2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Design of Thermal Discoloration Sensor for Material identification

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I. Introduction

As robots become more integrated into daily life, Human-Robot Interaction (HRI) technologies are gaining significant attention for enabling natural communication between humans and robots. Among various HRI technologies, sensing systems that acquire information about target objects are a critical research area and are expected to be applied in fields such as nursing care robots and prosthetic hands.

Sensing systems are typically categorized into contact-based systems, which utilize tactile sensing, and non-contact-based systems, which rely on visual sensing.

Furthermore, visuotactile sensors, which integrate both visual and tactile modalities, are capable of visually capturing physical contact. One such example is the GelSight sensor [1], which can determine the shape of an object. Additionally, a modified version of the GelSight sensor incorporating thermochromic pigments has been proposed in [2] to enable temperature measurements of objects.

However, several challenges remain in these sensing systems. Contact-type sensors are limited in spatial resolution due to constraints on sensor installation. On the other hand, non-contact sensors are unable to directly capture internal information such as deformation or heat transfer at the contact surface. These limitations make it difficult for a single sensor to perform multiple sensing tasks simultaneously.

To address this issue, we propose a novel haptic sensor that uses thermochromic pigments to visualize heat transfer through color changes upon contact. This approach enables the sensor to identify the material of an object based on information obtained from the contact surface. Furthermore, the sensor has the potential to recognize the shape and surface structure of objects in the future and to function as a temperature sensor.

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 thermochromic pigments, a thin film covering the pigment layer, and a camera. Fig. 1 shows the conceptual diagram of the proposed sensor.

This work was supported by JSPS KAKENHI Grant Number 25K03157.

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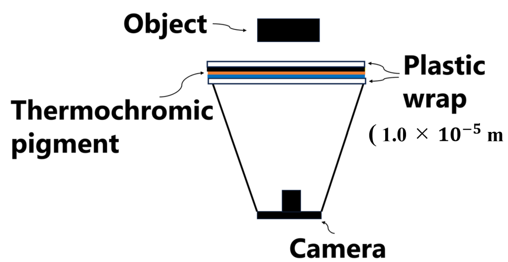

Fig. 1. The system configuration of the proposed sensor.

Thermochromic pigments are materials that change color 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. The pigments were applied in layers (blue, orange, black).

The sensing principle of the developed 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.

The sensor structure proposed in this study was designed with reference to the work [2]. In [2], 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.

B. Identification for materials

Material identification is performed by utilizing differences in experimental temperature values obtained from image data. This is because different materials have different thermal properties, resulting in varying temperature changes after contact with the sensor [3], [4]. The material identification process in this study consists of two main components: quantification of the color change in the acquired image data, and estimation of the temperature change based on the relationship between color and temperature.

III. Experimental verification

A. Outline of the experiments

We conducted two experiments: a preliminary experiment for material identification and a material identification experiment.

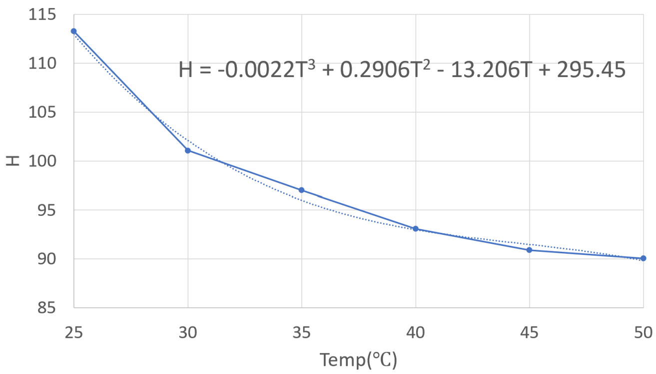

Fig. 2. Relationship between H and T.

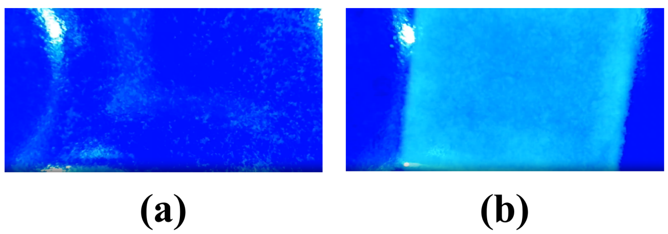

Fig. 3. (a) The color before contact. (b) The color 6 seconds after contact with copper.

1) The preliminary experiment: We conducted a preliminary experiment using a Peltier device to obtain the relationship between the discoloration of the pigment and temperature. Thermocouples for measuring temperature and the Peltier device were installed in the sensor module. The temperature of the Peltier device was controlled between 24 °C and 50 °C, and the resulting discoloration was photographed. The video was converted to HSV color space, and the region of interest (ROI) was specified. The relationship between the H value and temperature derived from the experiment is shown in Fig. 2. From Fig. 2, the relational equation between the H value and temperature T can be derived as shown in Eq. 1.

$$H = -0.0022T^3 + 0.2906T^2 - 13.206T + 294.5 \qquad (1)$$

2) Material identification: We prepared three materials for material identification (copper, acrylic, and sponge). To generate a temperature difference with the sensor, the objects were preheated to approximately 40 °C. The objects were then brought into contact with the sensor, and the temperature change was calculated based on the observed color change and Eq. 1. The color change after contact and the calculated temperature change are shown in Fig. 3 and Fig. 4, respectively.

From Fig. 4, it can be seen that the obtained temperature response values clearly reflect the differences between materials. Therefore, it can be concluded that the sensor proposed in this study is capable of distinguishing between copper, acrylic, and sponge based on the temperature change of the pigment film upon contact with each material.

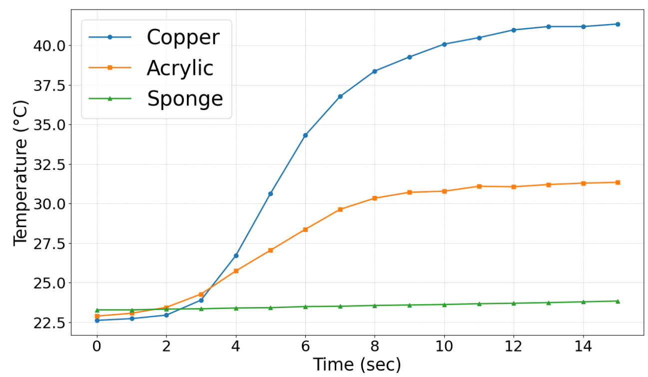

Fig. 4. Temperature change when each object comes in contact with the sensor, measured using the module.

IV. Conclusion

In this study, we proposed a novel thermosensitive haptic sensor using thermochromic pigments. The evaluation experiment using a Peltier device confirmed that there is a relationship between the color and temperature of the pigment film, as described by Eq. 1. In an experiment where the target objects were heated to 40°C, clear differences in the estimated temperatures were observed after contact for each material, successfully enabling the identification of the contact materials. Future work will involve integrating a heat source into the sensor to enable precise temperature control, enabling material identification of objects at room temperature. Furthermore, experiments will be conducted using composite objects made of multiple materials to evaluate the sensor's capability in identifying spatial material distribution. The ultimate goal is to develop an integrated system using a single sensor for material identification, spatial distribution mapping, and shape recognition.

References

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