Vol. 37 No. 3 Transactions of Information Processing Society of Japan Mar. 1996

Regular Paper

Tactile Display Presenting a Surface Texture Sensation

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Along with force sensations, tactile sensations originating in the surface textures of physical objects are principal clues enabling users of a virtual environment to perceive those objects. We have developed a tactile display that depicts tactile surface textures while a user is exploring a virtual object surface with his or her fingertip. The display imparts a vibratory stimulus to the fingertip, which is placed in contact with a vibrating tactor matrix. A piezoelectric actuator drives the individual tactors in accordance with both the finger movement and the surface texture being traced. Spatiotemporal display control schemes for presenting the fundamental surface texture elements were examined. The duration of the vibratory stimulus was experimentally optimized to simulate the adaptation process in the cutaneous sensation. For some edge shapes, a method based on augmented duration was investigated, in which afterimages of boundary edges are emphasized. The spatial resolution of the display was measured, with a number of lines presented both perpendicular and parallel to the axis of the finger. The ability of users to discriminate a mean density was also measured, with the texture presented by random dots to produce a pseudo-gray scale.

1. Introduction

Display systems that simulate somatic sensation have been developed in various configurations for the purpose of teleoperation since the 1960s. Recently, the emerging need for such devices in virtual reality technology has again given impetus to research on these haptic feedback devices. When the user of such a system interacts with physical objects in virtual space, two kinds of sensation must be reflected: the sense of force and the mechanoreception. The sense of force is excited when the motion of limbs is limited in speed or in position. In this case, a small number of force vectors that have a relatively large range is added to the limbs; these vectors should be exerted by a mechanical device called a force reflection device. The task of handling and establishing an object in an environment that causes interactions or constraints in motion between objects is facilitated by using such a force reflection device.

However, a force feedback device alone is insufficient when the user needs to examine details of object's properties, such as its shape and surface texture, by tactile sensation. The mechanoreception, or tactile sensation, by which the object's shape and surface texture are perceived, is also indispensable for augmenting the sense of presence of the displayed object. In addition to the deep sensation presented by the force feedback devices, the cutaneous sensation plays an important role, particularly in ensuring a human operator's sensor modality, which provides diverse cognitive cues, as in an ordinary environment.

Tactile sensations related to an object's surface texture depend on many aspects of the physical properties of the object surface, such as the microscopic geometry, coefficient of friction, kinetic elasticity, and thermal conductivity. The first study of such tactile sensations related to surface texture is said to have been carried out by Katz (1925)[1)], who listed many issues to be resolved. Recently, Hollins (1993)[2)] proposed a perceptual space in which surface texture properties could be discriminated in a three-dimensional model. To present a virtual texture in tactile space, the physical properties of a surface should be well-imitated in the above senses; however, it is extremely difficult to reproduce all of these properties. Therefore, an effective scheme in which tactile sensations can be stimulated according to the purpose has been the subject of considerable interest in the research area[3)].

One solution to the above difficulty is to reduce the contact dimension to a single point of exploration within the textured surface. Devices based on this idea were developed by Minsky (1990)[4)] and by Akamatsu (1994)[5)]; they produced surface texture sensations as measured at a single point, not representing it to the finger as the original two-dimensional surface contacted in a plane. This approach contributes to the simplicity of a device; how-

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ever, some intrinsic properties of spatially distributed cutaneous sensations are disregarded.

Vibratory stimuli, produced by mechanical devices have been investigated since the 1960s as effective means of transmitting information to the blind$^{6)\sim8)}$. The Optacon is a typical device that employs a vibratory stimulus to convert optical information into tactile sensations$^{9),10)}$. It was first developed by Linvill (1966), and became commercially available in 1971. Several display control modes were tested in order to represent letters on the Optacon by Craig (1981)$^{11)}$. Since the principal use of the Optacon was as a reading aid for the blind, the method of replicating a texture sensation was not a major consideration in its development.

We have developed a vibratory tactile display for presenting sensations related to the texture of object surfaces. This device has vibrating tactors similar to those of the Optacon; however, the individual tactors can be controlled with much greater flexibility in generating spatiotemporal patterns. The basic characteristics of the presented sensations were investigated experimentally, and control schemes for representing textures with simple edges and random dots were discussed.

2. Mechanism of a Vibratory Tactile Display

A prototype system for vibratory tactile display is shown in **Fig. 1**. A vibratory stimulus is imparted to the index fingerpad placed on a display window, measuring 10 × 20 mm^2, at the top of the display box. The display window is a matrix of "tactors," display elements made of piano wires 0.5 mm in diameter. Within a matrix, 5 × 10 tactors are arranged with a 2 mm pitch to form a rectangular window (**Fig. 2**). Each tactor is driven at 250 Hz by a piezoelectric actuator attached to a magnifying mechanism to yield an amplitude of about 80 microns. This frequency of the vibration was adopted because it is near the highest sensitivity, according to the equal sensation magnitude curve measured by Verrillo$^{6)}$. The user of the display explores the surface of a virtual object with his/her fingertip fixed on the window, moving his/her hand within a two-dimensional plane together with the display box. Data on the position of the user's finger, compatible with the position of the display, are tracked by a mouse attached to the display box. On the basis of the position data, which is equivalent to the relative finger movement within a presented virtual texture, a personal computer controls the spatiotemporal patterns of the tactor vibration. In addition, the computer also performs visual rendering on a CRT display, showing CG images of both the finger and virtual textures.

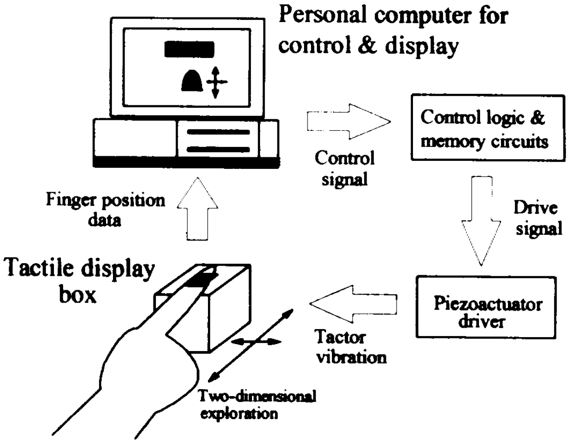

Fig. 1 Tactile display system.

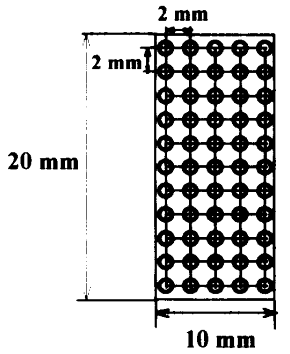

Fig. 2 Display window of a tactor matrix with a 2 mm pitch.

3. Stimulus Generation Schemes

The term "surface texture" is used here in a tactile sense as a geometrical profile of an uneven plane that contains slight differences in levels, or protrusions, that create inherent tactile stimuli when a fingertip is drawn across the plane. Other properties of a surface that would contribute to tactile sensation, such as frictional, kinetic, and thermal characteristics, are not represented, although they cannot be eliminated completely from our physical embodiment of the display. Thus, in the first step, we treat the texture as a binary-valued two-dimensional plane; the plane has spatially extended "high" and "low" portions, like a binary picture image. Given the simplified surface, a basic and natural mapping from the texture to the display window, where a set of tactors creates a stimulus, is one which the tactors within high portions on the texture generate vibratory stimuli in the display window, and the tactors within low portions stop vibrating. We incorporate this fundamental mapping in the display control as its static phase. This dynamic mapping for realizing temporal properties of tactile sensation has many alternatives, which will be discussed below.

3.1 Duration of a Stimulus for Reproducing an Adaptation Process

Tactile sensations from the surface texture of an object are usually obtained while the surface is being explored with the fingertips; minute protrusions in the texture create two-dimensionally varying stimuli during the exploration. In examining a surface, we often stop and restart the finger movement, not always intentionally, at places where a process of sensor adaptation occurs. When the movement stops, the sensation of touching a surface gradually decreases. The decay time of the adaptation process varies depending on the kinds of mechanoreceptors used, ranging from a few milliseconds to tens of seconds. (There are four different mechanoreceptors in the human skin, and they have inherent decay time distributions.) The decay time of the vibration receptor is very short, a few milliseconds, and that of the touch receptor ranges from about fifty to five-hundred milliseconds14).

Without taking account of this sensory adaptation, the display does not give a good representation of the tactual texture sensation, because, if the display continuously activates the raised portion of the texture even after the finger stops moving, the stimulus will be too intense to simulate static touching, and will also cause unwanted paralysis of cutaneous sensation. On the other hand, if the stimulus ceases as soon as the finger stops moving, the impression of the surface texture becomes very queer, as though the contact with the texture suddenly vanished at the moment the finger stopped moving.

To incorporate this adaptation process of cutaneous sensation into the tactile display's control of stimulus production, the intensity of the generated vibration must be regulated so that it follows a temporal transition. However, the amplitude of vibration of individual tactors cannot be regulated on this display, because the analog circuits needed to alter the driving voltages would be too large-scale to implement. Consequently, we have selected a method that gives an appropriate duration to each tactor after the finger exploration stops. By specifying an appropriate duration of vibration, equivalent to a diminishing sensation, we were able to simulate the adaptation process reasonably well.

Experiment

The effective duration was measured using the method of adjustment wherein a single line edge was presented on the display perpendicular to the finger axis. In the experiment, a standard stimulus was provided by a fixed fine wire 0.5 mm in diameter on the side of the display at the same height as the display plane. On the display, while the display box was moving, and the virtual line edge was within the display window, just a single row of tactors was excited, to avoid the cessation of the vibratory stimulus. (This assumed the virtual edge width to be 2 mm; however, it introduced a little uncertainty as to the position of the edge, rather than to its extended width of 2 mm.)

Subjects were instructed to touch and explore the standard wire with the right index finger about five times before each testing session. Each subject rested the index finger horizontally on the display window while holding the display box with the other fingers. A vibratory stimulus was then generated on the display window while the subject was exploring the virtual wire. During the experiment, the subject wore headphones, through which a white noise was presented to reduce auditory cues and distraction due to the sound of the display. After the finger movement stopped, the stimulus was extended by the initial duration, which was randomly set each time within either the ranges of [0, 10] or [40, 50] milliseconds for ascending and descending series, respectively. The subject was allowed to change the duration by means of specially allocated adjustment keys set to 1, 3, and 6 msec, until he/she judged that the similarity between the displayed wire and the real one was maximized. Each experiment for a subject consisted of twenty trials, ten for each series. The four subjects, who included a female, were in their 20s and 30s; two were inexperienced, having had only a few rehearsals before the experiment.

Results

Figure 3 shows the adjusted mean durations of four subjects for each series of adjustment di-

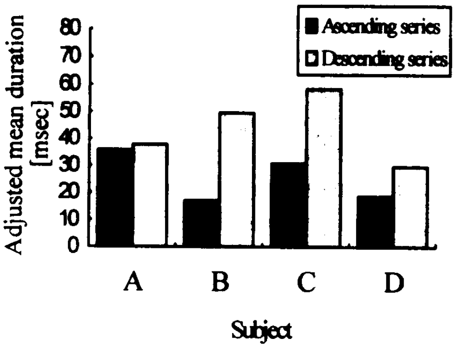

Fig. 3 Adjusted duration for a virtual wire.

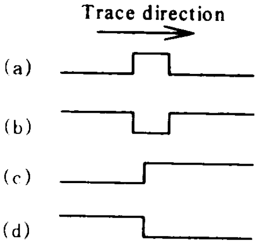

Fig. 4 Fundamental texture elements of a line edge.

rections. Analysis of the variance reveals significance at the .01 level in subject differences (F = 20.9, df = 3/72), series effects (F = 98.4, df = 1/72), and the subjects by series interaction (F = 14.8, df = 3/72). Subjects B and C were inexperienced, having had only a few rehearsals, and their results exhibited large mean duration differences between ascending and descending series. It seems that they did not perceive the results of their own changes precisely in the case of the descending series, since they sometimes increased the duration reversely. However, in the ascending series, the adjusted mean durations were not so small as to indicate that the subjects were completely unaware of the duration.

Consequently it appears that a duration not less than about ten milliseconds has the effect of producing a gradually vanishing afterimage in the user's finger. One possible choice for the duration implemented in the display is the average duration of the ascending series for experienced and inexperienced users. In this experiment, the average time was 25.6 msec. In general, the subjective impression was fairly good when the duration was appropriately selected. Support for this value of the duration is provided by the fact that the time threshold of tactile sensation is said to be about 27 milliseconds.

3.2 Representation Methods for Other Simple Edges

To implement fundamental display elements for representing rugged surface textures, we examined other simple edge patterns, illustrated in **Fig. 4**, that included protrusions and retractions, or recesses, wider than a single wire. With regard to protrusions over 2 millimeters wide, such as that in Fig. 4 (a), it was not appropriate to assign simply vibrating tactors to protruding regions. This is because the edges at the boundary between high and low regions were blurred as a result of the increased width of the high region; the sensed image around the edge was observed as a gentle slope rather than a definite line. The augmented vibration area gave too much stimulus for the user to be able to find the boundary between the excited region and the unexcited region; this resulted in a kind of masking.

An alternative assignment of vibrating tactors to avoid this diffusion of the edge image was examined. The tactor vibration was limited to a row at the boundary edges, with the vibration of tactors inside the boundary edges suppressed. However, the method was not effective for representing the protruding shape, since it produced a hollow impression between the edges; the image was rather similar to Fig. 4 (b) when the finger was exactly on the protrusion.

The same was true in the cases of Figs. 4 (c) and 4 (d). Eventually, if all tactors within the high region were excited, the impression given by the region was of a gently sloped swelling with some sense of friction, rather than of a plate with a sharply defined edge. Moreover, if only the tactor row at the edge was excited, of course, a single edge but no high plate region was perceived.

The above discussion indicates the need for stimulus intensity distribution control, in which the stimulus intensity, or density, varies across the edge, taking account of the directions of low-to-high or high-to-low region changes. At present, however, the vibration intensity is basically constant in this device. There should be an alternative scheme of making a spatial or temporal intensity gradient. A temporal modulation to alter the intensity as a time average was tentatively examined. To obtain an intensity gradient, the basic vibration at 250 Hz was reduced by between 10% and 90%, within a 25 Hz modulation interval. The result of this scheme, however, was not necessarily effective, since the additional frequency spectrum of 25 Hz caused another quite different sensation. The new stimulus exceeded the decrease in the ingredients of the basic frequency stimulus and produced the impression of a discontinuous change in the stimulus intensity.

3.3 Augmented Duration Method for Edge Representation

Another method for representing edges is to use a different duration after the finger stops moving. Since an edge is localized, a longer duration than that set inside the protruding area helps to highlight the edge, especially when the finger stops on the edge. In this scheme, an edge is not clearly represented while the finger is moving; however, we think that the impression of an edge obtained after the finger stops moving exceeds that obtained while the finger is moving. The most appropriate duration for the edges was measured by the method of adjustment.

Experiment

A 20 × 20 mm virtual plate was assumed and displayed on a CRT as a square region. Subjects traced the virtual plate one-dimensionally, back and forth in parallel to the finger axis, onto the plate and off the plate, stopping on both edges. After the finger exploration stopped, the vibration of all the tactors on the plate was extended by the same least duration of 10 msec; this duration was around the minimum that could avoid giving the impression of an inadequate vanishing image and ensure a contrast in duration to edges with a longer duration. The tactors on the rising edge, which had just climbed onto the plate, were assigned a constant duration of 30 msec; this was approximately the mean time selected in the previous experiment. This edge did not require longer than the standard duration, since the part of the finger that had not reached the plate was free from stimulus and then encountered the excited region, which produced a high contrast in stimulus at the boundary. On the falling edge, where the finger had just received a vibration stimulus, a longer duration was needed to emphasize the edge to the finger, which had lower sensitivity to the vibration since it had been subjected to the vibrations of the virtual plate.

Thus, we examined the preferable duration only for the falling edge. Before each session of twenty trials, ten for both ascending and descending series, subjects were asked to trace a standard plastic plate. The initial duration was set randomly in either the ranges of [0, 20] or [200, 220] milliseconds for ascending and descending series, respectively. The adjustment keys used to change the duration were set to ±3, ±10, and ±30. Two experienced male subjects in their 20s and 30s performed the experiment with the masking headphones.

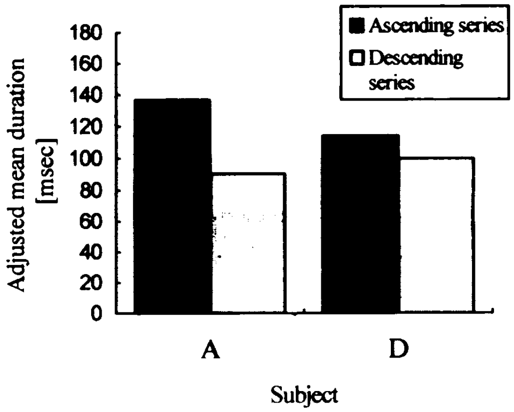

Fig. 5 Adjusted duration for a falling edge.

Results

Figure 5 shows the mean durations measured for the two subjects. The result indicates that the subject difference was not significant; a series effect was significant at the .01 level (F = 17.5, df = 1/36); the subjects by series interaction was significant at the .05 level (F = 5.0, df = 1/36). The mean durations of the ascending and descending series were 125.5 ms and 95.0, respectively. Both series had crossed mean values; the ascending series had a higher mean value, although it started from a smaller initial value. This effect may be attributed to the error of habituation, which postpones the transition point of response. A tentative standard duration for a falling edge seems to be the series mean of 115 ms. This value was sufficient for generating the impression of an edge and a protrusion for one of the authors who performed the experiment.

3.4 Spatial Resolution

Spatial resolution is a common index frequently referred to in describing the performance of a display device. The one-dimensional resolution of the tactile display was examined in both the horizontal and vertical directions. Although the resolution specified by the number of lines to be counted by finger exploration does not directly describe the overall presentation power with regard to the tactually perceivable surface texture, it seems to yield suggestive information for extensive discussion of the rela-

Table 1 Line pitches selected in thirteen ways.

Pitches of lines (mm)						
0.8	1.2	1.6	2.0	2.4	2.8	4.0
6.0	8.0	12.0	16.0	20.0	24.0	

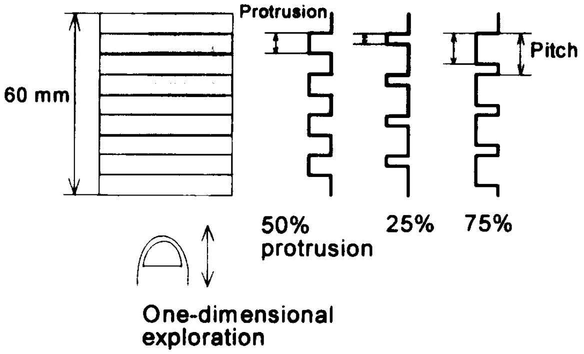

Fig. 6 One-dimensional virtual edges perpendicular to the finger axis.

tion between this device and tactile sensation.

Method

Several lines of virtual protrusions were displayed both perpendicular and parallel to the finger axis within a test region 60 mm in length, where a visual image of protrusions was suppressed and only a boundary frame was displayed. The line pitch was changed in thirteen cases, as shown in **Table 1**, and the ratio of the protrusion width to the pitch was variously set to 25%, 50%, and 75%, as shown in **Fig. 6** for perpendicular allocation. Subjects were asked to report the number of lines after examining the region until they were ready to answer. The experiment was repeated ten times for each pitch, selected from the pitch set in random order. The data were obtained from three male subjects in their twenties.

Results

The results are shown in **Figs. 7** and **8** for the perpendicular and parallel cases, respectively, averaged across subjects. The ordinate of the figures is the ratio of correct answers, and the abscissa is the pitch of the lines. The ratio of correct answers includes responses within plus or minus twenty percent, since counting lines by exploring with one's fingertip is rather difficult, and inevitably leads to some miscounting, even if it is done on a real surface with physically engraved lines. (Beforehand, we conducted a preliminary experiment to estimate people's ability to count lines with their fingertips on samples with real carved lines produced by a rapid photo-forming machine. The samples were made of plastic, and shaped to realize the edge patterns shown in Fig. 6, where the height of edges was 0.5 mm; the height actually had no significant effect on the discrimination of lines. Thereby, correct counting of lines was shown to require at least a pitch of about 4 to 6 mm.)

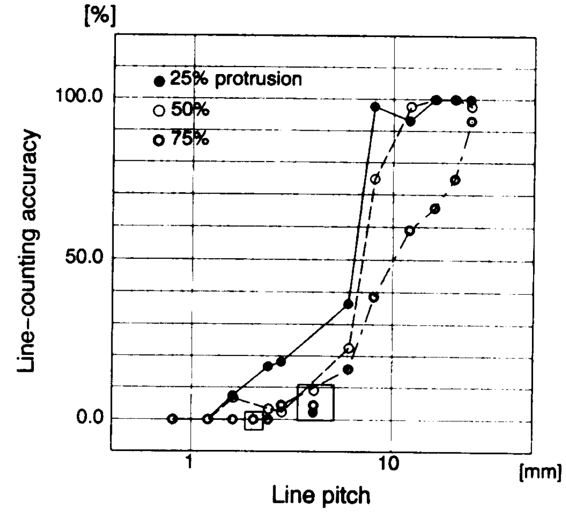

Fig. 7 Line-counting accuracy, for lines presented perpendicular to the finger axis.

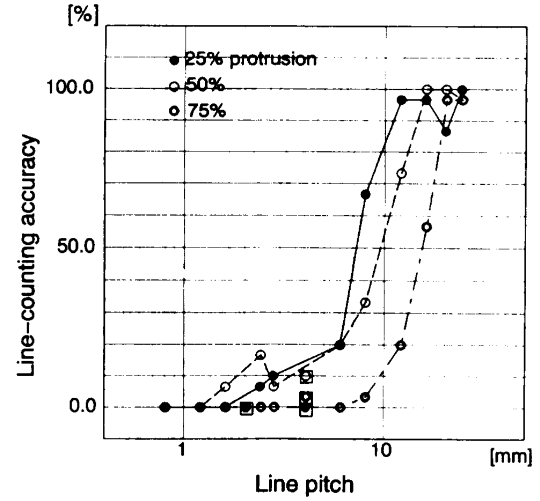

Fig. 8 Line-counting accuracy, for lines presented parallel to the finger axis.

In the case of the display, the ratio of correct answers reached over seventy-five percent at a pitch of 8 mm, except in of the 75% protrusion case (Fig. 7). This value seems acceptable, taking account of the display's tactor pitch of 2 mm. In the case of the 75% protrusion ratio, it was more difficult to discriminate the low parts between lines. Therefore, the counting accu-

(U: 25% L: 75%) (U: 40% L: 60%) (U: 50% L: 50%)

Fig. 9 Sample textures with 50% mean density.

racy was slow to rise.

The data points enclosed in an open square at the 2 and 4 mm pitches are abnormal values, since the pitches are equivalent to multiples of the display tactor pitch of 2 mm. Displaying the lines at these singular pitches produced a synchronized vibration of all tactors, which created a sensation very different from that usually experienced through tracing a physical surface.

Figure 8 shows the result of the experiment in which the lines were presented parallel to the finger axis. In this case, the finger exploration movement was valid only in the lateral direction. A general difference from the data obtained for perpendicular lines is the lower counting accuracy for almost all line pitches; the decrease in the accuracy for an eight-millimeter pitch is remarkable. In the parallel line case, a pitch of at least twelve millimeters was required to achieve approximately correct line counting for a 25% protrusion ratio, while an eight-millimeter pitch was sufficient for the lines displayed perpendicularly.

3.5 Discrimination of Texture Density

Natural surface textures in general produce stimuli with multiple magnitudes, equivalent to the gradations of a gray scale in a visual image, as well as stimuli with almost binary magnitudes, for the sharp edges described in the above sections. In order to represent multi-level textures, it is first necessary to determine the number of levels that can be displayed on the tactile display. Here, we assume that the multi-level textures are approximated by a binary dot image. This assumption leads to some difficulty in smoothness of presentation; however, it has the great merit of removing much of the control load of the display. The perceivable difference in density of binary random dots was examined by presenting a pair of regions that had different mean densities.

(U: 15% L: 65%) (U: 30% L: 50%) (U: 40% L: 40%)

Fig. 10 Sample textures with 40% mean density.

(U: 10% L: 50%) (U: 20% L: 40%) (U: 30% L: 30%)

Fig. 11 Sample textures with 30% mean density.

Experiment

Some sample textures that were used in the experiment are shown in **Figs. 9–11**. The size of the texture area was 30 × 60 mm; and the dot size was 2 × 2 mm. A black dot in the texture excited the display pin vibration. The texture area was divided vertically into two regions to provide a difference in density between the upper and lower sides by percentages ranging from −50% to +50%. In Fig. 9, all three textures have the same mean density of black dots, 50%; in Figs. 10 and 11, the mean densities are 40% and 30%, respectively. Subjects were requested to judge which side was more dense after exploring both sides. The visual display showed the rectangular wire frame of the area and a cursor indicating the finger position. A texture with a particular density difference was presented ten times in one session. Since there were eleven density differences, presented ten times each, 110 trials were needed for each of the three mean densities, 50%, 40%, and 30%. Subjects wore the headphones as in the previous experiments. This experiment was conducted by four subjects in their 20s and 30s, including a female.

Results

Figure 12 shows the ratio of correct answers

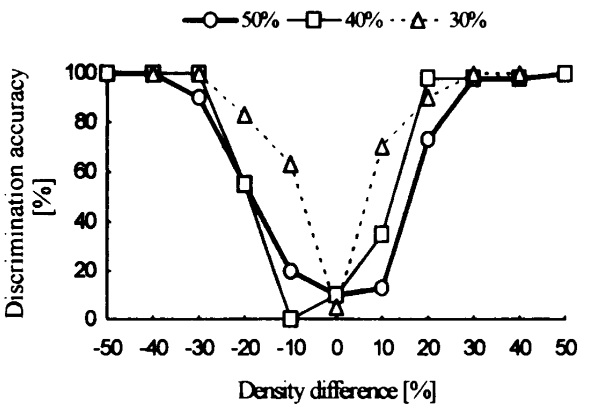

Fig. 12 Discrimination accuracy vs. density difference.

as a function of the density difference between the upper and lower sides. The ratio in the ordinate indicates the average data for the four subjects. Plotted circles correspond to the case in which the mean density was 50%, squares to 40%, and triangles to 30%, respectively. For 50% and 40% mean density textures, a 30% difference in both sides gives almost complete discrimination, and a difference of about 20% is a transition point. The lower mean density of 30% showed improved accuracy of discrimination, with a 10% difference being perceived much more accurately than in the other two cases.

4. Discussion

Line edges within a plane are among the surface texture elements that people most commonly sense with their fingertips. We have referred to the possibility of using the duration of a stimulus to represent the shape of an edge. We think that replicating the afterimage of a vanishing sensation increases the similarity of a touch impression to that produced by a real edge, and it can be well simulated by adding an appropriate stimulus duration after the finger stops moving. Moreover, a stimulus control that terminates the tactor vibration after the duration is an appropriate scheme for avoiding sensation paralysis. (The Optacon does not employ such a scheme, since its purpose is not to render a surface texture image but to realize distinctive translation of symbolic letters of printed matter.)

A single line edge and a boundary edge of a virtual plate were represented fairly well by the augmented duration method, which uses a diminishing stimulus to create the impression of a boundary edge after a person's finger stops moving across the edge. This technique of controlling the termination of the tactor vibration is a good alternative, especially when the task of exploring a surface lasts for a long time, as in design work, which would cause severe fatigue in the user's tactile sensation. (In the above experiments, we divided the experiment into short sessions, because fatigue in the cutaneous sensation appeared strongly in long sessions of about twenty trials or more.)

Inside the region of a plate bounded by the edges, the tactile sensation experienced by the user was a sort of a friction, although the display did not produce a shearing force. It may be an illusion, perhaps caused by people's habituation to experiencing tactile sensations when making tracing movements, which ordinarily produce a shearing force. The lack of shearing sensation is also compensated for by an apparent movement that can be sensed as long as the surface has any variation in its geometrical state.

Another principal element of a texture is the periodical variation of a surface. Repetition of a line edge was presented successfully by the display in the sense that it created a wave-like feeling, although it was as difficult to count the simulated lines as to count real lines. We should note that the line-counting test for pitches of under four millimeters was discussed along with the test for other pitches in the section on spatial resolution measurement. Taking account of the Nyquist criterion, however, this range of spatial frequency must be displayed inaccurately. Including the range, a further analysis of the display spectrum is needed from the viewpoint of tactile sensation.

The measured spatial resolution as a counted value was not necessarily high enough, partly because of the display tactor pitch of 2 mm. Regarding the spatial sensitivity of a fingertip, the spatial resolution has been measured by Weinstein (1968)[12] and others, and referred to as ranging from 2 to 4 mm for a simultaneous spatial threshold, or a two-point limen. In this sense, the display tactor pitch might be adequate. However, this value of a spatial threshold is valid only when the stimuli are statically provided. The successive spatial threshold, when two stimuli are presented sequentially, is reported to be of the order of 10 to 30 times smaller (Loomis, 1978)[13]. Accordingly, the presentation bandwidth of the display, in which the surface image is dynamically produced, is considered to be restricted by its tactor pitch. Display control needs more extended schemes to surmount this hardware limitation.

Tactile discrimination of the mean intensity of random dots was very close to visual discrimination, although we cannot show all the texture patterns here owing to the space limitation. This was an unexpected result, in contrast to the result of the spatial resolution experiment, and leaves one possibility in presenting a gray-scale image in this display form. Future work to augment the display capacity also includes control of the intensity, which could be partially realized by hardware for controlling the frequency and the phase of vibration. According to our tentative observations, tactile sensitivity to frequency change and phase offset is acute. These parameters will surely improve the rendering versatility of the display, especially in the representation of gray-scale images.

5. Conclusion

The results of the research are summarized as follows:

(1) Control schemes for representing a surface texture were proposed for a vibratory tactile display developed by the authors.

(2) Tactile impressions of edge shapes were satisfactorily simulated by adding an appropriate stimulus duration to take account of the adaptation process of the cutaneous sensation.

(3) An appropriate duration for the adaptation was 25.6 ms for a line edge. On the other hand, an augmented duration of about 115 ms was obtained for the falling edge of a plate.

(4) Stopping the vibratory stimulus while the finger remained motionless was effective in preventing paralysis of sensation.

(5) The spatial resolution was measured to have a range from 8 to 12 mm in which the displayed lines were counted correctly.

(6) The discrimination of the pseudo-gray scale presented by binary dots was sufficiently accurate for lower densities, suggesting that the scheme is practical.

Acknowledgement

This research was supported by the special research fund of TMIT.

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(Received June 27, 1995)
(Accepted December 8, 1995)

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