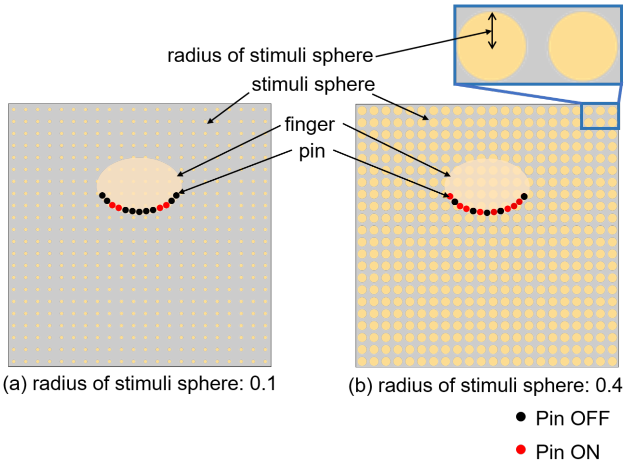


FIGURE 6: Example of stimuli patterns; (a) radius of stimuli sphere is 0.1 and (b) radius of stimuli sphere is 0.4.

impairment. All participants were naive to the purpose of the study. Written informed consent was obtained from each individual before the experiments were performed.

There were three tactile sensation conditions and three grouping conditions. Thus, there were a total of nine conditions. Participants conducted the experiment three times for the nine conditions, for a total of 27 trials. The presentation order of 27 trials was pseudo-randomly assigned across participants.

1) Task Design

This experiment used a within-participants design.

On the HMD screen, an explanatory text, a cube with a spherical area inside, a finger object, and a slider for answering the radius of the stimuli patterns were displayed (Fig. 7). In each trial, the participant touched the inside of the cube from top to bottom while viewing the cube and the finger object. Then, the radius of the stimuli patterns was configured to feel the same as the description of the tactile feeling presented on the screen. The speed of finger movement was not constrained. In addition, participants were allowed to move their fingers from top to bottom several times.

When configuring the radius of stimuli patterns, participants pressed the button on the controller of the non-dominant hand. After the adjustment, the enter button was pressed to end the trial. Participants were instructed so that they should adjust the radius in terms of tactile sensation instead of force.

2) Results

Table1 presents the average configured radius of the stimuli patterns with the standard error for each tactile sensation and grouping conditions. We performed a two-way repeated ANOVA of the tactile sensation and grouping condition factors on the configured radius of the stimuli patterns. According to the ANOVA results, there was a significant effect of the tactile sensation condition ($F(2, 171) = 15.27$, $p = 7.9 \times 10^{-7}$), and a significant effect of the grouping condition ($F(2, 171) = 44.5$, $p = 2.7 \times 10^{-16}$). There was no significant interaction effect between the two factors ($F(4, 171) = 0.92$, $p = 4.5 \times 10^{-1}$). The ANOVA results suggest differences in the radius for each combination of the tactile sensation and grouping conditions. Under all the grouping conditions, the order of the configured radii tended to be "Chiri-Chiri" < "Tsubu-Tsubu" < "Zara-Zara". Furthermore, there was a tendency for the configured radii to be larger as the simulated spatial resolution was smaller.

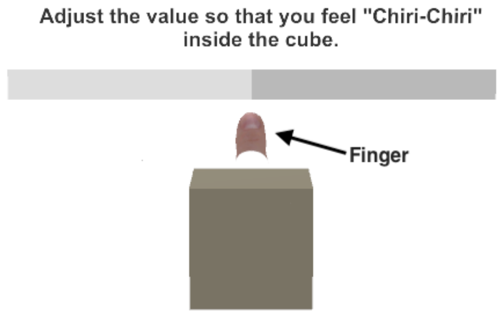


FIGURE 7: Screen of presented to participants by head-mounted display in user study 1

TABLE 1: Configured radius of stimuli patterns

(unit: mm)

	Chiri-Chiri (Sparse)	Tsubu-Tsubu (Grainy)	Zara-Zara (Rough)
Grouping0 (pin pitch: 1.4mm)	0.421 ± 0.056	0.532 ± 0.051	0.697 ± 0.066
Grouping1 (pin pitch: 2.1mm)	0.845 ± 0.103	0.857 ± 0.069	1.203 ± 0.081
Grouping2 (pin pitch: 2.8mm)	0.907 ± 0.098	1.175 ± 0.079	1.320 ± 0.084

B. USER STUDY 2: STIMULI DISCRIMINATION

Using the configured stimuli patterns in User Study 1, User Study 2 answered the questions stated in the introduction section.

The same ten participants were used for this study. For the trial in this experiment, participants discriminated three tactile feelings with certain grouping conditions. There were 12 trials for each condition; thus, the total number of trials was 36 for each participant. The configured average radius value was used for each combination of the grouping and tactile sensation conditions, as shown in Table 1.

1) Task Design

This experiment used a within-participants design.

On the HMD screen, we displayed explanatory text, three cubes with configured stimuli patterns inside, finger objects, and three dropdowns for selecting textures (shown in Fig. 8). Based on the results of Experiment 1, the stimuli patterns for the radii were configured to feel "Chiri-Chiri", "Tsubu-Tsubu", and "Zara-Zara" in random order. The participant touched the cubes one at a time from top to bottom while viewing the three cubes and the finger object. Then, the participant discriminated which tactile feeling they felt inside of the three cubes and selected the texture from the drop-down category.

The speed of finger movement was not constrained. In addition, participants were allowed to move their fingers several times from top to bottom.

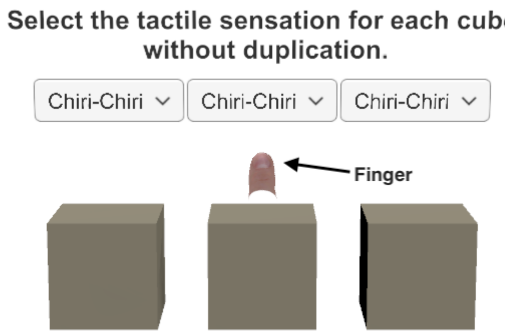
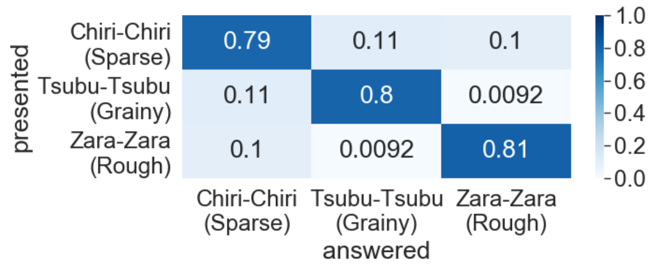
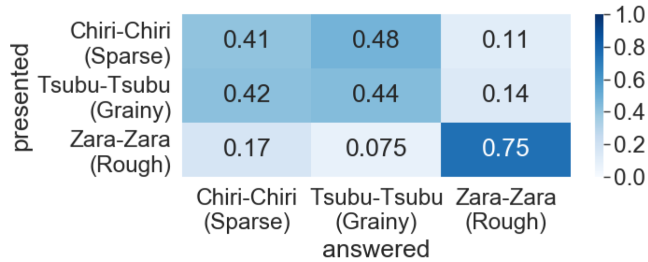


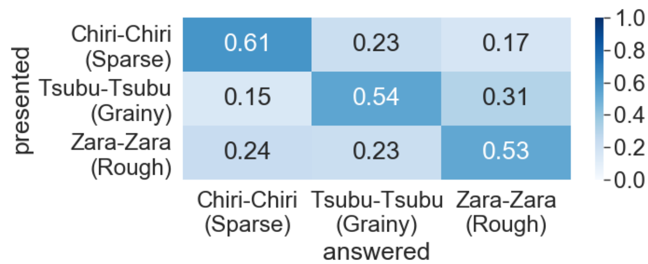
FIGURE 8: Screen of presented to participants by head-mounted display in user study 2



(a) Grouping0 (Pin pitch: 1.4mm)



(b) Grouping1 (Pin pitch: 2.1mm)



(c) Grouping2 (Pin pitch: 2.8mm)

FIGURE 9: Results of correct answer rate in user study 2.

2) Results and Discussions

The result of selection probability is shown in the confusion matrix for each grouping condition (in Fig. 9). The proportion of discrimination accuracy under the Grouping 0 condition was 0.8, while those under Grouping 1 and Grouping 2 were 0.53 and 0.56, respectively. The result of Grouping 0 demonstrates that we can present three different tactile sensations inside objects. In contrast, the discrimination was difficult with Grouping 1 or Grouping 2. To determine whether there is a difference in the three conditions' population proportions, we performed a two-proportion z-test with Bonferroni correction. The null hypothesis indicates that the two population proportions are the same. A significant difference was found between the Grouping 0 and Grouping 1 conditions ($z = 0.99$, $p < 0.01$). Another significant difference was found between the Grouping 0 and Grouping 2 conditions ($z = 0.99$, $p < 0.01$). This analysis addressed the concerns stated in the introduction sections. Namely, the spatial resolution needs to be high to present the tactile sensation inside an object. In addition, if the radii are 0.421, 0.532, or 0.697, the users can recognize the "Chiri-Chiri," "Tsubu-Tsubu," or "Zara-Zara" impressions.

V. GENERAL DISCUSSIONS

1) Application of Inside Touch

In this study, a novel attempt was made to present the tactile feeling inside an object. The result indicated the possibility that we can present at least three kinds of tactile feeling. This section describes the use cases where such a tactile presentation could be applied. There are two main different use cases. The first one is the use case where users touch space inside the solid surface of the object that is untouchable and the second one is the use case where users touch space inside liquid or air.

As one of the examples of the first use case, it can be used as educational material for understanding the structure inside an object by touching it that is untouchable in the real world. Recently, anatomical teaching materials for medical use, teaching materials that utilize the five senses have recently been developed. For example, the utilization of computer graphics that resort to a vision for the understanding of the human body has been developed [9]. Here, if educational materials that use tactile sensation are developed, there is a possibility that it may lead to further promotion of understanding. Here, if educational materials that use tactile sensation are developed, there is a possibility that it may lead to further promotion of understanding. In this use case, users penetrate the virtual body and touch the various body parts inside the body which gives users different tactile feelings. Since the human body is actually "touched" in surgery and palpation in the real world, it may be effective to learn by associating anatomical material of the body with the sense of touch. Of course, it can be used not only for the human body but also for various structural things such as the structure of buildings and the structure of industrial products.

The second is the idea of using it for the tactile presentation of space inside liquids and gases. Actually, in the real world, humans can penetrate the inside of the liquids and gases with a finger and feel the tactile sensation, and thus, if the tactile sensation inside the virtual liquid or gas can be presented, the realism for the virtual liquid or gas can be enhanced.

These applications have not been tested in this study. We need to find out how effective the application can be in the future.

2) Limitations

There are several limitations in this study, Which includes the limited space of the stimuli patterns used in this study. The control parameters of the stimuli patterns can be the sphere radius and spacing between spheres; however, we fixed the spacing at a 2 mm constant. We did this to reduce the exploration space of the stimuli patterns and avoid lengthening the experiment. However, if we made the participant adjust not only the radius but also the spacing, the configuration of the radius would change. Note, the results were obtained in an environment where the spacing was fixed at 2 mm.

Another limitation is the limited tactile feeling addressed in this study. We focused on the three tactile sensations empirically found in our informal experiment. However, there is a possibility that other tactile impressions can be presented with this high-density device. For example, if we use both spacing and radius as the control parameters, there is a possibility for more types of tactile feelings to be found. In the future, we plan to investigate the dimensional composition of the tactile sensations that can be presented.

VI. CONCLUSIONS

This study used a high-density finger-mounted pin-array display to provide tactile feeling inside a virtual object when fingers penetrate it. We conducted a series of experiments. The results clarified that we could provide three different tactile impressions in space with certain stimulus configurations. Also, the results demonstrated that participants recognized the tactile impression better with a larger spatial resolution configuration of the device. This study contributes to revealing a new field of tactile presentation, that is, tactile presentation inside an object.

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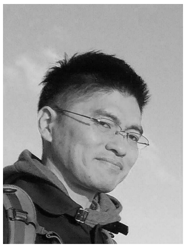

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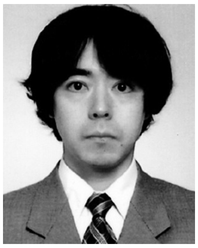

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