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VIBRATORY TACTILE DISPLAY FOR TEXTURES

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Abstract:
We have developed a tactile display that produces vibratory stimulus to a fingertip in contact with a vibrating tactor matrix. The display depicts tactile surface textures while the user is exploring a virtual object surface. A piezoelectric actuator drives the individual tactor in accordance with both the finger movement and the surface texture being traced. Spatiotemporal display control schemes were examined for presenting the fundamental surface texture elements. The temporal duration of vibratory stimulus was experimentally optimized to simulate the adaptation process of cutaneous sensation. The selected duration time for presenting a single line edge agreed with the time threshold of tactile sensation. Then spatial stimulus disposition schemes were discussed for representation of other edge shapes. As an alternative means not relying on amplitude control, a method of augmented duration at the edge was investigated. Spatial resolution of the display was measured for the lines presented both in perpendicular and parallel to a finger axis. Discrimination of texture density was also measured on random dot textures.

Keyword: Tactile Display, Vibrotactile Sensation, Surface Texture, Duration Time, Spatial Resolution, Density Discrimination, Virtual Reality

1. INTRODUCTION

Force reflection devices to somatic sensation have been developed in various configuration designs for the purpose of teleoperation from the 1960s. Recently emerging needs of such devices from virtual reality technology are again accelerating the research regarding these haptic feedback devices. When the user of such system interacts with physical objects presented virtually, however, force reflection device alone is insufficient. Tactile sensation, by which the shape and surface texture are perceived, is also crucial to increase the sense of presence of displayed object. In addition to the deep sensation presented by force feedback devices, the cutaneous sensation plays an important role particularly in ensuring the sensor modality of a human operator, by which cognitive cues are diversely provided in ordinary environment.

The surface texture sensation depends on many aspects of physical properties specifying the object surface, such as microscopic geometry, friction coefficient, kinetic elasticity, thermal conductivity, etc. Modern study on such tactile texture perception was originated by Katz(1925) [1] who set many agenda on the subject. Recently, Hollins(1993) [2] proposed a perceptual space in which surface texture properties were discriminated within a three-dimensional model. To present a virtual texture in the tactile space, the physical properties of a surface should be well-imitated in above senses, however, it is extremely difficult to reproduce all of these properties. Therefore, an effective scheme, by which the tactile sensation is purposively stimulated, has been an open interest in the research area [3]. One solution to that difficulty is to reduce contact dimension to a single point that explores within the textured surface. Such devices were developed by Minsky(1990) [4] and by Akamatsu (1994) [5] that produced surface texture sensation as traced by a point not representing it to the finger as the two-dimensional surface to be sensed simultaneously. This approach contributes to device simplicity, however a part of intrinsic properties of spatially distributed cutaneous sensation is dismissed unused.

A vibratory stimulus, produced by a mechanical device, has been investigated as an effective instrumentality to transmit information to the blind from the 1960s [6]-[8]. The Optacon is the typical device that employs vibratory stimulus to convert optical information to tactile sensation [9]-[10]. The device was first developed by Linvill(1966), and commercially

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available from 1971. Several display control modes were tested to represent letters on the Optacon by Craig(1981) [11]. Since the principal purpose of the Optacon was reading aid for the blind, the method for texture replication had not been treated as a principal theme.

We have developed a vibratory tactile display for presenting sensations related to the texture on object surfaces. This device has vibrating tactors similar to the Optacon, however the individual tactor can be controlled with much extended flexibility in spatiotemporal pattern generation. Basic characteristics of the presented sensation were investigated experimentally, in which control schemes were discussed in terms of representing simple edged and random dot textures.

2. MECHANISM OF VIBRATORY TACTILE DISPLAY

A prototype system of the vibratory tactile display is shown in Figure 1. Vibratory stimulus is given to the index fingertip pad placed on a display window, 10 x 20 mm^2, at the top of the display box. The display window is a matrix of 'tactor,' a display element made of a piano wire 0.5 mm in diameter. Within a matrix, 5 x 10 tactors are disposed with a 2 mm pitch forming a rectangular window (Figure 2). Each tactor is driven at 250 Hz by a piezoelectric actuator attached to a magnifying mechanism to yield about 80 micron amplitude. This frequency of vibration was adopted for its highest sensitivity on the basis of the equal sensation magnitude curve measured by Verrillo [6].

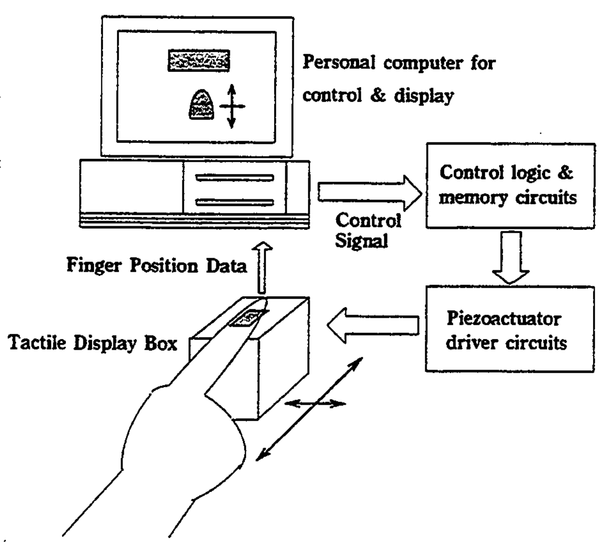

Figure 1 Tactile Display System

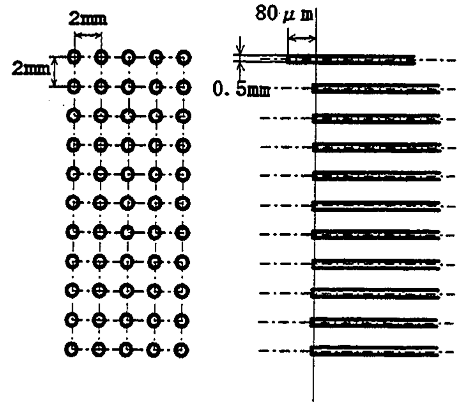

Figure 2 Five-by-ten matrix of tactor with 2mm pitch.

The user of the display explores a surface of a virtual object with the fingertip fixed on the window, moving his/her hand within a two-dimensional plane together with the display box. Position data of user's finger, compatible with the position of display, is tracked by a mouse attached to the display box. On the basis of the position data, which is equivalent to relative finger movement within a presented texture, a personal computer controls spatiotemporal patterns of tactor vibration. In addition, the computer also carries out the renderings on a CRT display showing CG images of both the finger and virtual textures.

3. STIMULUS GENERATION SCHEMES

The term, surface texture, in tactile sense is used here as a geometrical profile of an uneven plane that contains little difference of levels or protrusions that make inherent tactile stimuli when it is traced by a fingertip. Other properties of surface that are to contribute to tactile sensation such as frictional, kinetic and thermal characteristics are not considered to represent, although they cannot be eliminated completely from our physical embodiment of the display. Thus for the first step, we treat the texture as a binary valued two-dimensional plane; the plane has 'high' and 'low' portions extended similarly to a binary picture image. Given the simplified surface, a basic and natural mapping from a texture to the display window, by which each tactor is driven to make stimulus, is that tactors in high portions in the texture generate vibratory stimulus in the display window. We incorporate this fundamental mapping in the display control as its static phase. The dynamic mapping to realize temporal property of tactile sensation has much alternatives to be discussed as shown in the following.

3.1 Stimulus duration for reproduction of adaptation process

Tactile sensation of object surface texture is usually obtained while we explore the surface with the fingertip; minute protrudent profiles of the texture afford us two-dimensionally varying stimulus during the exploration. In doing that to examine the surface, we incidentally stop the finger movement and restart it again not always intentionally, where the process of sensor adaptation occurs. After the movement stopped, the sensation of touching a surface gradually decreases. The decay time of the adaptation differs depending on the kinds of mechanoreceptor ranging from a few milliseconds to tens of seconds. The decay time of vibration receptors is very short, a few milliseconds, and that of touch receptors has a range from about fifty to five-hundred milliseconds [14].

Without taking account of this sensory adaptation, the display does not give a good representation of tactual texture. Since, if the display continuously activates the high portion of texture after the finger stopped, the stimulus will be too intense for static touching, and it will cause unwanted paralysis of cutaneous sensation. Moreover, if it terminates the stimulus simultaneously with a finger stop, the impression of the surface texture becomes very queer as though the texture touching suddenly vanished.

To incorporate this adaptation process in stimulus producing control of the tactile display, the generated vibration must be adjusted temporally with respect to its intensity. However, the amplitude of individual tactor vibration cannot be regulated on this display, because the analog circuits to alter driving voltages would be too large to implement. Consequently, we have selected a method to give an appropriate duration to each tactor after the finger exploration stopped. A proper duration of vibration equivalent to diminishing sensation was able to simulate the adaptation process to a good extent.

Experiment
The effective duration time was measured by the method of adjustment where a single line edge was presented on the display perpendicularly to a finger axis. In the experiment, a standard stimulus of a fixed fine wire 0.5 mm in diameter was provided aside the display at the same height as the display plane. On the display while the display box has a velocity, just a single row of tactors was excited to avoid the termination of vibratory stimulus. (This assumes the virtual edge width to be 2 mm, however it introduced a little uncertainty of edge position rather than its extended width.) Subjects were instructed to trace the standard wire by the right index finger for about five times before each testing session. Then the subject rested the index finger horizontally on the display window holding the display box by other fingers. A vibratory stimulus was then generated on the display window while the subject was tracing on a 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 time randomly set each time within either the ranges [0, 10] or [40, 50] milliseconds for ascending and descending series, respectively. The subject was allowed to change the duration by the adjustment keys of ±1, ±3, and ±6 msec allocated on a keyboard, until he judged the similarity between the displayed wire and the real one was maximized. Each experiment for a subject consisted of twenty trials, ten for both series. The number of subjects was four, including a female, in their 20s or 30s; two were inexperienced with only a few rehearsal before the experiment.

Results
Figure 3 shows adjusted duration mean times of four subjects for each series of adjustment directions. An analysis of variance reveals significance at the .01 level in all of subject differences ($F=20.9$, $df=3/72$), series effects ($F=98.4$, $df=1/72$), and the subjects by series interaction ($F=14.8$, $df=3/72$). Subject B and C were inexperienced, and they exhibited large mean time differences between ascending and descending series. It seems that they had not precisely perceived the results of their own changes in the case of

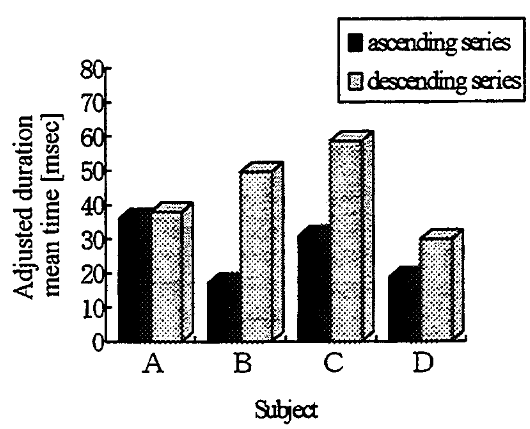

Figure 3 Adjusted duration time for a virtual wire

descending series, as they sometimes increased the duration time moreover. However in ascending series, adjusted mean times were not so small that they should be judged not realizing the duration at all. Consequently it appears that a duration no less than about ten milliseconds has an effect to produce an after image gradually vanishing at the user's finger. A possible duration time to implement in the display may be an average time of ascending series of both experienced and inexperienced users. Then, the time obtained in this experiment was 25.6 msec. In general, subjective impression was fairly good when the duration was properly added. A support of this figure of duration time may be obtained from a fact that the time threshold of tactile sensation is said to be around it, for example, about 27 millisecond, that agrees with our experimental data.

3.2 Representation methods of other simple edges

For implementing fundamental displayed elements to represent the rugged surface texture, we examined other simple edge patterns, illustrated in Figure 4, that included protrusions and retractions, or recesses, wider than a single wire. With regard to the protrusion such as Figure 4(a) of width over two millimeters, it was not appropriate to assign simply vibrating tactors to protrudent regions, since the edges at the region boundary were blurred consistently with the increase of the width. The sensed image at the edge was observed as rather a gentle slope than a definite line.

An alternative assignment of vibrating tactors to avoid the diffusion of edge image was examined, that limited the vibration tactors only at the edges where tactors inside the edges being suppressed. However, the method was not effective to represent the protrudent shape since it produced hollow impression at the inside between the edges; the image was rather near to Figure 4(b) when the finger was *on* the protrusion.

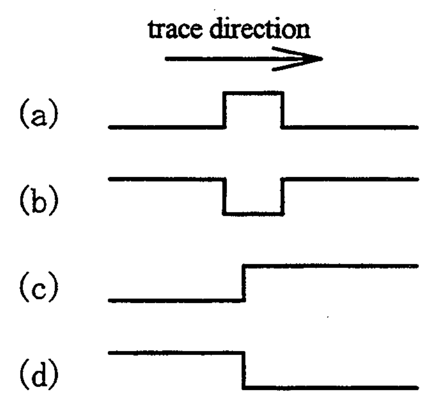

Figure 4 Fundamental texture elements of line edge.

The similar discussion was valid in the cases of Figures 4(c) and 4(d). Eventually, if all tactors within the high region were excited, the impression given from the region was rather a gentle sloped swelling attended with some sense of friction than a plate with a sharply defined edge. Moreover, if the tactors at the edge alone were excited, a high plate region was not perceived but a single edge was observed, naturally.

From above discussion, it is found that stimulus distribution control is required where the stimulus density, or intensity, varies across the edge, incorporating the directions of low to high or high to low. However, the vibration intensity is basically constant in this device at present. Thus, making a spatial or temporal intensity gradient should be an alternative scheme; a temporal modulation to alter intensity was examined tentatively.

The basic vibration at 250 Hz was ceased from 10 to 90 percent at 25 Hz modulation interval to obtain intensity gradient. The result of this scheme, however, was not necessarily effective, since additional frequency spectrum of 25 Hz caused another quite different sensation that surpassed the decrease of basic frequency stimulus.

3.3 Augmented duration method for edge representation

Another method to represent the edge is to utilize duration difference after the finger stopped. Since the edge is localized especially when the finger stopped on the edge, a longer duration than that set inside the protruded area can easily highlight the edge. Preferable duration time was measured by the method of adjustment.

Experiment

A 20 x 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, stopping on both edges, onto the plate and off from the plate. After the finger exploration movement stopped, all tactors *on the plate* were extended vibration by the same duration time of 10 msec; this duration time was around the minimum that could avoid inadequate vanishing image and ensure duration contrast to the edges. The tactors on the rising edge, that had just climbed onto the plate, were assigned 30 msec of constant duration time; which was about the mean time selected previous experiment. This side edge did not require additional duration other than a normal duration, since the finger region that had not reached the plate was free from stimulus which did produce high contrast of stimulus at the boundary. On the other side falling edge, across which the finger had just relieved a vibration stimulus, a longer duration was required to emphasize the edge to the finger which had degraded sensitivity after experienced vibration area of the virtual plate.

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

Results

Figure 5 shows the duration mean times in which the subject difference was not significant; a series effect was significant at .01 level (F=17.5, df=1/36); the subjects by series interaction was significant at .05 level (F=5.0, df=1/36). Means of ascending and descending series were 125.5 ms and 95.0, respectively. Both series had crossed mean values in the adjustment from initial values that may be attributed to the error of habituation. A tentative standard duration time for a falling edge seems to be the series mean of 115 ms.

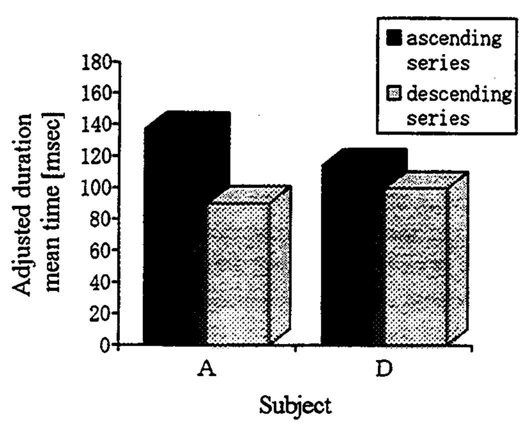

Figure 5 Adjusted duration time for a falling edge

3.4 Spatial resolution

A spatial resolution is a common index frequently referred to in describing the performance of a display device. One-dimensional resolution of the tactile display was examined in both the horizontal and vertical directions. While the resolution specified by the number of lines to be counted does not directly describe overall presentation power with regard to tactually perceivable surface texture, it seems to yield suggestive information by which the relation between this device and tactile sensation is extensively discussed.

Method

Several lines of virtual protrusions were displayed both perpendicular and parallel to the finger axis within the 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 I, and the ratio of protrusion width to a pitch was altered in three cases of 25, 50, and 75 % as illustrated in Figure 6 of perpendicular allocation. Subjects were asked to report the number of lines. The experiment was repeated ten times for each pitch, randomly selecting a pitch from the pitch set. The data was obtained from three male subjects in their twenties as the previous experiment.

Table I Line pitches selected in thirteen ways.

pitches of line (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	

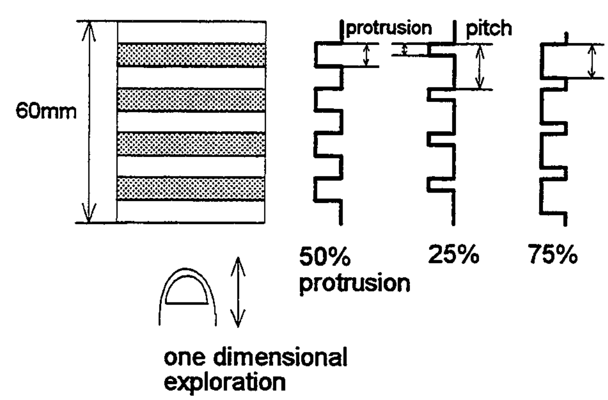

Figure 6 One dimensional virtual edges perpendicular to the finger axis

Results

The results are shown in Figures 7 and 8 for perpendicular and parallel cases, respectively. The ordinate of Figures is the ratio of correct answer, and the abscissa is a pitch of lines. In the correct answer ratio, the response within plus and minus twenty percent errors are included, since counting lines by fingertip exploration is rather difficult to contain an inevitable miscount, even if it is done on a real surface with physically engraved lines. (Beforehand, we have conducted a preliminary experiment estimating the line counting ability of fingertip on real line-carved samples produced by a rapid photo forming machine. The samples were shaped to realize edge patterns illustrated in Figure 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 measured to require at least about 4 to 6 mm pitch.)

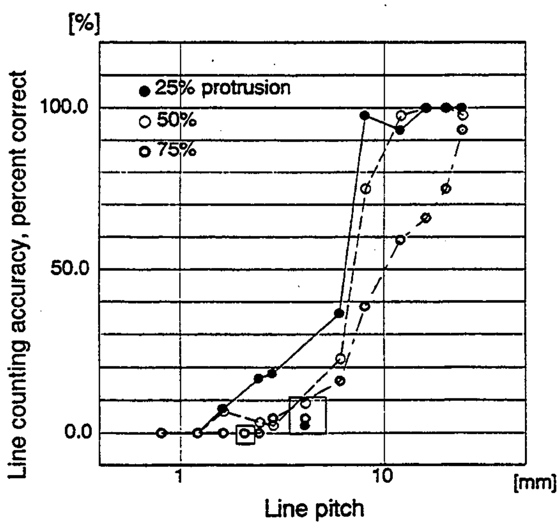

Figure 7 Line counting accuracy, where lines were presented *perpendicular* to the finger axis.

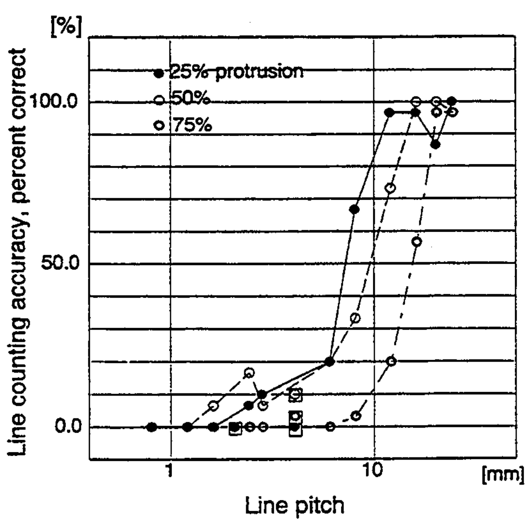

Figure 8 Line counting accuracy, where lines were presented *parallel* to the finger axis.

In the case of the display, the correct answer ratio reached over seventy-five percent at 8 mm pitch with the exception of 75 % protrusion case. This value seems acceptable taking account of the display's tactor pitch of 2 mm. In the case of 75 % protrusion ratio, it was more difficult to discriminate the 'low' position between lines than the other cases. Therefore, the counting accuracy was slow to rise.

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

Figure 8 indicates the result where the lines were presented parallel to the finger axis, and the finger exploration movement was valid only in the lateral direction. A general difference from the data obtained on perpendicular lines is lower counting accuracy at almost all line pitches; the decrease at eight millimeter pitch is remarkable. Twelve millimeter pitch was required for almost correct line counting at 25 % protrusion ratio in the parallel case, while eight millimeter pitch was sufficient for the lines displayed perpendicularly.

3.5 Discrimination of texture density

Natural surface textures in general produce multi-level stimulus magnitudes, that is equivalent to gray scale in a visual image, as well as sharp edges described in the previous section. To represent the multi-level textures, it is required first to determine the number of levels that can be displayed by this tactile display. Here it is assumed that multi-level textures are approximated by a binary dot image. The perceivable density difference of binary random dots was examined by presenting a pair of regions that had different mean densities.

Experiment

Some example textures that were used in the experiment are shown in Figures 9 - 11. The size of the texture area was 30 x 60 mm; each dot size was 2 x 2 mm. A black dot in the texture excited the display pin vibration. The texture area was divided vertically

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

Figure 9 Sample textures of 50 % mean density.

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

Figure10 Sample textures of 40 % mean density.

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

Figure 11 Sample textures of 30 % mean density.

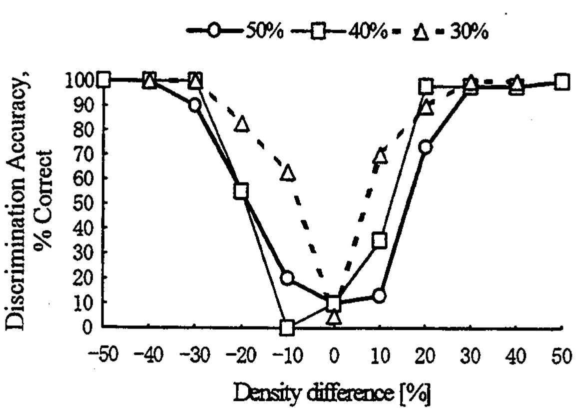

Figure 12 Discrimination accuracy vs. Density difference.

into two regions to provide density difference between the upper and lower sides by the percentages from -50 % to +50 %. In Figure 8, all of three textures have the same mean density of black dots of 50 %; in Figures 10 and 11, the mean densities are 40 % and 30 %, respectively. Subjects were required to judge which side was more dense after exploring both sides. On the visual display, the rectangular wire frame of the area and a cursor that indicated the finger position were presented. The texture with a particular difference was presented ten times in one session that included 110 trials for each of three mean density of 50, 40, and 30 %. Subjects wore the headphones similarly to previous experiments. Four subjects in 20s and 30s, including a female, executed this experiment.

Results

Figure 12 shows the ratio of correct answer as a function of density difference between the upper and lower sides. The ratio is the average data of four subjects. Plotted circles indicate the case where the mean density was 50 %, and squares for 40 %, triangles for 30 %, respectively. In cases of 50 and 40 % mean density textures, thirty percent difference in both sides gives almost complete discrimination, and about 20 % difference is a transition point. The lower mean density of 30 % exhibited improved accuracy of discrimination where 10 % difference was perceived much more than other two cases.

4. DISCUSSION

One of principal surface texture elements sensed by a fingertip is a line edge within a plane. We have referred to the possibility to employ duration for representing the edge shape. This is because we thought that to replicate the after image of vanishing sensation increases the similarity of touch impression to the real edge and it can be well simulated by the stimulus duration added properly after the finger movement stopped. Moreover, such stimulus control that terminates tactor vibration after the duration is an appropriate scheme which can avoid sensation paralysis. (Although the Optacon does not employ such termination of vibration, since its purpose is not rendering of surface texture image but translating symbolic letters of printed matter distinctively.)

A single edge and a boundary edge of a plete were presented fairly well by the augmented duration menthod. However, presenting the even inside of a plate bounded by edges was not suited to this display, since the display can not directly give a shearing force that must be introduced by finger tracing movement, although it does display a little sense of friction. The lack of shearing sensation is compensated in the edge representation case by an apparent movement that can be sensed as long as the surface has any variation in the geometrical state.

Another principal element of texture is a periodical variation of a surface. Repetition of lines is presented with ease by the display in the sense of perception, not counting. In the spatial resolution data obtained, the line counting under four millimeter pitch has been discussed equally to other pitches. However, tactile pattern recognized in this range of spatial frequency must be inaccurate taking account of the Nyquist criterion. Further analysis of the display spectrum is required from the tactile sensation point of view.

Spatial resolution as a counted value was not necessarily high enough, which is partially due to the display tactor pitch of 2mm. Regarding the spatial sensitivity of a fingertip, 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 two-point limen. Consequently in this sense, the display tactor pitch might be adequate in a sense. However this value of spatial threshold is valid while the stimuli is statically provided. The successive spatial threshold, where two stimuli are presented sequentially, is reported on the order of 10 to 30 times smaller than that (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 for surmounting this hardware limitation.

Tactile discrimination ability of mean intensity of random dots was close to that of vision although whole texture patterns are not shown here due to space limitaiton. That was an unexpected result in contrast to the result of spatial resolution experiment. This leaves one possibility to present a gray scale image in this form. Future work to augment the display presenting capacity also includes intensity control which is invoked partially by hardware controlling frequency and phase. Tactile sensitivity to the frequency change and phase offset is acute according to our tentative observation. These parameters will surely contribute to rendering versatility of the display, especially in representation of gray scale images.

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