EleTac: Pneumatic Elephant Trunk-Inspired Soft Gripper with Vision-Based Tactile Sensing

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***Abstract*—Inspired by the tip of the elephant's trunk, we present *EleTac*, a soft, vision-based tactile gripper that enables safe object grasping via a pinch-like motion and delivers high-resolution, full-surface tactile feedback for integrated proprioceptive and exteroceptive sensing. EleTac features a fully soft, hollow design actuated by negative pressure, enabling a compliant two-finger-like grasping motion. A camera embedded inside the gripper provides a global view of the inner surface, enabling large-area, high-coverage visual feedback. The captured images are processed by a deep neural network for contact estimation, the geometry of the contacted object, and the gripper proprioception. Overall, EleTac delivers stable tactile perception performance, validating the "manipulator-as-sensor" design philosophy—achieving high-quality tactile feedback without requiring additional sensing modules.**

I. Introduction

Soft robotic grippers are capable of securely handling delicate objects without causing damage while adapting to a wide variety of shapes [1]. However, due to their complex morphologies and non-linear nature, integrating sensing functions into soft robot hands has been a longstanding challenge [2]. One possible solution for tactile sensing for soft grippers could be the vision-based approach [3]. However, previous studies have primarily focused on sensors with no intrinsic movement, meaning their deformation occurs solely due to external stimuli [3], [4]. In contrast, soft grippers experience deformation from both their own actuation and contact with objects. In this work, we attempt to incorporate grasping and tactile sensing functions into a single soft gripper. The realization of the mentioned design will enable contact feedback and enhance safe interaction between robots and the environments.

II. Gripper Design and Grasping Capability

Figure 1 shows the structural design and fabrication of the proposed soft tactile gripper EleTac. Inspired by the anatomical structure of an elephant's trunk tip, the gripper body features a hollow geometry that enables it to deform and perform a two-finger grasping motion when negative air pressure is applied. The gripper consists of two elastomer layers: a transparent inner layer and an outer layer coated with a silver-colored material. The inner layer provides the primary deformation and support, while the outer layer reflects internal light and isolates external light. A camera is placed at the base of the gripper to observe the deformation of the elastomer, which arises from both the intrinsic actuation and extrinsic contact. We then utilize the captured image for tactile sensing tasks. A programmable LED ring with 18 LEDs, with red, blue, and green light evenly distributed, positioned beneath the elastomer to provide internal illumination.

To demonstrate the grasping function, the EleTac gripper was mounted on either the Dobot Magician robotic arm (Shenzhen Dobot Corp Ltd) or the UR5e robot arm (Universal Robots), with an air pump connected to the gripper's air channel to generate negative air pressure for pneumatic actuation. The gripper operated in an on-off manner with a constant pressure of 30 kPa, which enables the two fingers to fully close and establish complete contact. Figure 2 shows the robot arm, equipped with the EleTac gripper (hereafter referred to as the EleTac arm), successfully grasping and lifting objects with various shapes and sizes.

III. Tactile Sensing Methodology

The data collection setup and model choice for the contact estimation function are shown in Figure 3a. We mounted the Nano 17 force sensor equipped with a hemispherical indenter onto the end-effector of the Dobot Magician robot arm. The robot executed vertical indentation on both fingers of the EleTac gripper. We curated a dataset of 2,536 tactile images, each paired with a corresponding ground-truth vector containing the two-dimensional indentation location (x, y), the indentation depth d, and the contact force f.

The data collection setup and model choice for the geometry classification are shown in Figure 3b. We attached indenters with six distinct head geometries to the Dobot robot arm and performed indentations on each finger. The shapes of the indenters are circle, doughnut, dots, square, stripes, and triangle. The resulting dataset consists of 2,016 tactile images and corresponding labels.

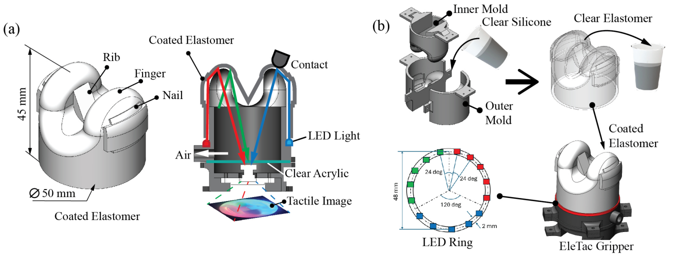

Fig. 1. Design of the gripper. (a) Anatomy, measurements, and layers of the soft elastomer. (b) Fabrication process of the gripper.

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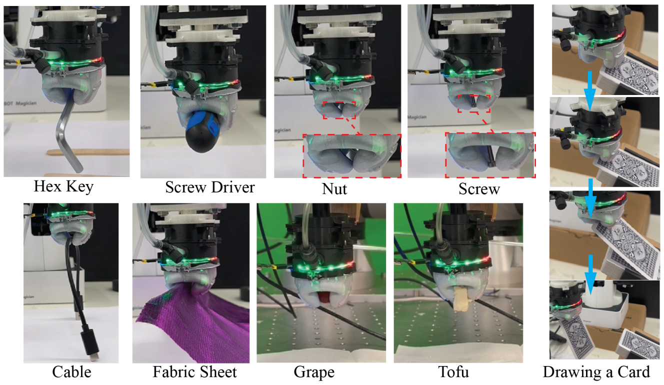

Fig. 2. Grasping demonstration on multiple objects with different sizes and shapes. The EleTac gripper is attached to the robot arm and performs grasping and picking up objects.

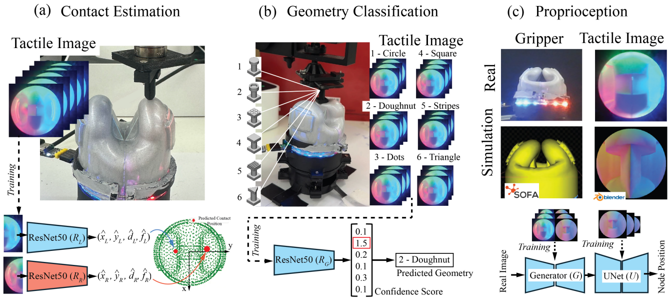

Fig. 3. Data collection for training tactile sensing models. (a) Contact estimation. (b) Geometry classification. (c) Proprioception.

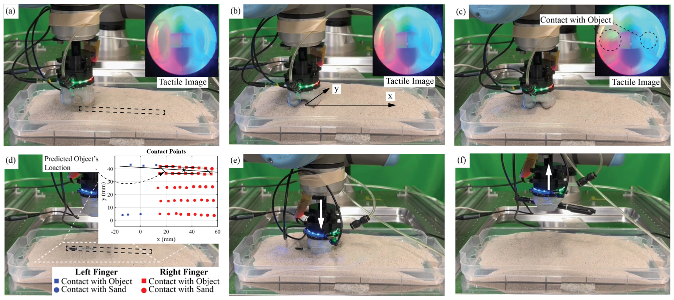

Fig. 4. Excavation of an object buried in a granular material. (a) A pen is buried in sand. (b) The EleTac presses onto the sand with no pen beneath, and the corresponding tactile image. (c) The EleTac presses onto the sand with the pen beneath, and the corresponding tactile image. (d) The location and the orientation of the pen are derived. (e), (f) The pen is excavated from the sand.

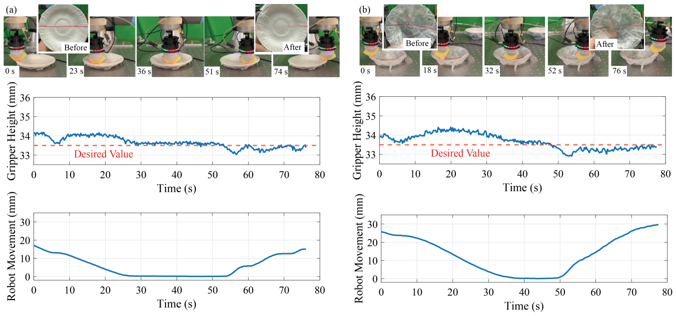

Fig. 5. Results of the surface-following task for the shallow plate (a) and the deep plate (b).

We propose a hybrid framework for estimating proprioception from tactile images, which combines simulation-based data generation, cross-domain image translation, and learning-based regression of finger position. We collected real-world gripper posture data by capturing tactile images during the gripper's opening and closing motions (as shown in Figure 3c). We then built an FEM model using the SOFA framework and replicated these gripping motions. Based on the mesh generated from the SOFA simulation, we employed Blender to render synthetic tactile images. In total, we collected 150 distinct finger postures in both real-world and simulated environments, resulting in 150 pairs of tactile images. The data was then used to train a U-Net network [5] for proprioception and a generator network from the CycleGAN framework [6].

IV. APPLICATIONS

This section presents the potential practical applications of the EleTac, including haptic-exploratory grasping in granular environments, and adaptive surface-following in cleaning tasks. EleTac was mounted onto a UR5 robot arm as an end-effector, with appropriate tactile sensing and proprioception functions integrated to enable autonomous and real-time tactile-based operations.

As shown in Figure 4, the EleTac gripper was tested on the task of excavating an elongated object buried in granular material. In this experiment, EleTac relied solely on tactile feedback to locate and retrieve the object. The target was a pen with a diameter of 10 mm, buried under approximately 3-5 mm of children's play sand. The gripper performed probing movements over the sand surface to gather tactile signals, which were processed by a classification network to distinguish contacts with sand from contacts with the object. A clustering method was then applied to estimate the object's position and orientation, after which the gripper aligned and executed a grasp to excavate the object.

As shown in Figure 5, the EleTac grasped a sponge and maintained sufficient contact between the sponge and various types of tableware while moving across their surfaces to clean a red line drawn on the objects. We utilized the proprioception function to estimate the gripper's height, which was then used as the feedback for the control of the UR5 robot arm.

V. CONCLUSION

The EleTac gripper features compliant fingers that can adapt to and pick up various objects using a simple grasping strategy. We also propose multiple neural networks for different tactile sensing functions. We then demonstrate the applicability of our design and sensing capabilities in practical tasks, highlighting the potential for real-world applications. Our work is expected to provide a foundation for the next generation of multi-function soft robots, simultaneously acting as manipulators and tactile sensing systems.

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