Haptic texture presentation in a three-dimensional space

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Abstract

This paper describes a new haptic display which imparts surface texture information on a three-dimensional (3D) object to the user's fingertip. First, a pin array type display device, the Texture Display F10, equipped with ten vibratory pins is introduced. The discrimination of texture patterns in a 3D space is investigated using the F10 display. A force feedback device (the PHANToM) is attached to the F10 to provide a repulsive force from the surface during the exploration of a finger on a texture. The difference threshold of a wavelength was measured to investigate the basic performance of the new composite haptic display. The waveform discrimination among three different waves was successfully demonstrated by using the display, which indicated a partial display capability.

Key words: Haptic texture, Pin-array Display, Tactile and Force Feedback

1. Introduction

A haptic texture sensation is evoked through an interaction between a part of a human body, particularly at a finger, and an object's surface which has a relatively small variation in properties. The properties related to haptic sensation consist of micro geometry, stiffness, the coefficient of friction, thermal conductivity and capacity etc. We observe an intricate texture sensation integrated from all these properties. The texture sensation is not clearly elucidated yet, although Hollins et al. [1] addressed a three-dimensional perceptual space based on analysis of limited common objects. There are few researches discussing a texture sensation in a physical 3D space which include free hand motion.

Displays for texture sensation have been developed in a restricted manner since Minsky [1] demonstrated a two dimensional force feedback device for presenting virtual textures. As the device for textures needs to reflect dense and minute changes on a surface in addition to covering fast and broad hand motion, the construction of the device is extremely difficult. Thus far, haptic texture rendering has been implemented with two approaches; producing stimulus distribution directly on a skin surface, and conveying the force perturbed at a textured surface by a force-reflecting device, somewhat indirectly. This approach is discussed within the method to render the shape of 3D objects as producing local perturbation [3, 4]. However, the method is not demonstrated with a quantitative experiment. The former approach is related to the devices that convey information to a handicapped person. An array of vibratory elements has been used for the purpose of transmitting a symbolic code or characters to the back or the fingertip. The device for non-symbolic information in this course started only recently as a novel virtual reality interface.

We have investigated the pin array type display for presenting haptic textures [5]. The display is equipped with fifty pins concentrated within a fingertip area, however the display is too large and heavy to be attached to the finger. A new type device was produced by changing actuators and reducing the number of pins to shrink the size appropriate for finger mount in order to enable 3D exploration of surfaces. The new display was reinforced again by mounting it to a force feedback device to provide it with both capabilities of cutaneous and kinesthetic stimulations. The next two sections describe the pin display which can be attached to the user's finger and allows it free three-dimensional motion. The two succeeding sections state the display with force feedback and its evaluation results.

2. Texture Display F10

The Texture Display F10 (Figure 1) is a compact haptic display which can be attached to the user's fingertip allowing the user three-dimensional exploration of surfaces of a spatial object. The F10 has ten pins driven by bimorph-like piezoelectric actuators (LSD2665X, Megacera, Inc.). The pins are arranged in a matrix of two columns and five rows with a 3-mm spacing as illustrated in Figure 2. The frame and contact pins of the display are fabricated of photo-curing resin. The dimension was determined from the size of the actuator. The weight of the display except the wiring is about 30 grams. The amplitude of each pin is controlled in forty ways in the range up to about 22 microns. Sensation scaling over the amplitude range through the JND method revealed that the adept users could distinguish fifteen levels of sensation intensity. We formed forty levels of output intensity change on the display along with these fifteen levels of sensation intensity.

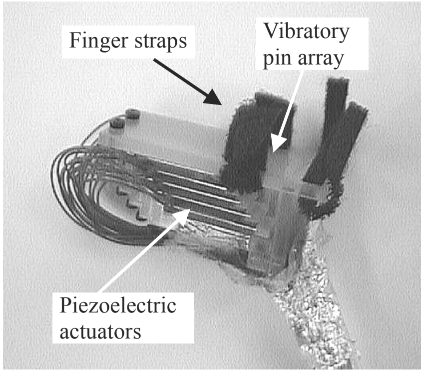


Fig. 1 Texture Display F10. Ten vibratory pins are driven individually by piezoelectric actuators. The F10 is mounted to the index fingertip with finger straps.

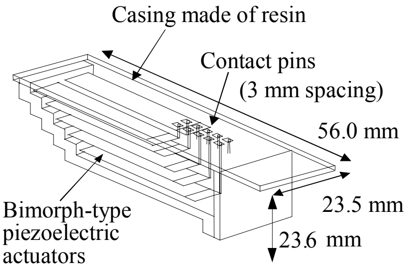
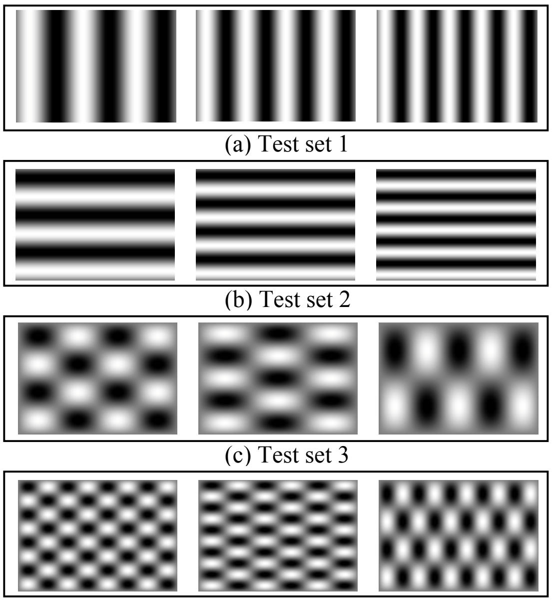


Fig. 2 The frame of Texture Display F10. The frame and contact pins were fabricated of photo-curing resin.

3. Performance test of the F10 display

A discrimination test regarding similar texture patterns was conducted to investigate the presentation quality of the F10 display. The textures provided for the test are shown in Figure 3. The textures have regular intensity distribution in normalized gray scale (ranging between 0.0 to 1.0), which were created by a sinusoidal function or its combination. This gray scale intensity was linearly mapped to the fifteen sensation intensity levels of the F10. The textures were grouped in three sets for three independent sessions. The size of every texture was 120 x 90 mm^2. The wavelengths of the sine functions are 40, 30, and 24 mm for the test set 1 (Figure 3a), and 30, 22.5, and 18 mm for the set 2 (Fig. 3b). For the sets 3 and 4, the wavelengths in the lateral (x-axis) direction were 60, 80, 48 mm, and 30, 40, 24 mm, respectively; for depth (z-axis) direction, 45, 36, 90 mm, and 22.5, 18, 45 mm, respectively.

In the session of the discrimination experiment, four test surfaces were placed in a virtual three-dimensional space as illustrated in Figure 4a. This scene was presented visually to the subject by a monocular 17' CRT screen. Each test surface was mapped by a single texture randomly selected from the same set. The mapped data



(a) Test set 1

(b) Test set 2

(c) Test set 3

(d) Test set 4

Fig. 3 Textures used in the discrimination test. Four sets were used individually in the session.

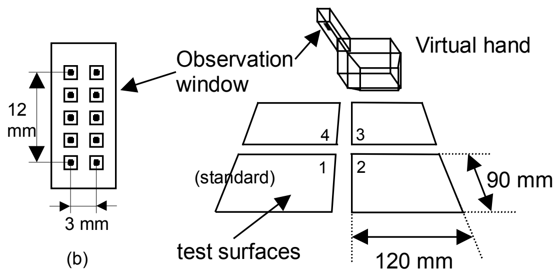


Fig. 4 Test surfaces in a virtual space (a), and pin layout of the virtual observation window at the fingertip (b).

was used only for haptic presentation; the surface was rendered in flat white on the screen.

The hand movement of a subject was measured by the FASTRAK (Polhemus Inc.) three-dimensional sensor. The intensity of pin vibration was determined according to two-dimensional position of the pin inside a test surface. Namely, when the tip of a pin intrudes under a test surface, the point projected orthogonally from the pin tip onto the test surface is located. Then the intensity of the point in the texture is calculated based on the sine function. The intensity data and the display command are transmitted to the device controller PC. The intensity data based on the hand position is updated at 30 Hz.

Two experienced subjects (ZJ, XH) and one inexperienced subject (MZ) performed the experiment putting on the F10 at the index finger and masking

Table 1 Correct answer ratio for texture discrimination

Subject	Set 1	Set 2	Set 3	Set 4
ZJ	100 %	100 %	100 %	100 %
XH	100 %	100 %	100 %	100 %
MZ	100 %	100 %	90 %	70 %

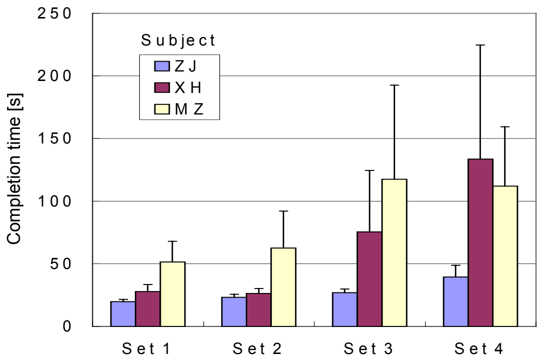


Fig. 5 Completion time for each texture set.

headphones. The subjects were asked to find whether the same texture(s) was on the test surfaces as a standard that was on the left-near surface. Ten judgements for the individual set were imposed to the subject.

Table 1 shows the correct answer ratio of the experiment. The subjects' answer were 100 percent correct except for the subject MZ who had little experience with the F10 display and missed the perfect discrimination for the sets 3 and 4. Two-dimensional discrimination requires an accurate voluntary trace motion and consequent pattern perception, which appears not necessarily easy for a novice user without doing some exercise.

Figure 5 shows the average completion time and SD for ten time trials. Tens of seconds were required inevitably to trace all of the four test surfaces; probably at least five seconds for each surface was necessary to capture the feature. No significant difference is observed between the set 1 and 2, however a remarkable increase of time occurred with sets 3 and 4 except for the subject ZJ. The pattern complexity normally added to the completion time, whereas it was observed only slightly with the subject ZJ since he was the primary system builder and had gained many experiences with the display output.

The interview with the subjects after the experiment collected the following observations. First, the trace movement on an unrestricted (without force feedback) plane did not evoke the parallel sense of exploration on a real physical surface. Since the finger penetrates the test surface, it was difficult to feel the exact position of the surface. Second, the bump shape of the texture which is normally perceived with a reference coordinate or a restricted motion was difficult to perceive with only a cutaneous sensation feedback. The recognition of a shape along the unclear trace path seemed to impose an increased perceptive load to the subjects.

4. Texture Display F10++

A force feedback device (PHANToM 151AG) was attached to the F10 display to provide it with force reflecting capability. Thus the Texture Display F10++ imparts haptic representations of both force and surface characteristics of a 3D object to the user's fingertip. The system in use is shown in Figure 6. The user holds a handle fixed to the F10 display to place his/her index

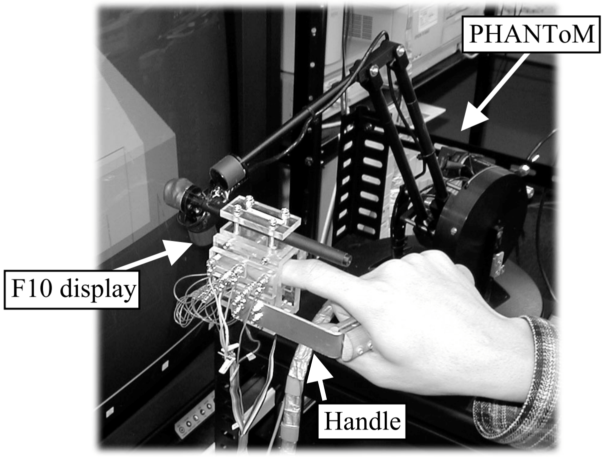


Fig. 6 Texture Display F10++. The F10 texture display is attached to the stylus of the PHANToM so that it can convey texture sensation of object's surface as well as touch reaction force from the virtual object to the user's finger.

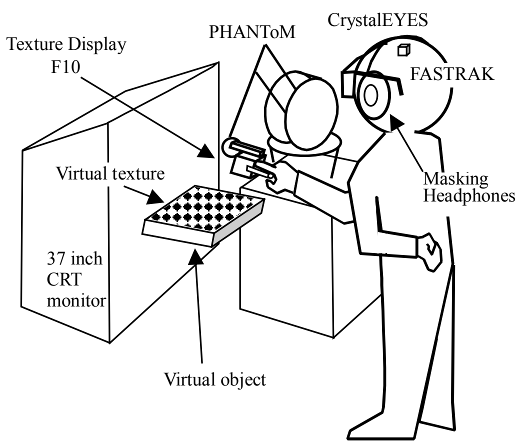


Fig. 7 Texture Display F10++ system setup. The F10 imparts texture information on a virtual object to the user along with force feedback provided by the PHANToM.

fingertip lightly on the pin array. Figure 7 shows the system setup. A virtual object with a texture on its surface is rendered three dimensionally within a workspace of the PHANToM carrying the F10 texture display.

This system is controlled by three PCs: the F10 controller, the PHANToM controller, and the rendering PC. The rendering PC calculates simulation loops that update both graphic and haptic information to be rendered. The rendering PC and F10 controller is connected by a serial communication line which enables data update at the F10 display at 76 Hz. The connection between the PHANToM controller and the rendering PC is established by a shared memory of 500 kilobyte/sec bandwidth. The position of the user's finger is reported from the PHANToM controller at 1 kHz, whereby the rendering PC updates texture information for the F10. The force feedback calculation is performed locally at the PHANToM controller that has a copy of object's data structure. Visual rendering at the rendering PC runs with a separated thread which depicts virtual objects at 18 Hz to the 37 inch CRT. (Stereo graphic images 800x600 dot are provided to each eye at 60 Hz through CrystalEYES PC.)

5. Evaluation of the F10++ system

5.1 Difference threshold of wavelength

The resolution of texture presentation was investigated by a psychophysical experiment. The differential threshold of wavelength was measured by using the constant method where five textures with different wavelengths were randomly presented to be compared with a standard stimulus. As the standard stimulus, a texture with a 1.2 mm interval, or wavelength, was used since it was around the minimum length as discussed later. Variable stimuli discriminated had wavelengths from 1.2, 1.6, 2.0, 2.4, and 2.8 mm. The standard stimulus and the variable stimulus were presented randomly on either the region A or B in Figure 8. The shape of wave used in the experiment was a clipped sinusoid indicated in Figure 9(a) where the intensity image and its cross section are depicted. At the peak of the intensity, the largest (level 15) stimulus was produced.

Five subjects (26 years old on average) performed the experiment. In order to control the condition, a velocity-index moving line was presented to indicate the trace velocity of 30 mm/sec. The subject mounted the Texture Display F10 to the right index finger, and traced on the both regions (standard/variable) following the velocity index. The both regions were painted in flat white with a separating central line and contour lines in black. One out of the five different wavelengths was randomly selected and presented paired with the standard.

The subject was asked to report within 60 seconds whether the pair had a same wavelength or not. Ten

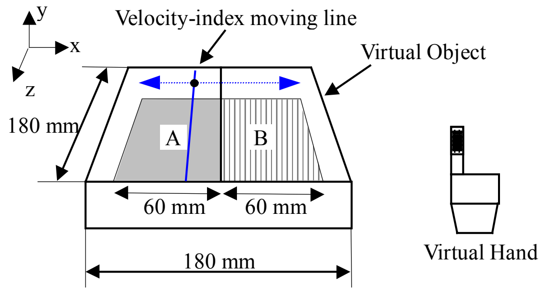


Fig. 8 Virtual surfaces provided for the discrimination of wave-lengths. Textures with different wavelengths were presented in the regions A and B 60 mm wide.

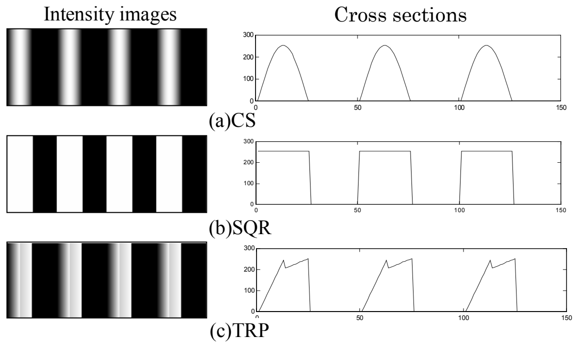


Fig. 9 Texture used in the experiment. (a) clipped sinusoidal, (b)square, and (c)trapezoidal wave forms.

trials form one session; each subject performed five sessions. As a reference, additional five sessions with no force feedback were performed as well. In this case, a repulsive force from the surface was not presented, whereas the weight of the F10 display and its handle was compensated to zero by adding a lifting force by the PHANToM. The force feedback limiting the finger from intruding into the object was added by 0.9 N/mm in proportion to the depth of intrusion at the center of the observation window, in the direction of a surface normal. A virtual hand was rendered with wire frames at the position shifted from the subject's own hand by about 100 mm to the screen. The orientation of the virtual hand was fixed to the z-axis (depth).

Figure 10 shows the upper difference threshold of the five subjects. The average among subjects was 0.48 mm in the case with force feedback, and 0.54 mm without force feedback. Regarding the sampling of the waveform at 76 Hz of the system update rate, the Nyquist wavelength is 0.79 mm when the subject's finger moves at 30 mm/sec. The standard wave length, 1.2 mm, is 1.52

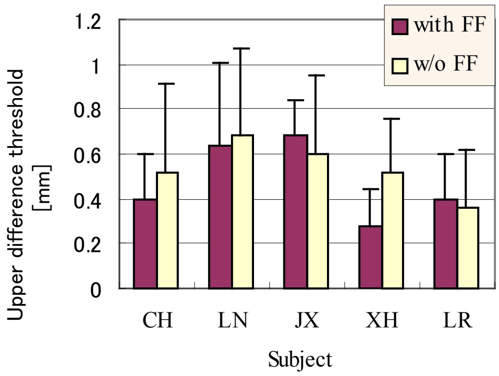
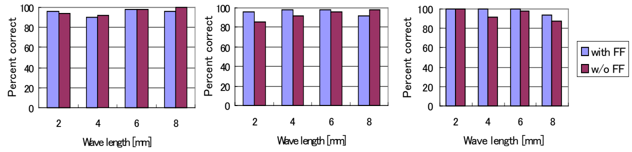


Fig. 10 Upper difference threshold (mean/std dev) calculated from the data by the summation method regarding the clipped sinusoidal waveform of 1.2 mm.



Discrimination between CS and SQR

Discrimination between CS and TRP

Discrimination between SQR and TRP

Fig. 11 Correct answer ratio for waveform discrimination.

times as long as the Nyquist wave length, and it produces a 25 Hz signal when it is traced at 30 mm/sec. If the wavelength of a variable stimulus is 1.68 mm, it produces a 17.9 Hz signal which is 7 Hz smaller than that of the standard. The result of the experiment shows that this difference was noticeable by 50 % rate on average.

The difference between subjects appears to be significant, although the difference between "with force feedback" and "without force feedback" is not significant. The reason the force feedback did not affect the difference threshold is considered to be the short and straight path required to complete this task. This means that fluctuation in the tracing trajectory did not act as a crucial hindrance to perception of the spatial frequency of the ridges.

5.2. Discrimination of waveforms

Discrimination of waveforms was investigated with respect to three waveform pairs: clipped sinusoid (CS)/square (SQR), CS/trapezoid (TRP), and SQR/TRP. The square and trapezoidal waveforms are depicted in Figure 9(b) and (c), respectively. The wavelength was varied from 8 mm to 2 mm with a 2 mm decrease. The same setup as the previous experiment was used except for the waveforms and the velocity-index line which was not indicated allowing the subject arbitrary comparison. Five subjects performed the experiment first without force feedback, then with force feedback. Paired identification test was used for analysis. The pair presented on the virtual object was randomly selected from CS/CS, CS/SQR, and SQR/SQR, and randomly placed on either of the regions in the case of CS/SQR discrimination. The duration before the decision whether the paired textures were identical or not was limited to 60 seconds. Ten decisions formed one session.

Figure 11 shows correct answer ratios averaged among subjects. No remarkable difference was observed over the three pairs, wavelengths, and force feedback modes. The overall average of correct answer ratio was 95.5 %. This figure indicates that the difference between three wave shapes was perceived clearly by the subjects. According to the interview with the subjects after these experiments, they could observe the difference even between the sensations occurred in tracing leftward and rightward in the case of the TRP waveform. Namely, the asymmetry of TRP's side inclinations was conveyed to the user’s tactile sensation.

The force feedback restricting the finger on the object’s surface provided an extremely natural feel of exploration as compared to the case lacks it. However, the correct answer ratio obtained here suggests that the force feedback did not work effectively in this experiment. Nevertheless, we believe there are reasons that helped the condition without a force feedback to achieve the correct discrimination. That is, the vibratory stimulation was presented regardless of the position as long as the finger penetrated under the surface. In addition, the trajectory of the subject’s finger was stable because the weight of the F10 display was cancelled by the PHANToM; and the orientation angle of the virtual hand was fixed. Moreover, the patterns discriminated were simple for capturing. We consider that this good perception will not persist if the texture pattern does not exist on a flat pane and contains a more complicated variation.

6. Conclusion and future work

A three dimensional haptic texturing in a virtual space is a challenging issue since it requires both cutaneous and kinesthetic sensations being evoked. The Texture Display F10 permitted to produce a stimulus distribution on a fingerpad successfully, which is related only to cutaneous sensation. Although it allows the subject to discriminate patterns after he got accustomed to the device, the sense of feeling a surface was not natural without a constraint force. This mode of haptic stimulation would be more suited to the presentation of a volume data which does not involve a rigid contact.

The subjective impression of a surface texture was greatly improved in the case of the F10++ display which presents both cutaneous and kinesthetic sensations. It was demonstrated that both the force feedback and the stimulus intensity distribution within a finger surface were crucial for three-dimensional haptic texturing. Although not discussed in the present study, the use of force perturbation in accordance with the texture profile will provide another control mode of interest on this display system. Further investigation of presentation accuracy with broader conditions would be involved in the course of clarifying the feature of this haptic texture display system.

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