Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

# Control of Thermal Tactile Display Based on Prediction of Contact Temperature

Akio Yamamoto*, Benjamin Cros*, Hironori Hashimoto*†, and Toshiro Higuchi*

(*) *Department of Precision Engineering, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

(†) *Hitachi Co., Ltd., Japan*

{akio, benjamin, hr_hashimoto, higuchi}@intellect.pe.u-tokyo.ac.jp

***Abstract*—Thermal sensation is one of the most important factors for material recognition in virtual environments. Thermal display functions must be embedded into tactile feeling display for satisfactory realism. Since our skin sensors are sensitive to rapid change of temperature and rapid changes occur on the moments of contacts, we need to precisely simulate thermal conditions for the moments, at which contacts occur, to display materials with satisfactory realism. The authors have proposed a thermal model for finger-object contact and principles of thermal tactile display based on the thermal model. In this paper, we mainly report experimental aspects of our thermal tactile display. Prototype thermal tactile display and results of discrimination experiments to evaluate device realism are reported.**

***Index Terms: thermal sensation, tactile display, Peltier element, contact temperature, thermal effusivity***

## I. Introduction

When we touch objects, we feel various thermal sensations. The sensations correspond to the characteristics of objects, and therefore, thermal sensations play an important role in material recognition. For example, if we touch a metal and a wood, both in a room temperature, we feel as if the metal is colder than the wood even though their temperatures are the same. This fact indicates that simulating thermal sensations is prerequisite for realistic object rendering in virtual reality environments.

Some studies have been reported on thermal tactile displays, in which subjects can feel thermal sensations by touching a contact pad with their fingers [1-2]. However, while there are a wide variety of studies for presenting roughness or surface shape features in tactile displays [3-9], thermal stimulus presentation has not been studied well in spite of its importance.

An interesting point can be found by reviewing reported thermal tactile displays, that is, whereas our skin sensors feel thermal flux, and not temperature, all the reported tactile displays focus on a temperature profile ignoring what happens at the instant when contact occurs. This does not produce satisfactory thermal sensations since the limited performances of thermal devices (typically Peltier device) impair good simulation of the temperature profile.

Roughly speaking, the profile when we touch an object could be divided into two consecutive phases. In the first phase, which we call *early times sensation* (ETS) phase, the finger experiences rapid temperature change (typically temperature drop) due to contact. The first phase is a momentary phase and corresponds to the moment when contact occurs. The second phase, which we call *later times sensation* (LTS) phase, follows the first phase. In the second phase, we have slow temperature change which is determined by various characteristics and conditions of the touched object and surrounding environment. Since human perception on temperature is sensitive against rapid change of temperature [10], we seem to gain more information from ETS than from LTS. Therefore, precisely simulating ETS has much importance in thermal tactile displays.

However, as mentioned above, all the reported tactile displays are controlled based on pre-measured temperature profiles. In those studies, the pre-measured profiles are fed into PID controllers to realize the same temperature profiles on the contact pads of the displays. In this case, even if we fed rapidly changing temperature profiles to the controllers, resultant temperature profiles exhibit slower temperature changes due to limited response frequency of the systems. Because of this reason, those displays cannot reproduce ETS correctly, which we believe most important in thermal tactile displays.

The authors have analyzed what happens on a finger surface at the moment contact occurs and have proposed a basic idea of new control technique for thermal tactile displays that let us reproduce ETS phase correctly [11, 12]. In the proposed technique, the temperature of contact pad is set to a certain value in advance, so that the resultant contact temperature achieved by a contact becomes a desired value. With this technique, we can reproduce the same thermal flux variation in a fingertip and can reproduce the same sensation as real at ETS phase.

In this paper, we describe the control technique and the apparatus, as well as the experimental results. In our control technique, measurements of thermal effusivities are essential. However, there were some difficulties in measuring them. To simplify the measurements, we introduce an idea of relative

This work was supported by *Industrial Technology Research Grant Program* in 2003 from the *New Energy and Industrial Technology Development Organization* (NEDO) in Japan.

effusivity. Also, measurement error in effusivity is critical problem in our technique. To reduce the error, we discuss how we should measure the temperature profiles.

## II. Analysis on Temperature Profile

### A. Temperature Profiles

When two homogenous objects that have constant homogenous temperatures make a contact, the temperature distribution around the contact surface at a certain moment after the contact can be illustrated as in Fig. 1. The temperatures on both surfaces become certain values, which approach to each other as time proceeds. Difference of two surface temperatures depends on thermal resistance between two objects; smaller resistance results in smaller temperature difference. If we can ignore the thermal resistance, the temperature difference is zero and both surface temperatures reach the same constant value just at the moment of contact.

At the initial moment, conduction characteristic lengths (depths of temperature change) $l_A$ and $l_B$ are infinitesimal. The lengths will grow with certain speeds defined by thermal characteristics of the objects. The growth is accompanied by the change of temperature gradients and surface temperatures. Fig. 2 (a) shows resultant temperature profiles of two surfaces with respect to time. The two temperatures converge to a certain value. If we can ignore the thermal resistance, two surface temperatures settle to the value at the moment of contact and keep the constant temperature as in Fig. 2 (b).

The above model does not apply to finger-object contact, because human finger is not homogenous and temperature distribution is not flat inside the finger. However, during the short period after the contact (especially at the moment when contact occurs), only superficial parts concern the contact temperatures since conduction characteristic length for a short moment is also short. Therefore, we can apply the above model to finger-object contact for the short period after the contact.

A typical temperature profile of finger-object contacts with sufficient contact force is plotted in Fig. 3. Initially, temperatures behave the same as in Fig. 2 (b). It shows rapid temperature change and two surface temperatures settle to the same value. Then, some short period after the contact, the temperatures behave differently from Fig. 2 (b). The behavior is determined by various factors, such as the thermal characteristics of the object, the initial temperature distribution of the finger, and the size of the object. In Fig. 3, we see the temperatures slowly increase after rapid change, but in some cases, they can slowly decrease or they can be flat.

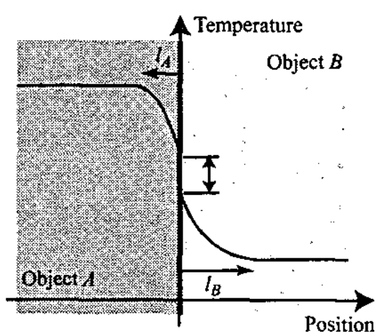


Figure 1. Typical temperature distribution inside two homogenous objects in contact

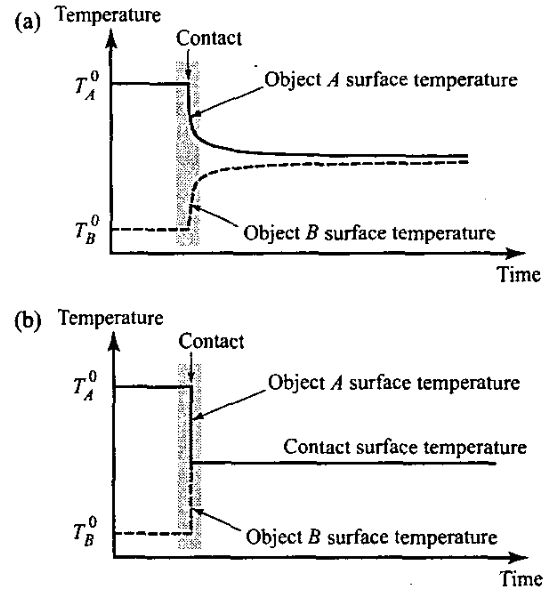


Figure 2. Surface temperature profiles of two objects: (a) with thermal resistance at boundary, (b) without thermal resistance

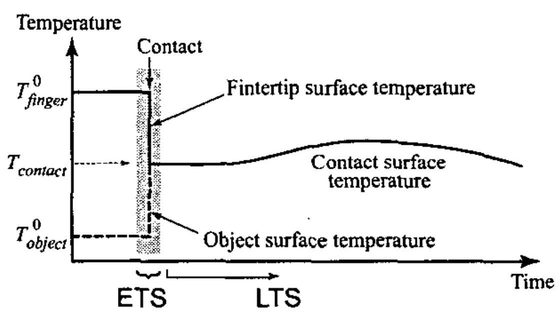


Figure 3. Typical temperature profiles in finger-object contact and definition of ETS and LTS phases

Here, we define the initial momentary phase, where finger experiences rapid temperature drop and approximation by homogeneous model is valid, as *early times sensation* (ETS) phase. Also, we define the remaining phase that follows ETS phase as *later times sensation* (LTS) phase. Since ETS phase contains rapid temperature drop and rapid temperature drop can invoke more intense sensation to human, we believe ETS plays an important role in material recognition.

### B. Measurements of Profiles

The temperature profiles of finger-object contact were measured under various contact force. Since thermal resistance relates with real contact area, increasing contact force results in

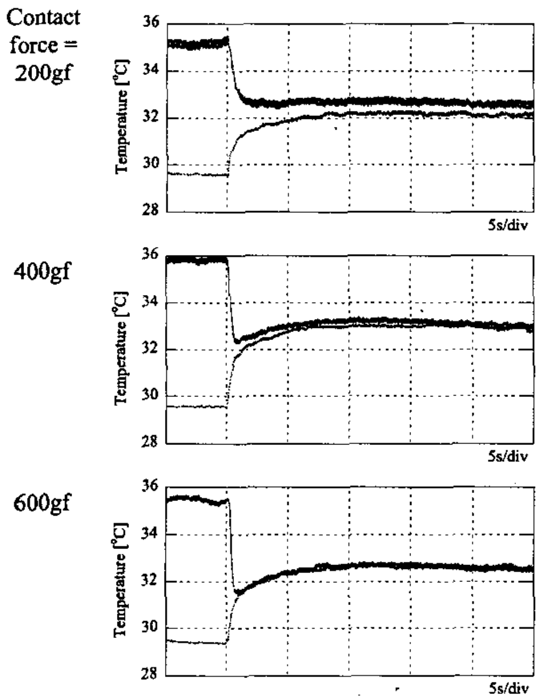


Figure 4. Temperature profiles when a finger touches ceramic (Peltier device) with various contact force

lower thermal resistance (that is, larger real contact area). The measured profiles are plotted in Fig. 4. In these measurements, we adopted a ceramic plate as the object touched. We put micro thermocouples (CHINO, NC600; K-type, ϕ0.5mm) on ceramic surface and on finger surface with silicon grease to measure the profiles.

The silicon grease was used to decrease the thermal resistance between the thermocouple and the measured surfaces. Without grease, we have large thermal resistance between thermocouple and the ceramic. (Resistance between fingertip and thermocouple is not so large even when there is no grease, because fingertip is soft and therefore can wrap the thermocouple to increase the contact area.) This leads to higher temperature measured, because temperature of thermocouple is pulled up to finger temperature due to the difference of thermal resistances. With higher measured temperature, the simulated thermal sensation on the device would be hotter than the real sensation.

In Fig. 4, more rapid temperature drop is observed as increasing the force. Since rapid drop can invoke more intense sensation, the differences of materials are more clearly perceived with larger contact force. For the contact force larger than 600gf, we see that there is almost no thermal resistance between finger and ceramic.

In this paper, we focus on the situation where thermal resistance can be ignored, since this situation gives us most intense material discrimination ability. Besides, we limit our focus on ETS phase simulation, since we believe ETS is the most important part in thermal sensation.

### C. Contact Temperature without Thermal Resistance

When thermal resistance is zero, the temperatures on both surfaces become the same temperature at the moment contact occurs. We call the temperature as contact temperature, $T_{contact}$. The contact temperature can be calculated as

$$T_{contact} = \frac{b_1 T_1^0 + b_2 T_2^0}{b_1 + b_2} \tag{1}$$

where $T_i^0$ ($i$ = 1,2) is initial temperature and $b_i$ is thermal effusivity of each material, which is defined by

$$b_i = \sqrt{\lambda_i c_{p_i} \rho_i} \tag{2}$$

using thermal conductivity $\lambda_i$, specific heat $c_{p_i}$, and density $\rho_i$ [11].

By reproducing the contact temperature using thermal tactile display, we can reproduce the same thermal feeling on the human nerve system, because we can realize the same thermal condition for finger, including thermal flux change inside the finger, by equalizing the contact temperature.

## III. Control Technique for Thermal Tactile Display to Reproduce Early Times Sensation

In this chapter, we discuss how we can reproduce the contact temperature on thermal tactile display.

### A. Contact Temperature Reproduction Based on Effusivity

When we touch contact pad of thermal tactile display with perfect contact condition, resultant contact temperature will be

$$T_{contact} = \frac{b_{finger} T_{finger}^0 + b_{pad} T_{pad}^0}{b_{finger} + b_{pad}} \tag{3}$$

where $T_{pad}^0$ and $T_{finger}^0$ are initial temperatures of contact pad and finger, and $b_{pad}$ and $b_{finger}$ are thermal effusivities of the pad and the finger. In this equation, the only variable we can control is $T_{pad}^0$. Therefore, we need to control $T_{pad}^0$ if we are willing to equalize $T_{contact}$ to a certain value.

Now we consider the situation where we need to simulate thermal sensation of a certain object which has an effusivity of $b_{obj}$ and initial temperature of $T_{obj}^0$. The real contact temperature when finger touches the object can be calculated using (1). To reproduce this situation on thermal tactile display, the system needs to satisfy the following equation.

$$\frac{b_{finger} T_{finger}^0 + b_{obj} T_{obj}^0}{b_{finger} + b_{obj}} = \frac{b_{finger} T_{finger}^0 + b_{pad} T_{pad}^0}{b_{finger} + b_{pad}} \tag{4}$$

By solving the equation in terms of $T_{pad}^0$, we obtain

$$T_{pad}^0 = \frac{(b_{finger}T_{finger}^0 + b_{obj}T_{obj}^0)(b_{finger} + b_{pad})}{(b_{finger} + b_{obj})(b_{pad})} - \frac{b_{finger}T_{finger}^0}{b_{pad}} \quad (5)$$

Therefore, by pre-setting $T_{pad}^0$ as to satisfy (5), we can simulate ETS of the given situation.

This technique allows us to simulate any temperature conditions, since (5) contains temperatures of finger and of the object to be rendered. Once we know the effusivity of the object, we can reproduce thermal sensations for any temperature conditions. On the other hand, this is not the case for the techniques reported in previous studies. Since previous studies focused on reproducing pre-measured temperature profiles, they are effective only for limited temperature ranges.

Another advantage of our technique is that this technique does not require high performance to the Peltier device. When a subject touches the pad which temperature is controlled as to satisfy (5), the subject's finger experiences a rapid temperature drop that *naturally* happens. This drop is a consequence of temperature difference between the finger and the pad, and is not affected by system's cooling or heating performance.

### B. Introduction of Relative Thermal Effusivities

To calculate $T_{pad}^0$ according to (5), we need to know thermal effusivities of three objects; finger, simulated object, and contact pad. One of the simplest methods to measure the thermal effusivity is to calculate them from temperature profiles. By looking at (1) and Fig. 2 (b), we realize that the ratio of temperature drop in the finger and temperature rise in the object is the same as the ratio of their effusivities. This fact let us to measure the ratio of effusivities from the profile. Here, if we know the effusivity of the finger, we can identify effusivity of any object by touching it, but in the most cases, the effusivity of the finger is not easily known.

For the reason, we introduce *relative thermal effusivity*. If we look at (5), we realize that all we need to know is the ratio between effusivities, and not their absolute value. In this paper, the relative thermal effusivity β is defined as a ratio of material effusivity against finger's one:

$$\beta_i = \frac{b_i}{b_{finger}} \quad (6)$$

By using relative effusivity, we can reform (5) as

$$T_{pad}^0 = \frac{(T_{finger}^0 + \beta_{obj}T_{obj}^0)(1+\beta_{pad})}{(1+\beta_{obj})(\beta_{pad})} - \frac{T_{finger}^0}{\beta_{pad}} \quad (7)$$

## IV. Experiments

In this chapter, we report experimental aspects of our work. First, we describe our experimental setup. Since our control technique is different from previous works, setup is also different from previous ones. Then, we describe materials that were used for our discrimination tests. Finally, we report results of discrimination tests on our thermal tactile display. The experiments are aimed to reveal the effectiveness of the proposed technique. Since the technique is specialized to ETS simulation, we focused on the short period after contact in each experiment.

### A. Experimental Setup

Fig. 5 shows our experimental setup. It consists of a contact pad using Peltier device and thermocouple #1 (CHINO, NC600), thermocouple #2 (OMEGA, C01-K) for measuring room temperature (= $T_{obj}^0$), a radiation thermometer, a current booster for the Peltier device, and a DSP system as a PID controller. Fig. 6 shows a photograph of the main part of the system.

Fig. 7 shows a close-up view of the contact pad. The pad consists of a Peltier device (15mm x 15mm), on which the thermocouple #1 (CHINO, NC600) is installed. The thermocouple is used for measuring temperature of contact pad $T_{pad}$. To install the thermocouple, the surface of the Peltier is grooved. The whole pad is situated on a radiator, on which an infra-red finger detector is installed. The finger detector consists of a pair of an infra-red LED and photo-diode and detects any contacts between a finger and the contact pad.

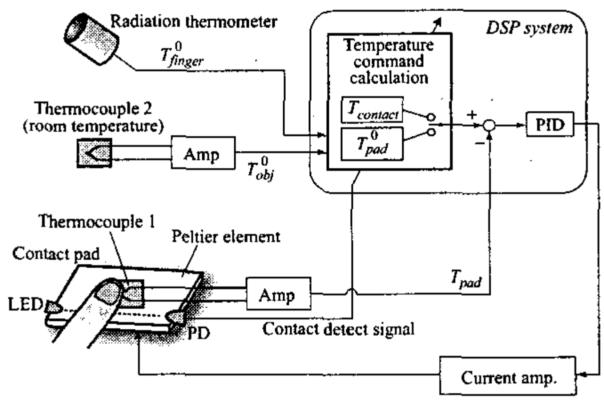


Figure 5. Diagram of thermal tactile display

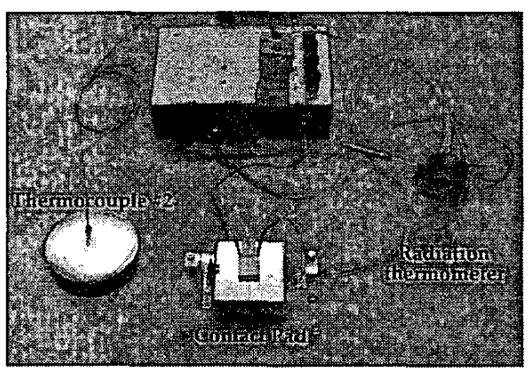


Figure 6. Photograph of the system

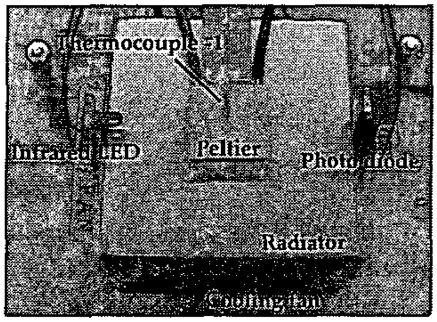


Figure 7. Close-up view of contact pad

The radiation thermometer is used to measure the initial temperature of a finger. Subjects, who are going to obtain thermal sensations from the device, first put their fingers on the radiation thermometer. Since the thermometer is also equipped with an infra-red finger detector like the contact pad, the finger is automatically detected and its surface temperature is measured. Then, subjects release their fingers from the thermometer to put them on contact pad to be presented thermal sensations.

The thermocouples, the radiation thermometer, and the finger detectors are connected to the DSP system through its A/D ports. A PID controller is built on the DSP system to control the $T_{pad}$. The controller has two command input branches, one of which is selected based on the detection signal from the finger detector mounted on the contact pad. Before contact is made (finger detector does not detect the contact), the lower branch is selected where temperature command to the controller is $T_{pad}^{0}$ calculated from (5). When contact is established between finger and the contact pad, the surface temperature of the contact pad should naturally settle to the contact temperature $T_{contact}$ as (3) predicts. Therefore, the moment when contact is detected, the temperature command input is switched to the other blanch, where $T_{contact}$ is given to the controller as a temperature command so that the contact temperature is kept after the contact. Resultant typical temperature command profile is plotted in Fig. 8.

## B. *Materials Used for the Experiments*

We used four different materials for our material discrimination experiments. The four materials were chosen so that they can cover a wide range of thermal effusivity. The materials are shown in Fig. 9. They are expanded polystyrene (EPS), oak (wood), Peltier device (ceramic), and brass. The surfaces of four materials are polished so that the surfaces become enough smooth to realize almost perfect contact with fingertips.

The relative thermal effusivity of each material was measured from temperature profiles and is summarized in Tab. 1. As the same manner as in the measurement of Fig. 4, we measured the temperature profile of finger-object contact for each material with sufficiently large contact force around 600gf.

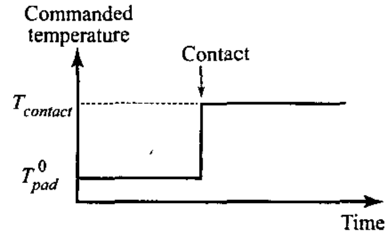


Figure 8. Temperature command for PID controller

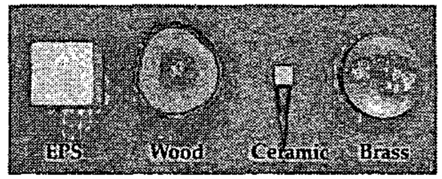


Figure 9. Sample materials used for discrimination tests

Table 1. Measured relative effusivities of the samples and contact pad (Contact pad and ceramic are the same material)

| Object | Contact Pad | EPS | Wood | Ceramic | Brass |
|---|---|---|---|---|---|
| $\beta$ | 2.23 | 0.043 | 0.74 | 2.23 | 5.60 |

## C. *Procedures*

We performed material discrimination tests. Five male subjects, with their ages from 24 to 31, participated in the tests. They were presented simulated thermal sensations by the thermal tactile display and were asked which material they thought was simulated on the display.

The detailed procedure is as follows. In each presentation, the subjects were presented one of four simulated materials. Presentations were made twelve times for each subject. Those twelve presentations consist of three presentations for each material. Presentations were made in a random but fixed order. In each presentation, they were allowed to touch the contact pad as many as possible. However, the duration of each touch was limited under three seconds, since this test was designed for ETS. At the same time they touch the pad, they touch one of the four real samples to compare the thermal sensations, with the fingertip on the other hand. In every touch (both to real samples and to contact pad), subjects were asked to touch objects with contact force of 600gf. (To perform it, the subjects had been imposed some practices on electric weight balance before tests.) Between touches, we tried to make some intervals. This is because once a subject touch any object, the fingertip temperature is lowered. To maintain a good condition for the tests, each touch trial should be done with certain intervals.

In each trial, subjects answered the material which they thought was simulated on the pad. However, when they could not be sure about the material, they were allowed to answer two possible materials. In that case, they were given four points which should be allocated to the two materials. Therefore, their answers were such as "3 points (= 75%) for wood and 1 point (= 25%) for ceramic".

### D. Results

The results are summarized in a recognition/confusion matrix shown as Tab. 2. During the tests, room temperature was between 25.8 °C and 26.3 °C.

In every sample, ratio of correct answers exceeds 50%. Considering that we can not completely discriminate materials only with thermal sensations even in the real world, we can say that these results are satisfactory.

Interesting point is that correct answers ratio is lowest in ceramic, even though the simulated ceramic is just the same as the contact pad. We think the reason many subjects made wrong discriminations for ceramic lies in differences of fingertip effusivities among individuals. The relative effusivities summarized in Tab. 1 were measured from results of only one person. If a subject in discrimination test has different fingertip effusivity, they can make wrong discriminations because calculation of $T_{contact}$ (and $T_{pad}^{0}$, in case of other samples than ceramic) can go wrong. Of course, such miscalculations could have happened in every sample. However, especially in case of ceramic, the difference in perception might have been psychologically emphasized, just because its appearance is the same as the contact pad. (Subjects might have been confused by visual information.) This problem can be solved by measuring effusivity of each subject.

## V. CONCLUSIONS

In this paper, we have described a control technique for thermal tactile display. First, we have discussed a classification for thermal sense when we touch objects. In our classification, the thermal sense comes from two phases, early times sensation (ETS) phase and later times sensation (LTS) phase. Since ETS corresponds to rapid temperature drop on finger, it is more important for material recognition.

To correctly simulate ETS phase, we proposed a control technique based on contact temperature. By equalizing contact temperature, we can realize the same thermal condition in our fingertip, thus being able to create the same thermal sensation. We have stated how we can measure materials' effusivities which are the most important factor in our technique. In the measurements, we introduced an idea of relative effusivity, which can ease the difficulties of effusivity identification tasks.

Finally, we have described our experimental aspects. By using measured effusivities, we carried out material discrimination tests. The results of the test shows satisfactory rate of correct recognition. We believe these results confirm the effectiveness of our technique as well as the importance of ETS simulation.

The proposed technique is now only applicable to ETS simulation. Since temperature changes in LTS phases are slow, LTS may be less important than ETS in terms of material recognition. However, only with ETS simulation, duration of presentations should be limited within a very short period. Simulating LTS correctly can allow us to perform longer presentation, which can enhance the realism of displayed thermal sensations. This will be the next challenge in our work on thermal tactile displays.

Table 2. Result of discrimination tests; recognition/confusion matrix

| | | *Answers in percentage* | | | |
|---|---|---|---|---|---|
| | | EPS | Wood | Ceramic | Brass |
| *Simulated material* | EPS | **86.7** | 13.3 | 0 | 0 |
| | Wood | 6.7 | **65** | 23.3 | 5 |
| | Ceramic | 0 | 3.3 | **53.3** | 43.3 |
| | Brass | 0 | 0 | 10 | **90** |

Our experimental results also showed that differences among individuals must be considered in thermal tactile presentation. This problem can be solved by measuring effusivity of each individual before making thermal tactile presentation.

## REFERENCES


[1] S. Ino, S. Shimizu, T. Odagawa, M. Sato, M. Takahashi, T. Izumi, T. Ifukube, "A tactile display for presenting quality of materials by changing the temperature of skin surface", Proc. Second IEEE International Workshop on Robot and Human Communication, pp. 220-224, 1993.

[2] D. G. Caldwell and C. Gosney, "Enhanced tactile feedback (tele-taction) using a multi-functional sensory system", Proc. ICRA 1993, pp. 955-960, 1993.

[3] R. Howe, W. Peine, D. Kontarinis, and J. Son, "Remote palpation technology for surgical applications," IEEE Engineering in Medicine and Biology Magazine, vol. 14, no. 3, pp. 318-323, 1995.

[4] N. Asamura, N. Yokoyama, and H. Shinoda, "Selectively stimulating skin receptors for tactile display", IEEE Computer Graphics and Applications, Issue of Nov/Dec, 1998, pp. 32-37, 1998.

[5] Y. Ikei, K. Wakamatsu, and S. Fukuda, "Image data transformation for tactile texture display", Proc. IEEE VRAIS, pp.51-58, 1998.

[6] T. Nara, M. Takasaki, T. Maeda, T. Higuchi, S. Ando, and S. Tachi, "Surface acoustic wave (SAW) tactile display based on properties of mechanoreceptors", Proc.VRAIS, pp.13-20, 2001.

[7] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi, "Tactile feeling display using functional electrical stimulation," Proc. ICAT'99, pp. 107-114, 1999.

[8] A. Yamamoto, T. Ishii, M. Takasaki, H. Yasui, and T. Higuchi, "Tactile interface using ultra-thin electrostatic actuator", Proc. the 32nd International Symposium on Robotics, pp. 1170-1174, 2001.

[9] A. Yamamoto, T. Ishii, and T. Higuchi, "Electrostatic tactile display for presenting surface roughness sensation", Proc. International Conference on Industrial Technology, pp. 680-684, 2003.

[10] D. R. Kenshalo, C. E. Holmes, and P. B. Wood, "Warm and cold thresholds as a function of rate of stimulus change", Perception and psychophysics, Vol. 3, pp. 81-84, 1968.

[11] B. Cros, A. Yamamoto, and T. Higuchi, "Simulation and analysis of the perception of the temperature factor for virtual reality applications", SICE System Integration Division Annual Conference, Vol.2, pp. 409-410, 2002.

[12] A. Yamamoto, H. Hashimoto, T. Higuchi, "Tactile display for presenting thermal characteristics of materials based on prediction of contact temperature", Proc. the 8th Annual Conference of the Virtual Reality Society of Japan, pp. 233-236, 2003 (in Japanese).