

# MICROSTRUCTURE-ENHANCED VISION-BASED TACTILE SENSOR

Mayue Shi<sup>1</sup>, Yongqi Zhang<sup>1</sup>, Xiaotong Guo<sup>1</sup>, and Eric M. Yeatman<sup>1</sup>

<sup>1</sup>Department of Electrical and Electronic Engineering, Imperial College London, UK

## ABSTRACT

This paper presents for the first time a vision-based tactile sensor (VBTS) enhanced by micro-structured features. Differing from conventional designs where tracking markers are added to unmodified structures, here an interface surface is constructed with micromachined trenches, which allow varying amounts of light to transmit according to the applied force, forming a matrix of bright cross-shaped patterns on the bottom surface. The variation of brightness, wire width, and location of the cross patterns was captured by a camera and used to sense force magnitude and contact location.

Compared to previously reported VBTSs, this microstructured sensor increases the sensitivity by magnifying the visual effect of shape distortion. With theoretical and experimental analysis, this sensor achieved a sensitivity of 20 mN. The resolution reached 1 mm for single-point touch. This sensor is entirely soft and compatible with soft robots and wearable electronics. Unlike piezoelectric sensor arrays, it is immune to electrical crosstalk and interference.

## KEYWORDS

Vision-based tactile sensor (VBTS), microstructure, stretchable, MEMS.

## INTRODUCTION

VBTSs have been investigated for robotic perception [1] because of their advantages in rich information, high robustness, low cost, multimodality, and compatibility with many computer vision methods, such as convolutional neural networks [2]. Computer vision methods can be used to extract features from the images captured by the camera module of the sensor. These features can then be used to estimate contact position and force distribution. VBTSs are mainly based on two principles [3]: displacement of markers with deformation of the sensor [1], and irregular refraction and reflection of light induced by surface deformation [4].

The structure of VBTS often contains a sensor body and camera, in which the sensor body is critical for the performance of perception. The optimization design of the sensor body is promising, which involves novel structures, advanced materials and fabrication processes. With the rapid improvement of hardware designs, the last decade has witnessed the development of the VBTS towards miniaturization, high performance and multimodality [3]. For example, the TacTip family realised high-resolution tactile sensing with a 3D printed sensor body with pins mimicking the function of intermediate ridges within the human fingertip [5]. The GelTip could localise the contacts with a finger-shaped sensor body. The average localisation error was around 5 mm [4]. A multi-camera design was presented by Truueb et. al [6]. By monitoring the different particle patterns in the sensor body, contact force

distribution was measured with a machine learning method. A transfer learning algorithm was investigated for reconstructing the normal force distribution and transferring the knowledge across different sensor gels [7].

There have been many studies investigating different structural designs for VBTSs, however, there are no studies into the performance enhancement by introducing micromachined features to the best of our knowledge. Here, we present for the first time a VBTS enhanced by micro-structured features, in both resolution and sensitivity. With micromachined cross-shaped structures on the stretchable sensor body, the variation of the cross patterns can effectively reflect the properties of the applied force including magnitude and contact location.

## WORKING PRINCIPLE

As shown in Figure 1, the stretchable sensor body consists of a transparent Polydimethylsiloxane (PDMS) layer and a thin black composite layer. The 5×5 cross-shaped trench structures were fabricated with ultraviolet laser cutting on the composite side halfway through the PDMS layer (Figure 1b). The distance between two adjoining cross centres is 2 mm, while both length and width of the cross are 1.5 mm. The sensor body was clamped using a 3D-printed frame with a square window, which is 1.6×1.6 cm (white part in Figure 1c).

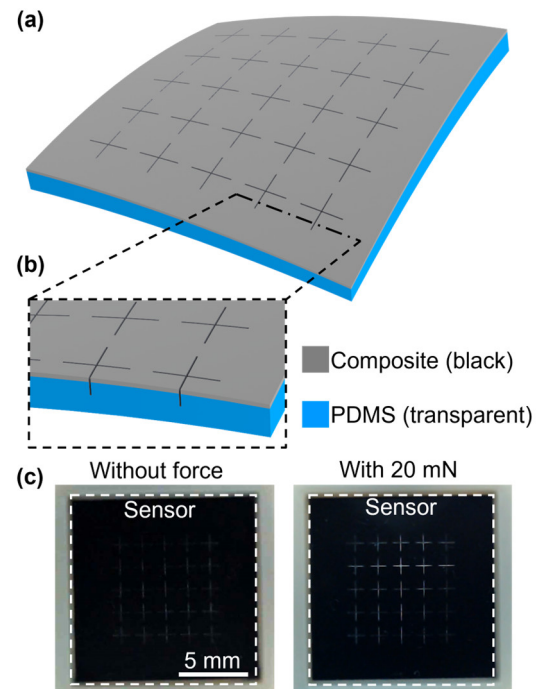


Figure 1: Structural schematic diagram and demonstration of sensor. (a) Structural design and (b) a sectional view showing trench structures in the film. (c) Experimental result with an applied force of 20 mN at the cross centre in row 2, column 3. Diameter of contact area: 1 mm.

When applying pressure on the transparent side (Figure 2), the deformation of the film led to an increase of micro trench width and luminous flux, and images were captured by a camera under the sensor body. According to experimental result, the images of our sensor body clearly showed the distinguishable features under an applied force of only 20 mN (Figure 1c), which indicates its high sensitivity. With the diaphragm structure, the sensor recovers spontaneously after deformation. We have modelled the deformation with finite element analysis, which indicates that the micro trenches lead to enhance film deformation under the same force.

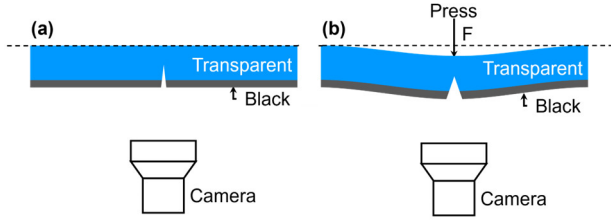


Figure 2: Principle of structure-enhanced vision-based sensor. (a) Without pressure. (b) With pressure.

## MODELLING AND ANALYSIS

We have modelled the deformation with finite element analysis (FEA). Figure 3 shows the displacement and stress distribution of the sensor body with upward applied force at the central cross (3,3). It indicates that the displacement of the diaphragm around the contact point was higher than other areas. The displacement caused the deformation of the micro trench, mainly involving the increased width of trenches and spatial displacement of cross patterns (Figure 3a,b). The deformation of micro trenches could lead to the variation of luminous flux and location, which was captured by the camera. In Figure 3c the stress was mainly distributed at the centre of the diaphragm, where the external force was applied, while the existence of micro trenches influenced the microscale distribution of stress. On the upper surface, there was less stress around each cross centre, and higher stress was reached at the bottom of the micro trenches.

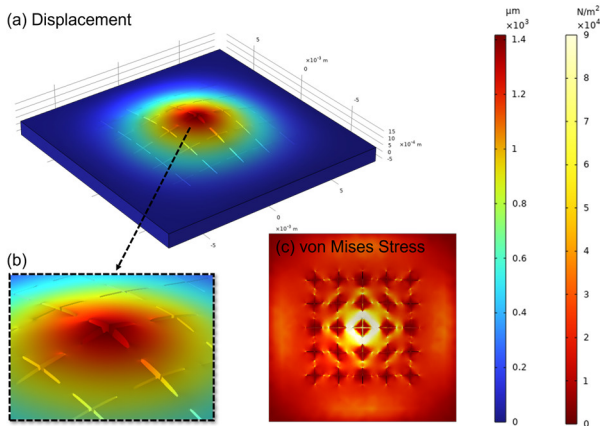


Figure 3: Finite element analysis of (a) deformation and (b) stress distribution, with a force of 60 mN applied at the bottom centre (3,3) of the sensor along y-direction (diameter of contact area: 1mm, COMSOL, same for other simulation results).

To evaluate the deformation of the micro trench, the average diagonal length of the quadrilateral at the cross center was used to represent the deformation of the micro trench under an applied force in this paper. The reason to choose average diagonal length is to balance the asymmetry in x and y direction deformations due to different proximity of each individual location to the boundaries. We selected six representative locations, (1,1), (1,2), (1,3), (2,2), (2,3), and (3,3), based on the symmetrical properties of the entire geometry, to examine the micro trenches' deformation in different locations of the  $5 \times 5$  array under various applied forces. Subsequently, we proceeded to run the COMSOL simulation where forces from 20mN to 80mN are applied to each of the above selected locations through a circular contact area of 1mm in diameter, and plotted the corresponding average central diagonal deformation. The results show a linear relationship between applied forces and deformation, and that locations closer to boundaries undergo smaller deformations, as expected.

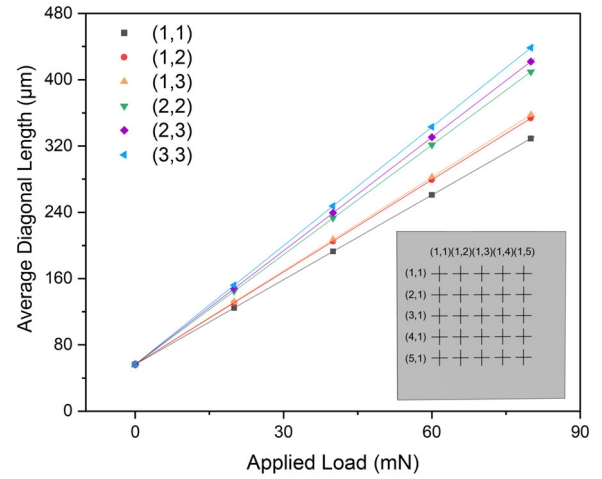


Figure 4: Deformation of the micro trench in average diagonal length under various applied forces at selected locations. The locations simulated are selected to be representative of all locations through symmetry.

To get a clear picture of how each individual location of the  $5 \times 5$  array deforms when force is applied to that particular location, we proceeded to simulate on COMSOL two scenarios where a force of 60 mN is applied to the central location (3,3) and an off-centre location (2,2) through a circular area of 1 mm in diameter. As expected, the result of deformation (left: average diagonal length, right: diaphragm displacement) shows a very radial-symmetrical deformation pattern throughout the  $5 \times 5$  array when (3,3) is pressed, where locations closer to the point of contact undergo larger deformation, and vice versa. The result for the second scenario where location (2,2) is pressed shows locations such as (5,1), (4,4), and (5,5) that are further away from the off-centre point of contact would undergo less deformation than its counterpart when the central location (3,3) is pressed.

Figure 6 shows the variation of average diagonal length at locations (2,3) and (3,3), with the applied force of 60mN moving from location (2,3) to (3,3) intermittently.

The result proves the capability of this sensor to achieve higher resolution than the cross-shaped trench density. It also implied the nonlinear variation of trench deformation when the contact point moves between crosses.

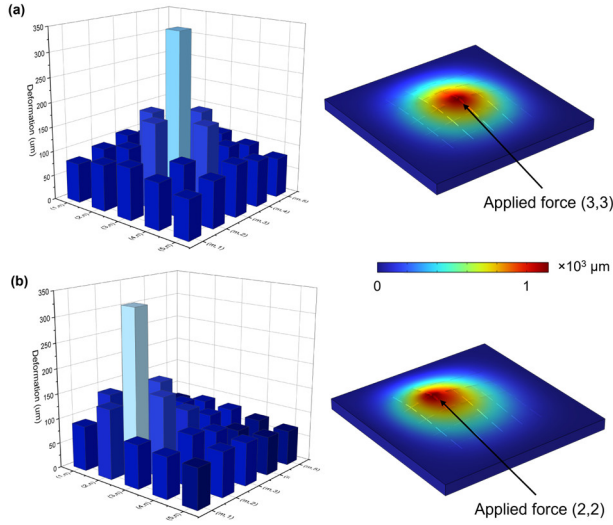


Figure 5: The deformation of all 25 micro trenches under an applied force of 60 mN at (a) location (3,3), and (b) location (2,2).

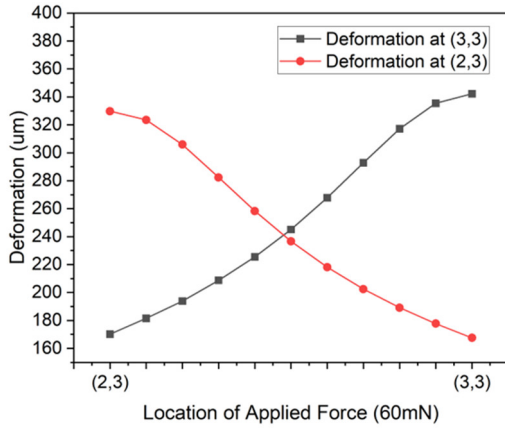


Figure 6. Comparison of sensor deformation in average diagonal length at (2,3) and (3,3), with the applied force of 60 mN moving from location (2,3) to (3,3) intermittently by 0.2 mm from each data point.

## FABRICATION

The sensor body was prepared with two materials: transparent PDMS elastomer and black graphite/PDMS composite (PDMS: Dow Corning, SYLGARD 184 silicone elastomer; graphite: Sigma-Aldrich, 282863). Figure 7 shows the fabrication process of the sensor body. First, we fabricated a thin PDMS substrate film. The PDMS base and curing agent were mixed in a ratio of 10:1 (w/w). Then, the mixture was spin-coated on a plate before being transferred to an oven for curing at 70 °C for 2 hours. To prepare the graphite/PDMS composite, 10 wt% graphite was fully mixed with uncured PDMS (base: curing agent = 10:1, w/w) to form a black composite, which increases image contrast. The mixture was spin-coated on the transparent PDMS film (300 rpm, 60 s) to ensure uniformity. The film

was transferred to an oven at 70 °C for 4 hours. According to SEM measurement, the total thickness of the film is 1 mm, while the composite layer is  $\sim 230 \mu\text{m}$ .

After preparing double-layer elastomer film, the micro trenches were fabricated with high-precision ultraviolet laser cutting. The process was shown in Figure 7b. First, the multilayer film was placed on a glass plate, after which the film was patterned with the cross-shaped trench using a computer-controlled laser cutter. The inset on the right side shows the cross-section of a deep v-shaped micro trench, which was formed with the laser-cutting process. The depth of the micro trench was  $\sim 510 \mu\text{m}$  based on the SEM measurement.

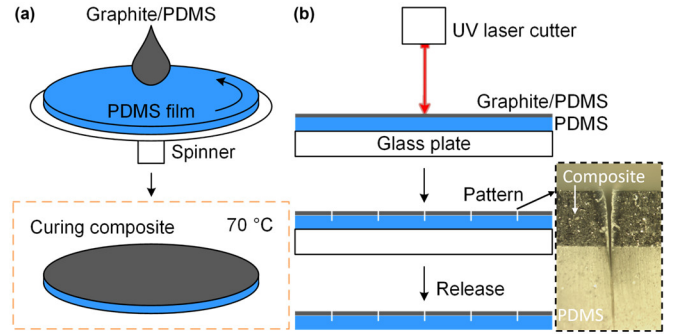


Figure 7: Fabrication processes. (a) preparation of the film with the spinning coating process. (b) micromachining with high-precision laser cutting.

## EXPERIMENTS AND DISCUSSIONS

A bespoke experimental setup has been developed for sensor characterization and validation (Figure 8a). The setup was designed to characterize the sensor by repeatedly applying a controllable vertical force on the sensor. This setup is mainly composed of the following components: a magnetic linear motor (Faulhaber LM038004001), a 3-D printed probe, a sensor holder, and mechanical connection components. The vertical force application is implemented by the 3-D printed cone-shaped probe with a circular tip (2 mm dia.), which transfers a controllable linear motion, delivered by the magnetic linear motor, into forces. The linear motor equips a position sensor (1  $\mu\text{m}$  precision), which enables continuous linear translation of its probe with a precise displacement and frequency. Additionally, all the mechanical connection components are 3-D printed, i.e., linear motor holder and connector.

The VBTS was tested under environmental light, with different vertical displacements of the linear motor from 0.5 mm to 1.5 mm. The resolution of the camera was 1920×1080 pixels (Logitech C922). We first tested the sensor with a single contact point located at the centre of each cross, after which the points between the two centres were tested. The camera images captured under different conditions are distinguishable, showing the resolution of the sensor was at least 1 mm. The results from three typical testing points of (3,3), (4,3) and (3.5,4.5) are shown in Figures 6b,c,d. The images indicate that crosses close to the contact point have high luminous flux and wide trenches. Additionally, the deformation of the film led to the displacement of crosses in images. This result was predicted by finite element simulation as well.

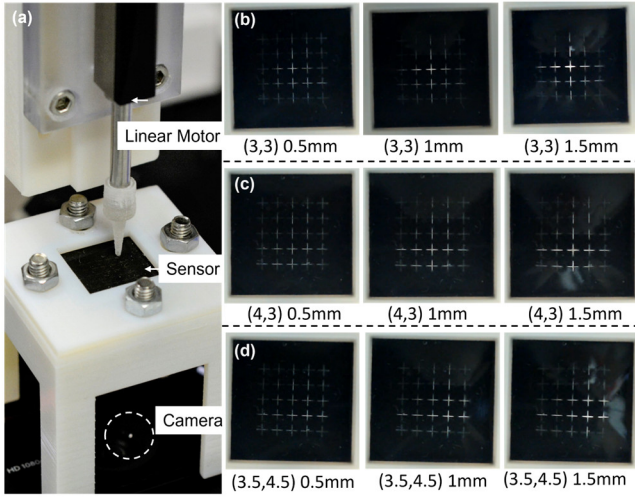


Figure 8: Experimental set-up and testing results. The setup includes a linear motor (Faulhaber LM083004001), a sensor, and a camera. Diameter of contact area: 1 mm. The data below images shows the contact location and displacement of linear motor towards the sensor. For example, (3, 3) indicate the applied force was at the cross centre in row 3, column 3.

The quantitative image analysis is shown in Figure 9. We calculated the average brightness of the square central region ( $60 \times 60$  pixels) of the images in Figure 8b, to reflect the response of the sensor to different vertical displacements. The calculation is performed using value channels of images in the HSV (hue, saturation, value) colorspace, in which the value describes the brightness. The figure clearly indicated that the average brightness increased with the displacement. Specifically, when the displacement varied from 0.5 mm to 1.5 mm, the average brightness increased to 3.2 times that of 0.5 mm displacement, which shows the outstanding sensitivity of our sensor in this range. If we only focus on the cross trench region, the variation of brightness was even higher. This is especially beneficial for further in-depth image processing and analysis to achieve higher sensitivity.

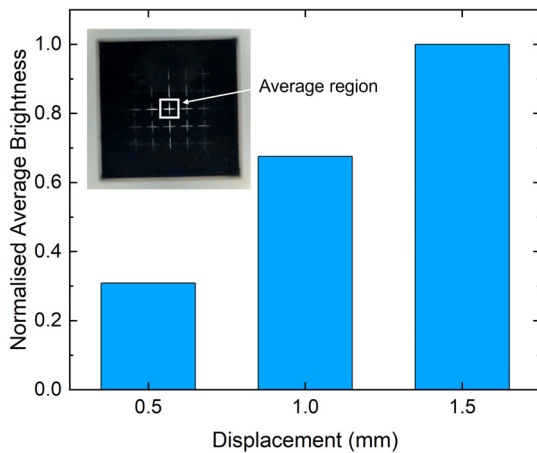


Figure 9: Variation of average brightness with different displacements. The contact point was at (3,3), the square average region fully included the central cross.

## CONCLUSIONS

In this paper, we developed a novel VBTS enhanced by the cross-shaped micro trench structure. The structure of the sensor body has a black composite layer with 25 cross trenches, allowing variable light luminous flux based on the magnitude and location of the applied force on the sensor body. The images of the sensor body were captured by a commercial webcam. We performed both theoretical and experimental analyses to investigate the sensing performance of our sensor. According to the experimental results, our sensor achieved a high sensitivity of 20 mN, while the resolution achieved 1 mm. The sensor body is entirely soft, therefore having the potential to be seamlessly integrated into soft robotics and wearable electronics. In addition, it is compatible with computer vision methods and also allows multi-point tactile sensing. In future research, it can be widely used for robotic sensing and human-machine interfaces.

## ACKNOWLEDGEMENTS

This work was supported by the Engineering and Physical Sciences Research Council, UK [grant number: EP/P012779/1]. The authors would like to thank Prof Andrew Holmes for providing the laser processing equipment.

## REFERENCES

- [1] L. Van Duong and V. A. Ho, "Large-Scale Vision-Based Tactile Sensing for Robot Links: Design, Modeling, and Evaluation," *IEEE Trans. Robot.*, vol. 37, no. 2, pp. 390–403, Apr. 2021.
- [2] A. C. Abad, D. Reid, and A. Ranasinghe, "HaptiTemp: A Next-Generation Thermosensitive GelSight-Like Visuotactile Sensor," *IEEE Sens. J.*, vol. 22, no. 3, pp. 2722–2734, 2022.
- [3] S. Zhang et al., "Hardware Technology of Vision-Based Tactile Sensor: A Review," *IEEE Sens. J.*, vol. 22, no. 22, pp. 21410–21427, 2022.
- [4] D. F. Gomes, Z. Lin, and S. Luo, "GelTip: A finger-shaped optical tactile sensor for robotic manipulation," *IEEE Int. Conf. Intell. Robot. Syst.*, pp. 9903–9909, 2020.
- [5] B. Ward-Cherrier et al., "The TacTip Family: Soft Optical Tactile Sensors with 3D-Printed Biomimetic Morphologies," *Soft Robot.*, vol. 5, no. 2, pp. 216–227, 2018.
- [6] C. Trueeb, C. Sferrazza, and R. D'Andrea, "Towards vision-based robotic skins: A data-driven, multi-camera tactile sensor," *2020 3rd IEEE Int. Conf. Soft Robot. RoboSoft 2020*, pp. 333–338, 2020.
- [7] C. Sferrazza and R. D'Andrea, "Transfer learning for vision-based tactile sensing," *IEEE Int. Conf. Intell. Robot. Syst.*, pp. 7961–7967, 2019.

## CONTACT

\*M. Shi, tel: +44-47465-944562;  
m.shi16@imperial.ac.uk