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Thin-Film Thermal Discoloration Sensor for Distributed Material Identification

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***Abstract*— This paper proposes a thin-film sensor that visualizes heat transfer at contact surfaces through color changes, using thermochromic pigments specifically designed for material identification. By capturing the color change as time-series image data, the spatial distribution of heat transfer across the contact surface can be obtained, enabling differentiation of contact materials. The sensor provides a visual representation of heat flow across the interface between the sensor and the object. Experimental results demonstrate the potential of the proposed sensor for material identification and spatial heat transfer analysis.**

I. INTRODUCTION

Robots are becoming an integral part of the real world, and the research field of Human-Robot Interaction (HRI) is gaining significant attention as humans and robots coexist. HRI research aims to enhance the comfort and practicality of interactions between humans and robots. In this context, haptic sensing systems that acquire information about target objects are a crucial study area and are expected to find applications in nursing care robots and prosthetic hands.

Most contact-type sensors are inspired by the human sense of touch and are referred to as tactile sensors [1]–[4]. For example, research has been conducted on technologies that utilize the thermal characteristics of an object to identify its material [5]–[8] and on force sensors that employ strain gauges to measure force during contact [9].

In contrast, a typical example of a non-contact sensor is a thermal imaging camera that relies on vision. Using infrared radiation, it can measure the temperature of an object [10]. Additionally, sensor technologies that identify materials based on the electrical capacitance of objects have also been studied [11].

However, challenges remain with these sensing systems. The spatial resolution of contact-type sensors is limited by the installation limitations of tactile sensors. Furthermore, incorporating multiple tactile sensors presents challenges such as spatial limitations and increased costs. On the other hand, non-contact sensors cannot directly obtain internal information like shape deformation or heat transfer through a contact surface. These challenges prevent many sensors from performing multiple tasks simultaneously. For instance, tactile sensors that rely on heat are effective in identifying an object's material but are not considered useful for shape identification.

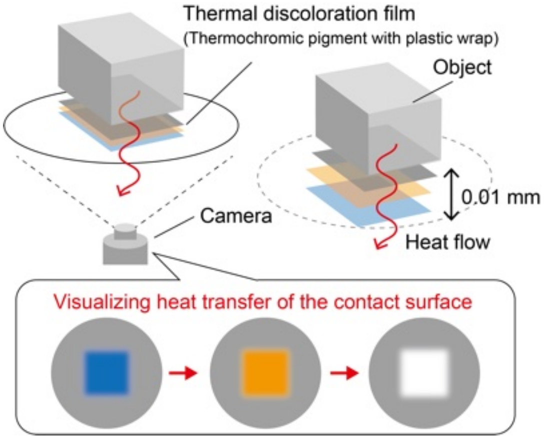

Fig. 1. The system configuration of the proposed sensor.

Therefore, multi-modal sensors that combine multiple sensing systems have also been studied for many years [12], [13]. Among them, the visuotactile sensor, which integrates a contact-based tactile sensor with a non-contact visual sensor, can visually capture physical contact and is particularly effective for understanding the shape of objects. A visuotactile sensor, developed in [14], utilizes light reflections to capture the deformation of an object upon contact, enabling the determination of the object's shape. This sensor later became known as the GelSight sensor [15].

In studies [16], [17], a modified version of the Gelsight sensor was proposed, capable of measuring an object's temperature by incorporating a thermochromic pigment into its structure. In particular, the study [17] identifies differences in contact objects and distinguishes their shapes based on changes in the LAB color space.

In this paper, we propose a haptic thin sensor that utilizes thermochromic pigments to visualize heat upon contact with an object for material identification. This sensor, with a thickness of less than 0.01 mm, visualizes the heat transfer between the sensor and the object during contact through a color change process. The spatial distribution of the contact material can then be identified by a single sensor, directly acquiring information from the contacting surface. In this study, we developed a sensor module through an inexpensive material and a simple manufacturing process, and conducted verification experiments focusing on achieving the identification of the material of a heated object. This research also mentioned the potential for identifying multiple

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Fig. 2. (a) The sensor module developed in this paper. (b) The internal state of the sensor.

materials with high spatial resolution. The color variations obtained using the proposed sensor enable estimation of the thermal response upon contact, based on the established correlation between the HSV color space and temperature. Leveraging a physical model of heat exchange at the contact interface, the observed temperature changes can be used to discriminate between different materials. The effectiveness of this approach is validated through a series of experimental results.

II. SENSING PRINCIPLE OF THE PROPOSED SENSOR MODULE

A. Modules with thermochromic pigments

The sensor module developed in this study consists of the following components: a module foundation, three types of thermally discolored pigments, a thin film covering the pigment layer, and a camera. Fig. 1 shows the conceptual diagram of the proposed sensor.

The thermochromic pigments are materials that change to translucent when a specific temperature threshold is reached. In this study, we used blue pigments with a threshold of 31 °C, orange pigments with a threshold of 43 °C, and black pigments with a threshold of 50 °C, which were purchased from HALI CHEMICAL CO. The colors were selected from several candidates based on their tendency to exhibit distinct changes in color space, while black was used for the outermost layer to block external light. The pigments were applied in layers (blue, orange, black). They were mixed with acrylic solvent and binder, and applied onto the thin film (one layer per color) using an airbrush to ensure uniform distribution. Figure 2 shows the sensor module that we developed. Figure 2 (a) shows the external appearance of the sensor, in which the black pigment film is visible. The internal structure, revealing the blue pigment film layer and the LED light, is illustrated in Fig. 2 (b).

The sensing principle of the developed sensor module is as follows.

1. A heated object is brought into contact with the sensor surface.
2. The discoloration of the pigment is photographed with a camera on the side of the blue layer.

Figure 3 shows the overall sensor module setup, including the camera and the object of interest.

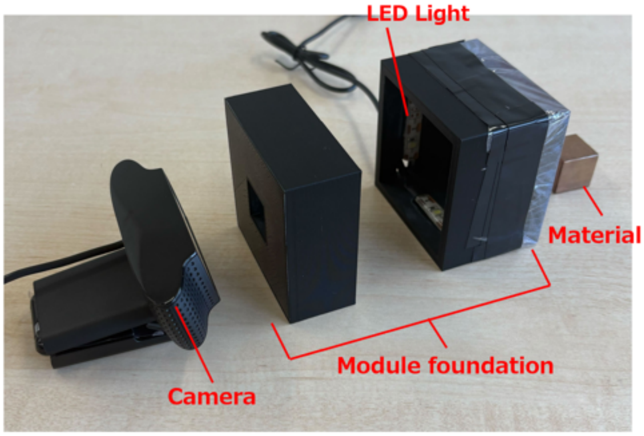

Fig. 3. The setup of the sensor module.

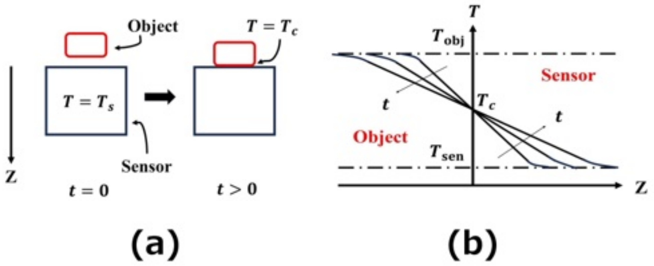

Fig. 4. (a) Contact between two objects. (b) Temperature change in two objects.

The sensor structure proposed in this study was designed with reference to the work [16]. In [16], the module had a gel-like contact surface with a pigment film layer applied directly to the top. In contrast, as shown in Fig. 1, our sensor features a thin film on the sensor surface and a layered contact structure underneath. This lapped structure is essential for material identification, and its specific role is discussed in Section II-B.2.

B. Identification for spatial distribution of materials

1) Estimation of the temperature change based on a theoretical heat transfer model: Temperature changes during the contact of two objects are generally described by a simplified heat transfer model. To utilize this simplified model, we treat the objects as ideal, semi-infinite solids with infinite planar surfaces, neglecting factors such as thermal contact resistance [18], [19]. In the simplified heat transfer model, the temperature change after object contact is illustrated in Fig. 4 (a) and (b).

The temperature change between the object and the sensor is depicted in Fig. 4 (b), where $T_{\mathbf{sen}}$ and $T_{\mathbf{obj}}$ represent the initial temperatures of the sensor and object, respectively. As time passes, the temperature inside each object approaches the surface temperature $T = T_{\mathbf{s}}$. We will focus on the temperature T at $Z = Z_{\mathbf{m}}$ at this time. The thermal properties of the objects follow the heat transfer equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial Z^2}, \tag{1}$$

where α is the thermal diffusivity of the object, which can be expressed as Eq. 2 using thermal conductivity k $[\mathrm{W/mK}]$, density ρ $[\mathrm{kg/m^3}]$, and specific heat capacity C $[\mathrm{J/kgK}]$, respectively.

$$\alpha = \frac{k}{\rho C}. \tag{2}$$

Using Eq. 1, $T_{\mathbf{sen}}$ and $T_{\mathbf{obj}}$, the object temperature T can be expressed as follows.

$$T = T_{\mathbf{sen}} + (T_{\mathbf{s}} - T_{\mathbf{sen}})\mathbf{erfc}(\frac{Z_{\mathbf{m}}}{2\sqrt{\alpha t}}), \tag{3}$$

where **erfc** is the complementary error function. The surface temperature $T_{\mathbf{s}}$ can be expressed as:

$$T_{\mathbf{s}} = \frac{T_{\mathbf{obj}} e_{\mathbf{obj}} + T_{\mathbf{sen}} e_{\mathbf{sen}}}{e_{\mathbf{obj}} + e_{\mathbf{sen}}}, \tag{4}$$

where $e_{\mathbf{obj}}$ and $e_{\mathbf{sen}}$ are the thermal effusivity of the object and sensor, respectively [20]. The thermal effusivity of the object is defined as:

$$e = \sqrt{\rho k C}. \tag{5}$$

From Eqs. 4 and 5, knowing the initial temperature and thermal effusivity of the sensor, the temperature T at $Z = Z_{\mathbf{m}}$ between the sensor after contact with the object depends on the initial temperature and thermal effusivity of the object. The sensor material is polyvinylidene chloride (PVDC), which is the main component of plastic wrap. In this study, standard physical property values for PVDC were used for calibration.

In the proposed system, the value of $Z_{\mathbf{m}}$ in Eq. 4 is 1.0×10^{-5} **m**, which corresponds to the thickness of the plastic wrap on the sensor surface. To apply temperature changes to material identification, the proposed sensor is covered with a wrap. Based on the principle that differences in thermal effusivity among materials lead to distinct temperature changes, which in turn result in variations in discoloration, this study verified whether the proposed sensor can discriminate the materials of objects.

2) Quantification of the color change of the obtained image data: Heat transfer between the module and a contact object must be induced to discolor the module's surface to obtain the temperature change of the module surface. Then, it is necessary to derive a mathematical formula that relates discoloration to temperature. To achieve this, the Peltier device, of which surface temperature was controlled, was in contact with the module to calibrate the temperature from the image data. In terms of material identification, the contact objects were pre-heated to create an initial temperature difference with the sensor.

The discoloration of the pigment film when contacting the Peltier device (or heated target objects) is recorded in the video. The recorded video is converted to the HSV (Hue, Saturation, Value) color space, and the hue (H) is extracted. We chose to use the H value in this paper, as it was found to be relatively insensitive to light through several experiments. Thus, the relationship between the H value and the pigment film temperature (T) is investigated for sensor calibration. After calibration, a heated target object (copper, acrylic, sponge) is brought into contact with the sensor surface. The H value corresponding to the observed color change is obtained, and the temperature of the pigment film at the contact point is calculated using the relationship between the H value and T.

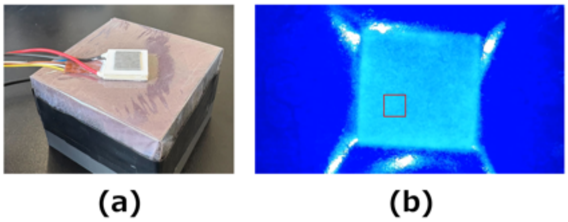

Fig. 5. (a) Experimental setup for sensor calibration. (b) Discoloration after controlling the Peltier device.

Therefore, the temperature response T estimated from the H value is expected to follow the physical model presented in Eq. 4, indicating that the sensor can be used for material identification. In particular, the proposed sensor, being fabricated as a thin film, offers high thermal conductivity between the object and the module, making it well-suited for visualizing heat exchange. While material identification may be achieved directly from color data, estimating temperature change provides the potential to identify contact materials through a physical model. Considering possible future use as a temperature sensor, this study focuses on establishing the correlation between color variation and temperature change. This capability is experimentally validated in the following section.

III. EXPERIMENTAL VERIFICATION

A. Outline of the experiments

We conducted two experiments: a preliminary experiment for sensor calibration and material identification. As for a sensor calibration, the correlation between the H value in the HSV color space and temperature is determined, and based on this correlation, the estimated temperature change is derived.

1) Sensor calibration: We conducted a preliminary experiment using a Peltier device to obtain the relationship between the discoloration of the pigment and the temperature. For testing purposes, thermocouples for measuring temperature and the Peltier device were installed in the sensor module (see Fig. 5 (a)). The room temperature was maintained at 24 °C throughout the experiments.

The temperature of the Peltier device was regulated in 5 °C increments, ranging from 24 °C to 50 °C, and the resulting discoloration was monitored. The video was converted to HSV color space, and the region of interest (ROI) was specified. The discoloration and the specified ROI are shown

TABLE I

PHYSICAL PROPERTY VALUES FOR EACH MATERIAL [20] [21]

Material	Conductivity $[\mathrm{W/mK}]$	Density $[\mathrm{kg/m^3}]$	Specific of Heat $[\mathrm{J/kgK}]$	Thermal effusivity $[\mathrm{J/m^2s^{1/2}K}]$
Copper	398	8954	384	36992
Acrylic	0.21	1190	1400	591
Sponge	0.029	24	1210	29
PVDC	0.12	1700	1339	527

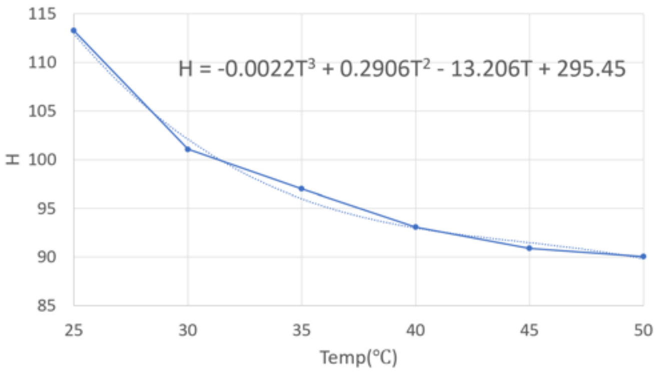

Fig. 6. The correlation between H value in color space and T.

in Fig. 5 (b). The H values of the film, measured by thermocouples at 25 °C, 30 °C, 35 °C, 40 °C, 45 °C, and 50 °C, were recorded and plotted against temperature. The relationship between the H value and temperature derived from the experiment is shown in Fig. 6. From Fig. 6, the relational equation between the H value and temperature T can be derived as shown in Eq. 6.

$$H = -0.0022T^3 + 0.2906T^2 - 13.206T + 295.45. \quad (6)$$

The Eq. 6 is used for estimating temperature from the color-changing image data, for recognizing the material of the contact object in the next section.

2) Material identification: We prepared three materials (20 mm × 20 mm × 20 mm cubes) for material identification (copper, acrylic, and sponge), shown in Fig. 7 (a). After heating the objects to 40 °C, they were brought into contact with the proposed sensor module (see Fig. 7 (b)). The H value was obtained from the discoloration of the module's surface when these objects were in contact with the sensor, and the temperature change was calculated using Eq. 6. From the temperature change, we evaluated whether the materials could be distinguished.

Furthermore, we conducted an experiment in which multiple materials were placed side by side to examine whether material differences would manifest spatially. The copper and acrylic cubes were heated to 40 °C and were simultaneously contacted with the sensor surface (see Fig. 7 (c)). The discoloration of the module was photographed, and the corresponding H values were extracted. Regions of interest (ROIs) were defined at the contact points with copper and acrylic, respectively, to obtain the H values. Based on these values, the temperature change of the pigment film was estimated.

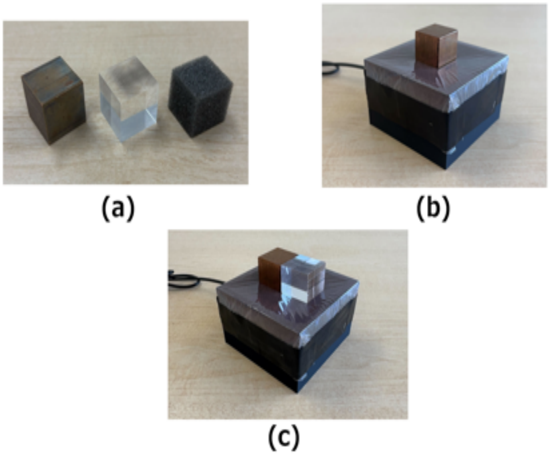

Fig. 7. (a) Target materials for identification. (b) The condition where copper is in contact with the sensor. (c) The condition where copper and acrylic are in contact with the sensor.

B. Experimental results

Section III-B.1 presents the experimental results of material identification, and Section III-B.2 shows the results of experiments verifying the future possibility of identifying object shapes and surface patterns.

1) Material identification: Fig. 8 shows the discoloration when copper, acrylic, and sponge were brought into contact with the proposed sensor module. The figure shows that the color-changing process varies depending on the contact material. The discoloration pattern shown in Fig. 8 was converted to the HSV color space, and the H values within the ROI were obtained. The temperature change of the pigment film was then calculated from the H value of each object using Eq. 6. Fig. 9 shows the obtained temperature change values when three objects are brought into contact. From Fig. 9, it can be clearly observed that differences in objects, i.e., differences in thermal effusivity, lead to distinct variations in temperature change after contact. From the above, we were able to experimentally determine the temperature change depending on the materials of the contact objects. In addition, it was confirmed that the sensor surface returned to its original color approximately 10 seconds after the object was removed.

The following presents the results of an experiment identifying the spatial distribution of copper and acrylic. As shown in Fig. 7 (c), heated copper and acrylic were simultaneously in contact with the sensor. The discoloration and specified ROI are shown in Fig. 10. Figure 11 shows the temperature changes obtained from the discoloration at

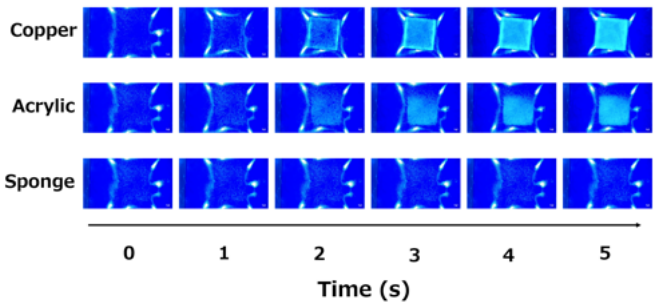

Fig. 8. Color change upon contact with copper, acrylic, and sponge.

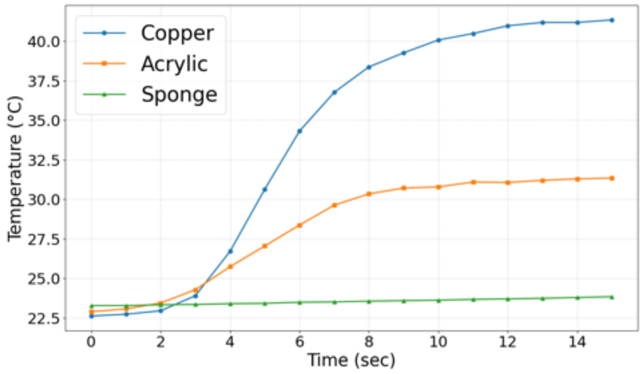

Fig. 9. Estimated temperature change when each object comes in contact with the proposed sensor.

the contact points when copper and acrylic were brought into contact simultaneously. Figures 10 and 11 show clear differences in the discoloration of copper and acrylic, as well as distinct variations in their temperature changes after contact. Therefore, the spatial distribution of copper and acrylic materials can be determined. To identify spatial distribution using conventional methods, multiple thermistors and thermocouples must be installed on the sensor, leading to limitations in installation location and increased costs. On the other hand, the proposed sensor does not face such issues, making it possible to identify materials with a single sensor. In the future, a sensing system will be developed to quantitatively assess material identification by training it to recognize temperature changes in the pigment film when each substance comes into contact with the sensor.

Although the estimated temperatures successfully reflected differences between the materials, some error is considered to be present—for example, a discrepancy of approximately 2 °C can be observed when comparing the values for copper and acrylic in Figs. 9 and 11. This error is likely due to the current sensor lacking an internal heat source and instead relying on the contact object for heating. This study focuses on the design of a sensor for material identification and the evaluation of its capabilities. As a future work, we plan to incorporate a temperature control mechanism into the sensor to improve the accuracy of material identification.

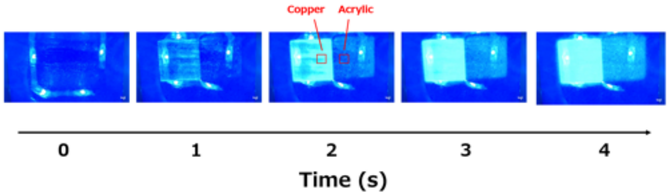

Fig. 10. Color change when copper and acrylic are in contact with the sensor.

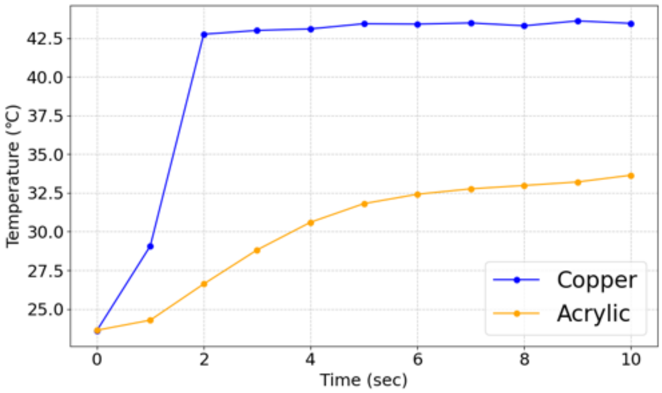

Fig. 11. Estimated temperature change when copper and acrylic are in contact with the sensor.

2) Experiments on target object shape: The sensor proposed in this paper also has the potential for future application in identifying the shape and surface patterns of target objects. To confirm the feasibility of these applications, we brought objects with varying contact surfaces into contact with the sensor, as shown in Fig. 12 (a). These objects included circular aluminum, aluminum with 3 mm interval grooves, and aluminum with 1.6 mm interval grooves.

Figures 12 (b) to (d) show the discoloration results when the contact objects depicted in Fig. 12 (a) were brought into contact. From Fig. 12 (b), we can identify the shape of the contact surface. Furthermore, Fig. 12 (c) and (d) demonstrated the ability to distinguish contact surface patterns and differences in groove spacing. These results indicate that the sensor proposed in this study can identify even subtle differences in material shape. Moving forward, we aim to develop methods that incorporate shape recognition into our identification process.

IV. CONCLUSION

In this paper, we propose a thin thermosensitive sensor using thermochromatic pigments explicitly designed for the material identification of contact objects. The proposed sensor visualizes thermal exchange at the contact surface through color changes, allowing differences in material, shape, and spatial distribution of the contact object to be observed. In this study, thermochromic pigments were applied in layers to a 0.01 mm-thick film, designed so that the degree of discoloration would correlate with temperature. This design enabled estimation of the thermal response based

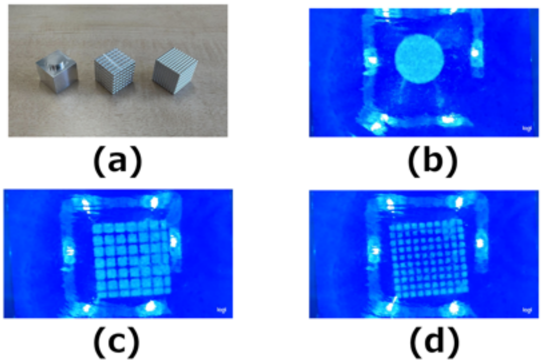

Fig. 12. (a) Aluminum cubes with a circular contact surface, 3 mm-interval grooves on its contact surface, and 1.6 mm-interval grooves on its contact surface. (b) Discoloration upon contact with the aluminum cube, having a circular contact surface. (c) Discoloration upon contact with the aluminum cube, having 3 mm interval grooves on its contact surface. (d) Discoloration upon contact with the aluminum cube, having 1.6 mm interval grooves on its contact surface.

on the relationship between H value in color space and temperature. In addition, a physical model of heat exchange was derived to evaluate the resulting temperature changes in relation to the physical properties of the contacted material. In the experiments, we quantified the relationship between color and temperature, used this correlation to estimate thermal responses, and successfully visualized differences between contact materials. This method utilized the principle that differences in the thermal effusivity of materials affect temperature changes, consequently leading to variations in the discoloration of the pigment. Furthermore, experiments with simultaneous contact of copper and acrylic confirmed the sensor's ability to distinguish the spatial distribution of different materials. The final experimental results suggest potential applications in identifying object shapes and surface patterns.

There are several challenges remaining to make this sensor practical. First, a temperature control system should be incorporated into the module to control the temperature, allowing objects at room temperature to be identified. Second, we plan to improve the durability of the sensor surface using a thin film of pigment mixed with resin. With these improvements, further verification will be conducted to assess the ability to identify the spatial distribution of materials and shapes simultaneously. In the future, the proposed sensor will be mounted on a robot end-effector, with the aim of extending its application to object recognition through robot grasping.

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