2011 IEEE International Conference on Robotics and Automation
Shanghai International Conference Center
May 9-13, 2011, Shanghai, China

Finger-shaped Thermal Sensor using Thermo-sensitive Paint and Camera for Telexistence

Katsunari Sato, Hiroyuki Shinoda, and Susumu Tachi,
The University of Tokyo, Keio University, Japan

Abstract— **A thermal change on a fingertip is essential for haptic perception. We have proposed a vision-based thermal sensor using thermo-sensitive paint and a CCD camera for telexistence. The thermo-sensitive paint is employed to measure thermal information on the basis of its color, which changes according to its temperature. The proposed sensor can simulate the physical interaction between a human fingertip and an object in order to measure surface thermal information correctly. Furthermore, because the proposed sensor can be easily integrated with our vision-based force sensor, a comprehensive measurement device for measuring haptic information can be realized. In this study, we constructed a prototype of the proposed thermal sensor and experimentally confirmed that this sensor could measure surface thermal information.**

I. INTRODUCTION

HAPTIC sensors are essential for telexistence (or telepresence) systems [1] involving robotic fingers; therefore, a number of sensors have already been developed. Conventional haptic sensors used in telexistence system mainly measure the mechanical deformation of a human fingertip, i.e., tactile information. For example, Maeno et al. developed a tactile sensor [2] for the transmission of textures of objects [3]. We have also developed a force sensor [4] and constructed a transmission system for spatial distribution of force [5]. However, haptics is perceived by humans as the integrated information of the deformation and thermal change experienced by the skin [6]. When a human touches a metal or wood left at room temperature (approximately 20–25°C), he/she can discriminate the difference between them from the thermal changes; he/she perceives the metal as cooler than wood. Such thermal information enhances the reality of the experience in a telexistence system. For example, when a user touches a remote person through a telexistence system, the user feels not only the softness but also the warmth of this person. We consider that the user can feel even closer to this remote person from these haptic senses in tele-communication. The haptic senses are also effective in a tele-palpation system, e.g., a doctor can feel the state of a remote patient more correctly. Therefore, haptic sensors need to measure not only tactile but also thermal information.

In the telexistence system, the measured thermal information is presented to a human in a manner that enables him/her to perceive the thermal change as if he/she is actually touching an object. In order to realize this, the sensor must fulfill three requirements. First, the sensor has to measure the distribution of temperature on its surface. Because a human perceives the temperature of his/her skin surface, the thermal information has to be measured on the sensor surface and presented to the skin surface. Second, the performance of the sensor has to be better than that of a human's fingertip. The performance parameters are the measuring range, measuring accuracy (resolution), spatial resolution, and time response. If these performance parameters are not satisfactory, a human may get the feeling that he/she is touching an object through a glove. Finally, the physical properties of the sensor, such as shape, compliance, and temperature, have to be similar to that of a human fingertip to simulate the interaction caused by the contact of an object with human skin. When a human actually touches an object, the contact area and contact time affects to the thermal change on the surface of his/her fingertip. Furthermore, the thermal change is also affected by the thermal properties of the fingertip, i.e., temperature and thermal conductivity.

Some previous studies have tried to measure the thermal along with tactile information [7][8][9]. These studies integrated a thermal sensing element such as a Peltier element with a tactile sensing unit. We can mimic the shape and compliance of human skin by placing the sensing element in an elastic body. In this case, the thermal change in the contact area cannot be measured, and the spatial and time responses of the sensor decrease. As a method that does not mimic the properties of the fingertip, Guiatni et al. proposed a thermal transmission system using the neural network and a database [10]. This system can transmit realistic thermal information but it requires the construction of a database by the actual measurement of the thermal change between the fingertip and the object. Another method of thermal measurement requires the use of an IR camera [11]. This method can measure the surface temperature of the fingertip when the fingertip comes into contact with an infrared transmissive object. Therefore, it is difficult to apply this method to the haptic sensor.

As a thermal sensor for telexistence, we have proposed a

Manuscript received September 15, 2010.

Katsunari Sato is with the Graduate School of Information Science and Technology, The University of Tokyo, Japan (phone: +81-3-5841-6927; e-mail: Katsunari_Sato@ ipc.i.u-tokyo.ac.jp).

Hiroyuki Shinoda is with the Graduate School of Information Science and Technology, The University of Tokyo, Japan (e-mail: Shino@alab.t.u-tokyo.ac.jp).

Susumu Tachi is with the Graduate School of Media Design, Keio University, Japan (e-mail: Tachi@tachilab.org).

vision-based thermal sensor using thermo-sensitive paint and a camera. The proposed sensor can mimic the shape, compliance, and temperature of a human fingertip and simulates the physical interaction between an object and a fingertip. Furthermore, one can readily built a haptic sensor that can measure both deformation and thermal change on the finger surface by adding a vision-based force sensor [4]. In this paper, we evaluated and discussed whether the proposed sensor is applicable to a telexistence system.

II. VISION-BASED THERMAL SENSOR

A. Thermal sensor requirements

Before we introduce the vision-based thermal sensor, we describe the required performance and properties of the thermal sensor for telexistence (summarized in Table 2 in section IV).

Jones and Ho [12] summarized the conventional studies about the thermal perception in humans. The temperature range within which a human can perceive thermal sensation is 15–45°C. If the temperature of the skin falls below 15°C or rises above 45°C, the thermal sensation changes to that of pain. Therefore, the temperature measurement range of the thermal sensor has to cover the range of 15–45°C. The thermal threshold of a human depends on the initial skin temperature of the skin and rate of thermal change (°C/s). In this study, we have determined that the target measurement accuracy of the sensor, based on the cold threshold of the index finger, is 0.2°C measured at a rate of 2.1°C/s [13]. If the measurement resolution is smaller than 0.2°C, then the measured thermal information is correctly presented to a human. The average localization error of the warm stimuli is approximately 19 mm [14]; therefore, the spatial resolution of the sensor has to be smaller than 20 mm. Because we have to measure the surface temperature of the sensor, a high time response is required. Ideally, the thermal change has to be measured exactly when the sensor comes touches the object. Furthermore, the temperature of human skin seems to change at the rate of 6°C/s [15]. Therefore, we have set the required measurement rate for the thermal change to more than 6°C/s.

In order to simulate the interaction between the fingertip and an object, the thermal and mechanical properties of the sensor and that of the fingertip have to be the equivalent. To discuss the thermal interaction, several studies have used the “two semi-infinite bodies in contact” model. On using this model, the surface temperature of the skin and the object change instantaneously to the interface temperature T_s:

$$T_s = \frac{T_{object,i}(k\rho c)^{1/2}_{object,i} + T_{skin,i}(k\rho c)^{1/2}_{skin,i}}{(k\rho c)^{1/2}_{object,i} + (k\rho c)^{1/2}_{skin,i}} \quad (1)$$

In this equation, k is the thermal conductivity, ρ is the density, c is the specific heat, $T_{object,i}$ is the initial temperature of the object, $T_{skin,i}$ is the initial temperature of the skin, and $(k\rho c)^{1/2}$ is the thermal contact coefficient [16]. Furthermore, during contact, the out-of the-skin heat flux q''_{skin} is calculated as follows:

$$q''_{skin} = \frac{k_{skin}(T_x - T_{skin,i})}{(\pi\alpha_{skin}t)^{1/2}} \quad (2)$$

where α_{skin} is the thermal diffusivity of the skin defined as $(k/\rho c)_{skin}$ and t is the time. These equations suggest that the thermal contact coefficient of the skin affects the thermal change, and therefore, it is also important for the sensor. These thermal properties of the fingertip are summarized by Ho and Jones [15]; the average $T_{skin,i}$ is 34.6°C, k is 0.37 W/mK, ρ is 1,000 kg/m^3, c is 3,770 J/kg K, and $(k\rho c)^{1/2}$ is 1,181 J/m^{2}s$^{1/2}$K. Furthermore, the sensor should be finger-shaped, and its compliance should be the same as that of a human fingertip. The compliance is denoted by Young’s modulus, which is 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 [17]. These mechanical properties are also important for the accurate measurement of tactile information.

B. Thermal measurement using thermo-sensitive paint and camera

To realize a thermal sensor that satisfies the abovementioned requirements, we have proposed a vision-based thermal sensor using thermo-sensitive paint and a camera. Thermo-sensitive paint changes its color corresponding to thermal change. This paint can visualize thermal information and hence, it is applied for temperature management of products such as food or industrial machines. Thermo-sensitive paint is also applied in scientific investigations such as the analysis of fluids [18]. In this study, we have used the thermo-sensitive paint to measure the thermal change on the surface of the haptic sensor for telexistence.

Figure 1 represents the configuration of the proposed vision-based thermal sensor. This sensor consists of an elastic seat with thermo-sensitive paint, a transparent elastic body, a camera, a heat source, and a light source. The thermo-sensitive paint is printed on the inner side of the sensor surface so that its color changes corresponding to the thermal change on the sensor surface, i.e., the interface temperature T_s in Eq. 1. The camera detects the color of the thermo-sensitive paint and converts it to the temperature of

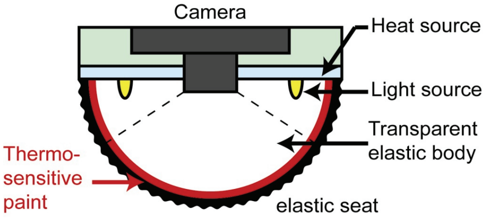


Fig. 1. The configuration of the proposed vision-based thermal sensor.

the sensor surface. We ensure that the compliance of the elastic body is the same as that of a human fingertip. Therefore, it can mimic the deformation of the skin caused by the contact. The heat source maintains the temperature of sensor and that of the human fingertip at the same level. The temperature of the sensor surface has to be controlled to mimic the temperature of the fingertip.

To convert color to temperature, we use the hue of the captured image. In a previous study [18], it was indicated that the hue change corresponds to the thermal change. Therefore, we consider that the temperature of the sensor surface can be calculated from an equation developed for converting hue, h, to temperature, T:

$$T = f(h) \tag{3}$$

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

Note that the color change of the normal thermal-sensitive paint finishes when the temperature changes more than 5°C or 10°C. In order to cover the temperature measurement range of 15–45°C, we have to use several paints that have different temperature ranges.

C. *Integration with vision-based force sensor*

The haptic sensor needs to measure the thermal along with tactile information, i.e., distribution of force applied to the sensor surface.

The basic configuration of the proposed thermal sensor is the same as that of vision-based force sensor [4]; therefore, we consider that these sensors can be easily integrated. Figure 2 represents the force measurement theory of the vision-based force sensor. It consists of a transparent elastic body with two-layered markers and a CCD camera. When a force is applied to the sensor, the markers are displaced. The CCD camera captures the displacement of the markers and then calculates the distribution of the applied force from these displacements. A haptic sensor that can measure both deformation and thermal change is basically achieved by incorporating the markers in the vision-based thermal sensor. Because we calibrate the initial marker positions, we can easily arrange two layered markers by hand. The markers have to be uniformly arranged not to eliminate overlap with each marker.

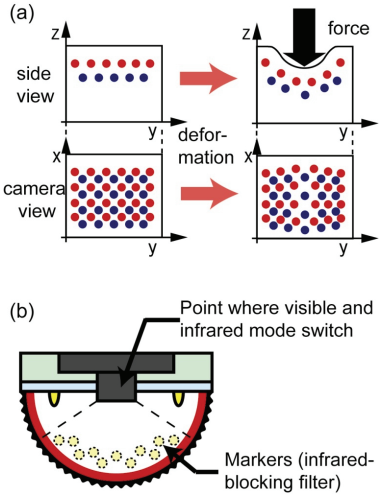


Fig. 2. (a) Basic theory of vision-based force sensor [4] and (b) configuration of vision-based force and thermal sensors.

III. EXPERIMENT

The proposed vision-based thermal sensor can measure the temperature on its surface. Furthermore, the physical properties of the sensor can be the same as that of the human fingertip when the elastic material is properly selected. Here, the question is "whether the performance of the proposed sensor is adequate." Therefore, we have evaluated the capability of the proposed thermal sensor for telexistence in terms of its performance.

A. *Prototype implementation*

Figure 3a represents the constructed prototype. For thermo-sensitive paint, we have used a thermo-sensitive liquid sheet (chromatic liquid, Japan Capsular Products Inc.). The seat is composed of a paper that is harder than human skin. Therefore, the nine 5.0 × 5.0 mm^2 blocks of the liquid seat are arranged on the elastic seat to maintain the elasticity of the sensor. The thickness of the elastic seat is 0.5 mm. The shape of the elastic body is partly spherical and cylindrical; hence, it resembles a human fingertip. The size of the elastic body is 18 × 9 × 19 mm^3. The elastic seat and transparent elastic body are composed of urethane gel (Human Skin Gel, Exseal Corp.) because their Young's modulus (5.0×10^4 Pa) resembles that of the human fingertip. However, the contact coefficient of this material (urethane rubber; 400~600

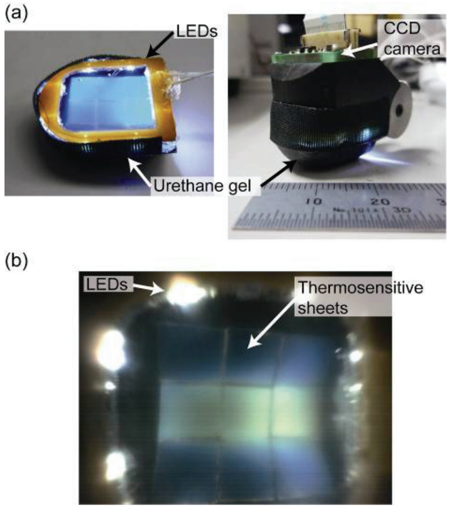


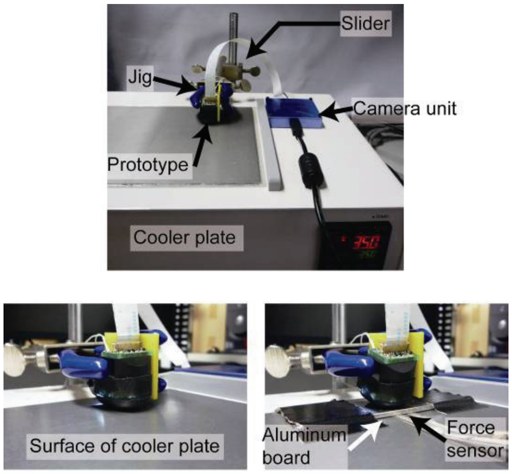
Fig. 3. (a) Constructed prototype and (b) image captured by the camera.

$J/m^2s^{1/2}K$) differs from that of human skin. In the future, we must appropriately select the material of the elastic body in order to consider its thermal properties.

Figure 3(b) shows the image captured by the camera. The frame rate and resolution of the CCD camera (ViewPlus, Inc.) are 15 Hz and 640 × 480 (VGA), respectively. The camera image is captured as a RGB format; therefore, we have converted it to the HSV format using the OpenCV (Open Source Computer Vision) library. The light source is eight LEDs. The temperature of the sensor surface is maintained at approximately 35°C by the heat from the LEDs when the surrounding air temperature is 26°C. We fix the amount of current that applies to LEDs to adequately maintain both the blitheness of the camera image and the temperature of the sensor. To eliminate the spatial noise of the image, we have divided the image into 10 × 10 pixel blocks and calculated the averaged hue within the blocks. In the image captured by the camera, the length of the thermal calculation block (10 pixels) is almost equivalent to 0.5 mm. Therefore, in this case, the temperature of the sensor surface could be measured at 0.5 mm intervals.

B. Calibration

Using the constructed prototype, we have created an equation to convert the hue of the captured image to the temperature of the sensor surface. Figure 4 represents the calibration setup. The sensor was fixed by the jig connected to the 1-axis slider. The center of the sensor surface is in contact with a cool plate (NCP-2215, Nissinrika Corp.). The temperature of the cool plate is controlled from 31 to 36°C with 0.5°C intervals. After the temperature of the cool plate was fixed at the target value, the contact between the sensor and plate was maintained for more than 120 s. Then, the hue at the center of the contact area was recorded. Ten values are recorded for each temperature.



Caliburation Evaluation

Fig. 4. Setupss for calibration and evaluation of time response.

Figure 5 represents the result of the calibration. From the graph, we can confirm that the function of the hue and temperature is monotonically decreasing in the temperature range of 31.5–35°C. Therefore, the proposed sensor can calculate the temperature from the hue of the captured image within this range. Using these results, we have set up the conversion functions of equation (3) as a linear function with 0.5°C intervals.

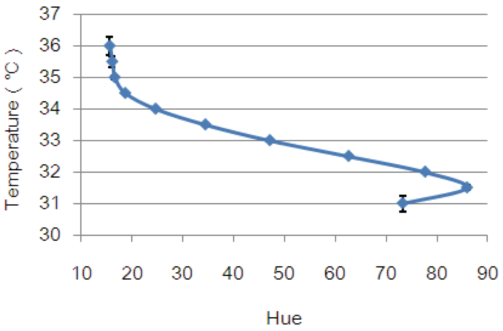


Fig. 5. The relationship between the hue of the captured thermo-sensitive liquid seat and its temperature. Error bar represents the standard deviation.

$$T = a \cdot h + b \tag{4}$$

The calculated coefficient a, and intercept b are shown in Table 1. Based on the conversion functions, we have also estimated the measurement resolution of the temperature. We defined the resolution as a product of the absolute value of $|a|$ and the hue standard deviation in each temperature interval. From the table, the resolutions of the prototype differ according to the temperature of the sensor.

C. Thermal measurement

Using the conversion equations created in the above subsection, we have measured the change in the temperature distribution on the surface of the sensor. At first, the sensor surface was not in contact with any object except air. The air temperature was maintained at approximately 26°C. Therefore, the temperature of the prototype is approximately 35°C. Then, the sensor surface is pressed to the surface of the cool plate maintained at 32°C. The temperature distribution was calculated at 15 Hz, and visualized on the display using OpenGL at 30 Hz.

Table 1. Calculated conversion function and resolution.

Temperature (°C)	a	b	standard deviation of h	Resolution (°C)
31.5~32.0	-0.06	36.7	0.44	0.03
32.0~32.5	-0.03	34.6	0.82	0.02
32.5~33.0	-0.03	34.5	0.40	0.01
33.0~33.5	-0.04	34.9	0.32	0.01
33.5~34.0	-0.05	35.3	0.35	0.02
34.0~34.5	-0.08	36.1	0.25	0.02
34.5~35	-0.24	39.0	0.18	0.04

Figure 6 represents the time variation of the temperature distribution of the sensor. In this figure, the temperature is represented by the color and height of the displayed surface; the color continuously changes from red at 36°C to green at 34°C to blue at 32°C. The temperature of the center decreases when the sensor surface contacts the cooler plate. Then, the temperature of the whole contact area gradually decreases. From this figure, we can confirm that the prototype sensor can measure the spatial and temporal changes in the temperature distribution.

D. *Time response*

To evaluate the time response of the sensor, we recorded the thermal change of the prototype when it was pressed to an aluminum board (Fig. 4). The thickness of the board was 2 mm. To approximate the moment of contact, we put a film-type force sensor (FlexiForce, Nitta Corp.) between the aluminum board and the cool plate. The force was measured at 200 Hz. The temperature at the center of the contact area was recorded at 0.2 s intervals after contact detection by the force sensor. Before the prototype touched the aluminum board at each temperature, we left it in air at 26°C.

At first, we evaluated the rate of thermal change. The three temperatures of the aluminum board were 20, 25, and 30°C. Figure 7 represents the recorded thermal change in the sensor at each temperature of the aluminum board. When the temperature of the aluminum board is low, the rate of thermal change becomes large. The largest rate of the thermal change is approximately 2°C/s.

Furthermore, we evaluated the delay of the sensor after contact. The sensor was pressed to the aluminum board that was at 30°C for 4 s. Then, we released the sensor from the aluminum board and recorded the temperature change. Figure 8 represents the results. In Figure 7 and 8, the delay of the initial response of the sensor is less than 0.2 s. However, in Figure 8, the sensor showed a delay of 1 s after the sensor was released from the aluminum board; same thermal change remained approximately 1 s after the contact.

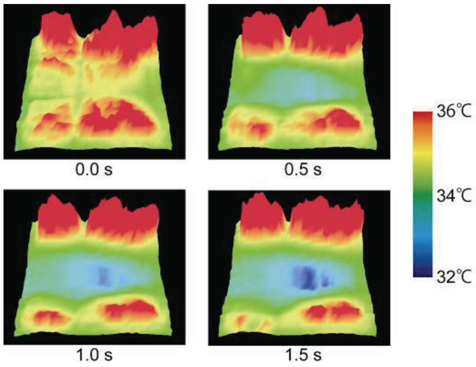


Fig. 6. Measurement of the thermal information.

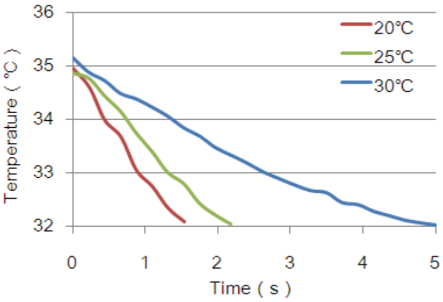


Fig. 7. The thermal change rate.

IV. DISCUSSION

We discuss in this section whether the proposed sensor is applicable to telexistence systems based on the experimental results (summarized in Table 2).

The temperature range of the thermo-sensitive liquid sheet is 31.5–35°C; therefore, the measurement range is also 31.5–35°C. Because the temperature range of a standard thermo-sensitive ink is approximately 5–10°C, to cover the measurement range of 15–45°C, we must use multiple thermo-sensitive paints that have different temperature ranges. Because the spatial resolution of a human to thermal stimulation is relatively low (approximately 20 mm), we consider of arranging several rectangular blocks of thermo-sensitive paint in a reticular pattern over an area of 20 × 20 mm^2. When we identify the position of each thermo-sensitive block and calculate the temperature of the reticular pattern area, the temperatures in the range of 15–45°C can be measured. The position of each thermo-sensitive block can be easily detected with markers put on the corner of the blocks. In Table 1, we see that the measurement accuracy seems to satisfy the requirement of 0.2°C. In the evaluation, the spatial resolution of the sensor was not quantitatively evaluated. However, from Figure 6, the spatial resolution of the sensor seems to be sufficiently small compared to that of human skin (19 mm).

The time response of the sensor is critical for the proposed sensor. The small rate of thermal change and delay of the

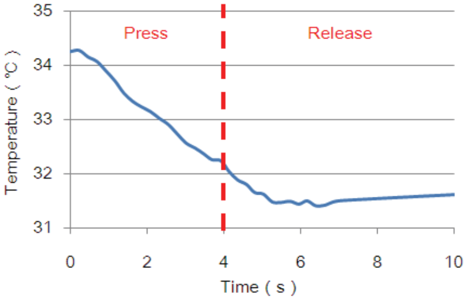


Fig. 8. Sensor delay after contact.

Table 2. Performance and physical properties of human skin of the finger [12] [13] [14] [15] [17] and prototype of the proposed sensor.

Performances or properties	Human skin	Prototype
Measurement range (°C)	15–45	32–35
Measurement accuracy (°C)	0.2	0.01–0.07
Spatial resolution (mm)	19	0.5
Rate of thermal change (°C/s)	6	2
Delay (s)	0 (Instant)	1
Initial temperature (°C)	34.6	35
Temperature contact coefficient ($J/m^2s^{1/2}K$)	1,181	400–600
Young's modulus (Pa)	3.4×10^5–1.36×10^5	5.0×10^4

prototype seems to be caused mainly by two factors: one is the thermal contact coefficient of the elastic material, and the other is the thickness of the elastic seat. Because we mimic the shape and compliance of a human fingertip, the prototype sensor simulates the mechanical interaction between the fingertip and the object. Therefore, the thermal distribution seems to be measured correctly (Fig. 6). However, the thermal contact coefficient of the elastic body is smaller than that of the skin and therefore, the rate of the thermal change in the sensor is lower than that of human skin. To improve the time response and accurately measure the thermal information of a human, the material for the elastic body not only has to possess the similar mechanical but also the similar thermal properties as the human skin. The thickness of the elastic seat also blocks the thermal change in the thermo-sensitive liquid seat. To increase the time response of the sensor, the thermo-sensitive paint should be painted as close to the surface of the sensor as possible. We believe that these improvements in the time response can be easily implemented. Furthermore, the 1 s delay of the prototype sensor after release (Figure 8) seems to be caused by the low temperature contact coefficient (approximately 5.5 $J/m^2s^{1/2}K$) of the air.

Based on the abovementioned evaluation, we conclude that the proposed method can be applied to the haptic sensors for telexistence by further improving its measurement range and time response.

V. CONCLUSION

In this study, we have proposed a vision-based thermal sensor using thermo-sensitive paint and a camera for telexistence. The proposed sensor can not only mimic the performance and physical properties of human skin but also be integrated with a vision-based force sensor. Therefore, this sensor can measure the haptic information adequately and correctly. Furthermore, the most important benefit of the vision-based haptic sensor is its simple structure; we can readily build it. From the results of the evaluation carried out using the prototype, we concluded that the proposed sensor could be applied to telexistence systems.

However, the conventional prototype has problems such as the measurement range and time response. In the future, we will select the appropriate thermo-sensitive paint and elastic material to accurately simulate the thermal interaction between an object and the human fingertip. Then, we will integrate the vision-based force sensing method and realize a telexistence system that can translate realistic haptic information.

ACKNOWLEDGMENT

This work was partly supported by Grant-in-Aid for CREST and JSPS Fellows (20•10009).

REFERENCES

[1] S. Tachi, N. Kawakami, H. Nii, K. Watanabe and K. Minamizawa, "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] Y. Mukaibo, H. Shirado, M. Konyo, and T. Maeno, "Development of a Texture Sensor Emulating the Tissue Structure and Perceptual Mechanism of Human Fingers," *Proc. of the 2005 IEEE Int'l Conf. on Robotics and Automation (ICRA'05)*, pp. 2565–2570, 2005.

[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, 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.

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

[6] L. A. Jones and S. J. Lederman, "Human Hand Function," *Oxford University Press*, 2006.

[7] 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.

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

[9] 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.

[10] 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.

[11] H.-N. Ho and L. A. Jones, "Infrared Thermal Measurement System for Evaluating Model-Based Thermal Displays," *Porc. of World Haptics Conference '07*, 2007.

[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.

[13] J.C. Stevens and K.C. Choo, "Temperature Sensitivity of the Body Surface over the Life Span," *Somatosensory and Motor Research*, Vol. 15, pp. 13-28, 1998.

[14] K. Parsons, "Human Thermal Environments, second ed." *Taylor &Francis*, 2003.

[15] H.-N. Ho. and L. A. Jones, "Modeling the Thermal Responses of the Skin Surface During Hand-Object Interactions," *Journal of Biomechanical Engineering,* Vol. 130, pp. 021005-1-8, 2008.

[16] 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.

[17] 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.

[18] 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.