A Conceptual Design of an Integrated Tactile Display Device

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Abstract: Tactile sensation is essential for many manipulation and exploration tasks not only in a real environment but also in a virtual environment. In this paper, we discuss a conceptual design of an integrated tactile display system. The system comprises two parts: a 2 DOF force feedback device for kinesthetic display and a tactile feedback device for displaying the normal stimulation to skin and the skin slip/stretch. Psychophysical experiments measure the effects of fingerpad selection, the direction of finger movements and the texture width on tactile sensitivity. We also investigate characteristics of lateral finger movement while subjects perceive different textures. From the experimental results, the principal parameters for designing a tactile display are suggested. A tactile display device is implemented using eight piezoelectric bimorphs and a linear actuator, and is attached to a 2 DOF translational force feedback device to simultaneously simulate texture and stiffness of the object.

Keywords: tactile sensation, tactile display, haptic, kinesthetic, vibration, skin slip/stretch, texture

1. INTRODUCTION

Tactile sensation is essential for many manipulation and exploration tasks. While touching or feeling the surface of an object with their fingers, humans can perceive complex shapes, texture and roughness through physical quantities such as pressure distribution, vibrations from slipping and stretching, and temperature. From this tactile information, we can understand the features of the object and can precisely manipulate the object not only in a real environment but also in a virtual environment. Tactile display devices stimulate the skin in order to generate these sensations.

A number of researchers have proposed their own tactile display systems to generate physical quantities. To provide tactile sensation to skin, they tried various display methods such as mechanical, electrical and thermal stimulation.

Most mechanical methods comprised an array of pins with a linear actuator such as a solenoid, piezoelectric actuator or pneumatic actuator. Ikei et al. proposed a vibrotactile device fixed at 250 Hz; it had fifty pins driven by adjusting the natural frequency to expand the displacement of a piezoelectric actuator[1]. Hayward and Cruz-Hernandez focused on the tactile sensation of lateral skin stretch[2]. They suggested a tactile display device for stimulating a small displacement of distributed lateral skin stretch up to several kilohertz but not for normal stimulation of pressure distribution. The device comprised 64 piezoelectric actuators connected to a membrane.

Konyo et al. used an electroactive polymer for the mechanical stimulation actuators. He proposed a tactile device to express the fine touch of a cloth surface using vibrations up to 100 Hz frequency[3]. The stiffness of the soft high polymer gel, however, was so low that it could not display the intensive stimulation of the virtual texture.

Compared with mechanical tactile display devices, an electrical tactile feedback device consumes less power and is lighter; it also has no moving parts and can maintain constant contact with the skin. Some research has been done on electrical tactile display devices because of their advantages over mechanical tactile display devices. Poletto and Doren developed a high-voltage electrocutaneous stimulator with small electrodes[4]. Kajimoto et al. modeled a nerve axon model from the properties of human skin and proposed an electrocutaneous display using anodic and cathodic current stimulation[5]. However, these tactile display devices sometimes involve user discomfort and even pain.

Thermal tactile feedback, along with mechanical and electrical tactile feedback, is one of the principal forms of sensory input presented to an operator. Thermal feedback can be used to convey information about the thermal conductivity of object identification or in the creation of a more realistic image of the objects. Several studies show that thermal information enables an object to be easily felt[6,7,8].

In this paper, we propose a new type of tactile display and an integrated tactile display system that can simultaneously provide kinesthetic and tactile feedback. The tactile display unit, which is capable of normal vibrotactile stimulation and lateral movement of the slip/stretch, is attached to a 2 DOF force feedback mechanism.

To design the tactile display unit, we performed several experiments. In section 2, we introduce characteristics of the human sense of touch and principles of designing a tactile display unit. In section 3, we discuss the measurements of the effects of fingerpad selection, the direction of finger movement and the texture width on tactile sensitivity. In section 4, we investigate the motion range and velocity as subjects perceive different textures with the thumb. From these results, we suggest the new tactile display unit in section 5; a 2 DOF kinesthetic feedback system is also introduced in this section.

2. HUMAN TOUCH SENSATION

The glabrous skin of the palmar and fingertip regions plays the most active role in tactile explorations. To perceive texture, humans generally use the thumb or index finger because, as shown in Figure 1, these parts of the body have a high sensorial density of specialized mechanoreceptors.

As shown in Figure 2, four mechanoreceptors exist in the

Fig. 1 The texture perception with thumb or index finger

glabrous skin of the palmar and fingertip regions[10,11]. Meissner corpuscles and Merkel's disks are located in upper layers, and Ruffini endings and Pacinian corpuscles are located deeper. These receptors are divided into two classes according to their adaptation rate: the slowly adapting afferent receptors and the rapidly adapting afferent receptors. The slowly adapting afferent receptors are Merkel's disks (SA I) and Ruffini endings (SA II), and the rapidly adapting afferent receptors are Meissner corpuscles (RA I) and Pacinian corpuscles (RA II).

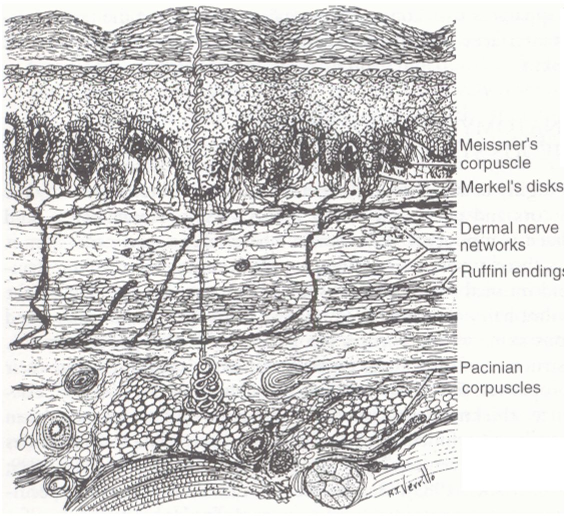


Fig. 2 The structure and location of mechanoreceptors in the glabrous skin [10]

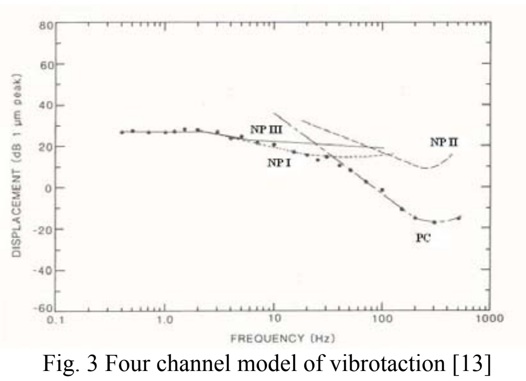


Fig. 3 Four channel model of vibrotaction [13]

The four mechanoreceptors each have different functions[10,11,12]. The SA I afferent receptors respond to the static deformation of skin such as pressure in the frequency range of 1 Hz to 10 Hz. They play an important role in detecting spatial structures such as an edge or a bar in static contact. The SA II afferent receptors provide a neural image related to the direction of skin stretch. The frequency response of the receptors ranges from 100 Hz to 500 Hz. The RA I afferent receptors with a frequency range of 2 Hz to 40 Hz detect the dynamic deformation of skin such as flutter. They are four times more sensitive than SA I afferent receptors. In addition, the RA II afferent receptors, which have a frequency response in the range of 40 Hz to 500 Hz, are the most sensitive to vibration. They are especially known to serve as acceleration or vibration detectors. Although the frequency ranges differ slightly under experimental condition of each research work, they have a similar range.

Bolanowski et al. claim that four distinct psychophysical channels contribute to taction in the glabrous skin[13]. They measured the threshold-frequency characteristics of the four channels by manipulating the stimulus parameters, as shown in Figure 3. They found that PC channels are mediated by Pacinian corpuscles and RA II fibers; the NP I channel is mediated by Meissner corpuscles and RA I fibers; the NP II channel, by Ruffini end organs and SA II fibers; and the NP III channel, by Merkel cell-neurite complexes and SA I fibers.

Hollins et al. argues that texture perception is mediated primarily by spatial encoding for coarse textures and by vibrotactile encoding for fine textures[14]. This point of view means that vibrotactile stimulation is essential for our proposed tactile display system. In addition, the lateral movement of the texture relative to the contact skin is needed to enable our system to correspond to the action of texture perception.

From the sum of their complex responses, humans can accurately perceive and discriminate the physical properties of a surface. However, some textures are so fine that lateral movement of the fingerpad across the surface of a texture and the normal vibration stimuli by lateral movement enable easy discernment and discrimination of physical properties.

From physiological and psychophysical studies on the human sense of touch, we determined the principal requirements of a tactile display device for simulating a realistic sense of touch. The requirements are as follows:

- A wide frequency range for the normal stimulation, from 1 Hz to more than 300 Hz
- A reversible lateral movement of the display regions for the skin slip/stretch, from the 0 cm/s to more than 5 cm/s
- The pressure distribution for displaying a small-scale shape
- A surface temperature control component

These guidelines are applied to the design of the new tactile display unit.

3. DESIGN PARAMETERS FOR THE ROUGHNESS DISPLAY

In this section, we discuss the psychophysical experiments for a conceptual design of a tactile display device that simultaneously generates vibrations and lateral movements.

3.1 The effect of finger selection and rubbing direction on a tactile sensation

In order to discern or discriminate texture, people usually rub the surface of material by moving their thumb or index finger in a lateral direction. Previous research show that the somatosensory cortex area related to these fingers is larger than others[17], and that the tactile resolution correlates well with the size of the corresponding representation in the somatosensory cortex.

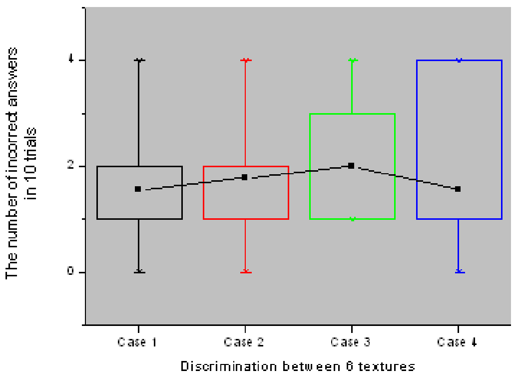
In section 3.1, we adopt two experimental approaches to design a tactile display unit in which a mouse is imbedded for manipulation by the thumb and index finger. The problems are as follows:

- different sensitivity of the touched finger
- different sensitivity according to the direction of finger movements on a contact surface

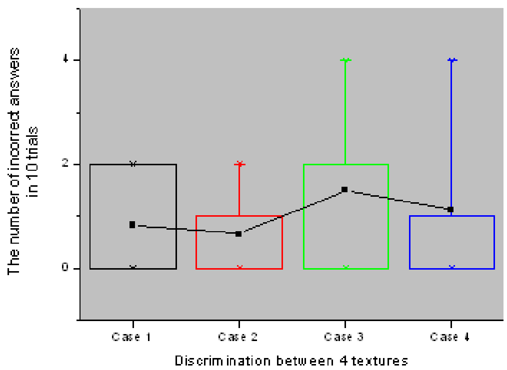
3.1.1 Experimental method

Six samples of sandpaper with different degrees of roughness are presented to a subject, and he chooses the samples to be discriminated according to its relative degree of roughness. Thereafter an arbitrary piece of sandpaper among the selected sandpaper is given to each subject. He can repeatedly compare it with the selected sandpaper, and answers the degree of roughness. The answers of each subject are scored in ten blind tests of random order. We measured the relative sensitivity of each subject based only on the fingerpad responses and not on the sense of sight. In this experiment, subjects are limited to using only their thumb and forefinger; while feeling the sandpaper, and they can only move their fingers up and down or side to side. Fifteen subjects are participated in experiment.

3.1.2 Results



(a) 6 texture discrimination of 9 subjects



(b) 4 texture discrimination of 6 subjects
Fig. 4 Result of finger and direction sensitivity.

Figure 4 shows the results of the experiment. Nine subjects chose six samples of sandpaper to be discriminated. And six subjects selected four samples of sandpaper to be discriminated. The number of incorrect answers is scored according to the following four cases:

- case 1: the thumb moves up and down
- case 2: the index finger moves up and down
- case 3: the thumb moves side to side
- case 4: the index finger moves side to side

The lower the score, the better the tactile sense. As shown in Figure 4. (a), the lowest score was obtained from the thumb moving up and down in the discrimination of six textures with an average value of 1.56. And the index finger moving up and down was the lowest score with an average value of 0.67 in the discrimination of four textures as shown in Figure 4. (b). In the discrimination of four textures, however, the thumb moving up and down with an average value of 0.83 was almost not different from the index finger moving up and down.

Therefore, we determined that the skin slip/stretch display should be designed to stimulate the thumb moving up and down, which have the ability of good perception.

3.2 The effect of texture width on a tactile sensation

3.2.1 Experimental method

To determine the optimum width of the tactile display region on the thumb, we measured the perception ability of fifteen subjects to distinguish the degree of texture roughness between six strips of sandpaper with the seven following variations in width: 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 12 mm and 14 mm. Subjects touched the six samples of sandpaper with different roughness in each width by moving the thumb up and down, and order the samples according to the relative degree of roughness. The correct order was scored. The test was performed under blind conditions.

3.2.2 Results

The experimental results show the effect of texture width on tactile sensation. As shown in Figure 5, the average value of correct order is 4.46, 4.23, 4.69, 5.23, 5.15, 5.31 and 5.15 in order of the width. There may be a threshold for discerning fine texture. We found out that subjects could precisely discriminate the roughness of fine texture with texture width above 6 mm.

From the results, we concluded that the tactile display region on the thumb must be at least 8 mm wide.

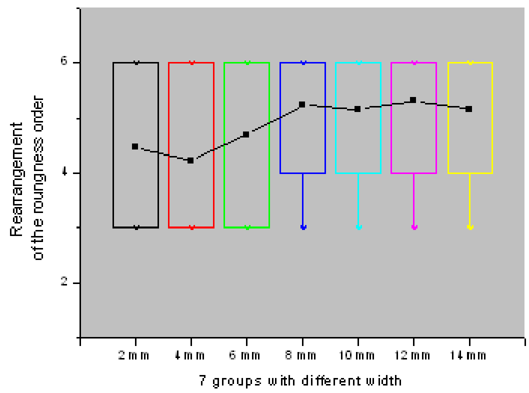


Fig. 5 Result of roughness rearrangement in different texture width

4. DESIGN PARAMETERS FOR THE SKIN SLIP/STRETCH DISPLAY

4.1 The lateral movement of finger in the texture perception

When a finger is moved across the surface of a texture, normal vibration stimulation and skin slip/stretch are provided to the contact surface of the skin by its spatial period and amplitude and the relative lateral movement. In this section, we investigate the lateral movement of the thumb on the texture. We designed a 1 DOF translation mechanism based on the thumb's motion range and velocity.

4.2 Experimental method

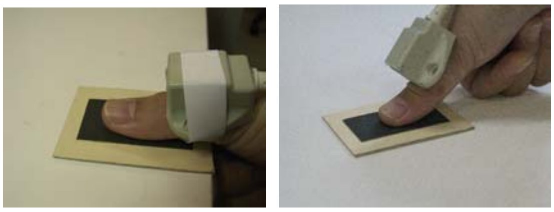


Fig. 6 Thumb finger with the receiver of magnetic position tracker

The purpose of this experiment is to measure the motion range and velocity in the lateral movement of the thumb as subjects discriminate textures. According to the conclusion in section 3.1, subjects could only move their thumb up and down.

The motion range was measured with a magnetic position tracker called a Flock of Bird (FOB), which can measure the position and orientation of a receiver relative to a transmitter with a 100 Hz sampling rate. In addition, the average velocity of the finger was calculated by dividing the total time by the total distance of the movement. The FOB's receiver was attached to each subject's thumb on the line of action of the movement, as shown in Figure 6. Five subjects participated in this experiment. Two subjects discriminated coarse textures and three subjects discriminated fine textures.

4.3 Results

	Motion range (mm)	Velocity (mm/s)
Subject 1 (coarse)	18.5	63.9
Subject 2 (coarse)	20.6	55.6
Subject 3 (fine)	44.9	99.9
Subject 4 (fine)	46.0	106.9
Subject 5 (fine)	48.7	113.4
Average	35.7	87.9

Table. 1 The motion range and average velocity of the thumb of each subject

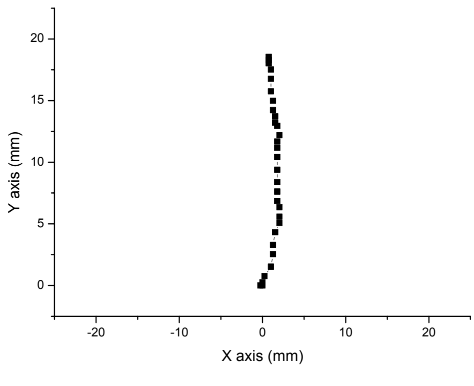


Fig. 7 The motion range of the thumb of subject 1

Table 1 shows the results of the five subjects, while Figure 7 shows the results of one subject. In Table 1, the motion range and the velocity appear to be higher for the fine texture than for the coarse texture, suggesting that discrimination of the fine texture needs a high-frequency vibration generated by the spatial periods and amplitude of the texture[14].

We chose a 1 DOF translation mechanism with a timing belt, pulley and a small motor for a lateral movement of the tactile display region because it can be actuated with 40.0 mm range and 90 mm/s velocity. The lateral movement of the display region can give rise to the skin slip/stretch.

5. INTEGRATED TACTILE DISPLAY DESIGN

5.1 Haptic mouse for 2 DOF force feedback

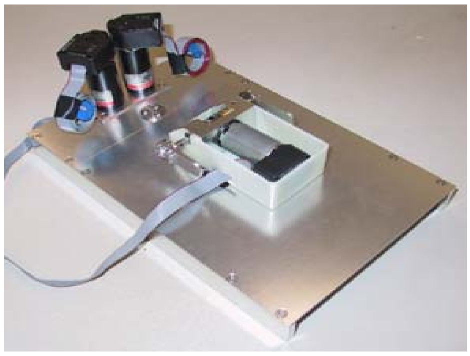


Fig. 8 Haptic Mouse System

A haptic mouse system was designed by adding force feedback capability to a conventional mouse[15,16]. A virtual environment for example, icons and menu bar of the Windows system can be felt through the touch senses. In addition, this device can be used as an interface for an Internet shopping mall, from which people currently obtain information regarding goods solely based on a visual channel. Figure 8 shows the overall configuration of the haptic mouse system.

Fig. 9 Front and rear view of five bar mechanism to feedback 2 DOF translational force

The hardware of the haptic mouse system can be divided into two parts. The first part provides 2 DOF translation force feedback. A five-bar mechanism was adapted for this purpose with the length of the ground link at zero, as shown in Figure 9. Since the Total footprint of the haptic mouse is about the size of a piece of A4 paper, the mouse is small enough to be used on a desk. The workspace of the five-bar linkage was mapped one-to-one to each pixel on the computer screen. A wire-driven mechanism was used to provide back-drivability as well as to eradicate problems arising from backlash. A tensioning mechanism composed of a bolt and a pair of nuts was used to prevent the pulley wire from slipping.

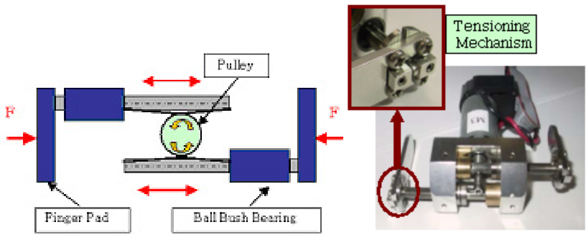


Fig. 10 Schematics and manufactured grabbing force feedback mechanism inside the mouse

The second part provides grabbing force feedback, as shown in Figure 10. A pulley attached to the axis of a DC motor provides the actuating force to the bar tangent on the pulley. Users feel the grabbing force by pressing the fingerpad on each side of the mouse. A wire-driven mechanism was used, and a tensioning mechanism was incorporated. The linear motion of the fingerpads is guaranteed by ball bush bearings.

We use the 2 DOF translation force feedback device of the haptic mouse for an integrated tactile display system. In addition, the grabbing force feedback part is substituted for the tactile display unit described in section 5.2.

5.2 Tactile display unit

The proposed tactile display unit is designed to simulate the pressure distribution, the vibration and the lateral movement across the contact regions. Although the fingerpad on the tactile display surface is immobile, it can provide normal vibrotactile stimulation and can be passively moved across the contact area of the skin. As a result, the hardware of the tactile display unit consists of two parts: one for normal vibrotactile stimulation and one for a lateral movement of the display region, which trigger the skin slip/stretch.

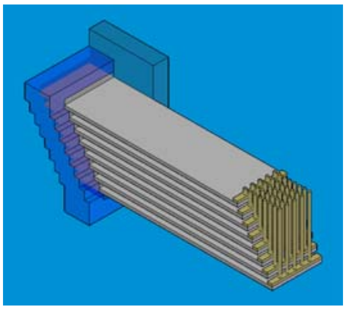


Fig. 11 The normal vibrotactile stimulation part with 8 piezoelectric bimorph clamping and 5x8 pin array

The first part comprises a pin array and eight piezoelectric bimorphs for normal vibrotactile stimulation. Compared with typical piezoelectric actuators, a piezoelectric bimorph has higher stiffness, a displacement larger than 1 mm and a lower operating input voltage. In addition, its response time is in the millisecond range and it can provide a force up to 1 N. A piezoelectric bimorph is therefore adequate for normal vibrotaction with required frequency range and stimulation intensity. As shown in Figure 11, piezoelectric bimorphs are clamped with 1 mm spacing. The 5 x 1 pin array is attached at the end of one bimorph. As indicated in the experimental results of section 3, the pin spacing is 1.5 mm and the diameter of each pin is 0.5 mm, enabling the display of a texture 8 mm wide. The clamping part is attached to a linear motion guide.

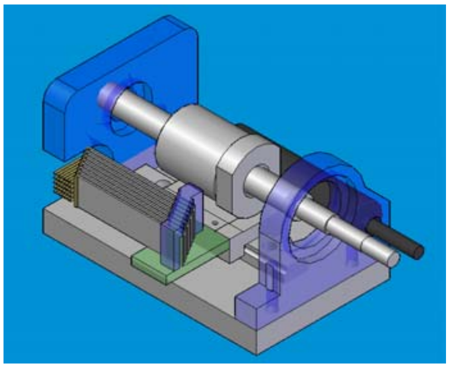


Fig. 12 Tactile display unit with the clamping part and 1 DOF translation mechanism

As shown in Figure 12, the second part is a 1 DOF translation mechanism with a small motor and timing belt for the lateral movement of the tactile display region, which triggers the skin slip/stretch. A DC motor rotates the pulley of the timing belt to provide the translation force to the clamp. The translation force can move the display region in a lateral direction across the skin. In addition, its driven workspace and velocity is designed to be consistent with the results of section 4.

5.3 Integrated tactile display

Figure 13 shows the integrated tactile display mouse that simultaneously simulates the shape and the texture. The proposed tactile display unit is attached to the joint of two link manipulators. As mentioned in section 5, the translational forces from the five-bar mechanism describe the shape and stiffness, and the tactile information from the proposed display unit describes the texture. The integrated tactile display mouse is expected to give users a more realistic sense of touch in a virtual environment as with online shopping, CAD or these kinds of tangible spaces.

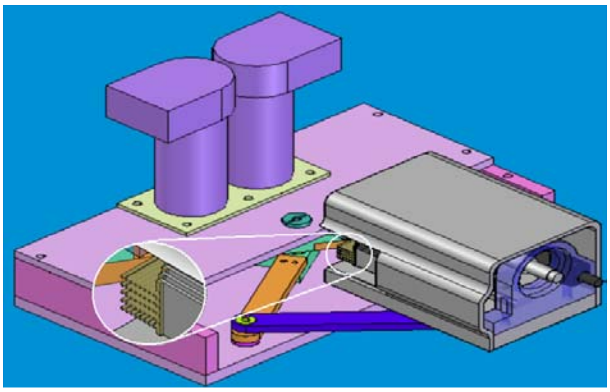


Fig. 13 The integrated tactile display device

6. CONCLUSION

In this paper, we propose an integrated tactile display system. The system is composed of two parts: a 2 DOF force feedback device for kinesthetic display and a tactile feedback device for displaying the normal stimulation to skin and the skin slip/stretch.

To design the tactile display unit, we performed three psychophysical experiments, in which we measured the effects of fingerpad selection, the direction of finger movements while feeling an object and the texture width on tactile sensitivity. Furthermore, we used a position sensor to examine the motion range and average velocity of lateral finger movement. As a result, we propose the conceptual design of a tactile display unit that has the capability of normal vibrotactile stimulation and can provide the skin slip/stretch by the lateral movement. The tactile display unit is expected to operate with 1 mm normal displacement, 0.5 N normal force up to 1 kHz and 90 mm/sec lateral movement with 40 mm range.

We plan to develop a tactile display algorithm to realize physical quantities such as the spatial period, amplitude and element magnitude of a texture. The algorithm will include the synchronization problem of normal vibrotactile stimulation and the velocity of the lateral movement. The performance will be evaluated later through psychophysical experiments.

In addition, we plan to implement a thermal feedback system to more easily identify material. The system will be integrated with the tactile display system. Since the Peltier element is light and small and can produce rapid heating and cooling in the order of 20 °C/sec over a temperature range of –5 °C to 50 °C [9], we will use a thermal feedback system based on the Peltier element. Moreover, we will explore how thermal information can be extracted from the environment and the extent to which it can be effectively presented in a tactile display.

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