Robotica (2007) volume 25, pp. 451–460. © 2007 Cambridge University Press
doi:10.1017/S0263574706003274 Printed in the United Kingdom

Figure and texture presentation capabilities of a tactile mouse equipped with a display pad of stimulus pins

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(Received in Final Form: December 12, 2006. First published online: February 12, 2007)

SUMMARY

To obtain specifications for a tactile display that would be effective in virtual reality and tele-existence systems, we have developed two types of matrix-type experimental tactile displays. One is for virtual figures (display A) and the other is for virtual textures (display B). Display A's pad has a 4 × 6 array of stimulus pins, each 0.8 mm in diameter. Three pad configurations, in which distances between any two adjacent pins (pin pitch) are 1.2, 1.9, or 2.5 mm, were developed to examine the influence of distance on a human operator's determination of virtual figures. Display B has an 8 × 8 array of stimulus pins, each 0.3 mm in diameter and with 1- or 1.8-mm pin pitch, because presentation of virtual textures was presumed to require a higher pin density. To establish a design method for these matrix-type tactile displays, we performed a series of psychophysical experiments using displays A and B. By evaluating variations in the correct answer percentage and threshold caused by different pin arrays and different pin strokes, we determined under what conditions the operator could best feel the virtual figures and textures. The results revealed that the two-point threshold should be adopted as the pitch between pins in the design of the tactile display, that a pin stroke should exceed 0.25 mm, and that the adjustment method is the most appropriate to evaluate the capabilities of tactile displays. Finally, when we compared the virtual texture with the real texture, we found that the threshold for the real texture is almost 1/3rd that of the virtual texture. This result implies that it is effective to present variations in patterns caused by rotation and variation in shearing force, itself produced by relative motion between the finger surface and object surface.

KEYWORDS: Human-machine systems; Virtual reality; Tactile display; Piezoelectric actuator; Matrix-type; Striped texture; Optimal pitch; Constant stimuli; Adjustment method; Perceptible pin stroke.

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1. Introduction

In the fields of virtual reality technology and tele-existence, several display mechanisms are being tentatively presented for tactile displays, while there are already established visual and auditory displays such as head-mounted displays and five-channel (5-ch) surround sound systems. For example, so far many researchers have adopted mechanical vibratory pin arrays,[1] surface acoustic waves,[2] pin arrays driven by pneumatic actuators,[3] a stepping-motor array,[4,5] a DC-servo motor array,[6] piezoelectric actuators,[7,8] and mechanochemical actuators[9] made of ICPF (ionic conducting polymer gel film) as display mechanisms. Since distributed pressure needs to be applied for tactile displays to imitate the effect on human tactile receptors distributed over the skin, very high-level actuator technology is required to realize high-density distributed actuator arrays. At present, it is still difficult to develop tactile displays capable of satisfying requirements for practical use in spite of many trials, though recent improvements in actuator technology are now giving rise to micro-actuator arrays (http://yokota-www.pi.titech.ac.jp/index-A.html).

In the present paper, we intend to obtain optimal specifications for designing a tactile display and to establish a method to evaluate the display. Since virtual figure and texture presentations are primitive elements for presenting virtual objects, we focus on the virtual figure and texture. Thus, we have developed two kinds of matrix-type experimental tactile displays in order. One is for presenting virtual figures (display A); the other is for presenting virtual texture presentation (display B). Display B was developed on the basis of experiences obtained in designing display A because it is more difficult to display virtual textures than virtual figures. Display A's pad has a 4 × 6 array of stimulus pins, each 0.8 mm in diameter. Three display pad configurations, in which distances between any two adjacent pins (called pin-pitch, hereafter) are 1.2, 1.9, or 2.5 mm, were developed to examine the influence of distance on a human operator's determination of virtual figures. Display B has an 8 × 8 array of stimulus pins, each 0.3 mm in diameter and with 1- or

1.8-mm pin pitch, because it was presumed that presentation of virtual textures would require a higher pin density.

The stimulus pins within the pads of displays A and B can be made to protrude above the surface of the display pad. The operator can thus feel various combinations of pins protruding according to the shape and texture of the virtual object. Piezoelectric bimorph ceramic actuators are used to perform the protruding motion. Displays A and B are incorporated into a tactile presentation system comprising of the tactile display, a computer, and a piezoelectric actuator driver.

In the virtual figure-presentation experiments using display A, participants felt five virtual figures: a circle, a triangle, a square, a pentagon, and a hexagon. Evaluations of the experimental results were then made based on the percentages of correct answers. We also examined the influence of pin pitch on the percentage of correct answers. In the texture presentation experiments using display B, the participants touched striped virtual textures composed of crossed-axis patterns and judged variations in the crossed-axis angles. In a series of psychophysical experiments, they palpated two virtual textures: a standard texture fixed during the entire experiment and a comparison texture that could be changed. To find the best method for evaluating the tactile displays, we applied both the constant stimuli method and the adjustment method. For each method we obtained a threshold, which we assumed to represent the sensitivity of human sensation. By evaluating changes in the threshold, we determined the optimum specifications for texture presentation such as the optimal pin pitch, display pad area, and pin stroke of the stimulus pin.

2. Tactile Display System

2.1. Pin protrude-typed tactile display

In the present paper, we intend to examine the presentation capability of pin protrusion-type tactile displays for virtual figures and textures. We developed two displays, display A and B, having a 4×6 and 8×8 array of stimulus pins, respectively. The stimulus pins within the pads can be made to protrude above the surface of the display pad, enabling the operator to feel various combinations of pin protrusions in accordance with the form and texture of the virtual object. Piezoelectric bimorph ceramic actuators perform the protruding motion; each piezoelectric actuator in the array generates a pin displacement of approximately 1 mm when 200 V is applied. Since display B was developed after the work on display A was completed, display B is more sophisticated than display A. However, display A is still sufficient for virtual figure presentation because the mesa-shaped 1-mm-high virtual figure is presented by on–off control of the piezoelectric actuators. Since the present actuator array is developed to be used for Brie dot cell, the stimulus pin can be kept protruded statically while DC voltage is applied to the actuator.

2.2 Display A

To display A, a Braille dot cell (Braille cells, http://www.kgs-jpn.co.jp/epiezo.html) (SC-2, KGS Co.) that employs bimorph actuators has been developed, as shown in Fig. 1. In this cell, a pattern of Braille dots is created by a 2×3 array of stimulating pins. The other two pins are used to represent the cursor of a word processor. Usually, 80 cells are aligned in a row to comprise a character display device for the blind.

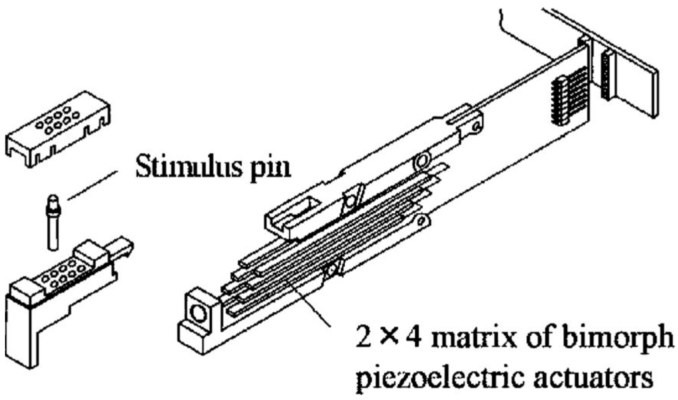


Fig. 1. Braille dot cell (KGS Co., SC-2).

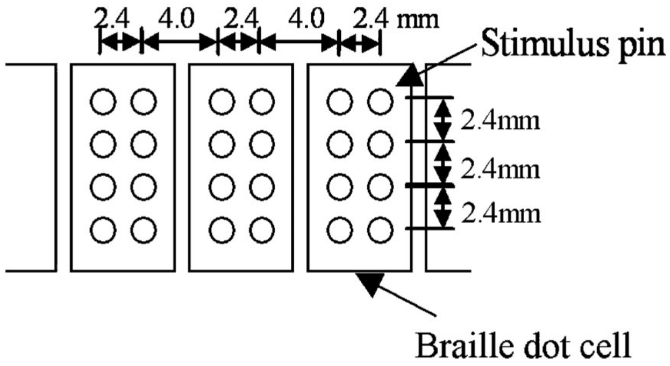


Fig. 2. Array of Braille dot cells.

Because it is used for presenting Braille dots, the distance between two stimulus pins in a Braille dot cell is slightly larger than the human two-point threshold for discriminating the distance between two stimuli. Further, the gap between two patterns of Braille dots is irregularly large compared to the distance between two stimulating pins within a cell. Therefore, the distance between any two pins in the array of stimulating pins is 2.4 or 4 mm as shown in Fig. 2. Since tactile receptors are distributed homogeneously throughout the skin surface, the distribution of stimulus pins in the cell must also be homogeneous. To overcome these problems, we have developed a tactile cell having a homogeneous distribution of stimulation pins, which are 0.8 mm in diameter. Additionally, we have developed three kinds of tactile cells to determine the optimal distance between two pins.

Figure 3 shows these three cell types. The pin pitch of the right, center, and left cells is 1.2, 1.9, and 2.5 mm, respectively. Using these cells, we performed a series of psychophysical experiments to determine the optimal pitch. The arrays, from left to right, of 1.2, 1.9, and 2.5 mm have display areas of approximately 31, 69, and 105 mm^2, respectively. These cells were mounted on a mouse whose position was determined by a Windows event process. After acquiring the present position, if a part of the cell was on the virtual texture, pins on the texture were pushed up by the bimorph actuators. For example, if the cell travels over a virtual triangle

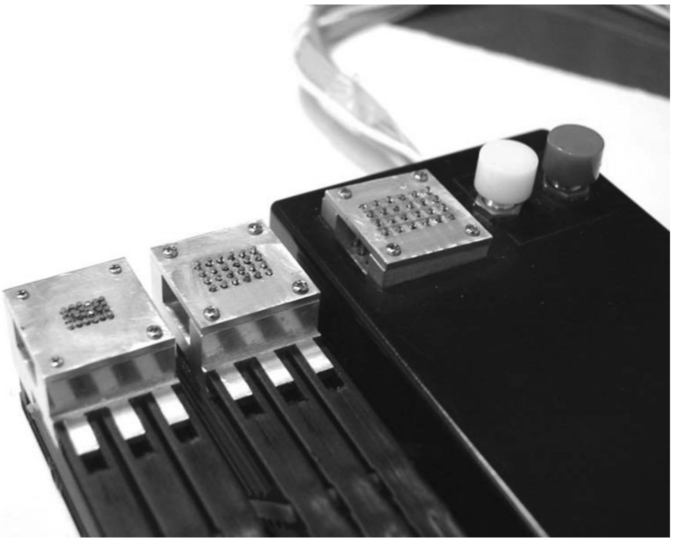
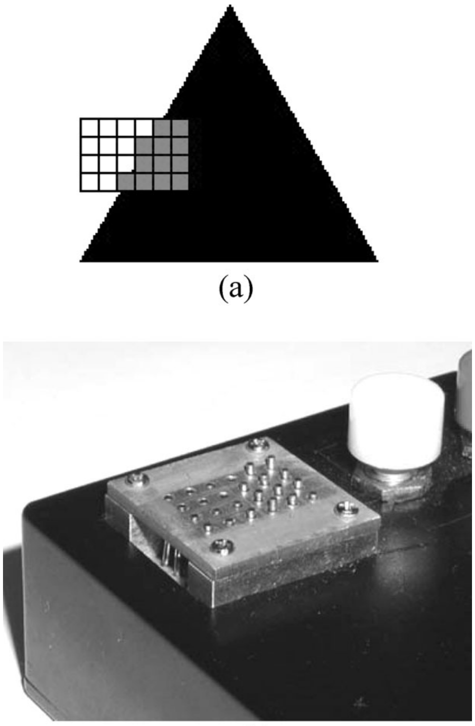


Fig. 3. Three tactile presentation pads for display A.



(a)

(b)

Fig. 4. Example of virtual figure presentation. (a) Virtual triangle and the cursor of a mouse. (b) Extruded stimulus pins on the tactile display panel according to the mouse cursor traveling on the virtual figure.

(Fig. 4(a)), pins are pushed up according to the part of the triangle's shape contacted, as shown in Fig. 4(b).

For display A, the pin-action is performed by on–off control and the pin status is either one of protrusion or subsidence. The address of a protruding pin is specified by a digital signal sent from a computer to a back-plane board attached to SC-2. An integrated circuit (IC) in the board then opens a gate corresponding to the specified address to close the circuit for the actuator driving the specified pin and to supply electricity to the specified actuator.

2.3. Display B

For display B, we used a graphic cell (SC-5, KGS Co.) having an 8×8 array of stimulus pins. Since the distance between two stimulus pins of the graphic cell is 3 mm, we developed the two display pads shown in Fig. 5. The pin pitch of the right and left cells is 1 and 1.8 mm. Both of these pitch arrays have display areas of approximately 49 and 193 mm^2, respectively. We adopted 0.3 mm as pin-diameter for display B because it is suitable for texture presentation. These tactile display pads were mounted in the same way as display A. Therefore, if the stimulus pins are located on the ridges of a virtual texture, they are pushed up by the bimorph actuators.

Contradictory to display A, for display B it is necessary to display intermediate pin protrusion except for full protrusion and subsidence. Since in the original SC-5 the pin-action is performed by on–off control and the pin-status is either one of protrusion or subsidence, we developed a new circuit to display intermediate pin protrusion. Since the tactile display features a large array of bimorph piezoelectric ceramic actuators, many lines are required to drive the actuators between the computer and the piezoelectric-actuator driver. Thus, we have adopted a way of sending digital signals to reduce the number of electrical lines from the computer to the piezoelectric-actuator driver, with specified voltage generated and sent to a specified channel in the piezoelectric-actuator driver.

Figure 6 shows a block diagram of the tactile presentation system equipped with the circuit. The system comprises a computer, a digital input/output board (DIO board) inserted into the relevant computer slot, a driver for the piezoelectric actuators, and a mouse equipped with the tactile display pad. To generate intermediate values between 0 to 1 mm, the driver outputs analog voltages of 0–200 V, and the computer generates 8-bit digital signals corresponding to the ridge heights of the virtual textures. The digital signals are subsequently transmitted to A/D converter tips TLC5628 and transformed to analog signals of 0–5 V. These analog signals are amplified by transistors 2SC5161. The A/D converter tips and transistors are housed in the mouse.

3. Experimental Procedure

3.1. Human subjects

For the psychophysical experiments, we chose male subjects in their twenties. The number of participants for figure and texture presentations was six and seven, respectively. Five persons were engaged in the experiment using real textures. The participants manipulated the tactile displays as shown in Fig. 7 to judge the presented objects without looking at the computer screen.

3.2. Virtual figures and textures

For figure presentation using display A, the participants distinguished five common shapes, these being a circle, a triangle, a square, a pentagon, and a hexagon. The operator displayed these figures randomly, and recorded the participants' answers as correct or incorrect and the time spent to take the decision.

On the other hand, in the texture presentation using display B, the participants touched virtual textures like those shown

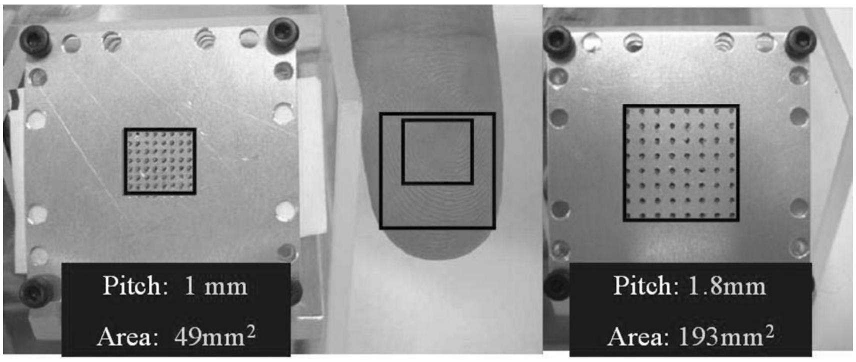


Fig. 5. Tactile display pads for display B; (*left*) 1-mm type; (*middle*) a finger for comparison; (*right*) 1.8-mm type.

in Fig. 8. A part of the texture, which is shown as Part A in Fig. 8, is presented in display B. The display area of the display pad is shown in Fig. 9; crossed-axis angle and ridge height are defined. The crossed-axis angle and ridge height are continuously changeable; the participants judged variations in the crossed-axis angles.

3.3. *Threshold and percentage of correct answers*

In the figure presentation we obtained the percentage of correct answers, which was taken to be the probability of correctly identifying the presented figures, and is suitable for examining the figure presentation. Since the figure could not be changed continuously, there is no other way to examine it besides taking the percentage of correct answers.

On the other hand, since the virtual texture can be changed continuously with change in an appropriate parameter as the crossed-axis angle, we can measure human sensitivity for change in the virtual texture. Thus, in the texture presentation experiments using display B, we obtained a threshold that we adopted as the evaluation parameter to measure human sensation in the psychophysical experiments, because it requires more precise evaluation than the figure presentation. To obtain the optimal evaluation method for tactile displays, we conducted two major psychophysical experiments using two different methods:[1] the constant stimuli method and the adjustment method. In the following subsections, the two methods that were used to obtain the threshold are described for a more precise discussion.

3.4. *Constant stimuli method*

In the constant stimuli method, the participants alternately palpated two virtual textures: a standard texture fixed during the entire experiment and a comparison texture. A number of pairs of standard and comparison textures were presented at random. For each presented pair, participants judged whether the two textures were the same or not. If the difference between the crossed-axis angles of standard and comparison textures was large, the participants could distinguish those textures. In contrast, if the difference was small, they could not. Therefore, the frequency of answers concluding that the two textures are different increases with an increase in the difference of the crossed-axis angle. Consequently, the relationship between the cumulative value of the frequency p and crossed-axes angle θ exhibits an S-shaped behavior pattern. The abovementioned statistical approach requires a large number of trials for each crossed-axis angle value.

After we obtained the relationship between the cumulative frequency and the crossed-axis angle, we obtained the threshold, which was defined as the mean value of the upper and lower thresholds. As shown in Fig. 10, the upper and

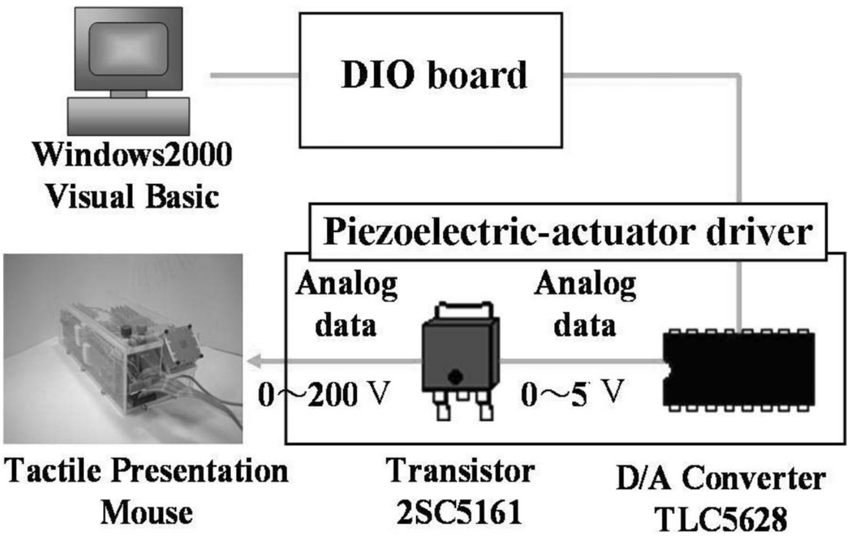


Fig. 6. Tactile display system.

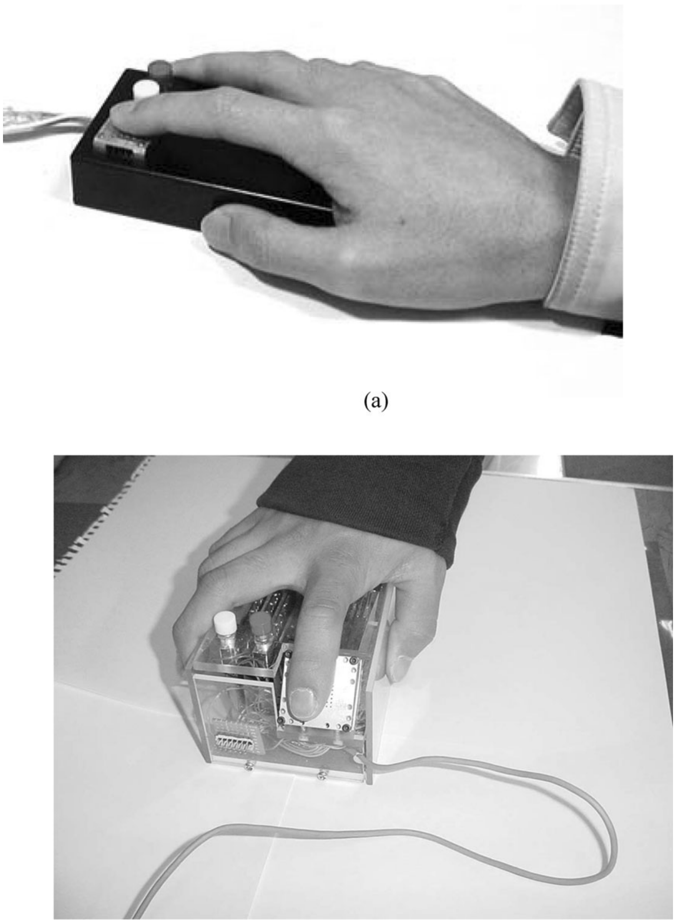


Fig. 7. Manipulating tactile displays. (a) Display A. (b) Display B.

lower thresholds ($\Delta\theta_u$ and $\Delta\theta_l$) are defined as the difference between a crossed-axis angle at $p = 0.75$ and one at $p = 0.5$, and the difference between a crossed-axis angle at $p = 0.5$ and one at $p = 0.75$, respectively. In the present paper, we adopt the mean value of the upper and lower thresholds as the (mean) threshold.

3.5. Adjustment method

In the adjustment method, the participants could change the crossed-axis angle of the texture by using specified keyboard keys during the experiments. In these experiments, we used our own program shown in Fig. 11. To increase the crossed-angle, the subjects pressed the right arrow key, while to decrease it, they pressed the left arrow key. The crossed angle changed by 10° with one stroke of the key. The participants attempted to change the comparison texture to match it with the standard texture. If the difference between the standard and comparison textures was large, they could notice the difference easily, while it became difficult to distinguish the difference with decreasing angles. Therefore, the cumulative value of the occurrence probability of comparison crossed-axis angles exhibits an S-shaped behavior pattern as shown in Fig. 10. We obtained a threshold from these results in a manner similar to that explained above for the constant stimuli method.

4. Virtual Figure Presentation

The size of the mouse cursor on the CRT screen is 28 × 49 pixels in Fig. 4 (a); since each small square corresponding to a stimulus pin is composed of 7 × 7 pixels, the mouse cursor searches 4 × 6 squares. We adopted a circle, an equilateral triangle, a square, a pentagon, and a hexagon as the virtual figures and prepared six bitmap sizes of circumscribed circles for each figure: 50, 70, 90, 110, 130, and 150 pixels. Since five shaped and six sized figures ($5 \times 6 = 30$) were presented twice for each participant, 60 figures were judged. The participants distinguished the 60 virtual figures using 1.2-, 1.9-, and 2.5-mm pitch arrays, answering with the shape of the figure. A summary of these experiments is shown in Fig. 12, where variations in both the percentage of correct answers and consumption time for decisions are shown for low-, medium-, and high-density cells. Time consumption means the time needed to make a decision.

Since humans recognize virtual figures more easily when the figure size is enlarged, the percentage of correct answers increases with a larger bitmap size of circumscribed circle on the virtual figure. Furthermore, because the virtual figures become easier to recognize, the time needed for recognition becomes shorter. Although the medium-density cell gives the highest percentage of correct answers for small bitmap sizes, generally the low-density cell leads to the best results. At first, this result appears to contradict the notions of

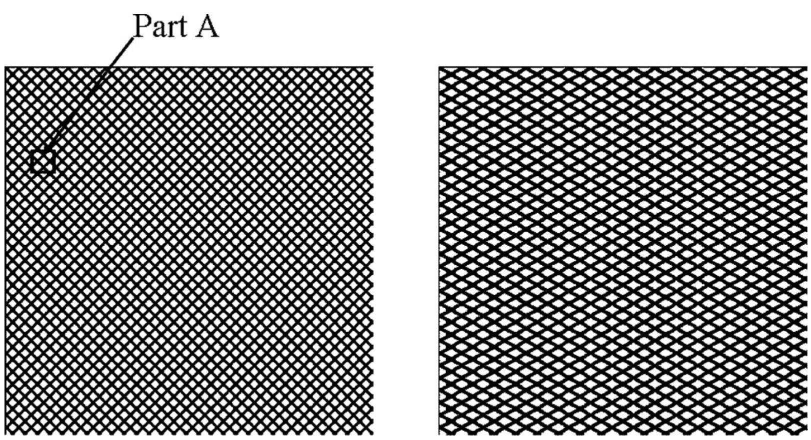


Fig. 8. Virtual textures: (*left*) $\theta = 90°$; (*right*) $\theta = 120°$.

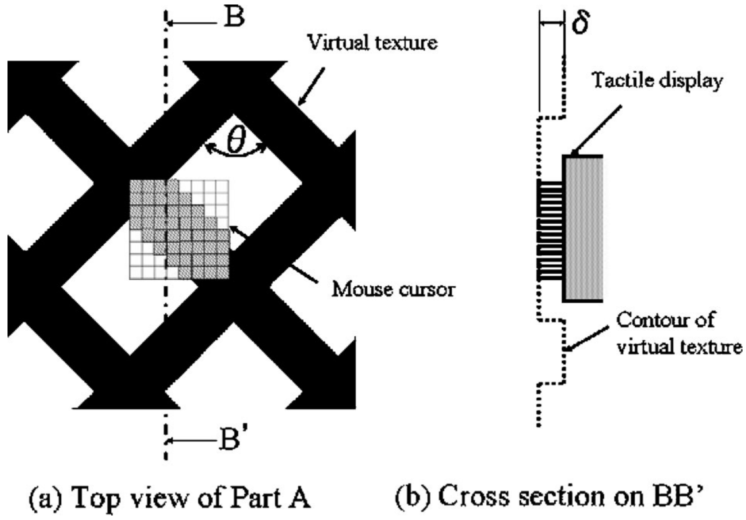


Fig. 9. Crossed-axis angle on the display area. (a) Top view. (b) Cross section (side view).

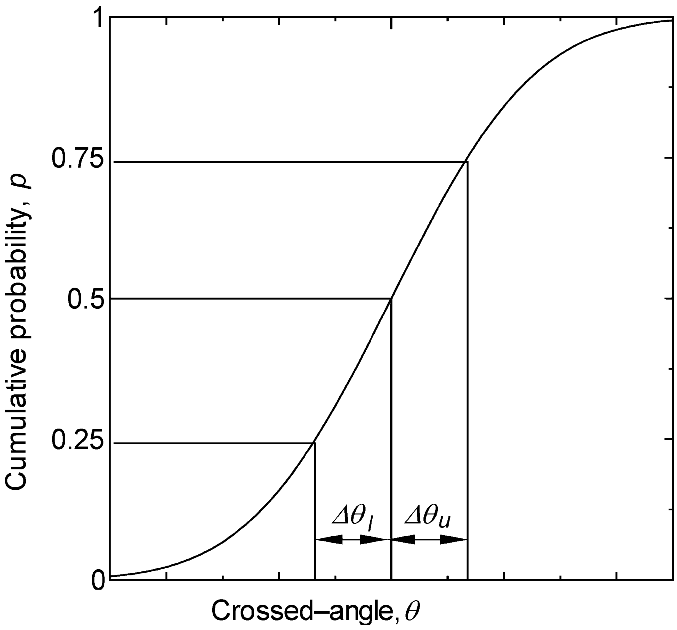


Fig. 10. Estimation method for upper and lower thresholds.

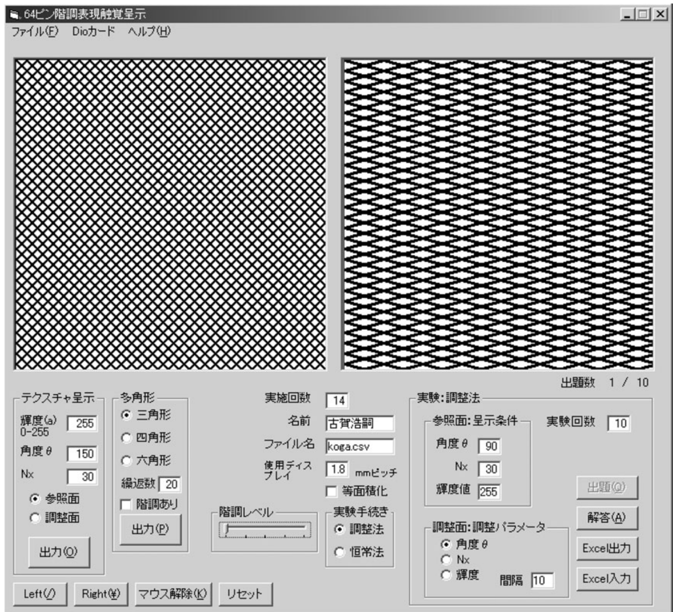


Fig. 11. Software for the presentation experiment.

human tactile sensation, i.e., the high-density cell seems most likely to yield a high percentage of correct answers and low consumption time. However, we notice that the high-density cell has a narrow display area because all cells have the same number of stimulus pins. Therefore, we also have to consider the influence of display area on the percentage of correct answers and consumption time.

In the medium- and low-density cells, some stimulus pins can be fixed by programming. If the 3×4 and 2×3 pin arrays are moved for medium- and low-density cells, respectively, the display area becomes approximately the same magnitude as that of the high-density cell. Figure 13 shows the relationship between the percentage of correct answers and the pitch between two adjacent pins. We could not find any difference between the high-density and medium-density cells; however, in the case of low density, the percentage of correct answers is markedly low compared to the other densities. Similarly, the consumption time abruptly increases. From the results in Fig. 13, it is found that high or medium pin density is comfortable for a tactile display.

5. Virtual Texture Presentation

5.1. Optimal evaluation method for tactile display

Next, we examined experimental results of texture presentations using display B. Figure 14 shows the relationship between probability and the crossed-axis angle of comparison textures. In this experiment, the crossed-axis angle of standard texture was 90°; we also adopted 30°, 50°, 70°, 90°, 110°, 120°, and 150° as the crossed-axis angles of comparison texture. The pair comprising of standard and comparison textures was presented randomly. For each tactile display, each participant judged the difference between the standard and comparison crossed-axis angle 252 times.

To examine the effect of contact area on texture, we performed another experiment on the 1.8-mm pitch array

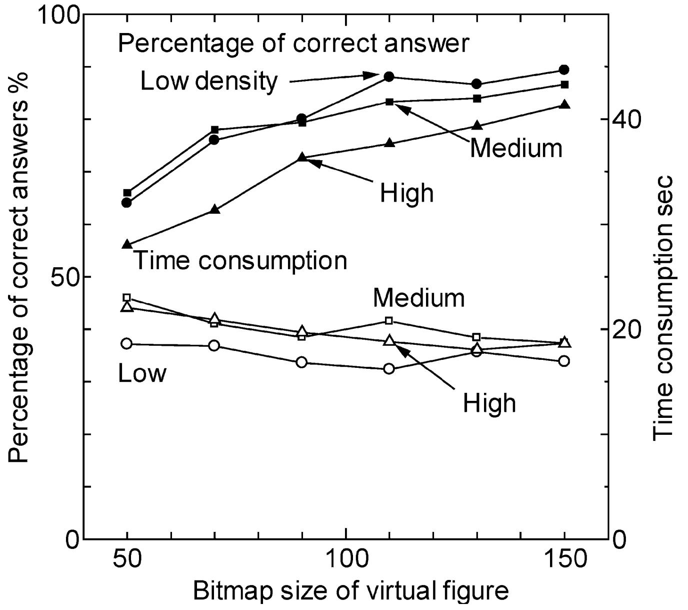


Fig. 12. Optimal pitch.

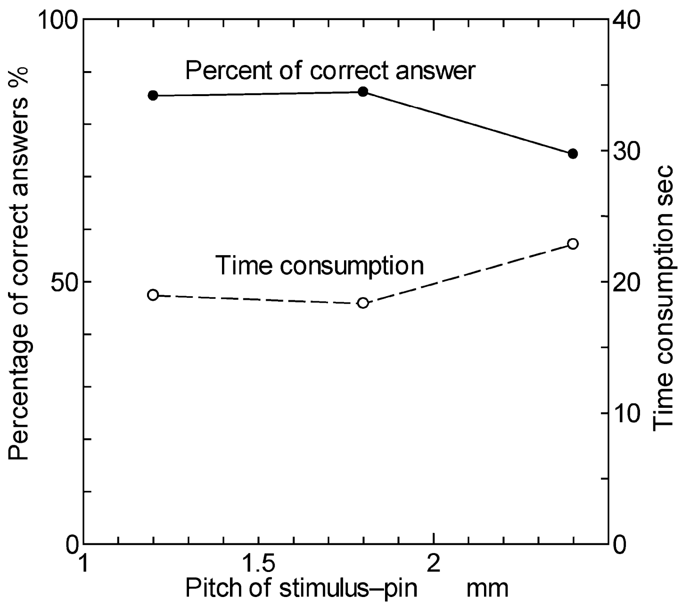


Fig. 13. Influence of pitch between two adjacent pins on the percentage of correct answers for the same display area.

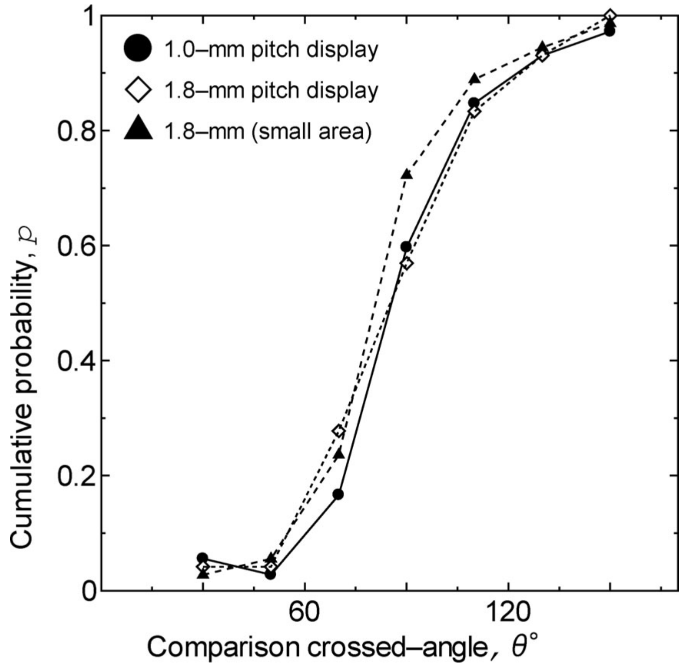


Fig. 14. Relationship between probability and cross-axis angle in constant stimuli method.

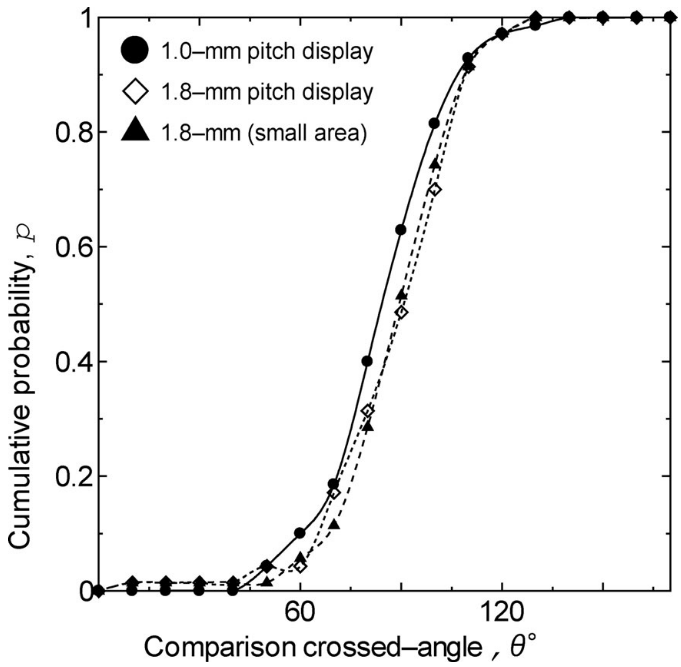


Fig. 15. Relationship between probability and cross-axis angle in adaptive method.

into which fewer pins was driven. In Fig. 14, this result is called “1.8-mm pitch (small area),” which has the same display area as the 1-mm pitch array. As the figure shows, the behavior patterns for probability are S-shaped and the three curves almost coincide with each other. If the thresholds of the three curves are obtained in the manner described in Section 3.4, the 1-mm, 1.8-mm, and 1.8-mm (small) pitch arrays are 15.3°, 16.9°, and 16.2°, respectively.

On the other hand, in the adjustment method, each participant adjusted the cross angle of virtual texture. In this experiment, the crossed-axis angle of standard texture was 90°; the initial value of the crossed-axis angle of the comparison texture was selected from 10° to 170° in intervals of 10°. Each subject adjusted the crossed angle of the comparison texture under 10 different initial comparison cross angles; the participant performed a set of 10 trials twice. From Fig. 15, it can be seen that the thresholds of both the 1- and 1.8-mm pitch arrays are 13.0° and that the threshold of the 1.8-mm (small area) pitch array is 11.4°. Since the difference between the thresholds of the 1- and 1.8-mm pitch arrays is not large, the 1.8-mm pitch array is sufficient for presenting virtual textures of striped patterns.

In the present paper, we used three experimental methods: obtaining the percentages of correct answers, the constant stimuli method, and the adjustment method. The method of obtaining the percentage of correct answers is simple

Table 1. Comparison between constant stimuli and adjustment method (DT: differential threshold, TC: time consumption).

	Display type	Constant stimuli method	Adjustment method
DT	1 mm	16.9°	13.0°
	1.8 mm	15.3°	13.0°
TC	1 mm	522 min	126 min
	1.8 mm	443 min	104 min

and suitable for feasibility studies such as checking the types of figures and textures. Additionally, there is almost no way but to employ the percentage of correct answers for the virtual figure experiments, since an appropriate continuous parameter for presenting stimulus has not been found for virtual figures. In contrast, the threshold, which can be obtained by both the constant stimuli and adjustment methods, can be used to precisely evaluate the presentation capability of tactile displays because it measures variations in physical quantities that can be sensed by humans.

Now, because both constant stimuli and adjustment methods can be used to obtain the threshold, let us discuss which method, constant stimuli or adaptive, is best suited to evaluate tactile displays. Table 1 summarizes the thresholds obtained by the constant stimuli method and adjustment method. These thresholds were estimated from Figs. 14 and 15. As Table 1 shows, the mean value of the threshold obtained by the adjustment method was smaller than that obtained by the constant stimuli method. This means that the participants could distinguish the crossed-axis angle more precisely using the adjustment method. A small threshold value was obtained because the subjects participated actively in the experiments in the adjustment method to prevent boredom. Moreover, Table 1 clearly shows that the constant stimuli method requires twice the time required by the adjustment method. If we regard time consumption as the most important specification for time saving, the adjustment method is the most appropriate for evaluating tactile displays.

5.2. *Perceptible pin stroke and texture density*

As mentioned in Section 2, the driver for the piezoelectric actuators generates variation in output voltage from 0 to 200 V. Since the piezoelectric actuator generates a pin displacement of 1 mm at 200 V, it can generate variation in displacement of 0–1 mm. In the presentation system, a pin displacement in the stimulus pin array is specified according to an 8-bit gray-scale value (0–255). In Fig. 9, the black portions of the left and right textures take gray-scale values of 255: this corresponds to displacements of 1 mm. We specified seven gray-scale values, 50, 60, 70, 90, 120, 185, and 255, which correspond to displacements of 0.03, 0.07, 0.1, 0.19, 0.36, 0.79, and 1 mm, respectively.

To obtain a value for a perceptible pin stroke, we performed a series of psychophysical experiments using several textures with varied gray-scale values of virtual ridges. In these experiments, the 1.8-mm pitch array of display B was used and other procedures, except for changing gray-scale values, were the same as in the previous experiments using the adjustment method.

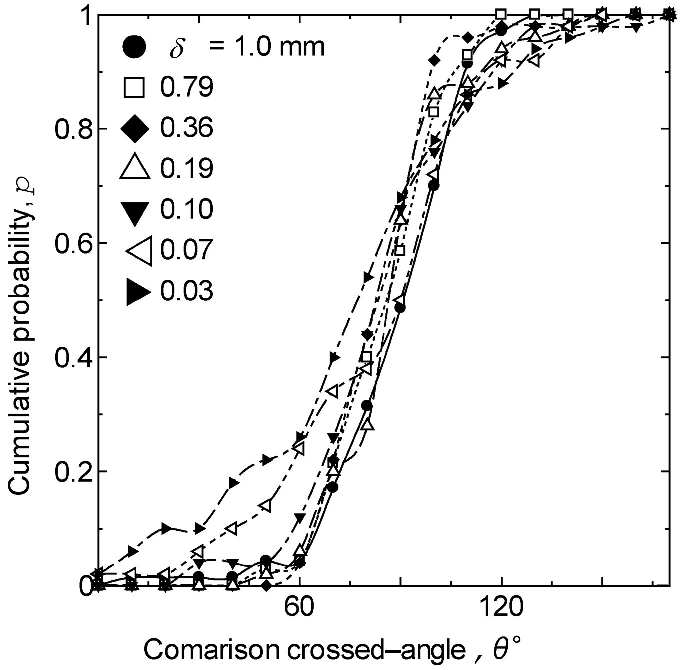


Fig. 16. Ogive curves obtained from experiments performed to evaluate presentable fringe height of virtual texture.

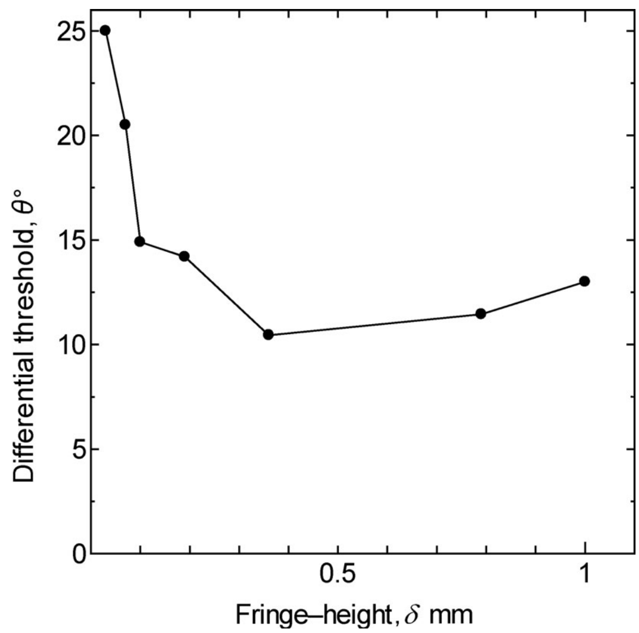


Fig. 17. Relationship between differential threshold and fringe height.

Figure 16 shows relationships between probability and the crossed-axis angle under several pin-stroke conditions. The behaviors of all curves exhibit S-shaped variations, which are the same as in the aforementioned experiments. If we precisely examine these shapes, it is evident that the shapes become disordered with a decrease in the height of the virtual ridge. Using this result we obtained threshold values of 25°, 21°, 15°, 14.8°, 10°, 12°, and 13° for respective strokes of 0.03, 0.07, 0.1, 0.19, 0.36, 0.79, and 1 mm.

Figure 17 illustrates the relationship between threshold and pin stroke. As in Fig. 17, the threshold changes at a pin

Fig. 18. Real texture on an aluminum plate and an index finger.

stroke of about 0.2 mm. The relationship is approximated as bi-linear to obtain a transition point. Each straight line is obtained by a least-squares approximation. From the bending point, since we specify 0.25 mm as the transition point, it is desirable that the pin stroke should be greater than 0.25 mm.

5.3. Comparing with real texture

To evaluate the realism of virtual textures presented by the tactile displays, we produced real textures of aluminum plate having convex–concave texture corresponding to the virtual texture. We prepared five textures of $\theta = 70°, 80°, 90°, 100°$, and $110°$, corresponding to the virtual texture as shown in Fig. 18. In the psychophysical experiments using the real texture, since we could not continuously change the crossed-angle, we performed the experiments according to the procedure of the constant stimuli method. We adopted the texture of $\theta = 70°$ as the standard, and presented the standard texture and comparison textures of $\theta = 70°, 80°, 90°, 100°$, or $110°$ to each participant, who judged whether the two textures coincided or not. The comparison texture was randomly chosen from the five textures and 80 trials were performed for each participant. We obtained the cumulative frequency of answers, and concluded that the two textures were the same.

Figure 19 presents a comparison of the experimental results for real textures and virtual textures. As the figure shows, the inclination of variation in cumulative probability p obtained from real specimens is larger than one obtained from virtual presentation, meaning that discrimination precision for the real specimen is higher than that for virtual presentation. If we had obtained thresholds from Fig. 19, thresholds for the real specimen and the virtual presentation would be 5.4° and 16.9°, respectively. The threshold for the real texture is almost 1/3rd that of the virtual texture.

When we observed the participants' behavior during the experiments, they pressed and massaged the real specimen with their finger. Since the present tactile display is mounted on the mouse with two-dimensional freedom, rotation of the virtual grid cannot be presented. Moreover, shearing force caused by relative motion between the finger surface and the object cannot produce any sensation despite the fact that this occurs normally with real texture, because the operator keeps his finger in contact with the display pad.

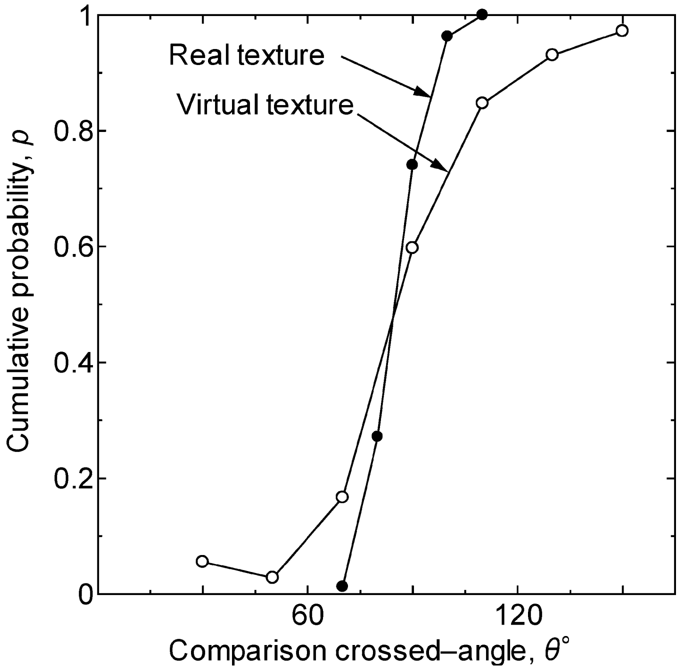


Fig. 19. Comparison of detection precision between virtual texture and real texture.

As described in Section 4, the experimental result for display A indicates that it is necessary to narrow the pitch to less than 1.9 mm. Besides the experiments for displays A and B, we performed a series of experiments to estimate the two-point threshold of human finger tips, i.e., the spatial resolution of pin stimuli, for the participants in the present experiment using stimulus pins of display A. As the results reveal, the mean value of the two-point threshold was 1.5 mm for the transverse direction and 1.7 mm for the longitudinal direction of their finger tips. Since these values are quite similar to 1.8 and 1.9 mm, we adopted the two-point threshold value as the pitch between pins in the design of the tactile display.

The presentation capability is not enhanced even if the distance between two adjacent stimulus pins is made shorter than the two-point threshold. Since the distance between two adjacent pins is 1 mm in the present tactile display and is smaller than the two-point threshold of about 1.7 mm, the density of pins is adequate for the tactile display. Therefore, in future work, we will present variations in patterns caused by rotation and variations in shearing force caused by relative motion between the finger surface and object surface.

6. Conclusion

We developed matrix-type experimental tactile displays for virtual reality systems. The tactile displays feature stimulus pin arrays, which are display pads able to protrude the pins above the surface of the display pad. The operator can feel various combinations of pins protruding according to the texture or shape of the virtual object. To obtain specifications for this type of tactile display, we performed a series of psychophysical experiments in which figures and striped virtual textures were presented.

By evaluating variation in the percentages of correct answers or threshold caused by different pin arrays and different pin strokes, we determined whether the operator could accurately feel the virtual figures and textures. Since presentation precision for the figure and texture is saturated when the distance between two adjacent pins is reduced to 1.8 or 1.9 mm for the same value of the two-point threshold, the value of the two-point threshold should be adopted as the pitch between pins in the tactile display's design. Since we could not find any difference in threshold between the constant stimuli method and the adjustment method, we could not conclusively determine the best method from the threshold value. If, however, we examine total time consumption, the constant stimuli method requires twice the time of the adjustment method. Therefore, we conclude that the adjustment method is the most appropriate for evaluating tactile displays. Moreover, it was found using the adjustment method whereby the pin stroke should exceed 0.25 mm and that the adjustment method is the most appropriate one to evaluate the capabilities of tactile displays.

Finally, we compared the virtual texture with the real texture. The threshold for the real texture is almost 1/3rd that of the virtual texture, and presentation capability does not improve even if distance between two adjacent stimulus pins is made to be shorter than the two-point threshold. This result implies that it is effective to present variations in patterns caused by rotation and variations in shearing force caused by relative motion between the finger surface and object surface. Therefore, in future work, we will develop a new tactile display presenting variations in patterns caused by rotation and variations in shearing force, themselves produced by the relative motion between the finger surface and object surface.

We are currently investigating two-axis micro-actuators in the Japan Scientific Research of Priority Areas 438 "Next-Generation Actuators Leading Breakthroughs" program to design a new tactile display capable of presenting shearing force distribution. We will continue to study the tactile display to improve its presentation capability and will present the results in future.

Acknowledgements

This paper was supported by fiscal 2005 grants from the Ministry of Education, Culture, Sports, Science and Technology (Grant-in-Aid for Priority Areas, No. 16078207) and a 2004 grant from the Tateisi Science and Technology Foundation.

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