A Method of Selective Stimulation to Epidermal Skin Receptors for Realistic Touch Feedback

Naoya ASAMURA, Nozomu YOKOYAMA and Hiroyuki SHINODA

Department of Electrical & Electronic Engineering,
Tokyo University of Agriculture & Technology
2-24-16 Koganei, Tokyo 184-8588 Japan

Abstract

In this paper, we propose a device to stimulate only the superficial mechanoreceptors in the skin, and report the feeling caused by the stimulus. We describe the principle of the selective stimulation using air pressure, and we show the selectivity is more advanced than that of our previous system using magnet chips which was presented last year. We experimentally confirmed that a sparse array of the superficial stimulators could display realistic touch on objects including finer virtual textures than the stimulator spacing.

Keywords: virtual reality, haptic interface, tactile feeling display, touch feedback, tactile texture.

1 Introduction

As Shimoga summarized [1], a lot of approaches of tactile display have been studied and developed. One typical method is an array of pins such as Optacon [2] which displays static/dynamic 2-D patterns [3,4,5] including characters and graphical features [6]. A simple vibrator is also used to inform whether an object is touching or to display slip of object [7]. But among such mechanical approaches, there have been no devices to display realistic touch on various objects. When we perceive a fine texture, we always move the finger along the surface to obtain dynamic signals. But if we vibrate the pins in order to give such dynamic signals, it induces vibratory sensation different from usual touch feeling.

In our previous paper [8], we proposed a method which stimulated mechanically only the epidermal receptors. And we reported such stimulation was associated with touch on a virtual object when the temporal signal was appropriate, in spite of the sparse placement of the stimulators. But in that system the selectivity was insufficient, and the reality was also incomplete. The setup of the experiment was laborious, and it was also difficult to obtain the reproducibility of the experiment. In this paper we propose a new apparatus which brings more advanced selective stimulation. And we show that it makes people feel finer virtual textures with reality than the stimulator spacing. The apparatus is simple and we expect this idea will develop into a device to display varieties of tactile feeling.

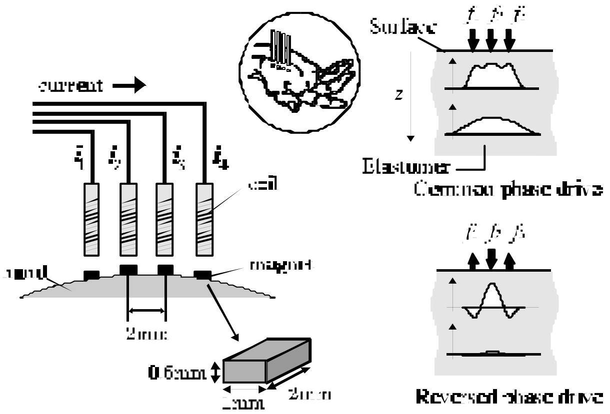


Fig. 1: Previous tactile feeling display using magnet chips. The shallow and deep receptors are stimulated selectively by the two kinds of driving mode for the successive three drivers [8].

2 A method of selective stimulation

Fig. 2 shows the cross-section of the human glabrous skin. It is said that there are four kinds of mechano-receptors in the tissue. And they have a key feature that each kind of receptor is located at a specific level. On the

1087-8270/99 $10.00 1999 IEEE

palm, it is said that the shallowest and the deepest mechanoreceptors (Meissner corpuscle and Pacini corpuscle, respectively) are located below the surface by about 0.7 mm and 2 mm, respectively [9,10]. The theme of the paper is to report the tactile feeling when the shallow and the deep receptors are stimulated selectively.

Here we propose a stimulator as shown in **Fig. 3**. A vibrator has depressions of 2mm in diameter with 0.5mm depth on the surface. And we can control the air pressure in the cave, while we give vertical vibration to the overall surface. The apparatus gives two kinds of stimulation on the skin as shown in **Fig. 4**.

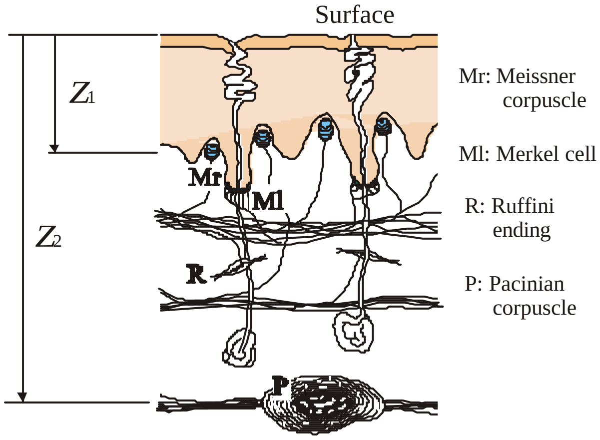


Fig. 2: Vertical section through the glabrous skin of the human hand [11].

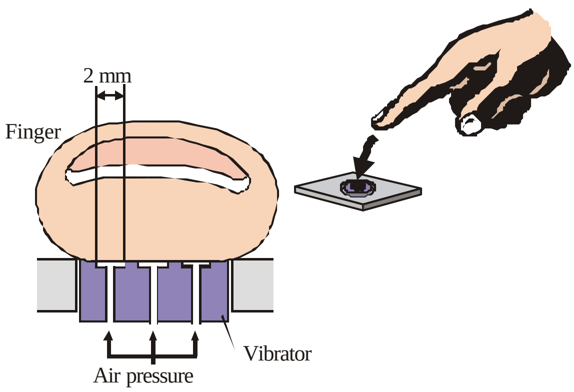
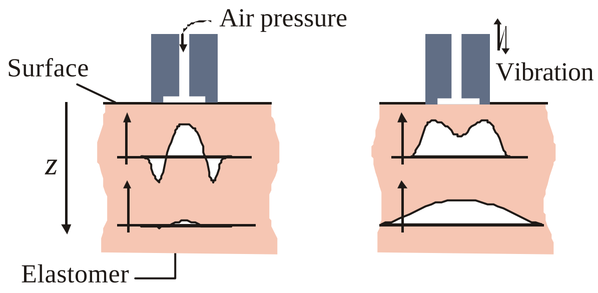


Fig. 3: The schematic diagram of the selective stimulator. The air pressure stimulates only shallow receptors, while the overall vibration stimulates both shallow and deep receptors.



(a) Superficial stimulation (b) Common stimulation

Fig. 4: Two kinds of stimulation mode. In the cross-sections of skins and stimulators, the stress distributions at a shallow level and a deep level are illustrated. The air pressure stimulates shallow receptors, while the overall vibration stimulates both shallow and deep receptors.

i) Superficial stimulation by air pressure

Consider the skin has sufficient contact with the apparatus and the air pressure in the cave is written as $P_a(t)$. If the display surface is rigid and pressed on the skin with offset pressure, (therefore, the skin at the edge of the cave can not move,) the edge gives the opposite force which cancels the total force by air [12]. Then, the stress is induced only near the surface. The horizontal pressure (normal stress) distribution on the skin is illustrated in **Fig. 5**, where the r is the distance from the center of the pressure circle. **Fig. 6** shows the theoretical value of inner stress at depth z, under the center of the air pressure circle, when we assume the skin as a homogeneous elastic body. The figure tells us typical parameters of stress, the isotropic pressure $s_{xx} + s_{yy} + s_{zz}$ and normal stress s_{zz} at the deep level (2mm) is smaller than 10% of that at the shallow level (0.7mm) if we let the radius of the cave r_0 to be 1mm.

The method gives more complete selective stimulation than the previous one proposed in [8]. And the laborious process of attachment and calibration is no longer necessary.

ii) Stimulation to the deep receptors

Contrarily, the vibration of the stimulator gives common stress to both the shallow and the deep receptors. The deep stimulation would be only required to display overall vibration induced by stick-slip which would cause subtle difference of texture feeling [13], while the superficial stimulation would play a major role to display virtual textures as Phillips and Johnson [14] have reported in experiments on monkeys.

Thus, we can selectively stimulate the receptors at different depths, although (1) the direction of the applied surface force is not controllable, and (2) the stimulation to intermediate receptors (Merkel cell and Ruffini endings) is not specified. In the following section, we show the results of the superficial stimulation, because we are mainly interested in a display of a fine texture now.

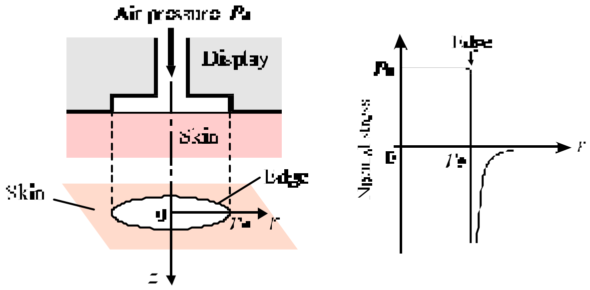


Fig. 5: The normal stress distribution on the skin under the air pressure. The r is the distance from the center of the pressure circle. If the skin at the cave edge can not move, the total force onto the skin becomes zero.

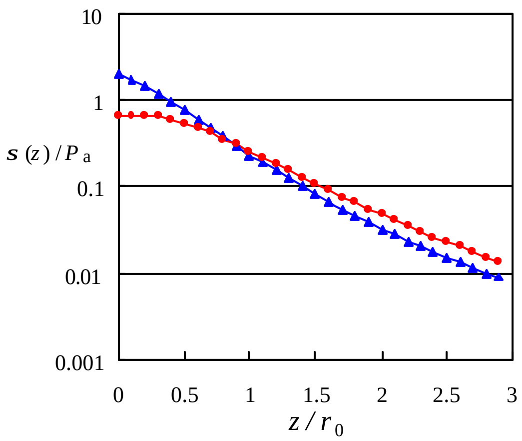


Fig. 6: Theoretical value of typical parameters of stress, isotropic pressure $s_{xx}+s_{yy}+s_{zz}$ (▲) and normal stress s_{zz} (●) in the elastic body vs. the depth z, under the center of the air pressure circle shown in **Fig. 5**. It is seen that both isotropic pressure and normal stress at the deep level (2mm) is smaller than 10% of that at the shallow level (0.7mm) if we let the radius of the cave r_0 to be 1mm.

3 Details of superficial stimulator

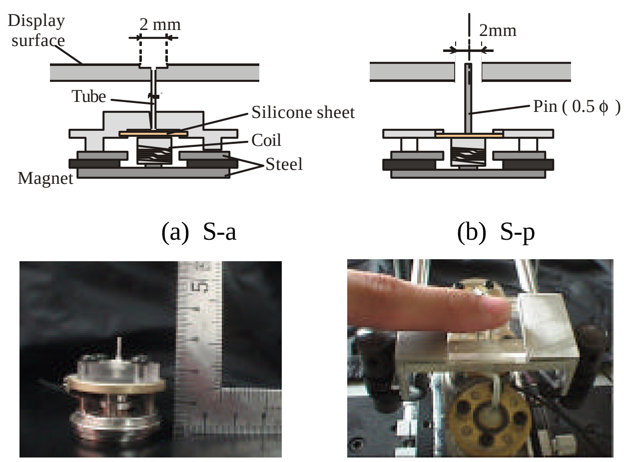
One mechanism of the superficial stimulators is based on air pressure as described above. We call this stimulator "S-a," and it enables us to fabricate various arrays easily. On the other hand, we also use another superficial stimulator for the basic experiments which has a similar structure but in which a fine pin (0.5 mm in diameter) is used instead of the air pressure. We call this "S-p."

The air pressure in the cave of "S-a" is controlled by a piston through a tube. (See **Fig. 7** (a).) **Fig. 8** shows the air pressure amplitude for constant amplitude of input sinusoidal voltage at each frequency. The pressure was measured with the cave being covered with pressure sensor airtightly. The frequency characteristics is nearly flat until 300 Hz. The relationship between the measured pressure and the input voltage was evaluated as

Input of 1 [V] $\Leftrightarrow$ 2.8 [kPa] = 28 [gf/cm^2] at 100 [Hz]

In the following experiments, we show experimental conditions using the input voltage.

Fig. 7 (d) shows the view of the experiment. The photograph is that of the apparatus having three superficial stimulators without the overall vibrator.



(a) S-a (b) S-p

(c) (d)

Fig. 7: The structures of the superficial stimulators S-a (a) and S-p (b). The photograph of air pressure controller (c) and a view of the experiment (d).

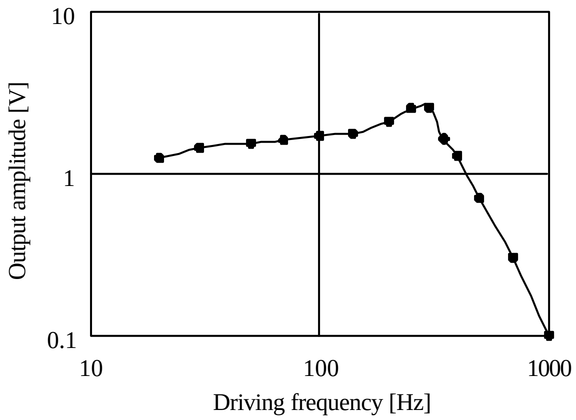


Fig. 8: Air-pressure-sensor output which was attached over the cave of S-a vs. frequency, under constant amplitude of sinusoidal driving voltage.

4 Experiment I

The first experiment is to confirm the difference of feeling between the superficial stimulation and a simple vibration.

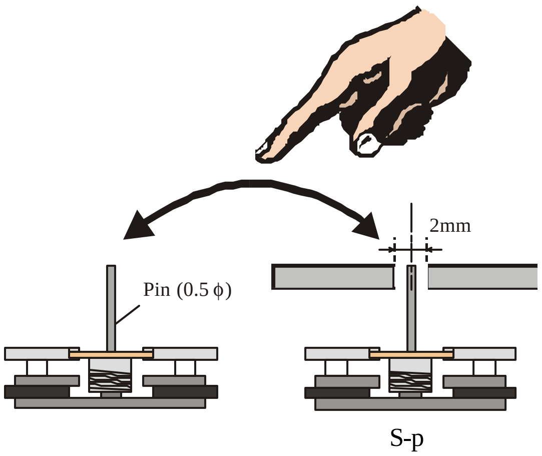


Fig. 9: An experiment to examine the difference of the feeling between the superficial stimulation and a simple contact to a pin vibration. (Experiment I.)

Procedures

The subject touches two kinds of stimulators successively, and answers whether there are any differences between them. (See **Fig. 9**.) One is the superficial stimulator S-p described in the previous section. The other is a simple touch on the same pin vibrator as that of S-p. A sinusoidal driving signal at 50 Hz is given to the both stimulators for 1 sec following 1 sec of no signal period. The amplitude of the input voltage is 4 times as large as the minimum sensible amplitude in S-p. The skin and the pin have tight contact each other before the signal is given. The experiments are done for the finger and the thenar of seven subjects in their twenties and thirties including we three authors.

Results and discussions

All of the subjects answered the two stimuli were clearly different. The simple pin gave a vibratory sensation similar to the feeling as we touch vibrating surface like an audio speaker cone. We felt a vibration rather than a touch. Then the stimulated point was vague, and it could be imagined that we were touching some larger object. On the other hand, the S-p did not make us sense vibration which reached the deep part of the skin, and it was as if a small bug was creeping on the skin. The stimulation area was felt small.

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

5 Experiment II

Experiment I shows the human ability to distinguish the difference of very small dimension of the pressure distribution. This is a reason why the pin arrays can not display real touch on a texture. Next we examine another discrimination test. Two kinds of stimulation have different local pressure distributions within 1 mm radius circle, but the stimulation given affects only the shallow receptors in both cases.

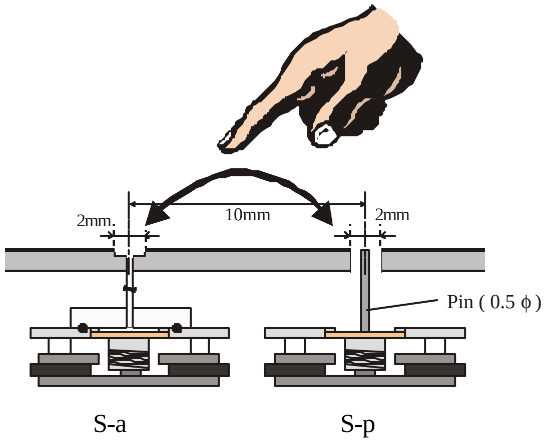


Fig. 10: Set up of air-pin discrimination test in Experiment II .

Procedures

First, the subject receives the stimuli from apparatuses S-a and S-p, successively, and memorizes the feelings. Then, for a randomly selected stimulus between S-a and S-p, she/he answers which is used. The tests are repeated twenty times for a subject, and we record the correct answer ratio. During the experiment, the subjects wears headphones and eye-masks not to obtain any cue from the sound and sight. Then the hand of the subject is guided by the observer. Before the test, we tuned the driving amplitude so that the feeling of S-a and S-p is most similar. The experiments are done for the index finger and the thenar of six subjects from their age twenties to thirties. (The authors are not included.) And we record each result for the four kinds of signals: 1) sinusoidal wave of 20 Hz with amplitude 3 [V]*, 2) sinusoidal wave of 100 Hz with amplitude 3 [V], 3) random phased signal** and 4) Pulse sequence.***

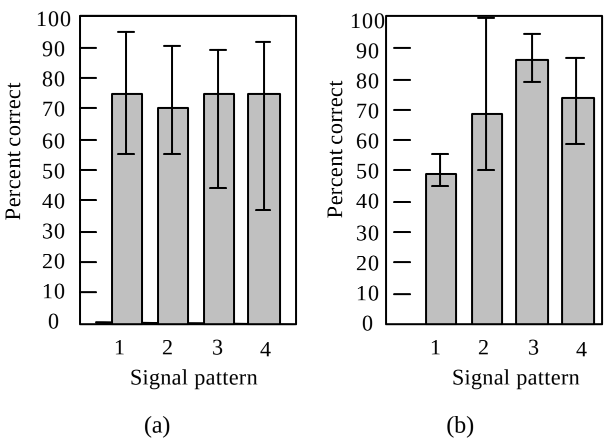


Fig. 11: Correct answer ratio of the air-pin discrimination test for fingerchip (a) and thenar (b), for signal patterns 1) sinusoidal wave of 20Hz, 2) sinusoidal wave of 100Hz, 3) random phase signal and 4) pulse sequence.

Results and discussions

Fig. 11 shows the correct answer ratios averaged among the subjects. The results say that the subject could find some differences between the two stimuli, but they were similar so that the subjects missed the judge at a 30% rate even if they concentrated the attention.

Thease results mean that the discrimination ability of fine stress distribution becomes remarkably degraded under the condition that the stimulation is limited to one level of receptors.

* The minimum sensible voltage was about 0.7 V (2 kPa) at 50 Hz.

** A band limited signal from 10 Hz to 200 Hz with an effective value 2 V.

*** The width and height of each pulse was 0.5 ms and 6 V, respectively, and the frequency was 6 pulse per second.

6 Experiment III

When several superficial stimulators are driven by adequate signals, we can feel something sliding on the skin. And some signals induce a finer virtual texture than the stimulator spacing. In this experiment we examine the relationship between the subjective fineness versus the driving signal.

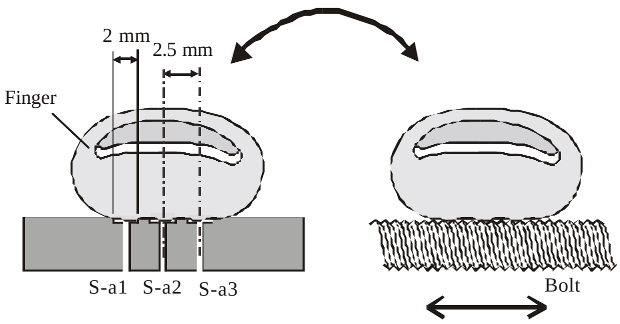


Fig. 12: An apparatus having three superficial stimulators (left). The subjects answer the subjective fineness comparing with three kinds of moving surfaces. (Experiment III.)

Procedures

Three superficial stimulators S-a1, S-a2 and S-a3 which are arrayed in a line are driven with sinusoidal signals with various frequencies and amplitudes. The center-to-center spacing of the stimulator is 2.5mm. In each test, the three drivers are given a common signal for 0.6 sec, and it is repeated with 2 sec period. (No signal for 1.4 sec.) The six subjects answer the perceived (horizontal) fineness comparing with the real touch of three objects which have groove widths of 0.6mm, 0.9mm and 1.2mm (Bolts of 3 mm, 6 mm, and 8 mm in diameter, respectively). The objects are reciprocating sinusoidally with 1.3 second period and the maximum speed 7.0 cm/s. The subject is not allowed to move the finger horizontally, but the contact pressure is arbitrary. It is up to the subject if he/she use the same finger for the comparison, or the finger of the other hand.

The answer is classified into the four categories: I) finer than 0.6mm, II) between 0.6mm and 0.9 mm, III) between 0.9mm and 1.2mm, and IV) coarser than 1.2mm.

Results and discussions

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, 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 0.9mm, 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 fine virtual texture. Unexpectedly, even at 20 Hz some subjects perceived the displayed stimuli as finer than the 1.2 mm pitch bolt.

In the series of researches of Kats, Stevens and Harris [15], Taylor and Lederman [16,17], 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.

Table 1: The assignment of the point to the category of the fineness of the virtual object.

Perceived Pitch [mm]	I	0.6	II	0.9	III	1.2	IV
Pint	0	0.5	1	1.5	2	2.5	3

Table 2: Subjective fineness vs. the signal frequency and amplitude. The numbers are the average points described in Table 1. The amplitude "×n" means n times of the minimum sensible amplitude.

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

7 Experiment IV

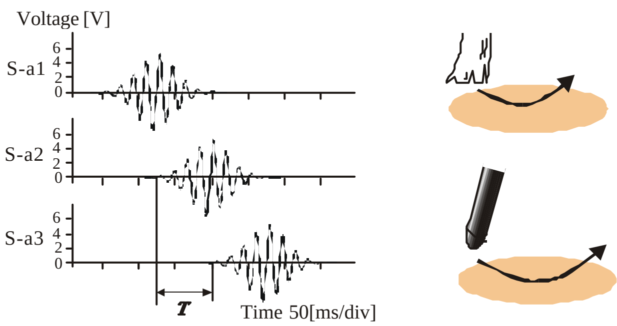
This experiment used an apparatus identical to that of Experiment III. When we presented time-delayed signal packets for the successive three stimulators, a realistic feeling arises as if something swept over the skin. See **Fig. 13**. Here we report the examples of the tactile feeling for some driving patterns. Evaluation of the reality remains subjective in this stage, but it gives us hints for future works to understand human tactile perception and to realize tactile feeling display.

Procedures

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

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

as shown in **Fig. 13**. The width of the envelope τ and the delay T are fixed to 37.5 [ms] and 75[ms], respectively. For the various amplitude A and carrier frequency f, the four subjects and we three authors described the sensation compared to touching real objects. Here the τ and T determined above induce realistic feeling, as if something swept over the finger -regardless of the A and the f.



(a) (b)

Fig. 13: Signal waveforms of the stimulators (a) and the image of tactile feeling (b). Subjects felt something to sweep over the finger. Perception of the associated object changed according to the carrier frequency and the amplitude.

Results and discussions

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 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, although the hardness was not so clear. For example, the "ball-point 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 felt a bundle of fibers (not a single fiber) inducing stick-slip.

Table 3: An associated object vs. the carrier frequency and the amplitude of the time-delayed signal. The amplitude "$\times n$" means n times of the minimum sensible amplitude at each frequency.

Frequency / Amplitude	30Hz	40Hz	70Hz	100Hz
×2	A soft fiber	A soft fiber	A soft fiber	A soft fiber
×4	A ball-point pen	A pin	A bundle of fibers	(An edge of felt ?)
×8	A grating with round ridges	A fine grating	A hard brush	?

8 Summary and discussions

We proposed a method to stimulate the superficial and deep mechanoreceptors selectively. We have not fully proven that our apparatus really selectively stimulates the receptors, however, we obtained some interesting results using it. Although humans can clearly discriminate a small difference of pressure distribution within a small area on the skin when there is difference in the 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 finer virtual texture than the stimulator spacing (Experiment III), and time-delayed signal displayed other realistic tactile feeling, like a brush sweeping across the skin.

Our research aimed to achieve realistic display of tactile feelings. This paper showed the 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.

Here we have left one 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 are hopefull about realizing the tactile feeling display.

Tactile hyperacuity [18] suggests a remarkable ability to detect the horizontal difference. And it would be important to detect geometric configuration as in brailles reading. However, any part of the skin -regardless of receptor density- perceives the tactile feeling almost identically, which 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 [19,20], our concept will prove effective.

Before getting the answer, we have to wait for the results of future works, including the experiments using a 2-D array of stimulators, as well as examination of the selective stimulation hypothesis based on a micro-neurographical approach.

Acknowledgment

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

References

[1] K. B. Shimoga, "A Survey of Perceptual Feedback Issue in Dexterous Telemanipulation: Part II. Finger Touch Feedback," Proc. VRAIS ‘93, pp. 271-279, 1993.

[2] Linvill, J.G. and Bliss, J. C., "A direct translation reading aid for the blind," Proc. IEEE, 54, pp. 40-51, 1966.

[3] M. Shimojo, M. Shinohara and Y. Fukui, "Shape Identification Performance and Pin-matrix Density in a 3 dimensional Tactile Display," Proc. VRAIS ‘97, pp. 180-187, 1997.

[4] Cohn M. B., M. Lam and R. S. Fearing, "Tactile Feedback for Teleoperation," Telemanipulator Technology Conf., Proc. SPIE, Vol. 1833, pp.15-16, 1992.

[5] Y. Ikei, K. Wakamatsu and S. Fukuda, “Image Data Transformation for Tactile Texture Display,” Proc. VRAIS ‘98, pp. 51-58, 1998.

[6] G. C. Vanderheiden, J. Mendenhall, K. L. Ford, T. Andersen, and W. L. Boyd, “Access to graphical-based operating systems for blind individuals ‘System 3’ model,” Trace R&D Center Annual Report, Trace R&D Center, University of Wisconsin, pp19-20, 1991.

[7] R. D. Howe, “A Force-Reflecting Teleoperated Hand System for the Study of Tactile Sensing in Precision Manipulation,” Proc. 1992 IEEE Int. Conf. Robotics and Automation, pp. 1321-1326, 1992.

[8] N.Asamura, N. Tomori and H. Shinoda “A Tactile Feeling Display Based on Selective Stimulation to Skin Receptors,” Proc. IEEE VRAIS ’98, pp.36-42, 1998.

[9] S. R. Geiger ed. “Handbook of Physiology, Section 1: The Nervous Sytem,” American Physiological Society, 1984.

[10] T. Maeno, K. Kobayashi and N. Yamazaki, “Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptors,” Bulletin of JSME International Journal, Vol. 41, No. 1, C, pp. 94-100, 1998.

[11] R. S. Johansson and A. B. Vallbo, “Tactile Sensory Coding in the Glabrous Skin of the Human Hand,” TINS, pp. 27-32, 1983.

[12] S. P. Timoshenko and J. N. Goodier: “Theory of Elasticity,” McGraw Hill, 1970.

[13] M. A. Srinivasan, J. M. Whitehouse and R. H. Lamotte, “Tactile Detection of Slip: Surface Microgeometry and Peripheral Neural Codes, Journal of Neurophysiology, Vol. 63, No. 6, pp. 1323-1332, 1990.

[14] J. R. Phillips and K. O. Johnson, “Tactile Spatial Resolution II. Neural Representation of Bars, Edges, and Gratings in Monkey Primary Afferents, Journal of Neurophysiology, Vol. 46, No. 6, pp. 1192-1203, 1981.

[15] S. S. Stevens and J. R. Harris, “The Scaling of Subjective Roughness and Smoothness,” Journal of Experimental Psychology, Vol. 64, No. 5, pp. 489-494, 1962.

[16] M. M. Taylor and S. J. Lederman, “Tactile Roughness of Grooved Surfaces: A Model and the Effect of Friction,” Perception & Psychophysics, Vol. 17, No. 1, pp.23-36, 1975.

[17] S. J. Lederman, “Tactile Roughness of Grooved Surfaces: The Touching Process and Effects of Macro-and Microsurface Structure,” Perception & Psychophysics, Vol. 16, No. 2, pp.385-395, 1974.

[18] J. M. Loomis and C. C. Collins, "Sensitivity to Shifts of a Point Stimulus: An Instance of Tactile Hyperacuity," Perception & Psychophysics, Vol. 24, No. 6, pp. 487-492, 1987.

[19] H. Shinoda, M. Uehara and S. Ando, “A Tactile Sensor Using Three-Dimensional Structure,” Proc. 1993 IEEE Int. Conf. Robotics and Automation, pp.435-441, 1993.

[20] P. Dario and G. Buttazzo, “An Anthropomorphic Robot Finger for Investigating Artificial Tactile Perception,” Int. J. Robotics Res., Vol.6, No.3, pp.25-48, 1987.