A New Design of Haptic Texture Display—Texture Display2—and Its Preliminary Evaluation

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Abstract

In this paper, we describe a new design of haptic Texture Display consisting of fifty vibratory pins that evoke a virtual touch sensation of textured surfaces contacted to the user's fingerpad. A pin drive mechanism was fabricated by adjusting a natural frequency to expand the displacement of a piezoelectric actuator efficiently. An improved control system enabled fine amplitude changes in 200 steps. Sensation intensity was scaled and indicated by a power function of pin amplitude. As a fundamental evaluation data, we measured the difference threshold of object's spatial frequency presented on the display, regarding four intensity waveforms. Moreover, matching tests between real and virtual textures were performed to evaluate the quality of presentation.

1. Introduction

A haptic display for skin sensation is among challenges in creating virtual reality with an enhanced sense of presence. Providing a skin sensation in a contact region enables the user to perceive the detailed property of spatial objects with a haptic event between a skin and the objects. For example, clinical palpation requires surface information imparted to the fingertips; a dexterous manipulation of a tool can be performed when a small change in position and orientation is conveyed to a hand through distribution of force or vibration on the tool.

Sensations evoked by a small variation of property on a surface—the texture sensations—are based on a complex process of interaction between a skin and the surface of an object [1][2]. An ideal approach to reproduce the texture sensation would be to make a copy of the contacting surface or a force distribution within the contact region of a skin by external surface/force devices. However, this suffers from increasing the spatial density of force distribution devices. The device needs to move within a real space to track the user's motion as well, which makes the construction of the device extremely difficult. Another ideal way might be an internal stimulation of nerve fibers in the skin directly as reported recently in Kajimoto et al.'s work [3]. The research exhibited a potential in discharging nerves by electric stimulation, whereas the implementation of the device leaves a problem; a sufficiently fine-spaced electrode with an electrically stable contact to the skin.

The both two approaches eventually produce a sensation arising from virtually equivalent stimulation to mechanoreceptors by entirely different devices. On the other hand, stimulating a skin by vibration is neither providing a physical copy of a surface shape nor skipping mechanoreceptors' activation. However, by setting vibration sources distributed on the skin, it produces virtual touch sensation through excited population of mechanoreceptors. Stimulation by vibration is advantageous in overall structural efficiency (it requires only a small amplitude), in addition, it is robust to disturbance in a contact status and has less possibility to cause pain.

We developed a haptic texture display consisting of fifty vibrating pins contacted to the fingerpad to present a bumpy surface of objects [4]. This first version of the Texture Display indicated reasonable promise in conveying fine variations on a surface. However, when textures contained more complicated and subtle changes, its spatiotemporal resolution turned out to be insufficient due to the structure and control used. Namely, a pin drive mechanism was designed less effectively without adjusting natural frequency of vibration relative to the operating frequency; the control bandwidth was limited due to the insufficient speed of a controller PC.

A new design was implemented fabricating a pin drive mechanism by cutting a brass plate to form an optimal frequency in a small dimension. In addition, the control system was reinforced to enable a fine amplitude change in vibration. Eventually, the pin drive mechanism shrank permitting the entire volume of the display to one-third of the previous design. The pin's amplitude controlled in two-hundred steps introduced remarkably improved presentation with intermediate intensities.

2. Vibratory haptics bases and related work

Regarding the sensation of vibration, Verrillo et al. [5] reported psychophysical sensation magnitude curves. Therein, the relation between the amplitude of vibration

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and a subjective sensation intensity conformed to a power-function, and the largest sensitivity was found at around 250 Hz. The frequency corresponds to the adequate stimulus for Pacinian Corpuscle (PC), one of four mechanoreceptors [6]. The sensitivity of a human skin to a vibratory stimulus is extremely acute owing to this sensory organ. LaMotte and Srinivasan [7] reported that 0.06-micron high periodical elements were detectable through PC. Another vibration sensitive RA (rapidly adapting) afferent has a smaller receptive field and a larger spatial resolution, which contributes as a motion detector.

A vibration type device conveying a two-dimensional pattern to a fingerpad was developed first by Linvill and Bliss [8]. Although the device, the Optacon, was designed to present characters to the blind person, it has also been used in psychophysical and physiological researches. Gardner and Palmer [9] reported Optacon stimulator excites PCs and RAs but not slowly adapting (SA) mechanoreceptors that affect shape recognition. However, the sense of apparent motion was clearly observed by continuous change in activated pin positions.

Other pin type display devices are still somewhat in an experimental stage. The SMA (strain memory alloy) actuators [10][11] are investigated to drive pins. Controlling stimulus including surround is discussed for selective stimulation of mechanoreceptors [12]. Johnson and his colleagues [13] built a new pin array stimulator for the purpose of neurophysiological and psychophysical research. The stimulator consists of 400 pins covering a large range of amplitude and frequency.

3. Haptic texture

The definition of a texture is not simple in haptics [1] in contrast to a graphic texture that is eventually reduced to an array data in colors. Textures in haptics are related to many aspects of real object's properties such as microstructures, stiffness, coefficient of friction, thermal property etc. as well as to the possible mechanical/thermal interaction of a human fingerpad to those properties. In addition to this physical complexity, evoked sensation integrated based on information collected from numerous mechanoreceptors in the skin has not been clearly identified yet. Although Hollins et al. [14] addressed a three-dimensional perceptual space of texture sensation (rough-smooth, hard-soft, springiness), production of arbitrary texture sensation using the dimension is not discussed so far.

Minsky [15] first demonstrated the computed generation of haptic texture sensation by a 2-dimensional force feedback device, where she used only a depth (height) map and its gradient to generate force variation added to the device. She discussed three representation levels of haptic sensation (World-, Perceptually-, and Representative-based) which should be approached, placing her system as perceptually-based concentrating to the roughness of a surface.

Srinivasan [16] surveyed various methods for generation and rendering of haptic stimuli as *computer haptics*. The texture presentation methods were discussed as force perturbation and displacement mapping that assumed to use a point-type force display, typically the Phantom. The same approach was discussed in Ruspini [17]. In these articles, the texture is presented through a tool or a probe where the interaction between the tool and a target object occurs at a single point. However, the use of such a probe inevitably fails to convey the 2-dimensional feature of the surface as Lederman and Klatzky [18] showed, while in a real touch the fingertip should have an extended contact area to gather surface information. The Phantom could successfully present a surface information such as stiffness, viscosity, roughness and friction by translating a probe across the surface. Nevertheless, these properties are observed based on the change along a trace path of zero width. Two-dimensional pattern will surely be conveyed more effectively through a two-dimensional window to the human sensory space.

We investigated the design of a two-dimensional array stimulator and its perceptual property. In this course of design and evaluation, a texture on objects was treated as a variation of a surface shape—a height distribution—leaving out other factors that would contribute to changing tactile sensation. The surface microstructure is expected to have the most profound influence on cutaneous sensation since it generates spatiotemporal fluctuation in pressure and vibration in the skin.

4. Texture Display2 (T50-2)

4.1. Basic features of the Texture Display2

Figure 1 shows the Texture Display2 (T50-2). The display permits two-dimensional motion on a desktop for the user to explore actively on virtual textures. A pin-array is at the center of a top board, where fifty blunt piano-wire pins 0.5-mm in diameter are arranged in a 5-column and 10-row lattice with a 2-mm spacing. (This spacing was

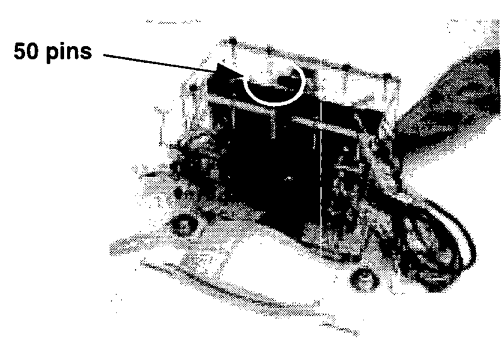


Figure 1. Texture display2. Fifty contact pins are arranged in 5-column x 10-row with a 2 mm spacing. The main body except for a mouse measures 70(w) x 140(d) x 145(h) mm.

determined by the size of an actuator.) The user places the index fingerpad on the array measuring approximately 8 x 18 mm^2, and holds the whole body by other fingers to move the pin array within a virtual texture. The display body size was reduced to 30 % in volume of the previous model. The reduction was achieved by the new design of a pin drive mechanism shown in the next section.

The frequency of pin vibration was set at 250 Hz where an absolute threshold of cutaneous sensation is minimized as discussed above. Although the frequency is captured most sensitively by Pacinian corpuscles, it is also known that RA afferent responds surely to each pulse indentation produced by the Optacon stimulator at least up to 100 Hz [9]. Past the frequency, the response decreases along with a frequency increase if the sinusoidal wave is constantly added [19]. However in a phasic stimulation, the onset of vibration that is frequently involved during texture exploration is considered to discharge RA afferents. In addition, more importantly the fast update of amplitude or intensity of each pin is crucial to provide information of fine shape changes during a normal finger movement.

Figure 2 shows the haptic presentation system consisting of a rendering PC, a device control PC (both Pentium II, 300MHz), and the T50-2. The two computers are connected by a shared memory 500K byte/second bandwidth. A virtual space containing a texture data is simulated by the rendering PC; the position of the user's

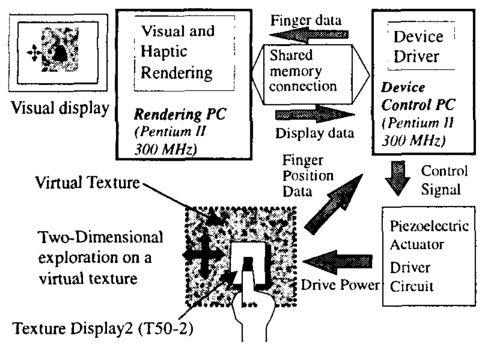
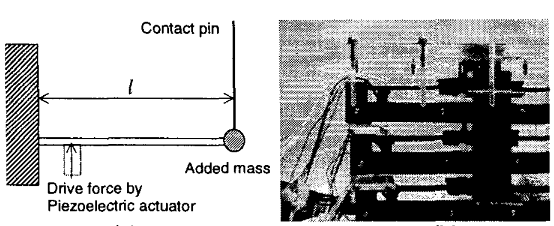


Figure 2. Haptic texture presentation system based on Texture Display2 (T50-2). A rendering calculation and a device control run on separate PCs synchronized via a shared memory.



(a) (b)

Figure 3. A cantilever structure fabricated to expand the amplitude of a piezoelectric actuator; (a) a model, (b) a close-up photo of pin drive structure.

finger is maintained based on a report from the device control PC that cares a tracking mouse. Based on a pin position, the intensity data is picked from the texture and given to the control PC. The update rate of the whole loop is maintained at 250 Hz.

4.2. Design of a pin drive mechanism

The pins producing vibratory stimuli are driven by piezo-electric actuators (AE0203D08, NEC Inc.) whose displacement is 9.1 microns at the largest input voltage of 150 V. The displacement is expanded by a cantilever structure illustrated in Figure 3a. A contact pin is attached to the tip of the cantilever. To find optimal parameters of structure design, the mechanism was analyzed by a simple cantilever model, a single fixed-end beam with a lumped mass added to a free end. The lumped mass including a contact pin was trimmed to accomplish a desired natural frequency. We set this natural frequency of a lever at 270 Hz, shifting it 20 Hz higher from the regular drive frequency of the display. This is because amplitude expansion using resonant structure is advantageous, however the amplitude at the natural frequency is readily affected by a slight change in the contact state between a user's fingerpad and a contact pin.

The natural frequency of the structure is calculated by Equation (1), where E denotes Young's modulus, A does cross section area, I geometrical moment of inertia, ρ density, and l length of a lever. The λ_l is the first eigen value which is calculated by Equation (2).

$$f_1 = \frac{1}{2\pi}\lambda_1^{\,2}\sqrt{\frac{EI}{\rho A}} \quad \text{.........(1)}$$

$$\lambda l \mu = \frac{1+\cos\lambda l \cosh\lambda l}{(\sin\lambda l \cosh\lambda l - \cos\lambda l \sinh\lambda l)} \quad \text{..........(2)}$$

$$\mu = \frac{m}{\rho A l}$$

To make the first order natural frequency fall at around 250 Hz, a brass plate was used to form the structure as it has relatively low Young's modulus (E=108Gpa). The thickness of a brass plate was selected to 2 mm reflecting the thickness of a piezoelectric actuator. After established charts indicating dependency of a natural frequency on the length l and height of a lever, we chose l of 35 mm and height of 1.5 mm, taking a balance between strength and natural frequency into account. The relation between natural frequency and added mass is shown in Figure 4.

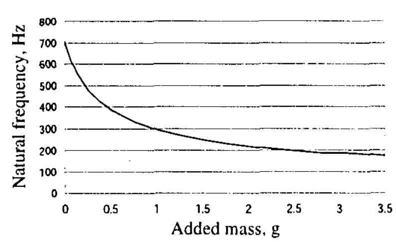


Figure 4. Natural frequency of the lever structure versus added mass.

Within the vicinity of the drive frequency of 250 Hz, a natural frequency deviates by about 10 Hz with 0.1-gram fluctuation in added mass. Figure 3b shows the fabricated lever structure in which the actuator pushes the lever at the point 7 mm from the fixed end.

4.3. Amplitude control of contact pins

The amplitude of a contact pin is controlled by changing the duty ratio of pulse-width-modulated input voltage to the piezoelectric actuator. (The input voltage was driven at binary—0 or 150 V—values.) The duty ratio ranges from 1/400 to 200/400 in two hundred ways with a unit of 10-microsecond interval that is a 1/400 of 4 milliseconds (the interval of vibration frequency of 250 Hz). The largest amplitude is reached at the duty ratio of 0.5 (200/400). This unit interval of 10 μsec is one fifth of that of the previous display.

The amplitude of a pin was measured at the tip by a laser displacement meter on two conditions, with- and without-load. The load was added by a human finger at approximately 40 mN as it contacts to pins in an actual use. Figure 5 shows the amplitude change by a duty ratio. Without a load, the largest amplitude was 51.7 microns at the maximum duty ratio (100/200), and the smallest 3 microns at below 7/400. With a load, the largest amplitude decreased to 45.5 microns. The dispersion of measured values increased by adding a load, which is considered due to the variance in contact forces. Despite the fluctuation, the mean ratio of amplitudes of loaded and unloaded conditions was sufficiently constant at about 0.89.

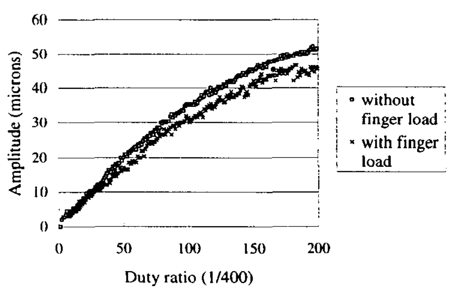


Figure 5. Amplitude versus duty ratio of PWM input. The amplitude decreases when a fingerpad contacts to the tip of a pin at an approximately 40 mN contact force.

5. Sensation scaling

5.1. Scaling based on difference threshold measurement

Since the amplitude of vibration is not parallel to the intensity of tactile sensation, scaling was performed to describe the relation. Among methods to establish a scale, we used a JND(Just Noticeable Difference)-based

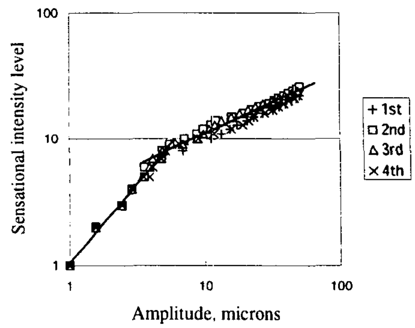


Figure 6. Relation between sensation intensity level and pin amplitude.

Fechner's approach [20]. The procedure selects a series of pin amplitudes which evoke sensation intensity change as compared to an adjacent amplitude. First, the smallest amplitude that could be noticed by the subject was searched, then the series of amplitudes was sought so that it forms smallest steps which could be distinguished. The method of limits was used to obtain each threshold.

Procedure Five subjects (three males and two females), the average age of 26, who reported to have normal tactile sensation, were called for in the laboratory and participated in the experiment. Each subject performed four sessions. In a session, a single series of amplitudes was obtained as follows. A standard stimulus and a variable stimulus are presented three times each reciprocally started from a standard. The duration of each presentation is one second and the interval is 0.2 second. After this short run, the subject is asked whether he/she could distinguish them or not. If the subject answered in the negative, the amplitude was increased. This run is repeated until the subject reported in the affirmative determining a difference threshold. This procedure continues to pick a series of amplitudes until the variable stimulus reaches to the largest amplitude. The subject wore headphones producing a band-limited noise to prevent hearing the sound of pin vibration.

Figure 6 shows the sensation intensity level as a function of amplitude, obtained from Subject A (other subjects produced quite similar data). The series of JND was numbered and it was simply regarded as sensation intensity level. Two line segments appear to approximate the relation. The same folding of the curve is observed in the previous research [5]. The number of intensity levels distinguished in the session was 23.5 in an average. Those of other subjects were 17.6, 24.5, 18.6, and 32.0. The average among subjects was 23.2. In the low amplitude region below the folding point, the difference between the subjects regarding amplitudes picked was very small. In the larger amplitude region, the series from the subjects exhibited more variability. To address this dispersion, the relation of this region is wrapped up by a power function as seen in the next section.

5.2. Description by a power function

A relation between the magnitude of stimulus and sensation intensity is known to be well described by Stevens' power law [18] written in Equation (3).

$$I = K \times (S - S_0)^n , \qquad (3)$$

I : Sensation intensity, S : Stimulus intensity,
S_0 : Absolute limen, K, n : Constant.

The value of the exponent n was calculated against the data shown in the previous section. The least square approximation was applied for the larger amplitude region. Table 1 shows the n's for five subjects. The difference among subjects was highly significant ($F^4_{15}=9.93$, $p = 3.93 \times 10^{-4}$). The average was calculated to 0.48. The variance among subjects is discussed in the later section.

The exponent for the data at lower amplitude region is calculated to slightly large value, and it has little difference between subjects.

Table 1. The *n* for the data for larger amplitude region.

Subject	A	B	C	D	E	Average
n	0.47	0.44	0.44	0.50	0.55	0.48
std dev.	0.018275	0.037792	0.024961	0.026166	0.038191	

5.3. Determination of the sensation scale

Based on these results, the sensation scale was determined as follows. Regarding the low amplitude region, instead of applying a power function, we adopted the median of the amplitudes observed to each specific sensation intensity value. This is because the number of amplitudes contributing to this region is small. The partial scale for the low amplitude region is described in Table 2.

For the high amplitude region, we used Equation (4) with the average exponent n. In this equation, the absolute threshold S_0 of Equation (3) was ignored as it is sufficiently small.

$$I = 3.42 \times \mu^{0.48}, 4.44 \le \mu \le 51.7 \qquad (4)$$

μ: Amplitude in micrometers

Here, the least μ, 4.44 micrometers, separating two regions was determined as small as possible provided that the contribution ratio of a regression line exceeded 0.98.

Eventually, based on these relations, the control PC calculates the amplitude in about 200 steps to evoke specific sensation intensity.

Table 2. Sensation scale in the low amplitude region.

Sensation intensity level	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Amplitude [x 10^{-6}m]	1.00	1.56	2.44	2.88	3.55	3.88	4.44

6. Evaluation of Texture Display2

6.1. Difference threshold of spatial frequency

As a fundamental index of display performance, a difference threshold of wavelength presented by the display was investigated. The spatial resolution of this display is basically limited by the resolution of a translational sensor of the display. The translation is measured by a mouse that has a 0.0635-mm unit (or 400 counts per inch) resolution. This determines the minimum wavelength of 0.127 mm (Nyquist wavelength). This minimum wavelength was perceivable for the subjects according to the experiment in which subjects counted the number of lines spaced by this length. In this pilot experiment, a single row of display pins parallel to the lines was driven during one-dimensional motion of the display. The displayed grating is observed as binary parallel lines in this condition. Five subjects achieved almost perfect counting of lines within a 20-mm test section wherein 157 lines existed.

Then two wavelengths were compared to find a difference threshold. A standard wavelength was selected sufficiently long at 1.2 mm so that the shape of a wave should be conveyed. The speed of a finger to feel the wave was set at 30 mm/sec where usual exploring motion of a finger can often be found. Since the pin amplitude is updated every 4 millisecond, this sampling determines a 0.24 mm Nyquist wavelength at a 30 mm/sec finger speed. The 1.2 mm wavelength is five times longer than this Nyquist limit. Figure 7 illustrates the setup of test sections. In the left section 60 x 40 mm^2, the standard wave length was presented, while in the right section a variable stimulus with a wave length from {1.2, 1.65, 2.1, 2.55, 3.0} mm is randomly selected and presented. Two regions were rendered on a CRT display by only contour lines with a flat inside; the user's finger was rendered by a short horizontal line; the velocity-index moving line segment went up and down on a CRT screen to indicate a trace velocity.

Procedure A constant method was used to measure a difference threshold, where 50 judgements were imposed to every subject and to each of four wave shapes. The shapes of waves are illustrated in Figure 8. The subject was asked to report whether the variable wavelength on the right section was the same as the standard or not, after they had traversed the both sections following the velocity index segment. The subject wore headphones for masking the sound of the display. The number of subjects was six.

Table 3 shows the difference thresholds calculated by the summation method that gives the center of distribution of a difference threshold. According to ANOVA, the difference among subjects was significant ($F^5_{15} = 4.56$, $p = 1.99 \times 10^{-7}$), however the difference among wave shapes was not significant. The difference among subjects was about two-fold (0.42 - 0.90 mm). Existence of this large difference is consistent with other experiments with this display. Subject B marked constant result at a small threshold, while Subject D did at a double of Subject B's data, both of them irrespective of waveforms. The total average, 0.65 mm, is approximately a half of a standard wave length. This causes an observed frequency change of 35-percent decrease (from 25 to 16.2 Hz).

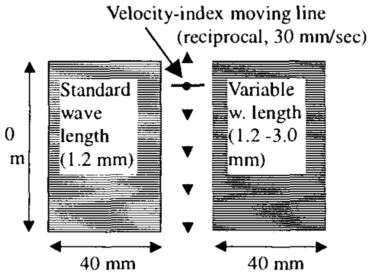
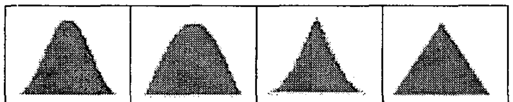


Figure 7. Test sections for measurement of wavelength discrimination.



Sine wave	Absolute sine wave	Inverted absolute sine wave	Triangular wave
(sin(x)+1.0)/2	|sin(x)|	1- |sin(x)|	-

Figure 8. Four waveforms used in the experiment.

Table 3. Difference threshold observed.

Subject / Waveforms	A	B	C	D	E	F	Average among subjects
Sine waves	0.90	0.41	0.38	0.87	0.41	0.63	0.60
Absolute sine waves	0.86	0.41	0.36	0.89	0.45	1.00	0.66
Inverted absolute sine waves	0.77	0.45	0.43	0.89	0.45	0.86	0.64
Triangular waves	1.08	0.41	0.54	0.90	0.36	0.95	0.71
Average among waves	0.90	0.42	0.43	0.89	0.42	0.86	0.65

6.2. Matching test of texture samples

To evaluate presentation quality of the display with more complicated objects, the accuracy of a subject's matching task which mates a real sample with a virtual texture on the display was investigated regarding textures consisting of various spatial frequencies. Figure 9 shows sensation intensity maps of ten texture samples provided for this experiment. These maps were created by the experimenter based on the histogram transformation method [4] introduced by the authors. The real textures are sample patches of wallpaper used for interior decoration. The original data is a height map of a surface measured by a laser displacement meter. The real patch is 80 x 60 mm^2 and it is made of resin fixed on a plastic plate.

Procedure The procedure of a matching test was as follows. The subject was asked to rearrange the order of the real texture samples to that of the virtual textures. The real textures were put in a box prohibiting visual observation. The subject was allowed

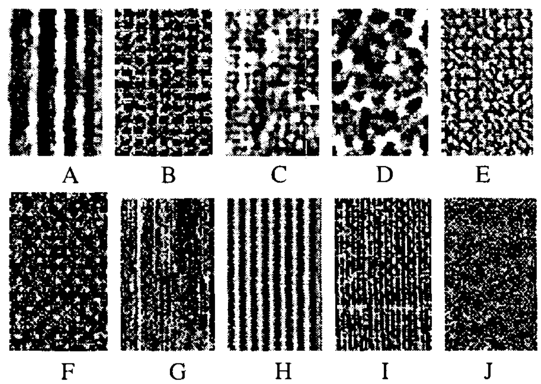


Figure 9. Sensation intensity maps of ten texture samples. (30 x 50 mm^2)

to touch both real and virtual textures arbitrarily without limiting a completion time.

The matching tests were performed in two conditions, five textures (*A,B,C,D,E* in Figure 9) and ten textures (All in Figure 9). Seven subjects, five males and two females of mean age 26, participated in the experiment. Each subject performed on the same condition for four times. After this matching test, the subjects were asked to rate the roughness of the real textures and order them in roughness magnitude.

Table 4 shows the mean of correctly matched pairs. A criterion for the matching test claims that a subject's discrimination is significant at the 5 % level, if the subject matched more than 2.25 pairs in the mean of four trials. In this sense, six out of seven subjects had significant discrimination. As compared with the ten-sample condition, the five-sample condition is easier since the difference between textures is more remarkable. The additional five textures from *F* to *J* have a higher frequency and weak intensity variation close to each other except for *H*. Therefore correct matching did not increase largely in the ten sample condition except for subject F who was the experimenter joined as a subject. The reason the experimenter marked high (complete) score is that the sensation intensity of virtual textures was adjusted by the person. The experimenter adjusted the sensation intensity closest to the sensation observed from the real textures. Thus the person easily restored the sample order.

Table 5 shows confusion matrices of seven subjects and their total for the five-sample condition. The number of

Table 4. Number of correctly matched pairs.

Subject	5 samples	10 samples
A	2.5	4
B	5	7
C	3	1.5
D	4	4.75
E	5	5
F	5	10
G	2.75	4.25
Average	3.89	5.21
(perfect)	(5)	(10)

matching times out of four is indicated individually. The order of textures in the axis index is the common order reported from the entire subject; the left-upper corresponds to a rougher texture. Three subjects (B,E,F) including the experimenter (F) answered a perfectly correct answer. The total result shows that the answers are plotted almost diagonally indicating the difference of the textures are properly conveyed.

The result for the ten-texture condition is depicted in Table 6. The order of textures on the axis is the individual rank reported by themselves. In the last total matrix, the average order was used. As compared to the five sample condition, the amount of dispersion increased for textures with low roughness or high frequency. Except for the perfect data of the experimenter, a salient feature is observed in Subject E. His result of matching was not correct for the right half, however the repetition at each selection was complete. This means the Subject E identified these particular intensities and mated them repeatedly with the same real samples. This misalignment is due to the intensity mapping that was not performed by the subject himself. It is expected that the Subject E would mate the pairs correctly if he adjusted the intensity maps by himself. The difference between intensity distributions of the textures with high spatial frequency is highly subtle which reflects the small difference in the real texture samples.

In this experiment, the entire preparation of intensity adjustment was performed by the experimenter, because the adjustment task would provide a considerable knowledge of each texture sensation to the subject prior to the matching test. In addition, it is of practical value to investigate discrimination of subjects based on the pre-adjusted intensities.

Table 5. Confusion matrices for five-sample matching.

Subject A (Displayed samples \ Real samples)	A	D	C	E	B
A	3	1			
D	1		2	1	
C		2	1	1	
E		1	1	2	
B					4

Subject B (Displayed samples \ Real samples)	A	D	C	E	B
A	4				
D		4			
C			4		
E				4	
B					4

Subject C (Displayed samples \ Real samples)	A	D	C	E	B
A	3	1			
D	1	1	2		
C		2	2		
E				3	1
B				1	3

Subject D (Displayed samples \ Real samples)	A	D	C	E	B
A	4				
D		2	2		
C		2	2		
E				4	
B					4

Subject E (Displayed samples \ Real samples)	A	D	C	E	B
A	4				
D		4			
C			4		
E				4	
B					4

Subject F (Displayed samples \ Real samples)	A	D	C	E	B
A	4				
D		4			
C			4		
E				4	
B					4

Subject G (Displayed samples \ Real samples)	A	D	C	E	B
A	4				
D			3	1	
C		4			
E			1	3	
B					4

Total (Displayed samples \ Real samples)	A	D	C	E	B
A	26	2			
D	2	15	9	2	
C		10	17	1	
E		1	2	24	1
B				1	27

7. Discussion and future work

The new pin-array display (T50-2) for virtual texture information has achieved a great improvement in device control accuracy and thereby sensation intensity resolution as compared to its ancestor. A notable device of this type is the Optacon that is pointed as lacking a stronger pin and larger displacement needed for stimulation of SAs [1]. Our observation agrees with this view in that the Optacon's stimulation is extremely weak for making indentation on a skin surface. By contrast, the T50-2 exerts poking by a much more rigid beam and pin, which effectively causes skin displacements being observed as completely different sensations from those by the Optacon. The force provided by the T50-2's pin appears to exceed the force threshold of SAs (1.3 mN [22]), although a physiological study on the display should maintain this stimulation fires SAs.

However, what considered of more importance is the relation of intensity change during lateral motion to the sense of motion, and to the perception of shape of a surface profile. The intensity change is perceivable at least on stationary contact condition, then whether the spatiotemporal change of burst or its onset forms the

Table 6. Confusion matrices for ten-sample matching.

Subject A (Displayed samples \ Real samples)	A	D	C	H	E	I	B	F	G	J
A	4									
D			3		1					
C		4								
H				3			1			
E			1		3					
I				1			2		1	
B						2		1	1	
F						2				2
G							1	1	2	
J								2		2

Subject B (Displayed samples \ Real samples)	A	D	C	H	E	B	I	F	G	J
A	4									
D		4								
C			4							
H				2		2				
E					4					
B						2	1	1		
I				2			2			
F								1	2	1
G								2	2	
J							1			3

Subject C (Displayed samples \ Real samples)	H	A	D	C	E	I	B	F	G	J
H	2		2							
A	1	3								
D					1				1	2
C		1	2							1
E	1			3						
I				1	2		1			
B					1	2		1		
F								1	2	1
G						2	1	1		
J							2	1	1	

Subject D (Displayed samples \ Real samples)	A	H	D	C	E	I	B	F	G	J
A	4									
H		4								
D			3	1						
C			1	3						
E					2	1		1		
I						1		1	2	
B						1	1	1	1	
F										4
G					1	1	1		1	
J					1		2	1		

Subject E (Displayed samples \ Real samples)	A	D	C	H	E	I	B	F	G	J
A	4									
D		4								
C			4							
H				4						
E					4					
I							4			
B						4				
F										4
G								4		
J									4	

Subject F (Displayed samples \ Real samples)	A	D	C	H	I	E	B	F	J	G
A	4									
D		4								
C			4							
H				4						
I					4					
E						4				
B							4			
F								4		
J									4	
G										4

Subject G (Displayed samples \ Real samples)	A	D	H	C	E	I	B	F	G	J
A	4									
D		1		2	1					
H			4							
C		3		1						
E				1	3					
I						3			1	
B						1	1	2		
F										4
G							2	2		
J							1		3	

Total (Displayed samples \ Real samples)	A	D	C	H	E	I	B	F	G	J
A	27			1						
D		16	6		3				1	2
C	2	12	16							1
H		2		23			3			
E			5	1	20	1		1		
I			1	3	2	10	7	1	4	
B					1	11	8	6	2	
F						2		6	4	16
G					1	3	5	10	9	
J					1	1	5	4	8	9

sensation of texture is the problem. We demonstrated that the vibratory stimulus on a fingerpad with a uniform lattice evoked the sensation of apparent movement during exploration of a virtual surface. Moreover, the imparted haptic image of the surface enabled the subjects to perceive the differences of arrangements of bumps in sample textures. Of course, the vibratory stimulus does not produce a static deformation on a fingerpad that would be produced when a static touch occurs. However, a static touch is not necessarily mandatory in normal active exploration for texture perception. The limited result of the present study has shown the accuracy of the texture perception on this form of virtual haptic presentation.

The individual difference observed in the experiments performed in this study was within possible expectation from other literatures. In a simpler pattern perception task, the subject exhibited a remarkable difference in perceptual performance [23]. The result of wavelength threshold measurement indicated the individual variability was evident whereas the dispersion within subject was small, which suggested inherent perceptual property. Despite this variability, the result of matching suggested that a complex spatial pattern could be delivered to the user, especially to the user with good perception, at sufficiently high accuracy. The individual difference needs to be discussed quantitatively for evaluation of the display, thus the preparation of haptic performance standard is underway.

The presentation of haptic textures should reflect all physical interaction between a human finger and a physical object. We only discussed a variation in height normal to a flat surface. Displaying other interaction related properties—a tangential force related to friction or a normal force perturbation—will be found in further research topics. The explicit model relating a vibratory stimulus and perceived sensation might be a problem addressed in a longer term.

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9. References

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