Exploiting Touch Sensing around Fingers

Daniel Fernandes Gomes[1], Zhonglin Lin[1,2], Shan Luo[2]

***Abstract*— Sensing contacts throughout the entire finger, is an highly valuable capability for a robot to perform manipulation tasks, as vision-based sensing often suffers from occlusions or inaccurate estimations. Current tactile sensors represent one of two compromises: low resolution readings, or a limited contact measurement area. In this paper, we propose a finger-shaped optical sensor that has the shape of a finger and can sense contacts on any location of its surface. Our extensive experiments show that the sensor can effectively localise these contacts at different locations of its finger body, with a small localisation error of approximately 5mm, on average, and under 1mm in the best cases. Furthermore, our grasping experiments demonstrate the advantages of leveraging touch sensing in manipulation tasks, together with remote sensing capabilities, such as vision.**

I. INTRODUCTION

All-around tactile sensing is an essential capability to be exploited when performing manipulation tasks in cluttered environments, as often vision sensing suffers from occlusions or inaccurate depth estimations. For instance, when attempting to grasp an object, contacts on the fingertips can be exploited to guide the grasp approach. And, contacts on the inner sides of the fingers, inform when to stop closing the gripper.

A wide range of tactile sensors has been developed in the literature [1], [2], ranging from flexible electronic skins [3], to flexible capacitive tactile sensors [4], and camera based optical tactile sensors [5], [6], many of which have been employed to aid robotic grasping. Electronic tactile skins and flexible capacitive tactile sensors can adapt to different body parts of the robot that have various curvatures and geometry shapes. However, due to the use of dielectrics for each sensing element, they suffer from complicated electronics, cross-talk problems and low resolution of tactile signals [7]. Thanks to the use of cameras, optical tactile sensors provide high-resolution images of the deformation caused by contacts.

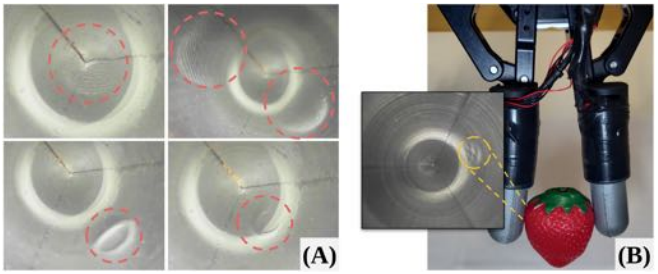

Fig. 1: **(A)** Contacts against fingerprints and an open cylinder solid. **(B)** A gripper equipped with the proposed sensors, grasping a strawberry.

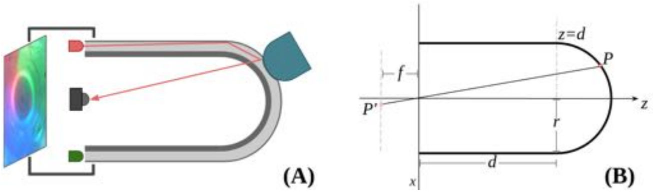

Fig. 2: **(A)** The path of a light ray travels through the elastomer, and is captured by the camera sensor. **(B)** Illustration of the projection model.

There are two main families of optical tactile sensors, TacTip sensors [5] and GelSight sensors [6]. TacTip exploits the tracking of markers printed on a soft domed membrane, while GelSight exploits colored illumination and photometric stereo analysis to reconstruct the membrane deformations. Therefore, TacTip only measures the surface on a few points, whereas GelSight sensors make use of the camera full resolution. However, to the authors' best knowledge, only flat surfaced GelSight sensors have been proposed. With such designs, these are not able to sense all areas of the finger. To take advantage of the full resolution of cameras, as GelSight, and also enable the detection of contacts from all the finger surface directions, we propose an optical tactile sensor that has the shape of a finger.

II. THE SENSOR

A. Overview

The proposed tactile sensor consists of a soft transparent membrane, coated with an opaque elastic paint, placed over a rigid transparent glass, shaped as a finger. When an object is pressed against the tactile membrane, the elastomer distorts and assumes the object shape. The pressed surface shape can then be observed from the opposite side of the membrane. A camera enclosed within the opaque shell is placed next to the finger base, with the tactile membrane being the only interface with the external environment. LEDs are placed adjacent to the base of the sensor and the light rays are guided through the glass and elastomer illuminating the finger inside. This working principle illustrated in Fig. 2-A, and ensures readings invariant to the object color or environment luminance.

B. Projective Sensor Model

Contacts with the finger happen throughout the tactile membrane 3D surface, however the obtained tactile image is a 2D projection. Therefore, it is desirable to study the mapping function between image pixels and world points. To that extent, the sensor surface is modeled as a joint semi-sphere and an open cylinder, both sharing the same radius r.

---

[1] smARTLab, Department of Computer Science, University of Liverpool, Liverpool, United Kingdom {danfergo, shan.luo}@liverpool.ac.uk;

[2] College of Mechanical Engineering and Automation, Fuzhou University, China.

The cylinder surface center axis and the z-axis are collinear. The semi-sphere center is set to $(x, y, z) = (0, 0, d)$. A side perspective of such modeling is shown in Fig. 2.

$$\begin{cases} x^2 + y^2 + (z-d)^2 = r^2 & \text{for } z > d \\ x^2 + y^2 = r^2 & \text{for } z <= d \end{cases} \quad (1)$$

By making the usual thin lens assumptions, we model the optical sensor as an ideal pinhole camera. The projective transformation that maps a point in the world space P into a point in the tactile image P', can be defined using the general camera model:

$$P' = K[\boldsymbol{R}|\boldsymbol{t}]P \quad (2)$$

$$K = \begin{bmatrix} fk & 0 & c_x & 0 \\ 0 & fl & c_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (3)$$

where $[R|t]$ is the camera's extrinsic matrix that encodes the rotation and translation of the camera, K is the camera intrinsic matrix (f is the focal length; k and l are the pixel-to-meters ratios; c_x and c_y are the offsets in the image frame). Assuming that the used camera produces square pixels, i.e., $k = l$, fk and fl can be replaced by α, for mathematical convenience. The desired mapping function, $x', y' \rightarrow x, y, z$, is then obtained by constraining the z coordinate through the intersection of the camera model with the sensor surface. The discontinuity region, a circumference, exists where $z = d$.

III. EVALUATION

A. Contact detection

To evaluate the sensor capability of sensing contacts throughout its entire surface, an actuator equipped with the touch fingers moves and taps 7 different 3D-printed solids in known positions, see Fig.3-A. Four orientations i.e., 0, $\pi/6$, $\pi/4$ and $\pi/3$, and three horizontal translations i.e., $15\,\mathrm{mm}$, $10\,\mathrm{mm}$, $5\,\mathrm{mm}$, are considered for each. To automatically detect the contact position, a simple image subtraction based algorithm is implemented. Before each contact, a reference image is captured. Then, the absolute difference between the reference and in-contact frames is computed. A convolution with a 15×15 kernel is performed, and the output thresholded. The *opencv findContours* and *fitEllipse* functions are used to find the obtained clusters center points. A final prediction is set as the weighted average of clusters centers. The previously described sensor model (see II-A) is used to find the corresponding point in world coordinates. The error between the contacted and predicted points is measured as the euclidean distance. We obtain an error of $5\,\mathrm{mm}$, on average, and under $1\,\mathrm{mm}$ in the best cases.

B. Touch-guided Grasping

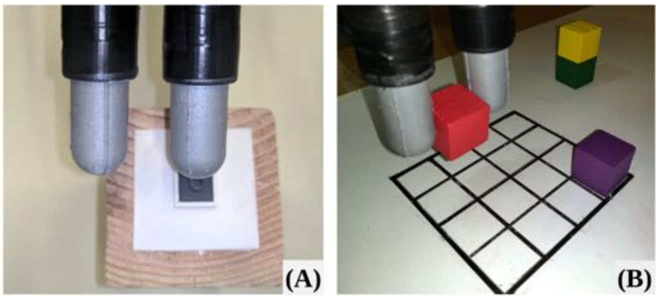

Fig. 3: The experimental setups: **(A)** Contact detection, and **(B)** Touch-guided grasping.

The potential of exploiting all-around tactile sensing is highlighted with an experiment where a robot has to pick up blocks. In this setup, Fig.3-B, blocks are randomly placed in a *4x4* grid and a robot arm picks them, one by one. Only one block exists in a given row. Mimicking the inaccuracies from remote sensing, e.g. vision, in each grasping attempt the horizontal position, i.e., the column, is uniformly randomly picked. Therefore, collisions between the blocks and finger tips often occur. If the robot fails to grasp a block within 5 attempts, this is considered a failure. Consequently, we study two re-grasp approaches: one that exploits Tactile Feedback (TF) and another that does not (No-TF). When a collision occurs, with TF enabled, the robot moves one column towards the contacted block. As a result, with No-TF the robot fails to grasp 20% of the blocks, and takes an average of 3.3 attempts to grasp each. And, with TF, the robot successfully grasps all the blocks and takes an average of 1.85 attempts per block.

IV. CONCLUSIONS

The proposed sensor can effectively capture high resolution contact readings throughout its entire surface and be used to facilitate the execution of manipulation tasks, such as grasping. However it should be highlighted that its fabrication and image analysis is more challenging than previous flat GelSight sensors. In the future, further improvements should be considered e.g. the introduction of markers, and its usage in more complex tasks such as mapping hollow objects.

REFERENCES

[1] R. S. Dahiya, P. Mittendorfer, M. Valle, G. Cheng, and V. J. Lumelsky, "Directions toward effective utilization of tactile skin: A review," *IEEE Sensors Journal*, vol. 13, no. 11, pp. 4121–4138, 2013.

[2] S. Luo, J. Bimbo, R. Dahiya, and H. Liu, "Robotic tactile perception of object properties: A review," *Mechatronics*, vol. 48, pp. 54–67, 2017.

[3] M. Kaltenbrunner, T. Sekitani, J. Reeder, T. Yokota, K. Kuribara, T. Tokuhara, M. Drack, R. Schwödiauer, I. Graz, S. Bauer-Gogonea, *et al.*, "An ultra-lightweight design for imperceptible plastic electronics," *Nature*, vol. 499, no. 7459, pp. 458–463, 2013.

[4] P. Maiolino, M. Maggiali, G. Cannata, G. Metta, and L. Natale, "A flexible and robust large scale capacitive tactile system for robots," *IEEE Sensors Journal*, vol. 13, no. 10, pp. 3910–3917, 2013.

[5] 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, 2018.

[6] W. Yuan, S. Dong, and E. H. Adelson, "GelSight: High-Resolution Robot Tactile Sensors for Estimating Geometry and Force.," *Sensors (Basel, Switzerland)*, vol. 17, 11 2017.

[7] S. Luo, W. Mou, K. Althoefer, and H. Liu, "Novel tactile-sift descriptor for object shape recognition," *IEEE Sensors Journal*, vol. 15, no. 9, pp. 5001–5009, 2015.