Insight: A Vision-based Haptic Sensor That Provides Rich Force Information about Contacts

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Robots need detailed haptic sensing that covers their surfaces in order to learn effective behaviors in unstructured environments. However, state-of-the-art sensors tend to focus on improving precision and sensitivity, increasing taxel density, or enlarging the sensed area, rather than prioritizing system robustness and the usability of the sensed haptic information. We thus present a robust, soft, low-cost, vision-based, thumb-sized 3D haptic sensor named Insight: it continually supplies the host robot with a directional force-distribution map over its entire conical sensing surface. Insight uses an internal monocular camera, photometric stereo, and structured light to detect the 3D deformation of the easily replaceable flexible outer shell, which is molded in a single layer over a stiff frame to guarantee sensitivity, robustness, and a soft contact surface. The force information is inferred by a deep network (ResNet) that maps images to the spatial distribution of 3D contact force (normal and shear), including numerous distinct contacts with widely varying contact area. Extensive experiments show that Insight has an overall spatial resolution of 0.4 mm, force magnitude accuracy around 0.03 N, and force direction accuracy around 5 degrees over a range of 0.03–2 N. The presented hardware and software design concepts can be extended to achieve robust and usable tactile sensing on a wide variety of robot parts with different shapes and sensing requirements.

Fig. 1. We design a soft thumb-sized vision-based haptic sensor that gives detailed force distribution information over its 3D sensing surface.

1. Introduction

High-fidelity haptic sensors with 3D sensing surfaces are needed to advance dexterous robotic manipulation. Compared to the 2D flat geometry of most state-of-the-art tactile sensors, a 3D sensing surface can enable robots to feel contact on all sides of their bodies, like human skin, which will let them work better in messy real-world environments [1, 2]. Beyond the shape of their sensing region, currently available sensors have other limitations that prevent their widespread application in the field of robotics, including low spatial accuracy, an inability to sense shear forces, complex fabrication processes, and/or low durability for long-term use. We sought to improve the situation by designing a durable high-resolution haptic sensor that has a 3D sensing surface and is easy to manufacture [3].

Among different sensor design options, vision-based haptic sensors are a new family of solutions, typically using an internal camera that views the soft contact surface from within [4]. The cameras available nowadays have high resolution, good quality, high robustness, and a low price. They can capture simultaneous data across a large area, which is very useful for creating a tactile sensor for robots. Moreover, advanced image-processing techniques offer references for an accurate way to transform the image data into tactile contact measurements.

In this paper, we design a vision-based haptic sensor and propose a machine-learning method to offer a 3D directional force distribution map over a 3D conical thumb-sized sensing surface, as shown in Fig. 1. We detail the sensor's working mechanisms in Fig. 2. The sensor comprises a miniature camera, an LED ring, and a soft-stiff hybrid surface. The hybrid structure of Insight's soft elastomer shell with a stiff metal skeleton inside ensures high sensitivity and robustness. Colored LED light is projected on the inner side of the opaque sensing surface, and the camera looks through the ring of lights to see the inner reflective surface. When an object contacts the outside of the sensor, the camera sees changes caused by the deformation. A trained machine-learning model runs to interpret each camera images as a force map. The force map describes the directional force distribution over the entire 3D sensing surface, i.e., 3D force vectors at a fine grid of points distributed all across the sensor. A testbed with 5-DoF actuation and 3-axis force measurement is built to carry a four millimeter spherical indenter to probe the sensing surface and collect the needed data to train the machine-learning model.

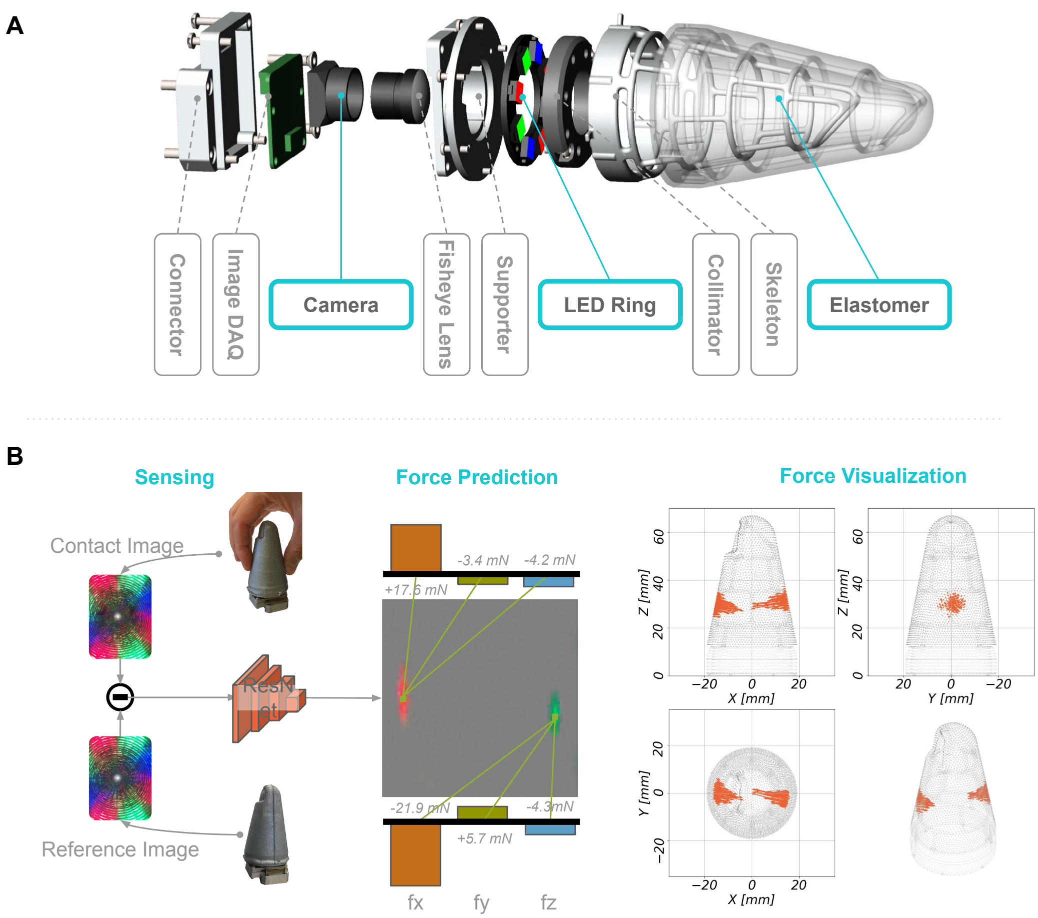

Fig. 2. **A**: Insight has a hybrid mechanical structure of a soft elastomer enclosing a stiff metal skeleton for both sensing light contact and sustaining high-impact force. An LED ring and a collimator are combined to create structured light for detecting 3D deformations of the surface from a single 2D image. **B**: A trained machine-learning model takes images from the camera and a reference image to estimate the force distribution all over the surface. Each pixel in the force prediction map has three values that indicate the force strength in three directions. In the force visualization on the right, each point (corresponding to one pixel in the force prediction) shows the force distribution of the contact in both normal and shear directions.

We quantitatively evaluate the sensor performance over a force range of 0.03–2 N. It can predict single contact by the four millimeter spherical indenter with an overall spatial precision (RMSE) of 0.4 mm and force magnitude around 0.03 N. It can tell the detailed directions (normal and shear) of the contact force on the surface with a direction accuracy around 5 degrees. The sensor can detect multiple contacts simultaneously and detail the contact shape when objects are pressed into the finger-nail zone. Finally, the sensor can precisely predict its own orientation (accuracy around 2 degrees) relative to gravity by visually observing the small gravity-induced deformations of the over-molded elastomer with ridges.

Our sensor design concept can be applied and extended to a wide variety of robot body parts with different shapes and precision requirements. We have open-sourced all the design files and code [5], and we have also provided ideas on how to adjust Insight's design parameters for other applications, such as the field of view of the camera, the arrangement of the light sources and the composition of the elastomer [3].

References

[1] J. A. Fishel and G. E. Loeb, "Sensing tactile microvibrations with the BioTac — Comparison with human sensitivity," in *Proceedings of the IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2012, pp. 1122–1127.

[2] B. Ward-Cherrier, N. Pestell, L. Cramphorn, B. Winstone, M. E. Giannaccini, J. Rossiter, and N. F. Lepora, "The TacTip Family: Soft Optical Tactile Sensors with 3D-Printed Biomimetic Morphologies," *Soft Robotics*, vol. 5, no. 2, pp. 216–227, Apr 2018.

[3] H. Sun, K. J. Kuchenbecker, and G. Martius, "A soft thumb-sized vision-based sensor with accurate all-round force perception," *Nature Machine Intelligence*, vol. 4, Feb. 2022. [Online]. Available: https://rdcu.be/cHCl9

[4] W. Yuan, S. Dong, and E. H. Adelson, "GelSight: High-Resolution Robot Tactile Sensors for Estimating Geometry and Force," *Sensors*, vol. 17, no. 12, p. 2762, Nov. 2017.

[5] H. Sun, "Insight: A haptic sensor powered by vision and machine learning," https://github.com/Huanbo-Sun/Haptics-for-Robots-Insight, 2022.