Fundamental Research on Tactile Perception for Development of a Tactile Feel Display

Iyo Kunimoto[1], Naoki Saiwaki[1], Osamu Katayama[2], and Yasuji Inobe[2]

[1] Grad. School of Nara Women's Univ. Kitauoya Nishi-machi, Nara 630-8506, Japan
iyoyoyo4@yahoo.co.jp, saiwaki@cc.nara-wu.ac.jp
[2] Research Laboratories, DENSO CORPORATION 500-1 Minamiyama, Komenoki-Cho, Nisshin-shi, Aichi 470-0111, Japan
okataya@rlab.denso.co.jp, YASUJI_INOBE@denso.co.jp

Abstract. In our daily life we use a large number of electronic devices incorporating a touch interface, e.g., mobile phones and the iPod Touch. This function is, however, in its infancy, permitting only input, with output being limited only to vibration to confirm input. Meanwhile, if we could create touch sensations with "qualitative information," such as the delicate sensation of materials or the feeling of touching an object, it would bring not only an improvement in the quality of touch sensations, but would also bring the possibility of developing new human interfaces such as more realistic VR systems and user-friendly universal communication tools for people with disability. Such human interfaces would be most effective if they did not require the development of special vibratory devices.On this basis, the authors have developed, based on knowledge gained from previous research, a prototype of a unique vibratory device employing a micro- motor, and employed it in evaluation experiment in which various differing tactile sensations are presented to study subjects.

1 Introduction

Conventional tactile feel displays such as Phantom are focused on presenting sensations of force such as shape and force feedback, and the texture was presented mainly through irregularities in the surface. As presented by the authors at HCI'05, an artificial tactile display is under development which will present the delicate sensations of non-rigid materials such as cloth [1]~[6]. This device is in the form of a small plate to which an ICPF (Ionic Conducting Polymer gel Film) has been applied, and produces minute vibrations when a voltage is applied to the film. By applying a signal incorporating a specific frequency component to multiple plates arrayed on a flat surface, a variety of tactile sensations can be created. On the other hand, manufacture of ICPF requires a considerable level of technology and generates large amounts of heat. The film has limited durability and is expensive, and its reliability leaves much to be desired. These defects have proved a hindrance to progress in research.This research has therefore employed cheap and readily available micro-motors, in the creation of a prototype system to present tactile sensations to the fingertips through mechanical vibration.[7]

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Use of this system permits expression of tactile sensations with a number of variations, albeit in a comparatively simple manner. Evaluation of these sensations by users were investigated, and based on the results, conclusions were drawn for generation of more diverse tactile sensations.

2 Development of a Tactile Feel Display

Micro-motors are fitted with an eccentric counterweight on the shaft, resulting in vibration when the shaft rotates. The motors are approximately 1cm in diameter, and are therefore readily incorporated in miniaturized devices. They are activated by simple application of a voltage and consume very little power, and are therefore employed in such applications as mobile phones and game controllers.

The authors constructed a vibration device comprising 25 micro-motors arrayed on a flat square surface (see Figure 2). To provide a smooth vibrating surface and to ensure that vibrations are transmitted directly, a thin sheet of recycled paper was applied over the motors. As shown in Figure 3, the device is used by touching the forefinger, middle finger, third finger lightly on the surface of the device, and using the thumb and little finger to move the device in the same manner as a mouse. A film with low friction coefficient is applied to the bottom surface of the device, permitting a tactile vibration to be felt while sliding the device freely over the desk in a manner characteristic of natural touching.

The arrangement of the vibrators as shown in Figure 2 initially gave rise to fears that the vibration might be reduced or biased in some way due to interference between vibratory motors, and that localized heating might occur; however, a preparatory experiment showed that vibration at each fingertip on the touch surface was similar, and that almost no heating was apparent.

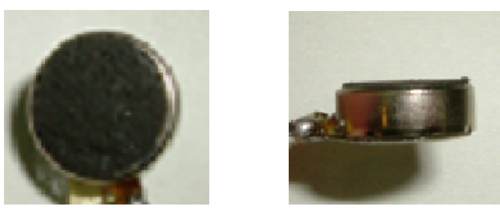

Fig. 1. Micro -motor

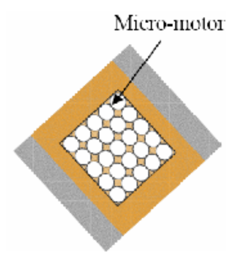

Fig. 2. Layout of micro-motors

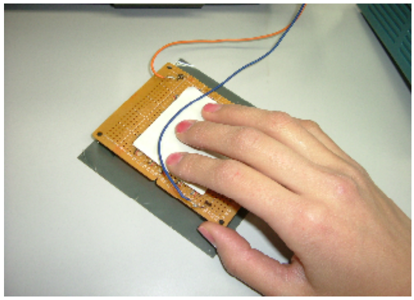

Fig. 3. Tactile Feel Display

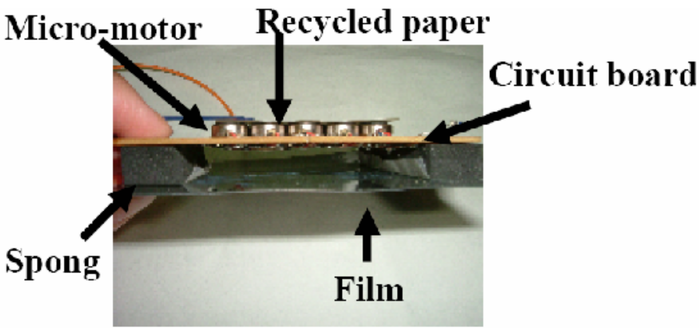

Fig. 4. Side View of Device

The voltage and frequency of the vibration applied to this tactile feel display is controlled with an oscillator able to generate any desired waveform. The signal from the oscillator is passed through an amplifier to the device to generate various vibrations, sensed by the fingertips as various sensations.

3 Method for Generating Tactile Sensations

This section describes the tactile sensation patterns created for evaluation experiments using the tactile feel display described in Section 2.

The authors varied the oscillator frequency, amplitude, offset and duty ratio to create six vibration patterns with distinctly different tactile sensations based on knowledge gained from previous research and subjective perceptions[1]~[6],[8],[9].

The vibration patterns were obtained with a programmable oscillator using the following parameters (see Figure 5).

Vibrations become finer as frequency increases from lower frequencies (e.g. 5Hz, 13Hz) to higher frequencies (e.g. 80Hz, 150Hz, 180Hz, 220Hz). The sensations associated with the changes in vibrations are often expressed subjectively with such terms as 'hard & lumpy', 'hard & grainy', 'slippery smooth' and 'dry smooth.'

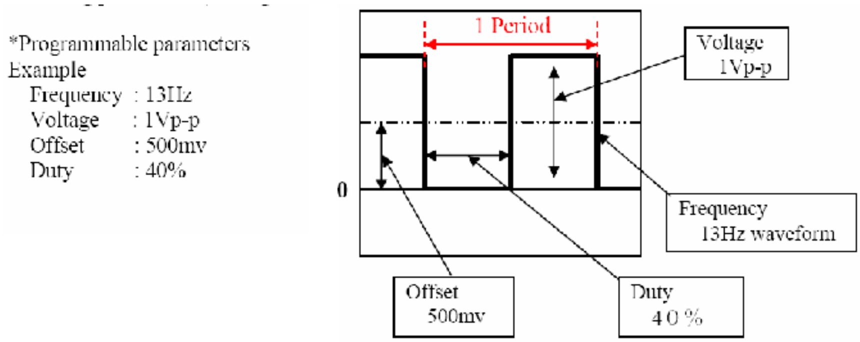

Fig. 5. Parameter Settings Example

On the other hand, offset, duty ratio and voltage were adjusted to improve the ability to sense these basic frequency characteristics at the fingertips. For instance, given the same voltage, vibrations are perceived to be transmitted to the fingertips less readily at higher frequencies than at lower frequencies. This is thought to be due to the fact that rotation characteristics of the micro-motor are such that when frequency increases, reverse rotation through a very small angle occurs repeatedly before sufficient torque develops, weakening the actual vibration produced.

In a preparatory experiment, it was found that doubling the voltage to $2_{Vp\text{-}p}$ at frequencies of 180Hz or more produced a strong perceived tactile sensation at the fingertips in a manner similar to that at frequencies below 180Hz. Following shows the tactile sensation patterns created for the evaluation experiments based on these observations.

Table 1. Six Tactile Sensation Patterns Employed in Evaluation Experiments

Fine-graininess		Frequency (Hz)	Voltage (Vp-p)	Offset (mv)	Duty (%)
	①	5	1	500	60
	②	13	1	500	40
Coarse	③	80	1	400	50
	④	150	1	400	50
↓	⑤	180	2	0	50
Fain	⑥	220	2	100	50

1 Soft & airy 2 Soft & lumpy 3 Sharp 4 Hard & grainy 5 Slippery smooth 6Silky smooth.

(From (1) to (6) are our subjective tactile sensations described using Japanese adjectives).

Note that frequency as used here is derived from the period of the alternating current signal presented to the tactile feel display, and is not the frequency component included in the vibration generated by the micro-motor. Laser distance measurement was employed in analyzing the vibration spectrum of the surface of the tactile feel display. These frequencies were observed as the primary component of the spectrum, however the spectrum also included secondary and tertiary frequencies associated with the mechanical structure and variations in torque. The effects of these subsidiary components, more effective vibration control incorporating these components, and methods of expressing the tactile sensations, are currently under consideration.

4 Evaluation Experiments

4.1 Preparatory Experiment

To investigate the relationship between the six basic tactile sensation patterns and the perceptions of these sensations by the subjects, an experiment was conducted in which patterns were applied randomly as stimuli. To isolate the subjects from information from other sensory organs, they were blindfolded and provided with earplugs. No limits were placed on the duration of exposure to the tactile sensations. Subjects were required to select from a list of 15 expressions describing the tactile sensations in a prepared questionnaire, or to enter responses in their own words.

The list of 15 expressions was as follows.

Slippery smooth	Slightly slippery-smooth	Silky smooth
Hard & grainy	Slightly hard & grainy	Sharp
Soft and airy	Slightly soft and airy	Pleasant
Dry smooth	Painful	Satiny
Soft	Normal	Don't know

The experiment showed that all subjects did not always employ the same expression each time to describe a given vibration pattern; however a definite tendency was apparent. For example, 'rocky ' appeared together with 'soft and airy', while not with 'fine-grained' or 'hard & grainy'. Furthermore, 'hard & grainy' and 'soft and airy' appearing frequently at low frequencies, and 'slippery smooth' and 'dry smooth' appearing frequently at high frequencies, were distinguishable in almost all cases. Overall, the experiment indicated that there are a number of categories expressing tactile sensations in an n-dimensional space. This is thought to show that the tactile feel display developed by the authors is able to present everyone with at least the number of categories of the differing tactile sensation stimuli, and that effective evaluation experiments are possible.

4.2 Evaluation Experiment

In this evaluation experiment the method of providing the tactile sensations, the questionnaire, the time for which the subjects were presented with the tactile sensations, the response time, and the method of operating the device were improved based on the results of the preparatory experiment. Practical details are as follows.

– Sequences of presenting tactile feel display patterns. Since changes were apparent in the evaluation criteria between the start and end of the experiment, tactile sensation patterns presented at the start were again presented at the end of the experiment to allow re-evaluation.
– Changes to questionnaire. The expressions ‘pleasant’ and ‘soft’, and ‘hard & lumpy’ and ‘rocky’, appearing frequently in entries in subjects’ own words, were added to the questionnaire used in the preparatory experiment. In addition, fine-graininess and softness were evaluated on a five-point scale.
– Time for which subjects were presented with tactile sensations, and response time. Since considerable differences were apparent between subjects in the length of exposure to the tactile sensations, and in response time, exposure time and response time were both limited to a maximum of 30 seconds. Furthermore, since movement, and speed of movement, of the hand were thought to be important factors in analysis, the experiment was recorded on video.
– Touching the tactile feel display. A blindfold had been employed to eliminate the influence of vision when touching the tactile feel display. This methodology was recognized as insufficient, and made subjects feel uncomfortable. For the evaluation experiments, a screen was therefore constructed to ensure that subjects were unable to see hand movement.

Furthermore, application of the questionnaire to the screen was useful in that it presented subjects with the expressions simultaneously with exposure to the tactile sensations.

These improvements were implemented and six tactile sensation patterns presented to 12 female university students aged around 20, using three methods in which the sequence of presentation was changed between ‘fine-graininess sequence’, ‘coarseness sequence’ and ‘random sequence’.

Three expressions were added to the 15 expressions employed in the preparatory experiment, so that a total of 18 expressions were provided in the questionnaire for subjects to describe the tactile stimuli. If a suitable expression was not available, subjects were able to describe sensations in their own words. Strength of expressions such as ‘fine-grained’ and ‘soft’ was evaluated subjectively on a five-point scale.

Examples of results obtained when presented in the random sequence are shown in Figure 6 and Figure 7. Using the tactile feel display, it was found that almost all subjects were able to perceive a hard, coarse vibration (hard & lumpy sensation) with a

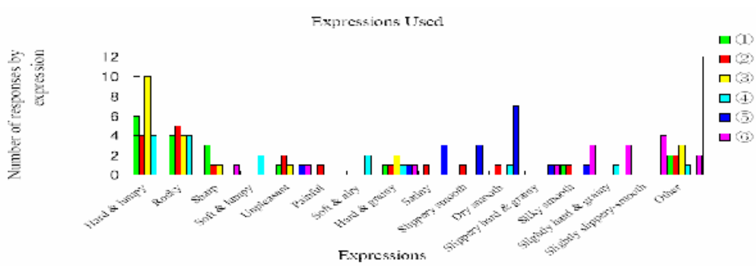

Fig. 6. Distribution of Expressions Used by Subjects to Describe Tactile Sensations for Presented Patterns

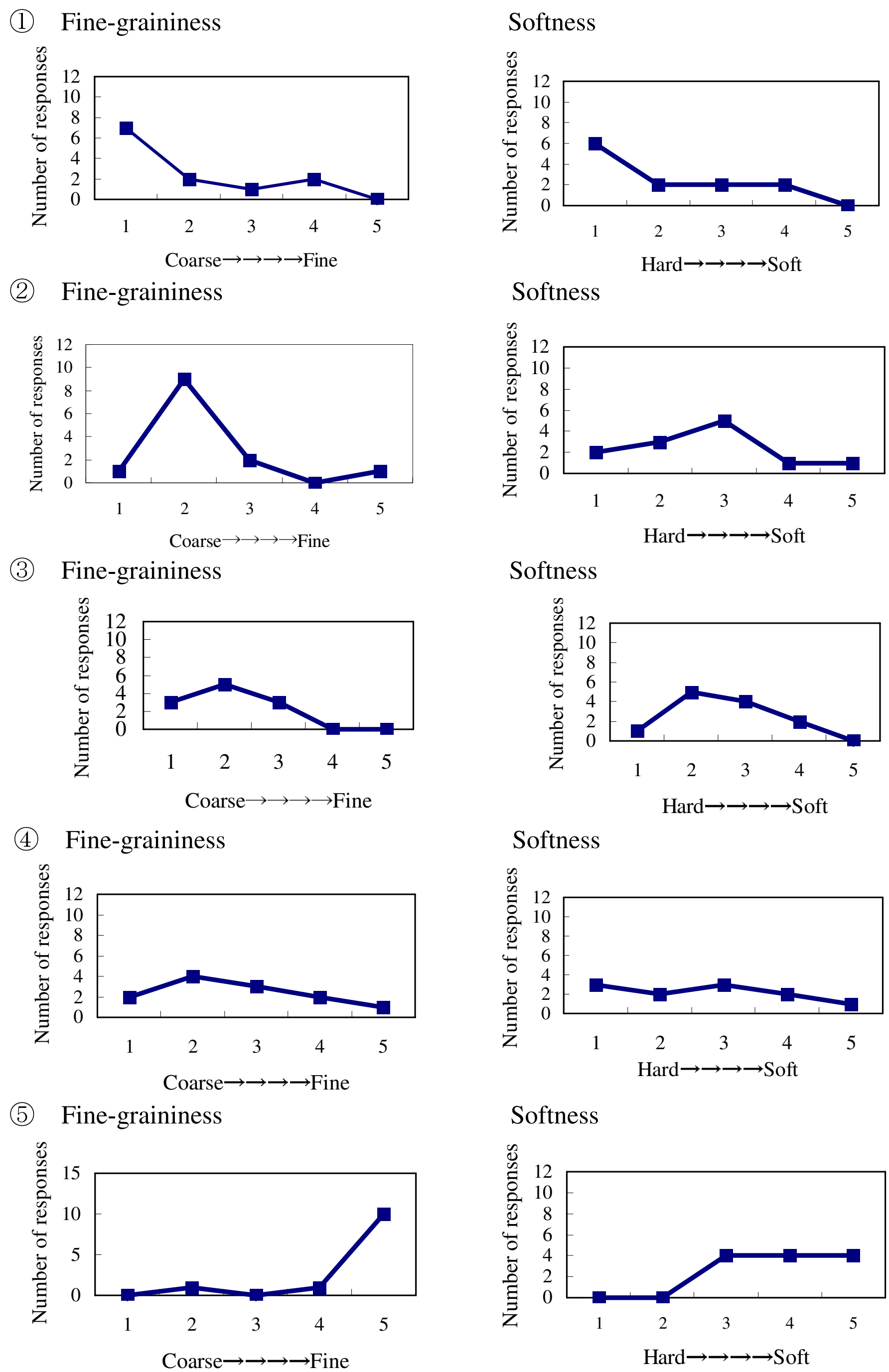

Fig. 7. Distribution of Evaluations of Fine-graininess and Softness for Tactile Sensation Patterns

⑥ Fine-graininess Softness

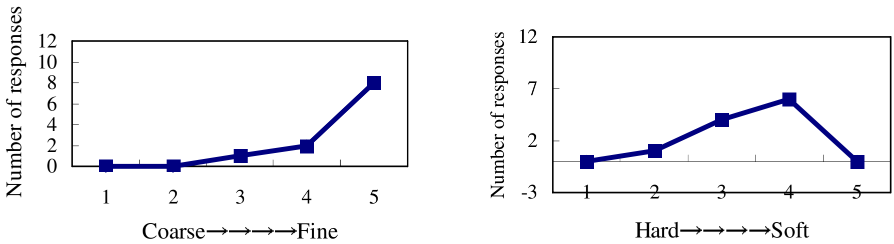

Fig. 7. (*continued*)

low frequency in the vicinity of 10Hz ((1) and (2)), and a fine soft vibration (slippery smooth sensation) with a high frequency in the vicinity of 200Hz. This corresponds accurately with a previously known model in which differing touch sensory nerves are stimulated by differing stimulating frequencies, resulting in differing sensations.

5 Observations and Topics for the Future

Results of evaluation of tactile sensation patterns in 4.2 may be summarized as follows.

1. Evaluation of the tactile sensation stimuli initially presented to the subjects contained considerable variation, and thus stimuli were presented again at the end of the experiment. Evaluation criteria were therefore not formulated the first time, and differences between individuals were considerable, however a variety of tactile sensations were experienced the second time, assisting in formulation of evaluation criteria. Responses of almost all subjects were then in agreement.
2. Results in Figure 7 show a mutual relationship between fine-graininess and softness. Subjects perceived fine-grained items as soft, and coarse items as hard, and indeed, textures such as fine-grained and hard rocks do exist in the real world. The ability to express and control these two qualities separately in the tactile feel display requires consideration.
3. In connection with the phenomena in (2) above, opinions as to whether the 150Hz tactile sensation patterns were soft or hard varied (see Figure 6 and Figure 7). This is thought to be due to variations between individuals; however, those considering the stimulus to be soft also selected 'soft & airy' and 'soft & lumpy', while those considering it to be hard tended to select 'hard & lumpy' and 'rocky'. The authors set the stimulus in reference to the intermediate 'hard & grainy.'

Consideration of the reason for the ambiguity surrounding the expression 'soft' leads to the conclusion that there exists a threshold around which the recognition result changes dynamically with minute changes in strength of vibrations with the frequency of the stimuli presented. Those replying with 'hard' and 'rocky' also responded that they perceived stimuli to be strong, while those replying with 'soft' and 'soft & lumpy' also responded that they perceived stimuli to be weak. For the future, it is necessary to investigate whether it is possible to identify the fine area in which perception changes with smooth change in frequency and strength of vibration, and to investigate the connection between this and the human perception of tactile sensations, and how it may be useful in control of the tactile feel display.

To facilitate control, the interface employed to present the tactile sensations must be such that these sensations can be perceived by most people. The 150Hz tactile sensation pattern used in the current experiments is therefore qualitatively inferior to the 180Hz pattern to which all subjects responded with 'soft', though the value of the interface is increased by increasing the perception of tactile sensations in this intermediate area. Furthermore, in order to investigate the flexibility inherent in the characteristics of human perception of tactile sensations, it was considered particularly effective to employ stimuli that can be perceived in different ways depending on the individual and on context in this manner. For example, it is possible that research may progress to a point at which differences in brain activity patterns between perception of, for instance, a presented 150Hz stimulus as hard or soft are analyzed using f-MRI. The authors have already commenced experiments in which f-MRI is employed to determine whether or not differences in perception of tactile sensations are able to be recognized.

4. When an 80Hz tactile stimulus was presented in the fine-graininess sequence, it was perceived as coarse and hard, though when presented in the coarseness sequence, it was perceived as slightly soft. This shows that the evaluation is affected by a comparison between the immediately previous and current stimuli.

The authors presented this stimulus as 'sharp', however only one subject responded with 'sharp', and most responded with 'hard & lumpy' or 'rocky'. The physical representations of the expressions 'sharp' and 'hard & lumpy' differ as 'sharp' and 'mild' vibrations respectively, with 'sharp' vibrations incorporating a greater high-frequency component. This may suggest that the authors, rather than the subjects, had become more sensitive to the high-frequency component during the progress of the experiments. Furthermore, passing signals with a considerable high-frequency component through a low pass filter (permitting user selection of cutoff frequency) before input to the tactile feel display may be able to create continuous changes in the tactile sensations.

5. The 13Hz tactile stimulus was intended to be perceived as 'soft & lumpy', however many subjects responded with 'hard & lumpy' or 'rocky'. One reason for this is the perception of the stimulus as 'hardness'. In contrast to the 80Hz tactile stimulus in (4) above, this shows the need to reduce the high-frequency component to present a 'rounder' sensation. As an aside, subjects responding to the effect that long-term application of this stimulus to the fingertips produced an unpleasant sensation noted that it occurred much more frequently than with any other tactile sensation pattern. This is thought to be due to a relationship with other bio-rhythms. While associated with LPF in (4) above, we intend to investigate the possibility of a tactile morphing providing a smooth transition from 'sharp' to 'soft & lumpy' sensations, and tactile equalizing in which a specific sensation is emphasized.

6. Based on the analysis by the authors of the factors in the evaluation of the tactile sensations of actual cloth, it is thought that if a distinct 'soft & airy' sensation can be presented, expression of tactile sensations to represent such aspects as 'fur liners' and 'piles' would be possible. However, in order to achieve this it is essential to control the sensation of an opposing force when pressed with the finger. A report has been received to the effect that a 'soft & airy' sensation is perceived when a low frequency is presented, however this is not a sponge-like sensation of an opposing force, and tends to be confused with softness.

Perception of tactile sensations suggest 'relativity', 'flexibility' and 'context dependency', and it is thought that consideration of these characteristics will permit highly realistic control of tactile sensations.

Keeping in mind the points noted in this paper, the authors wish to incorporate the tactile feel display in common devices used in daily life to create products useful in tactile communication.

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