Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

THERMO-TACTILE INTERACTION USING TACTILE DISPLAY DEVICE

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Abstract: This paper proposes a tactile display mouse providing both pin-array type tactile display and thermal display. Micro shape and vibrotactile stimuli can be generated by pin-arrayed tactile display and various planar distributed patterns can be also displayed such as Braille cell patterns. Temperature and thermophysical property of object can be displayed by the thermal display device that is composed of a thin film resistance temperature detector(RTD), a Peltier thermoelectric heat pump and a water cooling jacket. To investigate thermo-tactile interaction, an experiment asking perceived magnitude of vibrotactile stimulus according to different temperature condition was conducted. *Copyright © 2008 IFAC*

Keywords: perception, thermal sensing, haptics, tactile display, thermo-tactile interaction

1. INTRODUCTION

When we are interacting with virtual reality(VR) environments, humans tend to experience an object's haptic information such as large-scale shape, small-scale shape, stiffness, roughness and temperature including visual and aural information. A realistic VR experience is achieved when the user is able to discern these features. Generally speaking, haptic information for displaying above features can be categorized into two major areas: kinesthetic feedback, which is based on the force-feedback and tactile display, which is based on tactile sensation, which can be further subdivided into cutaneous display and thermal display. These classifications are determined based on the differences between the sensing receptors; while the mechano receptor is stimulated by mechanical stimulus, thermal sensing receptors are stimulated by temperature variation.

Unlike the force-feedback mechanism, tactile display has been researched thoroughly, with researchers considering everything from the actuator to the mechanism. M. Takasaki et al.(2005) researched on the transparent surface acoustic wave(SAW) tactile display, noting that a pulse modulated driving voltage excites temporal distribution of standing SAW to generate friction shift on the surface of a SAW. Konyo et al.(2003) used the ionic conducting polymergel film(ICPF) actuators in their fabrication of a wearable tactile display that could generate a total texture feeling display. Ikei et al.(2002) used a vibratory pin-array with piezoelectric bimorph actuator to create a virtual texture. Benali-Khoudja(2004) developed a 8x8 vibrotactile display system to transmit a small scale shape and vibration to a user's fingertip. However, each of these developed systems is limited in its ability to display quantitative tactile stimulation. In fact, it's merely found a broadband device which can display micro-shape, sufficient amplitude and wide range of vibratory stimulation together. Moreover, in achieving holistic feedback (Kammermeier, et al., 2004), there's also the drawback that only cutaneous display is utilized. Human can sense the material properties through temperature variation by touching an object in a real or VR environment. Because human fingers are often warmer than the room temperature objects in the environment, thermal perceptions are based on a combination of thermal conductivity, thermal capacity, and temperature. We can infer the material composition as well as temperature difference using thermal perception. Thermal display is relatively new research area(Howe, 2002), but Jones(2003), Caldwell(1997), Ino(1993) and Bergamasco(1997) have studied the thermal perception and display devices, researching experimental approaches and thermophysical factors that affect our ability to determine the material properties of an object. However, for kinesthetic or cutaneous display devices, research on thermal display is nascent, particularly in terms of combining the two main thermal display. In this research, we introduce a cutaneous and thermal display device that transmits a quantitative tactile display and we evaluate its performance.

In chapter 2, the hardware configuration of the pin-array type tactile display and thermal feedback device is described and the device is embedded into a conventional computer mouse. 30 piezoelectric bimorph actuators and pin tactors can stimulate the fingertip at a sufficient range of human tactile sensing levels. The thermal display device composed of Peltier element, water-cooling jacket and thin film RTD, and the device can display temperature variation when an object is touched to determine its material properties. In chapter 3, performance evaluation of the proposed device is conducted. Pattern displaying three kinds of samples was evaluated by asking subjects to discriminate among plain and textured polygons, round figures, and gratings. Thermal display evaluation was conducted by asking subjects to identify among diverse material properties using the thermal display device. In chapter 4, to investigate thermo-tactile interaction between tactile stimulus and thermal stimulus, an experiment asking perceived magnitude of vibrotactile stimuli was developed and conducted. In chapter 5, we discuss the effectiveness of our developed tactile display system and the effect of using combined cutaneous and thermal display in the perception of surface property. Also, potential applications are discussed and future works are delineated.

2. TACTILE DISPLAY DEVICE DESCRIPTION

2.1 Pin Array Type Tactile Display Unit

In this section, the overall structure and design specifications of a pin-array type tactile display unit is described. We have followed the example of Kyung et al.(2005) in trying to design a system based on a survey of the available literature and psychophysical experiments.

Based on the derived requirements(Kyung, et al., 2006), a pin-array type tactile display as shown in Fig. 1 is fabricated.

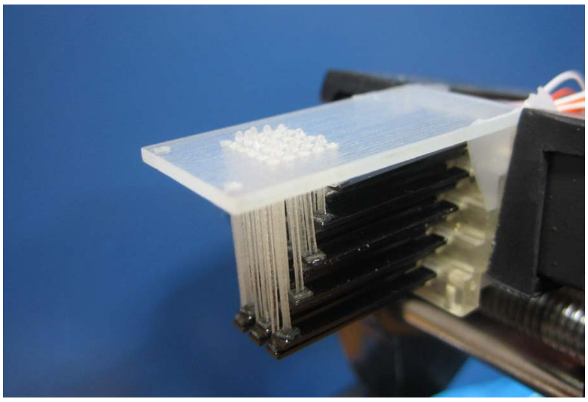

Fig. 1 Fabricated texture display unit

Each step of the stair-like bimorph support holds six bimorphs arranged in two rows. The pin (diameter=0.7mm) components of tactile display: cutaneous and attached to each actuator gives a normal deflection in response to electrically induced bending of the bimorph and the maximum deflection is over 700μm and the blocking force is 0.06N. The 30 pins were made by sterolithography (SLA) and the center to center distance of each pin is 1.8mm. The size of a bimorph is 35mm × 2.5mm and the thickness is 0.6mm. The wide range of amplitudes and frequencies this hardware supports makes it possible to apply almost any desired spatiotemporal pattern to the fingertip.

2.2 Thermal Display Unit

If two objects have same surface shape or roughness, humans discern the two objects using thermal sensation to determine different thermal properties of objects. To provide both pin-array stimulus and thermal stimulus with the tactile display device, the pin guide of texture display unit could be replaced by a thermal pad. Fig. 2 shows the mechanical structure of an integrated tactile display that provides texture and thermal stimulation simultaneously.

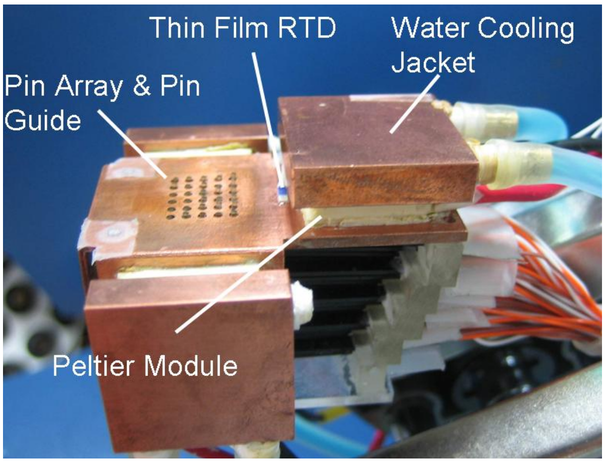

Fig. 2 The thermal feedback display setup

Since it has been supposed that thermal display is less important than other sensory modalities, like cutaneous or kinesthetic sensing, thermal display has not been a priority in tactile display research. However, recent research shows that thermal display is an essential part of tactile display for a holistic haptic display. For example, if two objects have same surface shape or roughness, humans can discern the two objects using thermal sensation to determine different thermal properties of objects. Likewise, if we touch an object in virtual environment, haptic display should display the thermal property as well as surface properties like roughness, shape, and texture to achieve a holistic haptic display through temperature variation while touching the object. As Howe(2002) noted, thermal display is a relatively new area of research and so far it has focused on experimental methods used for displaying material's thermal properties(Caldwell, et al.,1997; Ino, et al.,1993). Displaying a whole sensation which is true holistic haptic display, involves displaying kinesthetic, tactile, and thermal

display and has been attempted by several researchers (Caldwell, et al,1997; Kammermeier, et al., 2004; Caldwell, et al.,1995). However, the previously developed systems are limited in their ability to display vibration only in terms of tactile display.
The Peltier thermoelectric module is used as a heat pump because of its fast response and controllability. Totally 3 peltier cells are used to increase overall heat transfer ability of the thermal display part. Since performance of Peltier thermoelectric module depends on cooling the heat generation side of the module, we designed a miniaturized water cooling jacket that is attached to the heat generation side of the module to increase performance. As shown in Fig. 2, small size RTD for measuring temperature is attached to the pin guide. The pin guide is a thermal pad that user can touch and, for efficient heat transfer, the pin guide is made of copper. The developed thermal display module can transfer heat with a cooling rate of 4°C/s and a heating rate of 8°C/s. Its achievable range of temperature display spans from 0°C to 50°C, which is sufficient for simulating various heat transfer phenomena between a fingertip and an object.

2.3 Integration of Commercial Mouse and Tactile display unit

To use developed tactile display system as a user-friendly interface, we embedded the tactile display system to a conventional mouse with additionally designed cover referring to Kyung el al. (2006)'s previous work. The developed tactile display system is small enough to be embedded into a conventional mouse. Mouse is named as 'KAT II(KAIST Artificial Touch II)' as shown in Fig. 3. Outer shape of the mouse is made by rapid prototyping with plastic material and it can provide tactile display functions as well as conventional mouse function that can be used as a normal mouse when a user interacts with a computer.

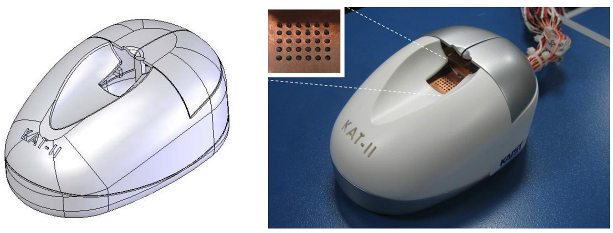

Fig. 3 The prototype of tactile display mouse 'KAT II'

3. EXPERIMENTAL RESULTS AND PERFORMANCE

In order to verify the performance and the effectiveness of the tactile display devices, the displaying capability of each part, individually and in combination with other parts, has been observed.

3.1. Pattern Display

In order to use the proposed device as a quantitative tactile display device, the system should haptically provide some kinds of symbols, icons or texts. For tactile display only, Kyung et.al(2005) already had conducted 3 kinds of pattern discrimination task. In his previous work, the performance of the tactile display was evaluated by asking subjects to discriminate among plain and textured polygons, round figures, and gratings as shown in Fig 4, 5, 6,(all figures in Kyung et al.,2005). Subjects were allowed to actively stroke the tactile array with their finger pad. Thus, the experiments were conducted under the condition of active touch with static display.

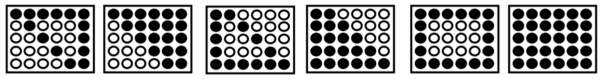

Fig. 4 Planar polygonal samples

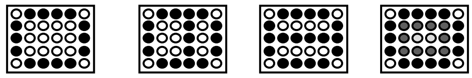

Fig. 5 Round shape samples

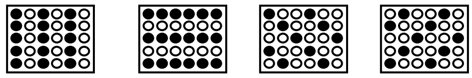

Fig. 6 Grating samples

Since discriminating the patterns showed quite good result using the tactile display based on the previous performance evaluation from Kyung et al.(2006) as shown in Table 1, we have confirmed that the developed tactile display can effectively display the various patterns reliably.

Sample No.		1	2	3	4	5	6
Percentage of Correct Answers	Exp. I	90.8	98.7	93.3	93.2	97.3	95.9
	Exp.II.	97.3	100	91.5	100		
	Exp.III	93.3	95.9	100	95.9		

Table 1: Experimental Results[13]

3.2. Thermal Display

Thermal cues can be used to discriminate between materials, but only when the difference among objects is at least 4 times differences in terms of heat capacity and 80 times in terms of thermal conductivity (Jones&Berris, 2003). For a performance evaluation of the thermal display device, a material discrimination test was conducted.

<u>Methods</u>

To exclude other sensory modalities, the subjects were asked to discriminate among the sample materials based on the thermal cues that were presented to the subjects' index finger. The pin arrays were fixed so that they would not move and would not supply any kind of tactile cue. With the tactile display system located in a specific zone, thermal display became activated so the subjects felt as though their index finger was touching real material. Five materials in a thermally equilibrium state at room temperature (24°C) were randomly presented to the subjects through the thermal display device. Then the subjects were instructed to check which of the listed objects they perceived. Ten subjects were participated in this experiment and each subjects conducted 30 test trials. To prevent the skin of the subjects' index finger from becoming insensitive to thermal perception from repeated tests, subjects were instructed to rest for 2 or 3 minutes after each trial. To simulate the feeling of contact of the fingertip with an object, a thermal model that describes the heat transfer between the object and fingertip is required. A number of thermal display models have been proposed (Kammermeier, et al. 2004; Yang, et al.,2005;Ho&Jones 2006b; Benali et al.,2003; Yamamoto, et al.,2004), most of which are based on a transient heat conduction process. A simple semi-infinite body model was initially selected by several of these authors (Ho&Jones 2006a;Yamamoto, et al.,2004) to model the contact between the finger and an object and appeared to simulate the various materials well. In order to produce a more realistic thermal contact, the thermal contact resistance and blood perfusion is considered in this paper. Based on the semi-infinite body model (Incropera, et al., 1994), the proposed model is changed slightly using equation (1) and boundary conditions (2) and (3). Based on this model, the response of the fingertip to contact with five different materials, (urethane, wood (oak), glass, stainless steel (SS), and copper) was simulated. The simulations are shown in Fig. 7.

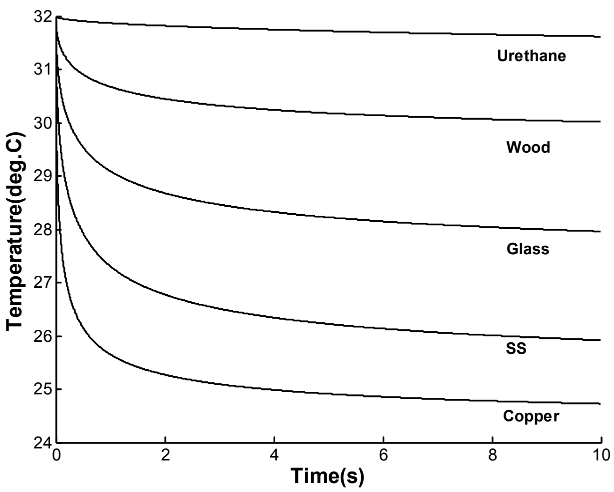

Fig. 7 Time domain temperature variation of material contact simulation

$$k_f \frac{\partial^2 T}{\partial^2 x} = \rho_f c_f \frac{\partial T_f}{\partial t} \qquad k_{obj} \frac{\partial^2 T_{obj}}{\partial x^2} = \rho_{obj} c_{obj} \frac{\partial T_{obj}}{\partial t} \tag{1}$$

$$-k_f A \frac{\partial T_f}{\partial x}\bigg|_{x=0} + \bar{h}(T_{blood} - T_f(0,t)) = k_{obj} A \frac{\partial T_{obj}}{\partial x}\bigg|_{x=0} = \frac{T_f(0,t) - T_{obj}(0,t)}{R_{t.c}} \tag{2}$$

$$-k_f \frac{\partial T_f}{\partial x}\bigg|_{x=\infty} = 0 \qquad -k_{obj} \frac{\partial T_{obj}}{\partial x}\bigg|_{x=\infty} = 0 \tag{3}$$

Results and Discussion

A comparison of the results with simulated materials to those of Ho and Jones (2006a) who used real materials with similar thermophysical properties (e.g. foam and urethane, wood and ABS, glass and granite) in an identification task are shown in Fig. 8. The data are from a single finger and reveal that the thermal display is capable of providing cues that are as effective as the thermal cues from real materials in enabling subjects to identify a material. An analysis of the results from the index finger in the two experiments indicated that there was no significant difference between them ($p=0.49$).

The thermal cues presented to the fingers provided the basis for identifying what material was being simulated. Subjects were able to use these cues effectively and achieved an overall identification rate of 61% correct for the five materials simulated. When these findings were compared with those from an earlier study(Ho&Jones 2006a) involving the same or similar real materials, there was no significant difference in the results obtained. The identification rate for the five real materials was 55% correct. The results from the present experiment indicate that the thermal display part can be used to present cues that enable subjects to identify the material composition of the object being simulated, and that performance with such a display is essentially the same as that achieved with real materials.

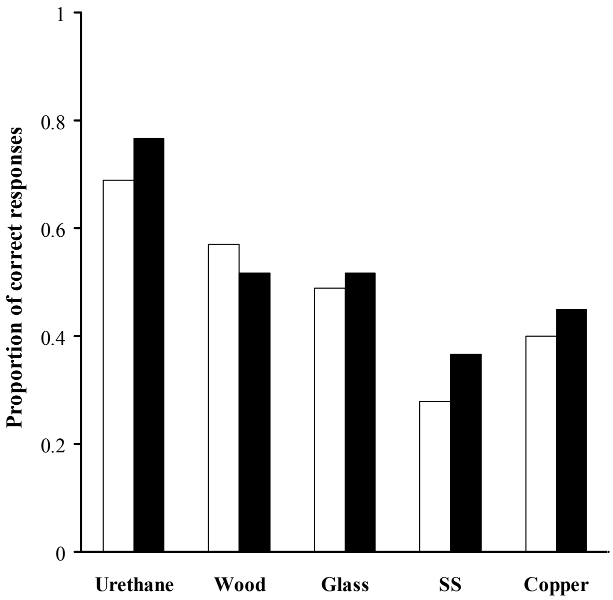

Fig 8. Proportion of correct responses when identifying simulated (white) or real (black) materials using a single finger. The data for the real materials are from Ho and Jones(2006a).

4. THERMO-TACTILE INTERACTION EXPERIMENT

Several illusion of thermal perception is based on thermo-tactile perceptual interaction. Thermo-tactile interactions are researched by several researchers (Green, et al, 1979; Green 1977; Stevens, et al., 1977; Stevens&Green 1978). They reported that vibrotactile threshold was increased for decreasing skin temperature. Green et al.(1979) reported that perceived roughness was decreased when skin temperature was decreased. Among 4 different mechanoreceptors, only Pacinian channel was affected by skin temperature (Green 1977), so high frequency perceptual characteristics was affected by temperature variation. Based on previous researches, our question is obvious. Can temperature varying the perceived magnitude of vibrotactile stimuli? That is, an experiment was designed to determine whether or not pin array's perceived indentation is affected by skin temperature. Based on previous works(Stevens, et al, 1977; Stevens &Green 1978), 3 different frequency components were selected including 30Hz, 150Hz, 250Hz and selected height of vibrotactile stimulation was ~0.2mm for avoiding pain perception of subject's skin(Kyung, et al.,2005).

Methods
Three different combinations of amplitude and frequency were selected for vibrotactile stimuli by pin array and twoo different thermal stimuli were applied. The selected vibrotactile stimuli were (0.2mm, 30Hz), (0.1mm, 250Hz), (0.2mm, 250Hz). Two different thermal stimuli consisted of neutral and simulated thermal cue of contacting a copper. Therefore, total 6 pairs were randomly displayed for four times. Seven normal, healthy subjects (six men and one woman) aged 23 to 30 years participated in this experiment. They had no known abnormalities of their tactile or thermal sensory systems and had no history of peripheral vascular disease. The tactile display mouse 'KAT II' was used as a stimulating device for displaying vibrotactile and thermal stimulus simultaneously. To masking the sound of piezo bimorph for actuating pin-arrays, pink noise was applied to subjects using a headphone during transmitting vibrotactile stimulus. Using a 7-point scale, subjects were instructed to evaluate the perceived magnitude of vibrotactile stimulus based on their index finger's feeling. Before starting their experiment, a test trial was applied to subjects to know a reference for 7 point stimulus. Because temperature is varied by experimental procedure, there was enough time between each stimulus and after end of 1 block of experiment consisted of 6 trials, 3min break was applied.

Results and Discussion
As expected, high-frequency sensitive mechano-receptor, Pacinian is strongly affected by temperature of skin as shown in Fig. 9. For same amplitude of pin array but different frequency condition, 30Hz stimulation was little affected by temperature condition but for 250Hz, perceived magnitude was strongly affected by temperature condition as shown in Fig 8. Almost 11% difference was revealed for 250Hz but only 3% variation was observed for 30Hz. Through this experimental result we have confirmed the previous experimental result was valid and Pacinian channel is strongly affected by temperature variation. Perceived magnitude of vibrotactile stimuli was affected by temperature variation only for high frequency (>150) vibrotactile stimulus. Cold stimulus also can reduce the sensitivity of Pacinian corpuscle and that is, other mechano receptors except Pacinian corpuscles are little affected by temperature variation. From Green(1979)'s study, perceived roughness is affected by temperature variation and Kyung et al.(2005) reported that high frequency component is strongly concerned with perception of roughness. When we stimulating a vibrotactile stimulus and temperature together, perceived magnitude and roughness of vibrotactile stimulus is affected by temperature. So we consider this effect to generate quantitative thermo-tactile stimulus using the tactile display.

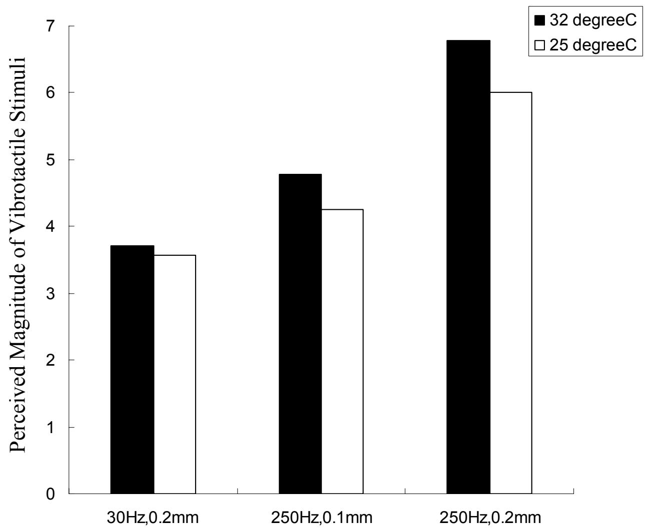

Fig. 9. Perceived magnitude of vibrotactile stimuli according to different temperature conditions

5. CONCLUSION

In this paper, we propose a tactile display mouse system to display both cutaneous and thermal display. To provide the cutaneous stimuli, a high performance 5x6 pin-array based tactile display actuated by piezoelectric bimorphs had been adopted. In the previous research (Kyung, el al., 2007), the performance of the tactile display had been verified by pattern display experiment. We added thermal display function to the tactile display using a thermal pad made of copper, 3 Peltier cells and a temperature sensor. The proposed cutaneous and thermal display system has been embedded into a computer mouse. The developed mouse named as 'KAT II' can be used as a test-bed for psychophysical study relating human touch sensation and perceived feeling of various combined stimuli.
For a performance evaluation of the thermal display device, a material identification task was conducted. The results indicate that a thermal display part can be used to present cues that enable subjects to identify the material composition of the object being simulated, and that performance with such a display is essentially the same as that achieved with real materials. In the investigation of thermo-tactile interaction, perceived magnitude of vibrotactile stimuli was affected by temperature variation only for high frequency (>150) vibrotactile stimulus. Through this experimental result, we have confirmed that the previous experimental results were valid and Pacinian channel is strongly affected by temperature variation. Moreover, we need to consider this characteristic to generate quantitative tactile and thermal stimulation using the tactile display mouse.

For future works, using the developed tactile display mouse, a realistic and innovative texture display, the relationship between texture discernment and physical quantities has to be considered, and visual information will also be investigated through several additional experiments. Also, several illusions of thermo-tactile interaction need to be investigated for effective display of tactile stimulation.

ACKNOWLEDGMENTS

This work has been supported by 'TSI-ITE(Immersive Tangible Environment)(KIST)' and 'Development of Smart Haptic Interface Device(2004-S-30, Korea Ministry of Information and Communication)'

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