Vision-based Cutaneous Sensor to Measure Both Tactile and Thermal Information for Telexistence

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ABSTRACT

We have proposed a vision-based cutaneous sensor for telexistence that can simulate the physical interaction between a human fingertip and an object. The proposed sensor comprises a finger-shaped GelForce and a thermo-sensitive paint. The finger-shaped GelForce enables us to measure tactile information in terms of the distribution of forces that are calculated from the displacements of markers inside the sensor body. The thermo-sensitive paint is employed to measure thermal information on the basis of its color, which changes according to its temperature. In this study, we have described the design of the proposed cutaneous sensor, constructed its prototype, and discussed its efficiency for telexistence.

KEYWORDS: Vision-based sensor, Force, Temperature, Telexistence.

INDEX TERMS: H.5.2 [Information System]: User Interfaces—Haptic I/O; I.2.9 [Computing Methodologies]: Robotics—Sensors

1 INTRODUCTION

The transmission technology of haptic information is essential for telexistence [1] (or telepresence) systems. When a human interacts with an object, he/she perceives the properties of the object such as stiffness, weight, shape, texture, and temperature through his/her haptic sense. Without haptic sense, a telexistence system user cannot perceive any property of an object that he/she touches, thereby eliminating the reality of the telexistence experience. Haptic sensors and displays are required to realize transmission of haptic information. The purpose of this study is to develop a haptic sensor for telexistence systems that involve robotic fingers.

Haptic sense can be divided into the following two types based on the position of the receptors that acquire sensory information: kinesthetic and cutaneous senses. Conventional haptic sensors for telexistence can also be classified into kinesthetic and cutaneous sensors based on the measured information. A number of three-axis force or torque sensors have been developed for application as kinesthetic sensors for robotic fingers. Moreover, to date, it has been difficult to develop cutaneous sensors primary because of two problems. One of the problems is that cutaneous sensors are required to measure two types of physical information, i.e., force and temperature. The cutaneous sense of a human consists of tactile and thermal senses that are required to perceive the mechanical deformation and temperature of the skin surface, respectively. Therefore, cutaneous sensors are expected to measure tactile and thermal information, i.e., they should be able to sense the applied forces and temperature changes on the sensor surface simultaneously. The other problem is associated with the interactivity of the haptic sensing. When a human actually touches an object, deformation and thermal changes occur on both his/her skin and the surface of the object. Therefore, the sensor should simulate the interaction caused by the contact of an object with the human skin so as to measure cutaneous information correctly. In order to appropriately simulate the interaction between the fingertip and an object, both the mechanical and thermal properties of the sensor should be the same as those of the fingertip. In particular, it is important that the shape, size, compliance, temperature, and thermal contact coefficient [2] of the sensor are the same as those of the fingertip.

Conventional cutaneous sensors for telexistence systems measure either tactile or thermal information. For example, Maeno et al. developed a tactile sensor for the transmission of textures of objects [3]. Sato et al. have also developed a force sensor and constructed a transmission system for the spatial distribution of force [4]. These sensors measure only tactile information and not thermal information. On the other hand, Guiatni et al. [5] proposed a thermal transmission system using a Peltier sensor and a display for transmitting realistic thermal information. However, this system could not sense and display tactile information. Some previous studies have attempted to measure both the tactile and the thermal information [6][7][8]. These studies integrated a thermal sensing element, such as a Peltier element, with a tactile sensing unit. These sensors were developed for an autonomously controlled robotic hand and not to simulate a physical interaction between a fingertip and an object.

As a cutaneous sensor for telexistence, we propose a vision-based cutaneous sensor that can measure both the tactile and the thermal information. The proposed sensor can simulate the interaction caused by the contact of an object with the human skin In this paper, we introduce the design of the vision-based cutaneous sensor and implement the proposed sensor.

2 VISION-BASED CUTANEOUS SENSOR FOR TELEXISTENCE

2.1 Vision-based sensing method

We have proposed a vision-based cutaneous sensor comprising a finger-shaped GelForce [9] and a thermo-sensitive paint [10].

2.1.1 Finger-shaped GelForce

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.

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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 (Figure 1). 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.

$$f = Hu \tag{1}$$

In this equation, the $2m \times 3n$ conversion matrix H is determined from observational method [9]. 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. Furthermore, the finger-shaped GelForce can easily implement a thermal measurement method described in below subsection.

2.1.2 Thermo-sensitive paint

We use the thermo-sensitive paint to measure thermal information. The color of this paint changes on the basis of a change in its temperature. This paint is used to make thermal information visible and, hence, it is applied for the temperature management of products such as food or industrial machines. Thermo-sensitive paint is also used for analysis of fluids. In this study, we have used thermo-sensitive paint to measure the change in the temperature of the surface of the haptic sensor, for telexistence. The thermo-sensitive paint 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 [10], it has been indicated that the change in the hue corresponds to the change in temperature of the thermo-sensitive paint. Therefore, we consider that the temperature of the sensor surface can be calculated from an equation developed for converting hue h to temperature T.

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

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

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

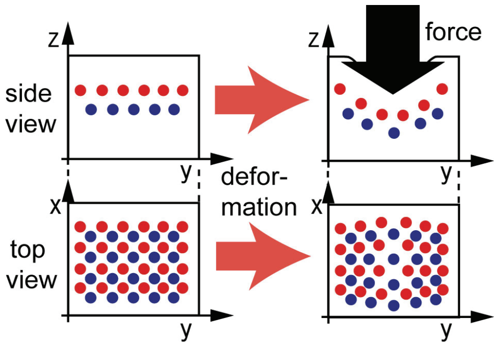

Figure 1. Displacements of markers in the elastic sensor body caused by force applied to the sensor surface [9].

2.2 Design of vision-based cutaneous sensor

Figure 2 shows the configuration of the proposed vision-based cutaneous sensor comprising the finger-shaped GelForce and the thermo-sensitive paint. This sensor consists of an elastic sheet coated with the thermo-sensitive paint, colored makers, a transparent elastic body, a CCD camera, a heat source, and a light source. The camera detects the displacement of the markers and the color of the thermo-sensitive paint; using this information we can determine the tactile and thermal information of the sensor surface.

We can control the shape, size, compliance (Young's modulus), temperature, and thermal contact coefficient of the elastic body to be the same as that of a human fingertip. A heat source is used to ensure that the temperature of the sensor is the same as that of the human fingertip. Therefore, the proposed sensor can simulate the interaction caused by the contact of an object with the human skin.

3 EVALUATION

We implemented a prototype of the proposed vision-based cutaneous sensor to ensure that it can simultaneously measure the distribution of the applied force and temperature.

3.1 Implementation of prototype

3.1.1 Components

Figure 3(a) shows the constructed prototype. 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 (1.36×10^5 Pa for the epidermis, 8.0×10^4 Pa for the dermis, and 3.4×10^4 Pa for the subcutaneous fat [11]). However, the thermal contact coefficient of this material (urethane rubber; 400–600 $\mathrm{J/m^2s^{1/2}K}$) differs from that of the human skin (1,181 $\mathrm{J/m^2s^{1/2}K}$ [12]). In future studies, we must appropriately select the material of the

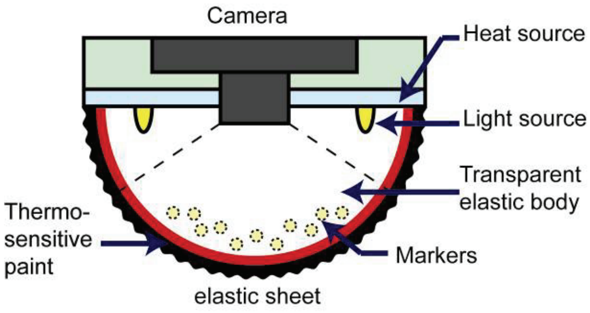

Figure 2. Configuration of proposed vision-based cutaneous sensor.

elastic body by considering its thermal properties. The frame rate and resolution of the CCD camera (ViewPlus, Inc.) are 15Hz and 640 pixel × 480 pixel (VGA), respectively. Figure 3(b) shows an image captured by the CCD 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 used a thermo-sensitive liquid sheet (c-task, Inc., JP) for thermo-sensitive paint. 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.

3.1.2 Force calculation

The proposed sensor calculates the applied forces from the displacement of the markers. The positions of the markers are calculated as the centroid of each R and G element of the captured RGB format image. Employing the observational method described in [9], we allocated 12 (3 × 4) force sampling points, which are 3.0 mm apart.

We evaluated the accuracy of the proposed sensor in measuring the applied force using the constructed prototype sensor. We fixed the prototype sensor to an xyz stage (VSQ-601XYV, Chuo Precision Industrial Co. Ltd.) and applied a force of 0–500 gf vertically to the sensor surface by increasing its magnitude in steps of 50 gf. The force was applied by a six-axis force sensor (BL NANO, BL Autotech Ltd.) with a cylindrical probe of diameter 10 mm. We recorded the measured force using the six-axis force sensor (applied force) and the total force at every sampling point (calculated force). The measurement procedure was repeated five times. Figure 4 shows the evaluation results. The graph shown in this figure indicates a liner relationship between the applied force and the calculated force, confirming the force measurement accuracy of the prototype sensor.

3.1.3 Thermal calculation

In order to calculate the temperature of the sensor surface, we have cropped a 10 pixel × 10 pixel block from the captured image and calculated the average hue within the block. The center of the cropped image is calculated from the positions of the markers at the four corner of the thermo-sensitive liquid sheet. The camera image is captured in an RGB format; it is then converted it to an HSV format using OpenCV (Open Source Computer Vision) library.

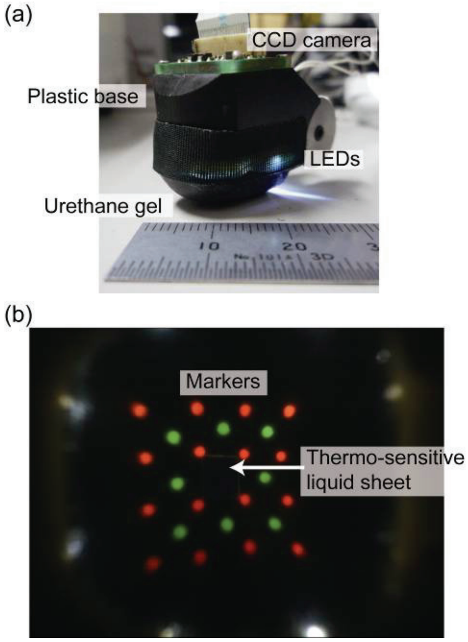

Figure 3. (a) Implemented prototype of the vision-based cutaneous sensor and (b) captured image.

To develop a function to convert the hue of the captured image to the temperature of the sensor surface ($g(\cdot)$ in equation (2)), we placed the center of the sensor surface on a cool plate (NCP-2215, Nissinrika Corp.). The temperature of the cool plate was increased from 31 to 36°C at intervals of 0.5°C. After the temperature of the cool plate was fixed at the target value, the contact between the sensor and the plate was maintained for more than 120 sec. The hue values of the thermo-sensitive liquid sheet were recorded 10 times for each temperature. Figure 5 shows the result of the calibration. From the graph shown in figure, we can confirm that the function of hue and temperature monotonically decreases in the temperature range of 31.5–35°C.

3.2 Measurement of cutaneous information

We measured the applied force and temperature simultaneously using the constructed prototype sensor. We fixed the prototype sensor to an xyz stage, and pressed the surface of the sensor against to an aluminum plate suspended in air at 26°C. Force was applied to the sensor at two different locations, by pressing the aluminum plate vertically to the sensor surface, producing displacements of approximately 1.0 mm and 2.0 mm. Then, we recorded the temporal changes in the applied force and temperature measured by the prototype sensor at intervals of 0.1 s when the temperature was 32–35°C.

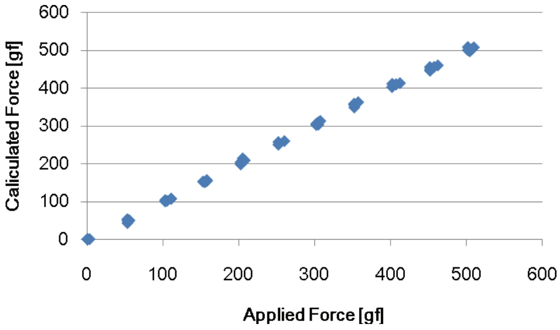

Figure 4. Relationship between applied force and calculated force by prototype sensor.

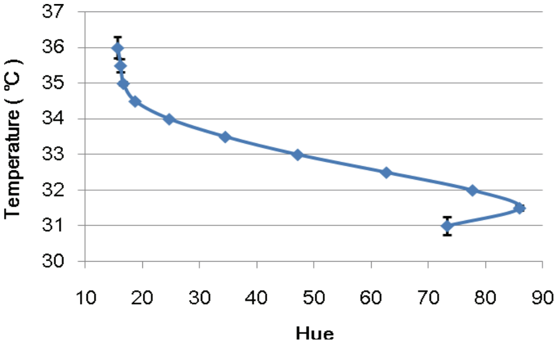

Figure 5. Relationship between temperature of the sensor surface and hue of thermo-sensitive liquid sheet.

Figures 6 and 7 show the recorded results. In Figure 6, the applied forces and temperatures are represented by arrows and their colors, respectively. The color continuously changes from red at 36°C, to green at 34°C, to blue at 32°C. The measured forces do not appear to change even when the temperature changes. In Figure 7, the solid and dashed lines represent the total force and temperature, respectively. The magnitude of force is constant irrespective of the change in temperature. The decrease in temperature was larger when the aluminum plate caused a displacement of 1 mm than the decrease when it caused a displacement of 2 mm. When the aluminum plate was pressed against sensor, the density of the sensor increased. From the thermal conductivity theory, we infer that the decrease in temperature is more pronounced with an increase in the density. However, the result of our measurement does not agree with this theory. We hypothesize that excess heat from the heat source could cause this unexpected disparity. Therefore, in the future, we will study this effect and make required changes to the design of the sensor.

From these measurements, we can confirm that the prototype sensor can measure tactile and thermal information simultaneously and independently.

4 CONCLUSION

In this paper, we proposed a vision-based cutaneous sensor to measure tactile and thermal information simultaneously. The proposed sensor comprises a finger-shaped GelForce and thermo-sensitive paint, enabling it to simulate the physical interactions between a human fingertip and an object so as to correctly measure cutaneous information. We implemented a prototype of the proposed sensor and confirmed that it could measure cutaneous information. However, the thermal measurement method was not adequately implemented and evaluated. We will further develop the thermal measurement method to realize a cutaneous sensor for telexistence. Then, we will also develop a cutaneous display that will be able to present both tactile and thermal senses.

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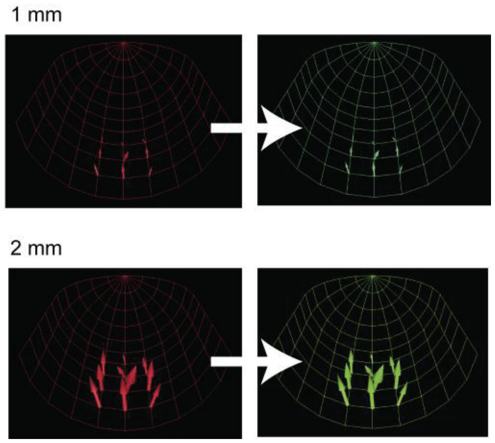

Figure 6. Visualized results of force and temperature measurement.

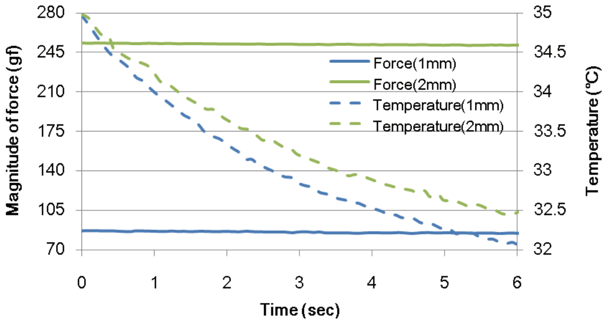

Figure 7. Recorded force and temperature measured by the prototype sensor.

REFERENCES

[1] Tachi, S., Kawakami, N., Nii, H., Watanabe, K. and Minamizawa, K, "TELEsarPHONE: Mutual Telexistence Master Slave Communication System based on Retroreflective Projection Technology," *SICE Journal of Control, Measurement, and System Integration*, Vol.1, No.5, pp.335–344, 2008.

[2] J. A. Businger and K.J.K. Buettner, "Thermal Contact Coefficient (A Term Proposed for Use in Heat Transfer)," *Journal of Atmospheric Sciences*, vol. 18, No. 3, pp.422–422, 1961.

[3] T. Yamauchi, S. Okamoto, M. Konyo, Y. Hidaka, T. Maeno and S. Tadokoro, "Real-Time Remote Transmission of Multiple Tactile Properties through Master-Slave Robot System," *Proc. of the 2010 IEEE Int'l Conf. on Robotics and Automation (ICRA'10)*, pp. 1753–1760, 2010.

[4] K. Sato and S. Tachi, "Evaluation of Transmission System for Spatially Distributed Tactile Information," *Proc. of EuroHaptics 2010*, Part I, pp. 279–284, 2010.

[5] M. Guiatni, A. Benallegue, and A. Kheddar, "Thermal Display for Telepresence Based on Neural Identification and Heat Flux Control," *Presence*, Vol. 18, No. 2, 2009.

[6] D. Siegel, I. Garabieta, and J. M.Hollerbach. "An integrated tactile and thermal sensor," Proc. of Int'l Conf. on Robotics and Automation (ICRA '86), pp. 1286–1291, 1986.

[7] G. J. Monkman and P. M. Taylor, "Thermal Tactile Sensing", *IEEE Trans. on Robotics and Automation*, Vol. 9, No. 3, pp. 313–318, 1993.

[8] D. Taddeucciand C.Laschi, R.Magni, P.Dario, and A.Starita, "An approach to integrate tactile perception," *Proc. of IEEE Int'l Conf. on Robotics and Automation (ICRA '96)*, pp. 3215–3221, 1996.

[9] K. Sato, K. Kamiyama, N. Kawakami, and S. Tachi, "Finger-Shaped GelForce: Sensor for Measuring Surface Traction Fields for Robotic Hand," *IEEE Trans. on Haptics*, Vol. 3, No. 1, pp.37–47, 2010.

[10] M. Ozawa, U. Miller, L.Kimura, and T. Takamori, "Flow and Temperature Measurement of Natural Convection in a Hele-Shaw Cell Using a Thermo-Sensitive Liquid Crystal," *Experiments in Fluids*, Vol. 12, pp. 213–222, 1992.

[11] T. Maeno, K. Kobayashi, and N. Yamazaki, "Relationship between the structure of human finger tissue and the location of tactile receptors," *JSME Int'l Journal*, Vol. 41, No. 1, pp. 94–100, 1998.

[12] L. A. Jones and H.-N. Ho, "Warm or Cool, Large or Small? The Challenge of Thermal Displays," *IEEE Trans. on Haptics*, Vol. 1, No. 1, 2008.