Pilot Study: A Visuotactile Haptic Primary Colors Sensor

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***Abstract*—In this paper, we present our preliminary studies on how to make a unified skin-like visuotactile sensor capable of sensing haptic primary colors, namely: force, vibration, and temperature. Our sensor is based on GelSight technology that has proven its worth in the field of haptics, robotics, and computer vision. In our previous studies, we proposed switchable UltraViolet (UV) markers that can be turned on using UV light. These markers can be tracked using an optical flow algorithm to visualize forces related to gel deformation. In this study, we introduced layers of thermochromic pigments on the reflective layer, making our visuotactile sensor capable of sensing not only force and vibration inferred from gel deformation but can also sense the temperature of the contacted object by analyzing the change of hue in the reflective coating.**

***Index Terms*—haptic primary colors, GelSight, visuotactile**

I. INTRODUCTION

A visuotactile sensor is like a flexible mirror that converts physical contact or pressure distribution on the reflective layer into a tactile image that can be seen or captured by a camera. A comprehensive literature review on visuotactile sensors is reported in [1]. The GelSight sensor is an ideal visuotactile sensor because of its high spatial resolution in vision [2] and high sensitivity in tactile [3]. The original GelSight sensor was created by Johnson and Adelson in 2009 [4] and has proven its worth in a wide range of applications from haptics, robotics, and computer vision [1]. However, the current GelSight sensor can be further improved to make it a stand-alone fully Haptic Primary Colors (HPC) smart visuotactile sensor; this is illustrated by the block diagram as shown in Fig. 1.

Tachi et al. theorized that haptics, like visible light, can be reduced to three components and named them as Haptic Primary Colors known as force, vibration, and temperature corresponding to tactile and thermal sensation receptors [5], [6]. According to HPC theory, force, vibration, and temperature are related to the seven haptic receptors in our skin, namely: 1) Merkel cells, 2) Ruffini endings, 3) Meissner's corpuscles, 4) Pacinian corpuscles, 5) cold receptors (free nerve endings), 6) warmth receptors (free nerve endings), and 7) pain receptors (free nerve endings) [6].

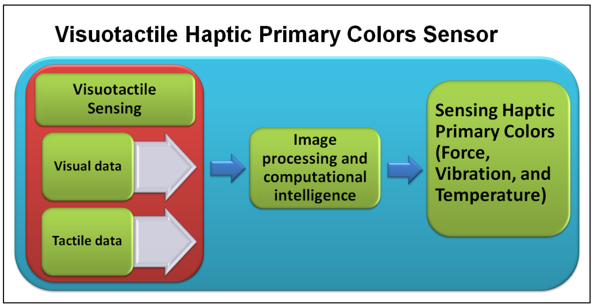

Fig. 1. Conceptual framework of a visuotactile haptic primary colors sensor.

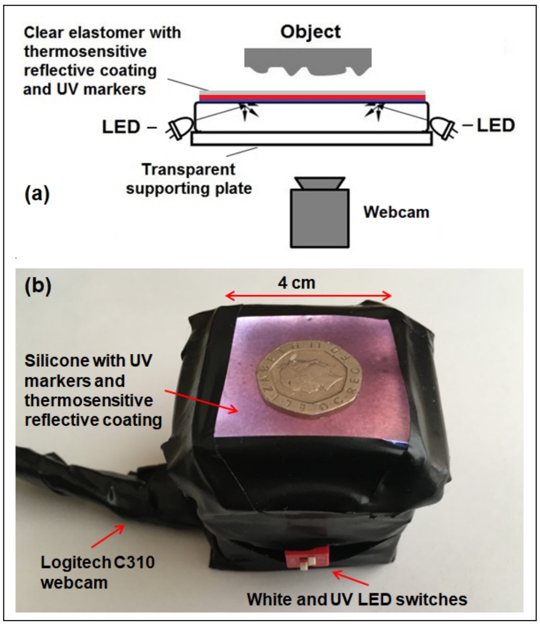

Fig. 2. (a) The sensor structure is composed of a clear elastomer with thermosensitive reflective coating supported by a clear acrylic plate with a webcam at the bottom, and (b) actual prototype of a visuotactile sensor with thermosensitive coating in a cubic structure with a side length of 4 cm.

GelSight sensor has been used in metrology, object or texture recognition or classification, and tactile forces analyses [1], [4], [7], [8]. It has been reported that GelSight sensor can sense vibration such as human pulse [9]. This paper proposes to add a temperature sensing capability to the GelSight sensor to make it a fully haptic primary colors sensor capable of sensing force, vibration, and temperature. Details on the prototype are discussed in the following sections: construction of the prototype in section II, experimental setup in section III, experimental results in section IV, followed by conclusion in section V.

II. CONSTRUCTION OF THE PROTOTYPE

The construction of the visuotactile haptic primary colors sensor focuses on two categories: They are hardware, and software.

A. *Hardware: sensor structure and actual prototype*

The sensor structure diagram is shown in Fig. 2(a), and the actual prototype is shown in Fig. 2(b). The square gel material was a cut from Fig. 3(b). We used Logitech C310 webcam. The box and the supporting plate for the gel material are made from clear acrylic plates. We used white, and UV LEDs mounted alternately on the top edge of the acrylic box to illuminate the side of the gel. We put a switch to turn on or off the white and UV LEDs. In our previous studies [10], [11], we reported how to create a low-cost GelSight sensor using a commercially available cosmetic sponge that enables us to skip the long hours of curing time of about six or seven hours [12], and the degassing procedure to eliminate the bubbles in the silicone gel [12]–[15]. We also demonstrated that UV markers could be incorporated into the gel and can be tracked using an optical flow algorithm and vector arrows to visualize slip, shear, and torsion.We discussed how our switchable UV markers helped us to create a unified visuotactile sensor that can be used for tactile image recognition and tactile forces analysis using one elastomeric slab [10]. In this study, unlike the finger-shaped GelForce that used thermosensitive liquid crystal sheets [16], [17], we introduced different layers of thermochromic pigments with different colors and thresholds on the reflective layer of our elastomer. We used three different thermochromic pigments bought from HALI CHEMICAL CO., LTD. [18] that become translucent when activated. We put three layers of thermochromic pigments with increasing thresholds so that when the bottom layer is activated and becomes translucent, the color of the upper pigment will be captured by the camera. The lowest threshold is 31°C, with the color blue painted close to the gel. The orange pigment with a 43°C threshold is on top of the blue pigment. The topmost layer is the black pigment with 50°C threshold. The gel structure and the layering of pigments are shown in Fig. 3(a). When our gel with the thermosensitive reflective coating is placed on top of a metal ruler heated at one end, different pigments are activated as shown in Fig. 3(b). The actual test video can be found here [19].

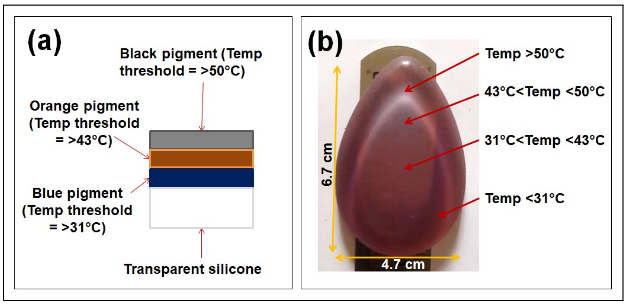

Fig. 3. (a) Cross section of the gel structure with different layers of thermosensitive pigments, and (b) actual gel material of the visuotactile sensor with thermosensitive reflective coating subjected to different temperatures using a metal ruler heated at one end. Actual test video is in this link [19].

B. *Software: firmware and application layer*

We used Python and OpenCV software in the image processing of pictures captured by the webcam. We used optical flow algorithm [20] and flow vector arrows to track the UV markers that enable us to visualize the forces as the gel deformed when an object contacted our sensor. Moreover, using blob detection algorithm [21], we were able to sense vibrations by counting how many times a blob has been detected for every second. We also used Arduino and PID controller to set a specific temperature to our ThermoElectric Generator (TEG) with a thermistor as its temperature feedback. The TEG was used to test the temperature sensing capability of our sensor. Using the OpenCV built-in function to record Hue-Saturation-Value (HSV) in a given Region Of Interest (ROI), we were able to record average hue values within an ROI at temperatures 25°C, 30°C, 35°C, 40°C, 45°C, and 50°C.

III. EXPERIMENTAL SETUP

Our experimental setup is shown 4. For the force and vibration tests, an object is pushed on the sensor, as shown Fig. 4(a). With the use of TEG with PID controller, we were able to test our sensor at different temperatures, as shown in Fig. 4(b). A thermistor was used as temperature feedback.

IV. EXPERIMENTAL RESULTS

1) Force Test: By switching on the UV markers using UV light and tracking them using an optical flow algorithm, we can draw vector arrows showing the direction and amount of force being exerted by the object contacting the gel as shown in Fig. 5(a) and Fig. 5(b). Another way of visualizing force and direction is to put a reference bounding box that does not rotate, and another dynamic bounding box that follows the contour of the blob [21]. The dynamic bounding box measures the approximate length and width of the contacted object, as shown in Fig. 5(c), and becomes bigger as the normal force increases. The tilt angle or shear angle can be computed relative to the reference bounding box, and the movement of the center of the blob can be tracked to know the direction of motion within the frame. This method is similar to the pose estimation presented in [23].

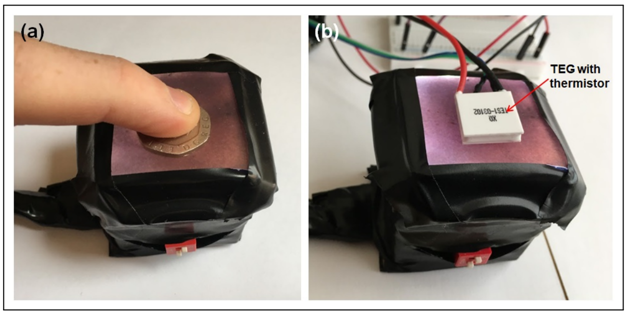

Fig. 4. (a) Setup for force and vibration tests, and (b) setup for temperature test using TEG with thermistor.

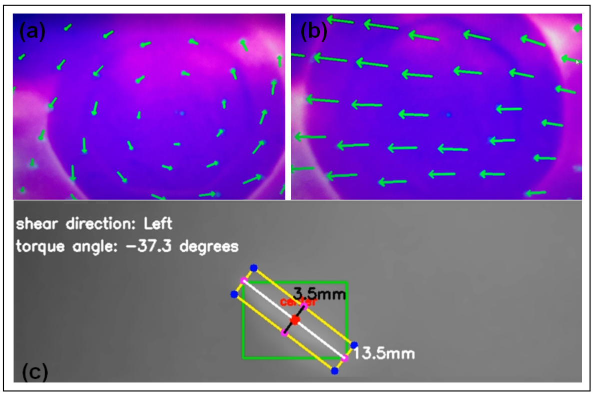

Fig. 5. Force test. (a) Vector arrows can show force magnitude (length of arrows) and direction such as (a) twisting force and (b) shear force. (c) Aside from vector arrows, direction and force magnitude can be deduced from the variations in the size and rotation of the bounding box.

2) Vibration Test: Using blob detection algorithm, machine cycle time, and beat or pulse counter, we were able to measure vibrations as shown Fig. 6. By counting the number of blobs detected or pulses per unit of time, we can calculate the frequency vibrations or beats per minute.

3) Temperature Test: The OpenCV library has a built-in function that can capture the HSV values within a given ROI. Using TEG, stabilized by a PID controller with thermistor temperature feedback as shown in Fig. 7(a), we were able to record average hue values within a 40 pixel x 40 pixel ROI at temperatures 25°C, 30°C, 35°C, 40°C, 45°C, and 50°C. We ran ten trials for each temperature, and we covered a wider range compared to the 32°C-35°C range of finger-shaped GelForce [16], [17]. The tabulated readings are shown in Table I. Similar to [16], [17], our hue value varies inversely proportional with temperature in the range of 25°C to 50°C, as shown in Fig. 7(b) and we can relate temperature as a function of hue, as shown in Eq. (1).

$$T = f(H) \tag{1}$$

We can write the calibration equation as:

$$T = mH + C \tag{2}$$

where *(T)* is temperature, *(m)* is the slope, *(H)* is the Hue value, and *(C)* is the offset value.

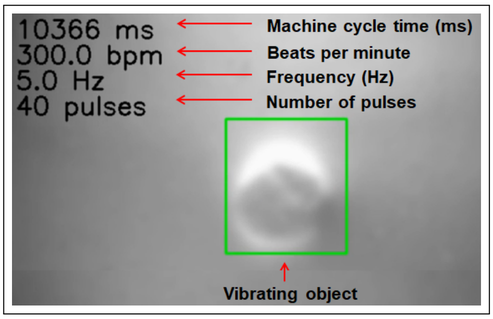

Fig. 6. Vibration test. Vibrations can be measured by counting how many times a blob appeared on the screen per unit time.

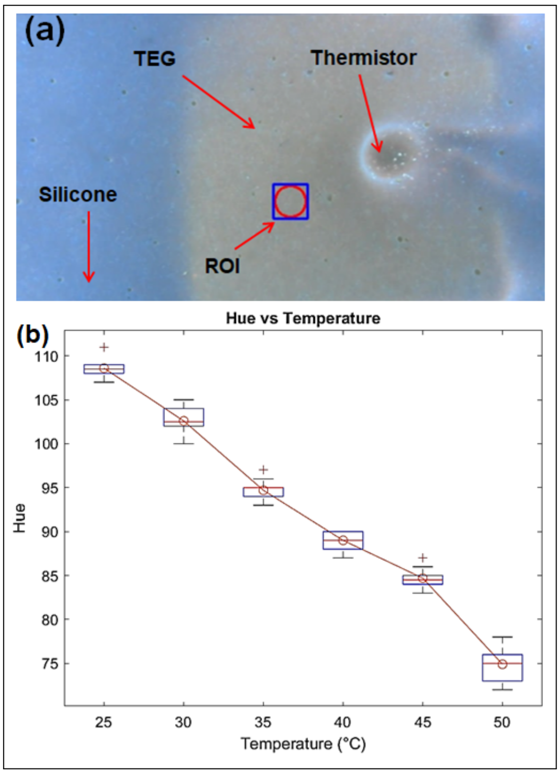

Fig. 7. Temperature test. (a) TEG with thermistor as temperature feedback was used as heating element. (b) Hue varies directly with temperature.

TABLE I
HUE VS TEMPERATURE.

	25°C	30°C	35°C	40°C	45°C	50°C
Hue(mean)	108.68	102.60	94.70	89.00	84.70	74.90
STDEV	1.07	1.51	1.25	1.05	1.16	1.91

V. CONCLUSION

This pilot study presented a novel visuotactile sensor that can sense force, vibration, and temperature using one elastomeric slab. We used a commercially available silicone cosmetic sponge as an elastomeric slab to create a GelSight-like sensor to skip the degassing process and the long hours of curing time. Moreover, we used switchable UV markings and vector arrows to show tactile forces. We also demonstrated how to measure vibrations by counting how many blobs are detected per unit of time. Furthermore, we used different layers of thermochromic pigments with different colors and activation thresholds to sense temperature. We recorded the HSV values within an ROI and found out the hue value changes inversely proportional with the temperature range 25°C-50°C. Therefore, we can say our prototype is a compact and unified visuotactile haptic primary colors sensor.

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