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A novel multi-modal tactile sensor design using thermochromic material

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Tactile sensors are important for ensuring robotic perception [1], and their performance directly affects a robot's capability for performing dexterous operations. These sensors mimic the tactile sensing capability of human hands. This is because the skin of human hands is involved in considerably meticulous works and can provide multi-modal perceptions of various factors, including the thermal conductivity, weight, surface texture, and stiffness. Therefore, the investigation of multi-modal tactile sensors has recently become increasingly popular.

BioTAC [2] is a remarkable example of a multi-modal tactile sensor, which is a highly integrated and finger-like tactile sensor that can be used to measure the temperature, vibration and exerted pressure. In [3], a biomimetic tactile sensor was used to successfully identify various materials. Furthermore, BioTac is installed on the Shadow robotic hand and is employed to recognize the objects based on their surface textures with a high recognition accuracy [4]. However, BioTAC can be easily damaged, and its conformation is not customized for achieving garment manipulation. Hence, it is ineffective if it is applied to industrial grippers having limited manipulation capabilities. Because vision-based tactile sensing exhibits a higher value of performance than that exhibited by other multi-modal tactile sensors, majority of the recent studies are focused in this direction. GelSight [5] is a typical vision-based multi-modal tactile sensor comprising a piece of clear elastomer, which is coated with a reflective membrane and black markers, a camera, and light sources. Yuan et al. [6] introduced a method for sensing slipping and for measuring the normal, shear and torsional load on the contact surface using the GelSight tactile sensor. Recently, Pestell et al. [7] presented a cheap, compliant, dual-modal tactile sensor, which is capable of high-speed sensing (analogous to pain reception in humans) and high-resolution sensing (analogous to the sensing provided by the Merkel cell complexes of human fingertips). However, the thermal modal is not considered in the current vision-based tactile sensor. Furthermore, thermal conductivity is considered to be important tactile information. Hence, the novel multi-modal tactile sensor is developed using thermochromic material for achieving robotic perception.

In this study, a novel vision-based multi-modal tactile sensor is partially developed, and its fabrication is proposed. The multi-modal tactile perception method is finally described and the results are presented for proving the effectiveness of the proposed sensor.

Sensor design. The vision-based tactile sensor consists of camera, transparent elastomer, light sources and supporting structure. The structure design of the proposed sensor is shown as Figure 1(a). The camera should be considered to be important in the design because its size and focal length directly affect the structure of a tac-

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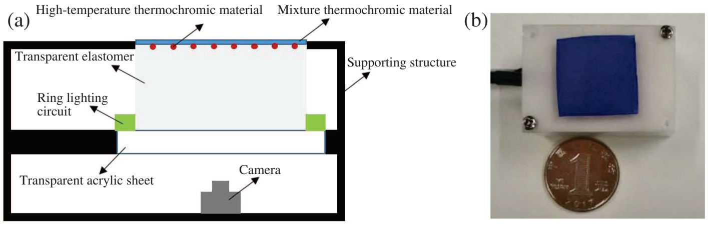

Figure 1 (Color online) Multi-modal tactile sensor. (a) The sensor structure and (b) the sensor prototype.

tile sensor and the range of images that can be captured. This tactile sensor aims to provide the robot with information related to the objects during manipulation. It is generally mounted on the robot's hand, and its size should also be considered. Therefore, the size, focal length and visual range of the camera should be appropriately selected. A custom miniature ultra-short focal length camera with a focal length of 1/6 inch and with 300000 high-definition pixels is used in the proposed tactile sensor.

Meanwhile, the softness of the elastomer and the attachment of the surface layer on the elastomer can be used to determine the information quality obtained using the sensor. As previously described, the sensor acquires multi-modal information by capturing the images of the upper surface of the elastic body that is in contact with the objects. Further, the sensor obtains the information related to multiple modalities of the object through the deformation of the elastic body and the surface attachments. The elastomer deformation is related to the softness of the elastomer. Meanwhile, the surface attachments determine the modal of perception. The thermochromic material was used to construct the markers and the reflective membrane. A thermochromic material is a reversible colored material that transforms from dark to colorless in the presence of heat and returns to its original color in a cold environment. This material exhibits superior adaptability, and several thermochromic materials can be mixed according to the individual preferences that are required for sensing multiple temperature intervals. When the mixture material is exposed to different temperatures, it becomes sensitive, rapidly discolors, and exhibits a strong stability. This material is extensively used in daily necessities, including color-changing cups and t-shirts. However, this material has not been applied in the tactile sensors. In the proposed design, the thermochromic material is used to sense various temperature intervals to construct reflective membranes. Further, the high-temperature thermochromic material is employed to develop markers that maintain the invariance at a low temperature.

Fabrication. In the vision-based tactile sensor, an elastomer is considered to be a medium that transforms the tactile information into image information. Hence the elastomer material must be transparent and flexible. First, polydimethylsiloxane (PDMS) was selected. The softness of the elastomer is dependent on the ratio of the two components contained in PDMS. The elastomer mold is designed in a cuboid shape. Further, the mold of aluminum alloy should be polished to prevent the prepared elastomer from contacting with the rough surfaces, thereby affecting the image quality obtained using the sensor. Additionally, the two components were mixed in a certain proportion, and the mixture was poured into the mold. Thereafter, the mixture in the mold was placed in a vacuum- incubator to extract the air bubbles from PDMS and to obtain a consistent temperature for curing. After approximately half an hour, the cured PDMS can be eliminated from the mold.

Further, the elastomer's surface attachment that resists light transmission and renders the texture was constructed. The elastomer is optically transparent, and the camera is highly susceptible to external light sources while capturing the images of an elastomer surface. Hence, the surface attachment must exhibit the characteristics of reflection, adhesion, and ductility as well as the presence of fine particles. The existing attachments of such sensors include silver powder or copper that cannot be used to sense temperatures. Thus, the thermochromic material is employed as an attachment to simultaneously sense the temperatures and textures. Two thermochromic materials were individually coated on the surface of the elastomer to form two layers. The first layer was coated with the first thermochromic material to form a 7×6 marker array. After the marker array was shaped, the second thermochromic material with a 0.15 mm thickness was applied to the second layer. Furthermore, the color difference observed between the two materials in an equal temperature condition should be evident. The first thermochromic material becomes red when the temperature is lower than 65°C, whereas the color of the thermochromic material becomes white when the temperature becomes greater than 65°C. Meanwhile, the second thermochromic material exhibits four color-changing intervals. It becomes dark purple when the temperature is lower than 5°C, purple when the temperature is between 5°C and 22°C, blue when the temperature is between 22°C and 45°C, and white when the temperature is greater than 45°C. Further, the colors are observed to vary in different temperature ranges. Therefore, the device can achieve the required contact force, texture and temperature value ranges when it contacts an object at a temperature lower than 65°C. The prototype of the sensor is depicted in Figure 1(b).

Multi-modal tactile perception. The temperature perception of a multi-modal tactile sensor is reflected in terms of color. The response color of the sensor to the four temperature states can be given as follows: ice: black; cool: purple; normal temperature: blue; and hot: white. The color difference between the temperature states is observed to be significant, and the sensor's transition between the two states is considerably sensitive. Furthermore, a warm tone matching method is proposed for determining the object's temperature. Further, the standard templates of the color histogram obtained by considering the warm tones of the images in the four states were constructed, and the nearest neighbor method was used to match the temperatures of the objects' surface.

The multi-modal tactile sensor's force perception was computed based on the marker movements. To detect and localize the markers, we propose an algorithm that distinguishes the markers from the background based on their colors. The basic concept of this method is to preprocess the image and to perform binarization, identify the connected domain, and eliminate the connected domain that does not satisfy the requirements. The remaining connected domain corresponds to the marked point and subsequently locates the centroid of the connected domain. Further, the centroid position is located at the center of the marker. The back propagation (BP) neural network is designed to fit the three-dimensional contact force using the displacements of the markers. Hence, the forces can be estimated using the tactile sensor. The details of the force sensing method are presented in [8].

Texture indicates the smoothness or roughness of an object and is considered to be an important feature for obtaining robotic perception. A total of 43 materials were utilized for developing a dataset. During data collection, we switched the status of the Robotiq hand and fixed the UR5 arm to accelerate this process. Further, we manually placed our sample objects between the fingers. The robotic hand grasped the objects 100 times with varying forces. In our dataset, the value of the grasping force ranges from 0.5 to 50 N with a step of 0.5 N. Thus, we can obtain 200 (i.e., 100×2 fingers) different texture images for one sample object. Further, we verified both the traditional texture and deep features extracted using NNs for identifying the texture. Notably, deep features exhibit a better performance than that exhibited by other traditional features, such as Gabor response and Fisher vectors, based on the SIFT features. The texture recognition accuracy is higher than 98%.

The advantage of the proposed tactile sensor is that the force, the surface texture and thermal sensing use the same principle of vision-based. It entails a simpler and more compact integration in robotic hand for perception and manipulation.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Zhang W C, Sun F C, Wu H, et al. A framework for the fusion of visual and tactile modalities for improving robot perception. Sci China Inf Sci, 2017, 60: 012201
2 Wong R D P, Hellman R B, Santos V J. Haptic exploration of fingertip-sized geometric features using a multimodal tactile sensor. In: Proceedings of SPIE, 2014. 911605
3 Kerr E, McGinnity T M, Coleman S. Material recognition using tactile sensing. Expert Syst Appl, 2018, 94: 94–111
4 Kaboli M, Walker R, Cheng G. Re-using prior tactile experience by robotic hands to discriminate in-hand objects via texture properties. In: Proceedings of IEEE International Conference on Robotics and Automation (ICRA). New York: IEEE, 2016. 2242–2247
5 Li R, Platt J R, Yuan W, et al. Localization and manipulation of small parts using gelsight tactile sensing. In: Proceedings of IEEE International Conference on Intelligent Robots and Systems. New York: IEEE, 2014. 3988–3993
6 Yuan W, Li R, Srinivasan M A. Measurement of shear and slip with a GelSight tactile sensor. In: Proceedings of IEEE International Conference on Robotics and Automation (ICRA). New York: IEEE, 2015. 304–311
7 Pestell N, Lloyd J, Rossiter J, et al. Dual-modal tactile perception and exploration. IEEE Robot Autom Lett, 2018, 3: 1033–1040
8 Fang B, Sun F, Yang C, et al. A dual-modal vision-based tactile sensor for robotic hand grasping. In: Proceedings of IEEE International Conference on Robotics and Automation (ICRA). New York: IEEE, 2018. 4740–4745