Selectively Stimulating Skin Receptors for Tactile Display

Naoya Asamura, Nozomu Yokoyama, and Hiroyuki Shinoda
Tokyo University of Agriculture and Technology

A method to display realistic tactile feelings selectively stimulates mechano-receptors in the skin. A sparse array of stimulators controls pressure both on the shallow and deep receptors.

Recent research in virtual reality has recognized the need for more realistic tactile display in addition to touch and non-touch display and force display.[1] Researchers have proposed various mechanisms of pin or vibrator arrays[2] to present the sensations of 3D local shapes, fine textures,[3] and slippage of grasped objects.[4] Watanabe[5] demonstrated an interesting method of controlling surface roughness using ultrasonic vibration.

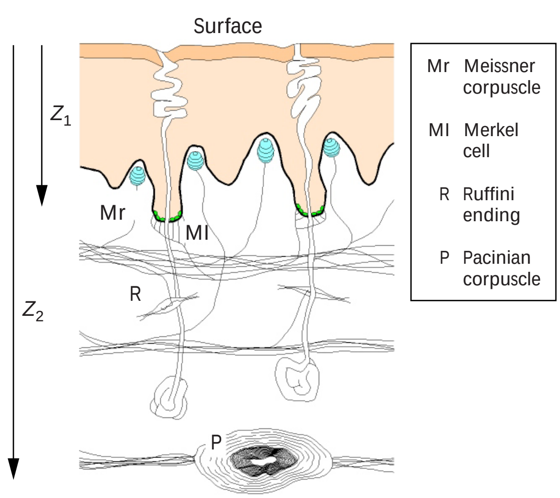
In all these efforts, researchers regarded one of the most attractive themes—the realistic display of tactile feelings—as work for the far future. Since human skin can distinguish very fine mechanical and geometrical properties,[6] many have felt it indispensable to prepare a sophisticated apparatus to control very fine pressure patterns. Actually, we suspect that previous pin arrays could not produce the realistic feeling of touching a texture even if the display caused vibratory sensations or displayed static macroscopic pin geometry.

In this article we propose a method of selectively stimulating only superficial mechanoreceptors.[7] Moreover, we show that it makes people feel a more realistic, finer virtual texture than possible by adjusting the stimulator spacing. The apparatus is simple, and we expect this idea to develop into a device to display varieties of tactile feeling.

A method of selective stimulation

Figure 1 shows a cross-section of human glabrous skin.[8] The tissue includes four kinds of mechanoreceptors, with each kind located at a specific level. On the palm, the shallowest and the deepest mechanoreceptors (Meissner corpuscle and Pacini corpuscle, respectively) lie below the surface at about 0.7 mm and 2 mm, respectively.[9] This article reports the tactile feelings caused by selectively stimulating the shallow and the deep receptors.

Here we propose a stimulator as shown in Figure 2. A vibrator has depressions of 2 mm in diameter with 0.5 mm depth on the surface. We can control air pressure in the "caves" between stimulators and skin while vertically vibrating the overall surface. The apparatus gives two kinds of stimulation on the skin, as shown in Figure 3.

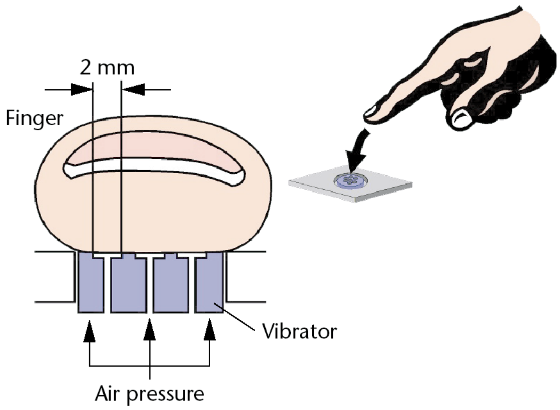


1 Vertical cross-section through the glabrous skin of the human hand.[8]

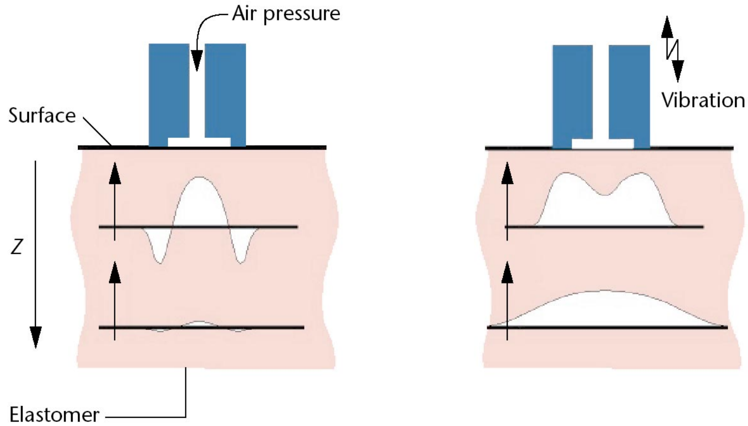
Superficial stimulation by air pressure

Assume the skin has close contact with the apparatus. Write the air pressure in the cave as $P_a(t)$. If the display surface is rigid and presses on the skin with offset pressure (so the skin at the edge of the cave cannot move), the edge produces an opposite force that cancels the total force of the air.[10] In this case, the sys-

0272-1716/98/$10.00 © 1998 IEEE



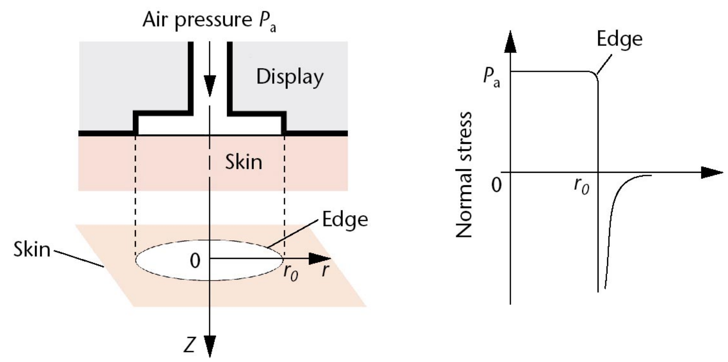
2 Schematic diagram of the selective stimulator. The air pressure stimulates only shallow receptors, while the overall vibration stimulates both shallow and deep receptors.



3 Two kinds of stimulation seen in cross-section, illustrating the stress distributions at a shallow level and a deep level. The air pressure stimulates shallow receptors, while the overall vibration stimulates both shallow and deep receptors.

tem induces stress only near the surface. Figure 4 illustrates the horizontal pressure (normal stress) distribution on the skin, where r represents the distance from the center of the pressure circle. Figure 5 shows the theoretical value of inner stress at depth z, under the center of the air-pressure circle, when we assume the skin is a homogeneous elastic body. The figure tells us that typical parameters of stress—the isotropic pressure $s_{xx} + s_{yy} + s_{zz}$ and normal stress s_{zz}—at the deep level (2 mm) are less than 10 percent of the values at the shallow level (0.7 mm) if we set the radius of the cave r_0 at 1 mm.

This method gives more complete selective stimulation than the one proposed previously.[7] In addition, the laborious process of attachment and calibration becomes unnecessary.

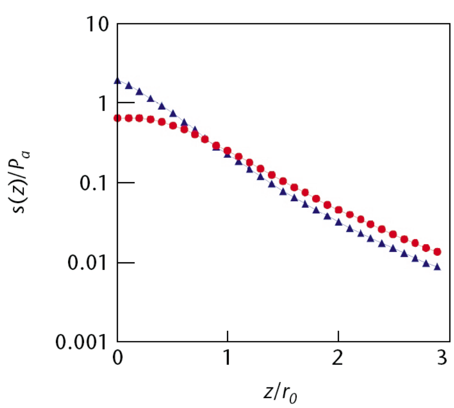


4 Normal stress distribution on the skin under air pressure. The *r* is the distance from the center of the air-pressure circle. If the skin at the cave edge cannot move, the total force onto the skin becomes zero.

Stimulation of deep receptors

Contrarily, the stimulator's vibration applies common stress to both the shallow and the deep receptors. Deep stimulation would be required only to display overall vibration induced by stick-slip, which would cause subtle differences in texture sensations. Superficial stimulation would play a major role in displaying virtual textures, as Phillips and Johnson[11] reported in experiments on monkeys.

Thus, we can selectively stimulate the receptors at different depths, although



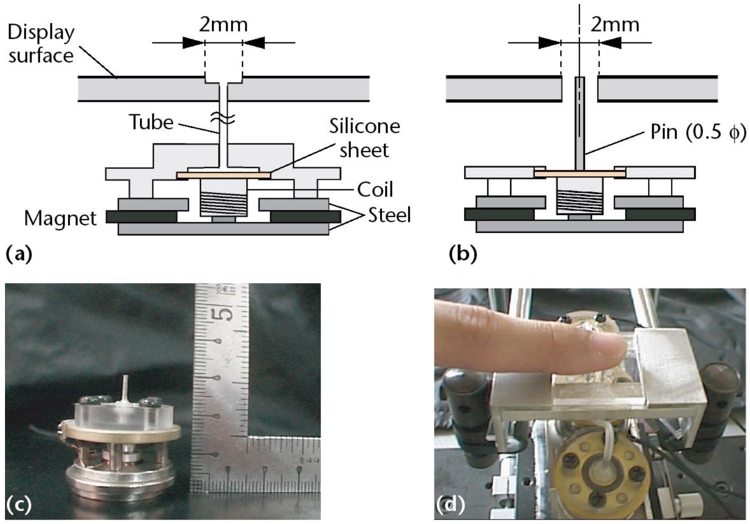
5 Theoretical value of typical parameters of stress, isotropic pressure $s_{xx} + s_{yy} + s_{zz}$ (blue triangles) and normal stress s_{zz} (red circles) in the elastic body versus the depth *z*, under the center of the air-pressure circle shown in Figure 4.

1. the direction of the applied surface force is not controllable, and
2. the stimulation of intermediate receptors (Merkel cell and Ruffini endings) is not specified.

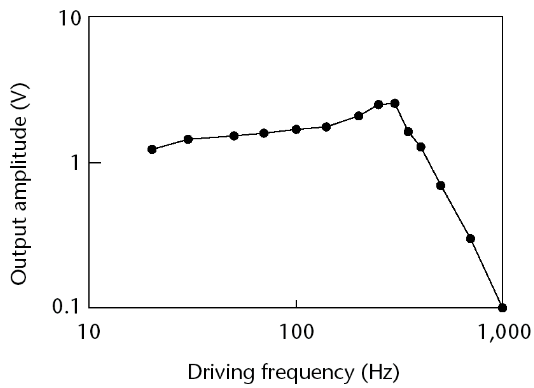
In the following section, we show the results of superficial stimulation because we're mainly interested in displaying fine textures.

Details of superficial stimulator

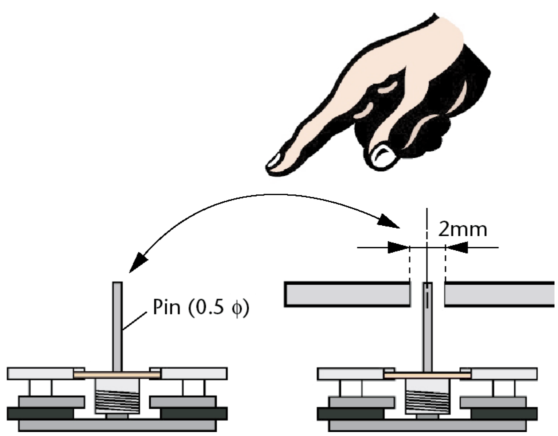
One mechanism of the superficial stimulators relies on air pressure, as already described. This stimulator, which we call "S-a," lets us fabricate various arrays easily. On the other hand, we also use another superficial stimulator for basic experiments that has a similar structure but uses a fine pin (0.5 mm in diameter) instead of air pressure. We call this "S-p."



6 **The structures of the superficial stimulators (a) S-a and (b) S-p. (c) A photograph of the air-pressure controller and (d) a view of the experiment.**



7 **Air-pressure-sensor output, which was attached over the cave of S-a, versus frequency, under constant amplitude of sinusoidal driving voltage.**



8 **An experiment (Experiment I) to examine the difference in feeling between superficial stimulation and simple contact with a vibrating pin.**

The air pressure in the S-a cave is controlled by a piston through a tube (see Figure 6a). Figure 7 shows the air-pressure amplitude for a constant input sinusoidal voltage amplitude at each frequency. We measured the pressure with the cave covered by an air-tight pressure sensor. The frequency characteristics are nearly flat until 300 Hz. We evaluated the relationship between the measured pressure and the input voltage as

$$\text{Input of 1V} \Leftrightarrow 2.8\text{ kPa} = 28\ gf/\text{cm}^2 \text{ at 100 Hz}$$

The following experiments showed experimental conditions using the input voltage. Figure 6d shows a photograph of the apparatus with three superficial stimulators and without the overall vibrator.

Experiment I

The first experiment confirmed the different sensations of superficial stimulation and simple vibration.

Procedures

Subjects touched two kinds of stimulators successively and answered whether they felt any differences between them. (See Figure 8.) One was the superficial stimulator S-p described previously. The other was a simple touch on the same pin vibrator as that of S-p. A sinusoidal driving signal at 50 Hz went to both stimulators for 1 second following 1 second of no signal. The input voltage's amplitude was four times as large as the minimum sensible amplitude in S-p. The skin and the pin had tight contact with each other before the signal was given. We did the experiments for the finger and the thenar of six subjects in their twenties and thirties.

Results and discussion

All the subjects answered that the two stimuli clearly differed. The simple pin produced a vibratory sensation similar to touching a vibrating surface like an audio speaker cone. Subjects felt a vibration rather than a touch. Also, the stimulated point felt vague, and they could imagine that they were touching some larger object. On the other hand, the S-p did not make them sense vibration to reach the depths of the skin, and they felt as if a small bug were creeping on their skin. The stimulation area seemed small to them.

For both stimuli, the given pressure was localized within a small area. But the total force received at the Pacinian level played an important role in the feeling.

Experiment II

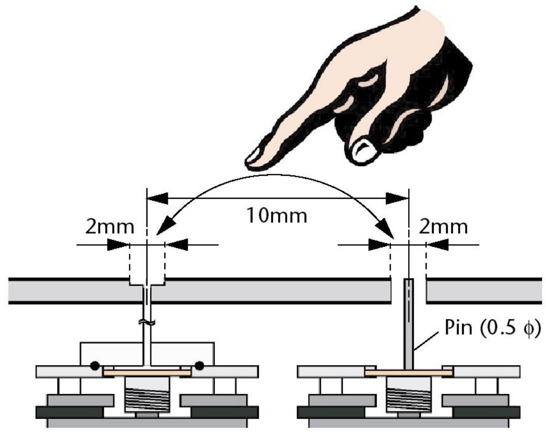
Experiment I shows the human ability to distinguish differences of very small dimension in a pressure distribution. For this reason pin arrays cannot display realistic touch on a texture. Next we examine another discrimination test. Two kinds of stimulation have different local pressure distributions within a 2ϕ circle, but the stimulation given affects only the shallow receptors in both cases.

Procedures

First, subjects received stimuli from apparatuses S-a and S-p, successively, and memorized the feelings. Then, for a randomly selected stimulus—S-a or S-p—subjects identified the apparatus used. We repeated the tests 20 times per subject and recorded the correct answer ratio. During the experiment, the subjects wore headphones and eye-masks so as not to obtain cues from sound and sight. The observer guided each subject's hand. Before the test, we tuned the driving amplitude to make the sensations induced by S-a and S-p as similar as possible. See Figure 9.

We did the experiments for the index finger and the thenar of six subjects in their twenties to thirties. We recorded results for four kinds of signals:

1. Sinusoidal wave of 20 Hz with an amplitude of 3V; the minimum sensible voltage was about 0.7V (2 kPa) at 50 Hz.
2. Sinusoidal wave of 100 Hz with an amplitude of 3V.
3. Random phased signal; a band-limited signal from 10 Hz to 200 Hz with an effective value of 2V.
4. Pulse sequence; the width and height of each pulse was 0.5 ms and 6V, respectively, and the frequency was 6 pulses per second.

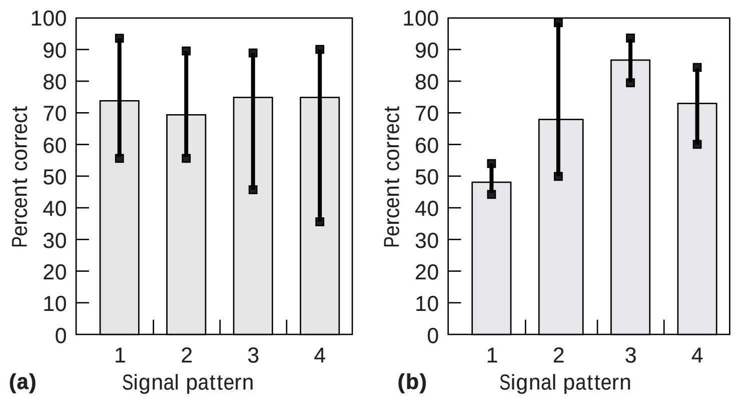


9 Set-up of the air-pin discrimination test of Experiment II.

Results and discussion

Figure 10 shows the correct answer ratios averaged among the subjects. The results reveal that the subjects could find some differences between the two stimuli, but they seemed so similar that the subjects missed the correct answer at a 30 percent rate.

The results mean that the human ability to discriminate fine stress distribution degrades remarkably when the stimulation affects just one level of receptors.



10 Correct answer ratio of the air-pin discrimination test for (a) fingertip and (b) thenar, for the signal patterns (1) sinusoidal wave of 20 Hz, (2) sinusoidal wave of 100 Hz, (3) random phase signal, and (4) pulse sequence.

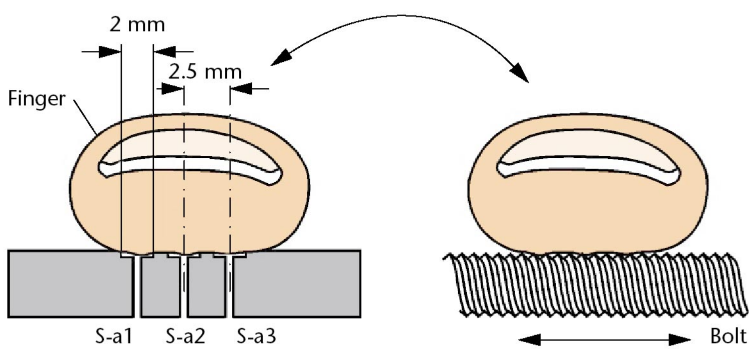
Experiment III

When adequate signals drive several superficial stimulators, you can feel something sliding over the skin. Some signals induce a finer virtual texture than the stimulator spacing. In this experiment we examined the relationship between subjective fineness and the driving signal.

Procedures

Three superficial stimulators—S-a1, S-a2, and S-a3—arrayed in a line were driven by sinusoidal signals with various frequencies and amplitudes (see Figure 11). The center-to-center spacing of the stimulator was 2.5 mm. In each test, the three drivers received a common signal for 0.6 second, repeated at 2-second periods (no signal for 1.4 seconds). Subjects evaluated the perceived (horizontal) fineness compared to touching three real objects with groove widths of 0.6 mm, 0.9 mm, and 1.2 mm (bolts of 3ϕ, 6ϕ, and 8ϕ, respectively). The objects reciprocated sinusoidally with a 1.3-second period and a maximum speed of 7.0 cm/s. Subjects were not allowed to move their finger horizontally—the contact pressure was arbitrary. We permitted subjects to choose whether to use the same finger for the comparison, or the finger of the other hand.

We classified their answers into four categories: (I) finer than 0.6 mm, (II) between 0.6 mm and 0.9 mm, (III) between 0.9 mm and 1.2 mm, and (IV) coarser than 1.2 mm.



11 The apparatus for Experiment III had three superficial stimulators (left). The subjects evaluated the subjective fineness compared with three kinds of moving surfaces (bolts).

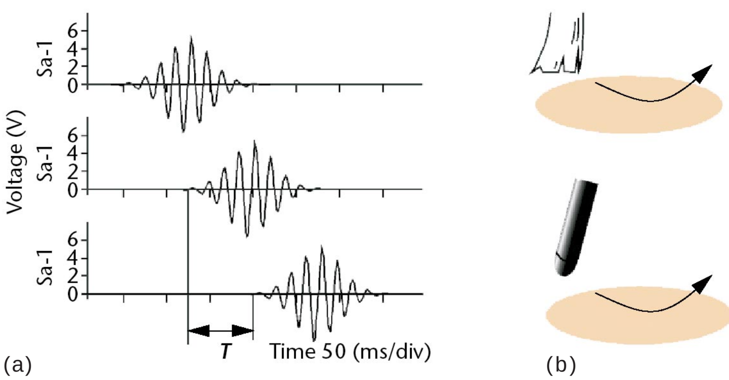
Results and discussion

We gave the four categories of fineness (I, II, III, and IV) points of 0, 1, 2, and 3 respectively, as shown in Table 1 (next page), and averaged them among the subjects. Table 2 shows the perceived fineness. When the subject felt the fineness was the same as a reference object, that case received an intermediate point. (For example, if it felt the same as 0.9 mm, we gave it point 1.5. See Table 1.) Although the stimulator sensation and that of real touch were not identical, comparison was possible.

The subjective fineness depended on both the signal's amplitude and frequency. The experiment confirmed that the sparsely located stimulators could display a very

Table 1. Assigning points to the fineness categories of the virtual object.

Perceived Pitch (mm)	I	0.6	II	0.9	III	1.2	IV
Point	0	0.5	1	1.5	2	2.5	3



12 **(a) Signal waveforms of the stimulators and (b) the image of tactile feeling. Subjects felt something sweep over the finger. Perception of the associated object changed according to the carrier frequency and the amplitude.**

fine virtual texture. Unexpectedly, even at 20 Hz some subjects perceived the displayed stimuli as finer than the 1.2-mm pitch bolt.

In research by Stevens and Harris,[6] Taylor and Lederman,[6] and others, they found that the subjective roughness depends on the contact force and the width of the groove—the temporal frequency is a minor factor. Our results partially agree with this.

Experiment IV

This experiment used an apparatus identical to that of Experiment III (see Figure 11). When we presented time-delayed signal packets for the three successive stimulators, a realistic feeling arose as if something swept over the skin (see Figure 12). Here we report examples of the tactile feeling for some driving patterns. Evaluation of reality remains subjective at this stage, but it hints at future work needed to understand human tactile perception and to realize tactile feeling display.

Procedures

The three stimulators S*n* (n = 1, 2, and 3) are driven by Gaussian envelope signals of

$$p_n(t) = A\sin(2\pi t)e^{-\frac{(t-nT)^2}{\tau^2}}$$

as shown in Figure 12. The width of the envelope t and the delay *T* are fixed at 37.5 ms and 75 ms, respectively. For the various amplitudes *A* and carrier frequencies *f*, the four subjects and we three authors described the sensations compared to touching real objects. Here the t and *T* determined above induce a realistic feeling, as if something swept over the finger—regardless of the *A* and the *f*.

Table 2. Subjective fineness versus the signal frequency and amplitude. The numbers are the averaged points of Table 1.

Amplitude*	Frequency (Hz) 20 Hz	50 Hz	100 Hz
×5	2.7	2.2	0.7
×10	3	2.3	1.2
×15	3	3	2.0

* Amplitude "*n*" means *n* times the minimum sensible amplitude.

Results and discussion

Table 3 summarizes the subjective feeling versus the carrier frequency and the amplitude. The amplitude is expressed by the multiple of the minimum sensible amplitude at each condition. Regardless of the conditions, subjects perceived the contact area as very small.

The weakest stimuli induced a common feeling regardless of the carrier frequency. We all felt as if something like a thin elastic fiber swept over our finger and did not perceive vibration of the carrier frequency. The larger the amplitude, the harder we perceived the objects to be. For example, the "ballpoint pen" at 30 Hz in Table 3 represents a sensation of smoother sliding with less friction than that of the "pin." When the carrier frequency became as high as 70 Hz, we all felt a bundle of fibers—not a single fiber—inducing a stick-slip sensation.

Summary and discussion

We proposed a method to selectively stimulate superficial and deep mechanoreceptors. Although humans can clearly discriminate a small difference in pressure distribution within a small area on the skin given a different stimulus amplitude to shallow and deep receptors (Experiment I), the discrimination ability degraded when only shallow receptors were stimulated (Experiment II). Superficial stimulation made people feel a finer virtual texture than the stimulator spacing (Experiment III), and a time-delayed signal displayed other realistic tactile feelings, like a brush sweeping across the skin.

Our research aimed to achieve realistic display of tactile feelings. This article showed that selective stimulation displayed fine virtual patterns beyond the stimulator array's resolution. However, the variation of tactile feeling from cotton towel to fur coat, wood, smooth metal, or other materials is vast, even if we focus on the tactile feeling of a sweeping motion with slight contact pressure.

This brings up a final concern: How wide a range of tactile feeling can we cover by preparing temporal signal form patterns for the stimulators? The answer depends on whether the human tactile organ treats the horizontal difference among neighbor receptors as an important feature. If not, we're hopeful about realizing the tactile feeling display.

Tactile hyperacuity[6] suggests a remarkable ability to detect horizontal differences, important in detecting geometric configurations as in Braille. However, any part of the skin—regardless of receptor density—perceives the tactile feeling almost identically, which

Table 3. An associated object versus the carrier frequency and the amplitude of the time-delayed signal.

Amplitude*	Frequency 30 Hz	40 Hz	70 Hz	100 Hz
×2	A soft fiber	A soft fiber	A soft fiber	A soft fiber
×4	A ballpoint pen	A pin	A bundle of fibers	An edge of felt
×8	A grating with rounded ridges	A fine grating with sharp ridges	A hard brush	?

* The amplitude "*n*" means *n* times the minimum sensible amplitude at each frequency.

suggests humans use another channel independent of the horizontal resolution to obtain the tactile feeling.

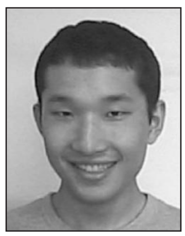
Human eyes know the spectrum feature of light—color—by RGB signals from the retina. If tactile feeling results from the stimulus amplitude perceived by each kind of receptor using the skin's spatial filtering property,[12] our concept will prove effective. Before getting the answer, we must wait for the results of future work, including experiments using a 2D array of stimulators. ■

Acknowledgment

The research was partly supported by JSPS-RFTF 96P00801, the Japan Society for the Promotion of Science. We appreciate the reviewers' advice.

References

1. K.B. Shimoga, "A Survey of Perceptual Feedback Issues in Dexterous Telemanipulation: Part II, Finger Touch Feedback," *Proc. VRAIS 93*, IEEE Press, N.Y., 1993, pp. 271-279.
2. M.B. Cohn, M. Lam, and R.S. Fearing, "Tactile Feedback for Teleoperation," *Telemanipulator Technology Conf. Proc. SPIE*, Vol. 1833, SPIE (Soc. of Photo-optical Instrumentation Engineers), Bellingham, Wa., 1993, pp. 240-254.
3. Y. Ikei, K. Wakamatsu, and S. Fukuda, "Texture Presentation by Vibratory Tactile Display," *Proc. VRAIS 97*, IEEE CS Press, Los Alamitos, Calif., 1997, pp. 199-205.
4. R.D. Howe, "A Force-Reflecting Teleoperated Hand System for the Study of Tactile Sensing in Precision Manipulation," *Proc. 1992 IEEE Int'l Conf. Robotics and Automation*, Computer Society Press, Los Alamitos, Calif., 1992, pp. 199-205.
5. T. Watanabe and S. Fukui, "A Method for Controlling Tactile Sensation of Surface Roughness Using Ultrasonic Vibration," *Proc. 1995 IEEE Int'l Conf. Robotics and Automation*, Vol. 1, IEEE Press, Piscataway, N.J., 1995, pp. 1134-1139.
6. H.R. Nicholls, ed., "Advanced Tactile Sensing for Robotics," Ch. 8, *World Scientific Series in Robotics and Intelligent Systems*, Vol. 5, World Scientific, River Edge, N.J., 1992.
7. N. Asamura, N. Tomori, and H. Shinoda, "A Tactile Feeling Display Based on Selective Stimulation to Skin Receptors," *Proc. IEEE VRAIS 98*, IEEE CS Press, Los Alamitos, Calif., 1998, pp. 36-42.
8. R.S. Johansson and A.B. Vallbo, "Tactile Sensory Coding in the Glabrous Skin of the Human Hand," *Trends in Neurosciences (TINS)*, Vol. 6, No. 1, Elsevier Biomedical Press, New York, 1983, pp. 27-32.
9. T. Maeno, K. Kobayashi, and N. Yamazaki, "Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptor," *Bulletin of Japan Society of Mechanical Engineers (JSME) Int'l J.*, Vol. 41, No. 1, C, 1998, pp. 94-100.
10. S.P. Timoshenko and J.N. Goodier, *Theory of Elasticity*, McGraw-Hill, New York, 1970.
11. J.R. Phillips and K.O. Johnson, "Tactile Spatial Resolution II: Neural Representation of Bars, Edges, and Gratings in Monkey Primary Afferents, *J. Neuophysiology*, Vol. 46, No. 5, 1962, pp. 1192-1203.
12. H. Shinoda, M. Uehara, and S. Ando, "A Tactile Sensor Using Three-Dimensional Structure," *Proc. 1993 IEEE Int. Conf. Robotics and Automation*, Computer Society Press, Los Alamitos, Calif., 1993, pp.435-441.



Naoya Asamura *is currently a student at the graduate school of Tokyo University of Agriculture and Technology. He is interested in haptic displays and sensors. He received a BS degree in electronic and information engineering from Tokyo University of Agriculture and Technology in 1997.*

Nozomu Yokoyama *is currently a student at the graduate school of Tokyo University of Agriculture and Technology. His current interest is in haptic displays and sensors. He received a BS degree in electronic and information engineering from Tokyo University of Agriculture and Technology in 1998.*

Hiroyuki Shinoda *is currently an associate professor of electrical and electronic engineering on the Faculty of Engineering at Tokyo University of Agriculture and Technology. His current research focuses on haptic displays in VR, sensor systems and devices including tactile sensors and optical/acoustic measurement, and micro-electro-mechanical systems. He received doctoral degrees in engineering from the University of Tokyo.*

Readers may contact Shinoda at the Dept. of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Koganei, Tokyo 184-8588, Japan, e-mail shino@cc.tuat.ac.jp.