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Design and Implementation of Transmission System of Initial Haptic Impression

Katsunari Sato[1] Hiroyuki Shinoda[2], and Susumu Tachi[3]

[1]Department of System Design and Management, Keio University, Kanagawa, Japan
(Tel : +81-45-564-2518; E-mail: katsunari.sato@sdm.keio.ac.jp)
[2]Department of Information Science and Technology, The University of Tokyo, Tokyo, Japan
(Tel : +81-3-5841-6927; shino@alab.u-tokyo.ac.jp)
[3]Department of Media Design, Keio University, Kanagawa, Japan
(Tel : +81-45-564-2499; E-mail: tachi@tachilab.org)

Abstract: This study proposes and implements a transmission system of haptic information employing the vision-based cutaneous sensor and the cutaneous display consists of electrotactile display. The proposed system can transmit not only kinesthetic but also spatially distributed tactile and thermal information. The implemented prototype system enabled a user to perceive the shape and material information of a remote object as the initial haptic impression.

Keywords: haptic transmission system, vision-based cutaneous sensor, electrotactile display.

1. INTRODUCTION

The haptic sense is essential as it enables humans to perceive the existence of objects and to handle them properly. As such, this sense is important in the context of telexistence (or telepresence) technology, which enables interaction with remote objects. A great deal research [1][2][3] has been conducted on the development of haptic devices that treat one or more pieces of haptic information, i.e., cutaneous (tactile and thermal) and kinesthetic information, so as to enable a user to perceive the properties of a remote object through active touch. For example, users of the transmission system developed by Yamauchi et al. [1] can stroke the surface of a remote object so as to perceive roughness of it.

In addition to these conventional studies, we focus on the "initial haptic impression" that is caused after a human fingertip contacts an object. A human can instantly perceive the properties of an object, such as the shape, material, texture, and compliance as an initial haptic impression [4]. For example, a human can perceive the difference between the edge and the flat surface of an object (Fig. 1). Furthermore, a human can distinguish the material of an object through changes in the temperature of a fingertip. If there is no initial haptic impression in a haptic transmission system, the reality of haptic sense perceived from a haptic transmission system appears to be decreased.

We aim to transmit shape and material information of an object as an initial haptic impression. The results of the object identification experiment conducted by Klatzky et al. [5] revealed that the performance of identification decreased slightly when the participants wore a glove. Under this condition, the participants could not perceive spatially distributed tactile and thermal information, and were thus unable to identify the object correctly. Lederman and Klatzky [6] indicated that human haptic perception decreases except for vibration or roughness perception when a latex surgical glove is worn to eliminate the spatially distributed information. Humans appear to use thermal information, i.e., the pattern of thermal changes of his/her fingertip, to identify the materials of objects [7][8]. On the basis of these conventional studies, we believe that spatially distributed tactile and thermal information, i.e., cutaneous information should be transmitted with other haptic information. However, because of the technical difficulties involved in the measurement and presentation of cutaneous information, a transmission system that enables a user to perceive an initial haptic impression has not yet been realized.

In this study, we aim to realize a haptic transmission system that enables a user to perceive the initial haptic impression by developing a cutaneous sensor and display.

2. REQUIREMENTS

In this chapter, we design a transmission system of haptic information that enables us to perceive the initial haptic impression.

2.1 Haptic information

Previous studies have demonstrated that a human can recognize the shape, material, texture, and compliance of an object as an initial haptic impression [4]. It has also been reported that both spatially distributed tactile and thermal senses are important in recognizing these properties of an object [5][6][7][8]. The force distribution and temperature on the skin surface

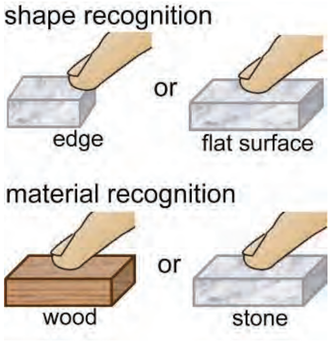

Fig.1 Examples of initial haptic perception.

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correspond to spatially distributed tactile and thermal senses, respectively, so that the cutaneous devices must simultaneously transmit the force distribution and temperature.

2.2 Device size

Furthermore, the cutaneous devices should be implemented to the multi fingered robotic hand system [2] in order to perceive haptic senses from both active and passive touch. Therefore, cutaneous devices should be compact, i.e, small, light, and easy to control, so that they are easily integrated with a multi fingered system.

2.3 Performances

We consider the performance of the sensor and display that enables a user to perceive initial haptic impression. If these performance parameters are not satisfactory, the user may get the feeling that he/she is touching an object through a glove.

In tactile information, spatial distribution is important for this thesis. The measurement and presentation of the high frequency vibration should be conducted up to 500 Hz, while the low frequency vibration and pressure (spatially distributed information) is enough up to 100 Hz [9]. The high frequency vibration should be measured and presented at a point of the skin surface, while the low frequency vibration and pressure should be measured and presented at the skin surface as spatially distributed information. The spatial resolution of the tactile information should be 1 mm [10].

The temperature measurement and presentation range of the thermal sensor should cover the range of 15-45˚C [11]. The accuracies of the sensor and display are more than 0.3˚C [12] and the spatial resolutions of the sensor and display should be smaller than 20 mm [13]. Because we have to measure and present the surface temperature of the sensor and display, respectively, a high time response is required. Ideally, the thermal change should be measured and presented at the moment the sensor comes into contact with an object. We have set the required measurement and presentation rate for thermal change to more than 6˚C/s [10]. Thermal information should be measured and presented at the surface of the sensor and fingertip, respectively.

3. CUTANEOUS DEVICES

In order to satisfy the above-mentioned requirements, we propose a cutaneous sensor and display that apply a vision-based measurement method and electrotactile stimulation methods, respectively.

3.1 Vision based cutaneous sensor

In order to realize haptic sensor for the haptic transmission system, this thesis proposes the haptic sensor using vision-based measurement method. The proposed haptic sensor applies two technologies: one is a force sensing technology named GelForce [14] and another is thermal sensing technology using thermo-sensitive ink with a camera [15].

We use the finger-shaped GelForce to measure tactile information, in terms of the distribution of three-dimensional forces (or a surface traction field). This sensor consists of a transparent elastic body, colored marker matrixes, and a color charge-coupled device (CCD) camera that captures the displacements of the markers. When force is applied to the surface of the sensor, the markers are displaced in response to the magnitude and direction of the applied force. The displacements of the markers are captured by the camera. We determine the center of the markers before and after the application of the force in order to calculate their degree of displacement. When we assume that the deformation of the elastic body is linear, we find that the relationship between the two-dimensional displacements of m-markers, **u**, and the three dimensional n-force vectors, **f**, is expressed in terms of the conversion matrix **H**.

$$\mathbf{f} = \mathbf{H}\mathbf{u} \tag{1}$$

In this equation, the $2m \times 3n$ conversion matrix **H** is determined from observational method [14]. First, we applied forces at each force sampling point and recorded the applied force. Then, we measured the movement of the markers. We estimated **H** from the recorded forces and the measured movement of the markers.

The finger-shaped GelForce does not require any electronic components such as resistors or capacitors. Therefore, it is easy to adapt the shape and size of the GelForce to those of a human fingertip. In addition, new developments in camera technology may help us to improve the spatial and temporal resolutions of the sensor.

We use the thermo-sensitive ink to measure thermal information. The color of this ink changes on the basis of a change in its temperature. This ink is used to make thermal information visible and, hence, it is applied for the temperature management of products such as food or industrial machines. In this study, we have used thermo-sensitive ink to measure the change in the temperature of the surface of the haptic sensor, for telexistence. The thermo-sensitive ink is applied on the inner side of the sensor surface so that its color changes according to the change in temperature of the sensor surface.

In order to convert the data from a color to a temperature format, we use the hue of the captured image. In a previous study, it has been indicated that the

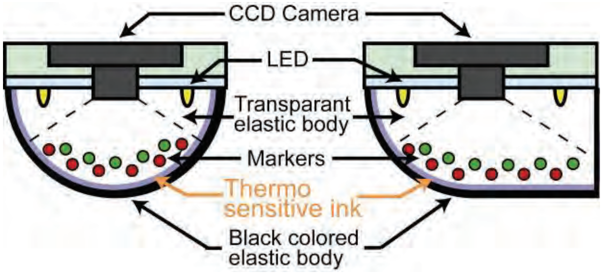

Fig.2 Configurations of vision-based cutaneous sensor

change in the hue corresponds to the change in temperature of the thermo-sensitive ink. Therefore, we consider that the temperature of the sensor surface can be calculated from an equation developed for converting hue h to temperature T_s.

$$T_s = g(h) \tag{2}$$

In this equation, $g(\bullet)$ denotes the conversion function from the hue of the captured thermo-sensitive ink to its temperature.

As in the case of the finger-shaped GelForce, the thermal measurement method involving the use of the thermo-sensitive ink does not require any electronic components. Therefore, this method does not influence the physical properties of the finger-shaped GelForce.

3.2 Cutaneous display using electrotactile stimulation

The electrotactile display [16] operates by activating the nerve fibers that are connected to mechanoreceptors, thereby producing a tactile sensation (Fig. 3a). The electrodes are placed on the skin surface and a flow of electrical currents is applied to the skin. It is possible to apply a consistent stimulation to the nerve fibers bearing the electrodes by using two coaxial electrodes. Furthermore, arranging the pin-electrodes into a matrix pattern, the electrotactile display is capable of producing two-dimensional patterns [17]. The electrotactile display has a simple structure and is therefore easily controlled. Because of these advantages, the electrotactile display can be used not only in the contest of physiological studies, but also in the context of technological applications. In the proposed display, we integrated it with a Peltier element so as to present thermal change to the user (Fig. 3b).

The electrotactile display outputs spatially distributed tactile information depending on the strength of electrotactile stimuli. The vision-based cutaneous sensor measures the distribution of force vectors applied on the sensor surface. In the proposed system, the electrotactile display can only output the magnitude and distribution of the force vectors, not angle of them. The magnitude of the force vector $|f_i|$ is calculated as follows:

$$|f_i| = \sqrt{f_{ix}^2 + f_{iy}^2 + f_{iz}^2} \tag{3}$$

where, i represents the number of the force sampling point. The magnitude and position of the force is related to the amplitude and position of the electrotactile stimuli. In the electrotactile display, the amplitude threshold of electrotactile stimuli differs among users. Therefore, users have to determine the threshold before using the transmission system. The amplitude of the electrotactile, stimulus at a pin electrode, Ii, is given as follows [18]:

$$I_i = \begin{cases} 0 & (|f_i| < f_{RES}) \\ \alpha |f_i| + I_{THR} & (|f_i| \geq f_{RES}) \end{cases} \tag{4}$$

where, i, α, and I_{THR} denote the number of pin electrode, gain, and bias, respectively, that are pre-examined by a user. We have already showed that the electrotactile stimulation is useful for presentation of shape information of an object [16][18].

The temperature measured by the vision-based cutaneous sensor T_s is presented to a user through Peltier element. The surface temperature of the display (electrotactile display) T_d is controlled by the electrical current passing through the Peltier element I_p, which is calculated from T_s and T_d as follows:

$$I_p = K_T (T_s - T_d) \tag{5}$$

where K_T is gain that controls the change rate of the temperature. We can implement the film-type electrode plate so as to effectively present thermal information even if there is an electrode plate between Peltier element and surface of the human skin.

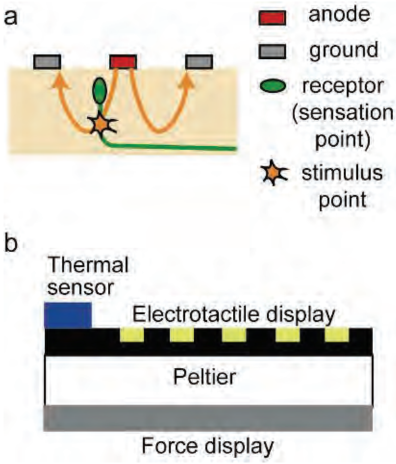

Fig.3 (a) Electrotactile stimulation. (b) Configurations of cutaneous display using electro tactile display.

4. IMPLEMENTATION

4.1 One-fingered transmission system

We constructed the prototype of the transmission system of haptic information. The implemented cutaneous sensor and display are attached to the end-effector of master-slave system then employs PHANToM Omni (SensAble Tech., Inc.) as shown in Fig. 4 so as to transmit not only cutaneous but also kinesthetic information.

Fig. 5a shows the constructed cutaneous sensor. The shape of the transparent elastic body is partly spherical and partly cylindrical resembling a human fingertip. The dimensions of the elastic body are 18 mm × 9 mm × 19 mm. The transparent elastic body is composed of urethane gel (Human Skin Gel, Exseal Corp.) owing to the fact that its Young's modulus (5.0×10^4 Pa) is approximately the same that of a human fingertip.

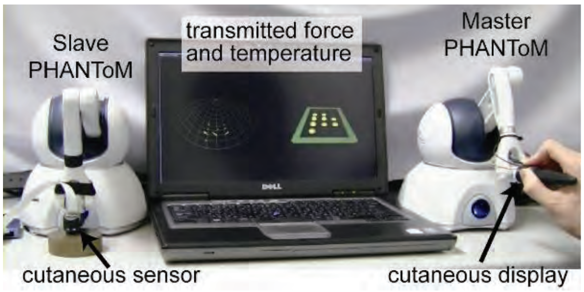

Fig.4 Implemented transmission system.

However, the thermal contact coefficient of this material (urethane rubber; 400¬–600 J/m^{2}s$^{1/2}$K) differs from that of the human skin (1,181 J/m^{2}s$^{1/2}$K [11]). In future studies, we must appropriately select the material of the elastic body by considering its thermal properties. The frame rate and resolution of the CCD camera (ViewPlus, Inc.) are 15 Hz and 640 pixel × 480 pixel (VGA), respectively. Fig. 5b represents the captured image of the camera. 16 red and 8 green circular markers are arranged at different depths of the transparent elastic body. The diameter of the markers is 1.0 mm and the centers of the markers are separated by 3.0 mm. We have sat 15 force sampling points that are separated 2.5 mm. We have used a thermo-sensitive liquid sheet (Japan Capsular Products, Inc.) for thermo-sensitive ink. The 3.0 mm × 3.0 mm liquid sheet is placed at the center of the elastic sheet. The thickness of the elastic sheet is 0.5 mm. The light source comprises 8 LEDs. The temperature of the sensor is maintained at approximately 35°C by the heat generated from the LEDs when the surrounding air temperature is 26°C.

Fig. 6 shows constructed cutaneous display. We integrated the electrotactile display that has 15 electrodes that are separated 2.5 mm with the Peltier element (T150－60－017S, S. T. S. Co.). The material and thickness of the electrode plate are glass epoxy (heat conductivity: 30 W/mK) and 1.0 mm, respectively. An aluminum plate (1.0 mm thickness) was attached between the electrode plate of the electrotactile display and Peltier element. The thermal sensor (LM35, National Semiconductor Co.) was attached at the chip of the aluminum plate to monitor and control the temperature of display surface. Furthermore, another aluminum plate (1.0 mm thickness) was attached between the Peltier element and the base of the PHANToM Omni in order to release the heat discharged by the Peltier element. The electrode plate, aluminum plates, Peltier element, and thermal sensor were bonded by the heat-conductive double-faced tape.

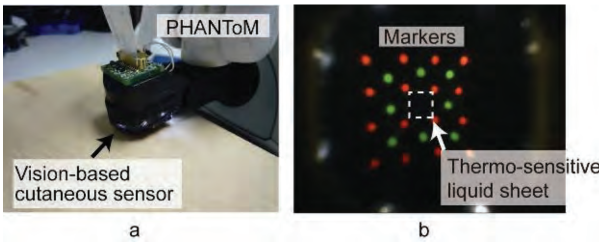

Fig.5 (a) Vision-based cutaneous sensor and (b) captured image of it.

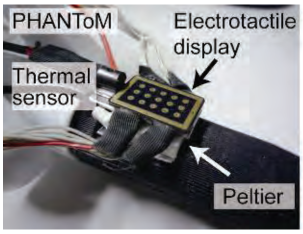

Fig.6 Cutaneous display using electrotactile display.

The electrotactile stimulation is calculated from the measured forces by the sensor based on Equation (3) and (4). The control of the temperature of the display was conducted by the Arduino Duemilanove (Arduino Software). The target temperature, i.e., the temperature measured by the vision-based haptic sensor T_s is transmitted from PC to the Arduino through serial communication. The surface temperature of the display T_d is measured through LM35 and A/D converter of the Arduino. Furthermore, we control the direction of I_p using a power switch so as to warm up and cool down the surface temperature of the display.

The participants had to place the tip of their index finger on the cutaneous display and move the end-effector of the master PHANToM to control the cutaneous sensor on the slave PHANToM. In this system, we used the simplest symmetric position servo type control algorithm for robotic master-slave control, which can be represented by the following equations:

$$f_s = (x_m - x_s)K_p, \quad f_m = -f_s \tag{5}$$

where f_s and f_m denote the forces of the slave and master systems, respectively; x_s and x_m, the positions of the slave and master systems, respectively; K_p, the gain.

4.2 Transmission of shape and material information

Users of the constructed transmission system could perceive the initial haptic impression of a remote object mainly from spatially distributed tactile and thermal information. The users could control the slave PHANToM by manipulatting the master PHANToM so as to touch remote objects and discriminate the difference between shape (edged or flat surface) and material (wood or metal).

Fig. 7 and 8 represent the force distribution and temperature transmitted when the user touches with wood surface, wood edge, metal surface, and metal edge through the constructed system, respectively. The width of edge is 5.0 mm and the metal is aluminum. The user can discriminate the difference of shape based on the electrotactile stimulation based on the measured force vectors by the vision-based cutaneous sensor. Furthermore, the cutaneous sensor effectively measures the difference of material in terms of temperature

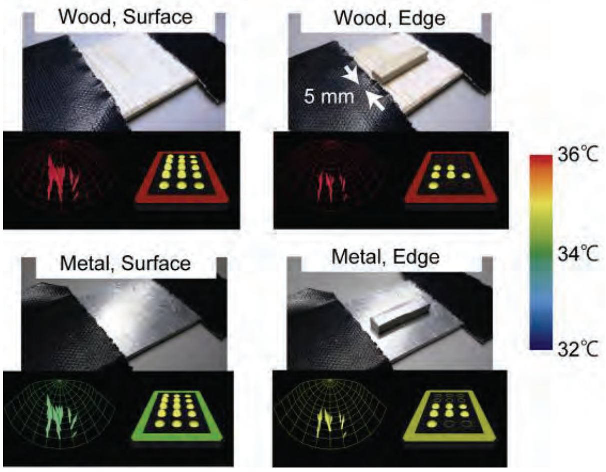

Fig.7 Examples of transmitted force vector distribution and temperature. The lengths of the arrows represent the magnitude of the measured force, whereas the size of the yellow sphere represents the amplitude of the electrostimulus. The color of the arrows and electrode plate represents temperature.

change so that the user of the transmission system could perceive the difference between wood and metal. Currently, because of the small heat conductivity and thickness of the electrode plate, the time response of thermal display does not well: it is difficult to perceive thermal information within 1 s. We consider that the time response will be easily improved when we change the electrode plate to the alumina substrates (heat conductivity: 30 W/mK) which is 0.1 mm thickness.

It should be noted that the user cannot perceive realistic thermal change, whereas he/she can discriminate the difference of thermal change. Because the thermal change of a fingertip is depends on a contact area, the thermal display should present temperature distribution. However, the constructed transmission system presents temperature at a point and does not apply any algorithms to correct measured temperature. Therefore, the thermal change of a fingertip differs from the actual change when fingertip contacts with edged object. In the future, we will investigate a relationship between thermal change and contact area in order to develop thermal display and its algorithm.

4. CONCLUSION

This study proposed and implemented a transmission system of haptic information employing the vision-based cutaneous sensor and the cutaneous display consists of electrotactile display. The implemented prototype system enabled a user to perceive the shape and material information of a remote object as the initial haptic impression.

In the future, we will develop a multi fingered haptic transmission system using the cutaneous devices proposed in this paper. Furthermore, we will develop the algorithm to transmit haptic information. When we develop a suitable algorithm, humans will be able to recognize remote objects more effectively and precisely. In order to construct such a transmission algorithm, the cross interaction among the different haptic senses should be studied further. Because humans perceive the haptic sense as integrated information from the kinesthetic, tactile, and thermal senses, each sense has some influences on the perception of the others. If we utilize these cross interactions effectively, a smart algorithm for a haptic transmission system can be achieved. We believe that the investigation of these multi sensory cross interactions is useful not only for the construction of a transmission algorithm but also in the pursuit of the more suitable haptic devices design.

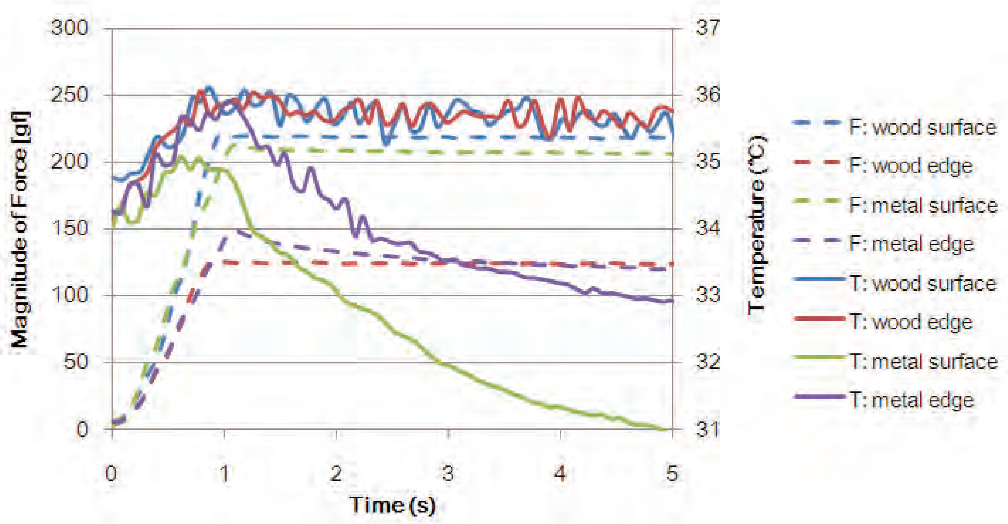

Fig.8 Temporal changes of measured force and temperature by the cutaneous sensor. Dashed line and strait line represent sum of the force magnitudes measured at each sampling points and temperature, respectively. The color of each line represents the four objects.

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