

# Real-time friction- and load-dependent dynamic grip-force-controlled grasping and lifting using a PapillArray tactile sensor

Heba Khamis, *Member IEEE*, Benjamin Xia, and Stephen J. Redmond, *Senior Member, IEEE*

**Abstract**— While the sophistication of robotic/prosthetic gripping systems continues to advance, they still fall far short of achieving human-like dexterity. One major limitation of these systems is a lack of adequate tactile sensing in the gripper fingers – feedback required for grip-force control. The PapillArray is a sensor array of soft silicone pillars that can measure 3D deflection, 3D force and 3D vibration at each array element, as well as torque, incipient slip and friction – important tactile parameters for robotic dexterity. In this work we show the real-time measurement of friction and 3D force from a PapillArray sensor mounted on a two-finger gripper. A closed-loop grip-force control algorithm is implemented that uses the sensor output to dynamically determine the target grip force. A simple lifting task with four objects (two differing weights, and two differing surface materials) demonstrates that knowing friction allows the grip force magnitude to be optimized to avoid dropping the grasped object; contrary to applying a fixed, pre-determined grip force. Future work will focus on incorporating real-time torque measurement into the grip force feedback control. This will significantly advance the state-of-the-art in artificial tactile sensing and bring us closer to robotic dexterity.

## I. INTRODUCTION

The human hand can perform complex object manipulations with ease. Our sense of touch can estimate important properties of an object and the contact interface, which is believed to be the key to our dexterity. Each of our fingertips contains ~2,000 mechanoreceptors embedded in the glabrous (hairless) skin regions, which individually sense vibration, pressure and skin-stretch [1] and as a population can provide information about object shape [2], texture, and even friction [3]. Although robotic and prosthetic gripper designs continue to try to emulate or replicate the dexterity of the human hand, these designs are still far from achieving comparable performance. One major limitation of robotic and prosthetic grippers is the lack of adequate tactile sensation, which provides feedback for grip control [4].

The increasingly active field of tactile sensor research aims to close this technological gap; however, the majority of existing tactile sensors focus on determining the normal and tangential forces at the contact interface [5]. While these quantities are important, there are certainly other tactile

parameters that are also important for dexterous manipulation – for example, the coefficient of static friction ( $\mu_s$ ) and the occurrence of incipient slip.

$\mu_s$  of the contact interface helps to determine the minimum grip (normal) force required to hold an object of a specific weight (tangential force). In certain grip poses, if  $\mu_s$  is accurately estimated and the tangential force can also be measured, then the grip force can be adjusted to securely hold the object. Methods of tactile sensing for grip force control which attempt to detect gross slip of an object and estimate  $\mu_s$  during this gross slip event in order to adjust the grip force so as to arrest the slip may be undesirable, as the gripper may respond too slowly to avoid dropping the object [6]. Some sensors attempt to detect  $\mu_s$  on contact, however, these sensors either have a limited range and/or poor precision, are overly complex and thus present significant miniaturisation challenges, or are only able to measure a  $\mu_s$  range rather than a discrete value [6]. These sensors also suffer from an inability to provide a continuous  $\mu_s$  measurement in the case of changing frictional conditions [6].

Another approach to achieving robotic grip security has been to detect incipient slip and increase the grip force by some prescribed amount following such an event; incipient slip is detected as relative shear displacement on the sensing surface caused by slippage of part but not all of the contact interface. Various sensors are described in the literature for measuring incipient slip [6]. However, most of these overlook one or more of the important indicators which makes the detection of incipient slip robust and practicable, such as the need to allow different regions of the sensor to displace independently where it interfaces with the object, and the need to instrument these relative displacements rather than only detecting the vibration/acceleration caused when incipient slip occurs; vibration/acceleration transduction mechanisms alone have consistently demonstrated a lack of robustness against other environmental sources of vibration and perturbation [6].

A promising incipient slip and friction sensor under development by our group is the PapillArray sensor [7, 8]. This sensor addresses some of the shortcomings of previous incipient slip sensors [6], namely: i) it allows different regions of the sensor to move and slip independently; (ii) it promotes a non-uniform pressure and hence traction distribution across the sensor array when gripping an object, encouraging slip first where the local grip force (and hence traction) is smallest. In this work, we demonstrate the real-time operation of the PapillArray sensor in a simple lifting task where the sensor outputs (real-time 3D force, incipient slip detection and friction estimation) are used to dynamically set the target grip force for a two-finger gripper. We show that knowing friction allows the grip force to be optimized/minimized to

\* Research supported by the Office of Naval Research (US Department of the Navy) / Navy and Marine Corps Science and Technology [GRANT12395989], Australian Research Council Future Fellowships [FT130100858], and Science Foundation Ireland President of Ireland Future Research Leaders Award [17/FRL/4832].

H. Khamis, B. Xia, and S. J. Redmond are with the Graduate School of Biomedical Engineering, UNSW Sydney, Sydney Australia (phone: +61293853911; e-mail: h.khamis@unsw.edu.au).

S. J. Redmond is also with the UCD School of Electrical and Electronic Engineering, the UCD Centre for Biomedical Engineering, and the Insight Centre for Data Analytics. University College Dublin, Dublin, Ireland.

avoid dropping the grasped object; contrary to applying a fixed, pre-determined grip force.

## II. METHODS

### A. PapillArray sensor

The design concept of the PapillArray sensor is described in [7]. The PapillArray sensor is an array of silicone pillars with different unloaded heights. When the sensor is pressed against a surface or object, the difference in pillar heights results in each of the pillars experiencing a different normal force. When a tangential force is also applied, all of the pillars of the sensor experience a similar tangential force. This means that the ratio of tangential-to-normal force experienced by each pillar is different; if the tangential force increases, the pillar under the lowest normal force will slip first when the tangential-to-normal force ratio is greater than  $\mu_s$ . As the tangential force increases further, the next shortest pillar will slip, and so on, until the tallest pillar slips (gross slip of the object against the sensor).

The instrumentation of the PapillArray pillars is described in [8]. For each pillar of the PapillArray sensor, a pinhole camera is created by making a pinhole aperture on a printed circuit board at the base of the silicone pillar, and embedding a diffuse reflector disk at the top end of a hollow cavity that is moulded inside the silicone pillar. The diffuse reflector is illuminated by two light-emitting diodes on either side of the pinhole aperture. Below the aperture, the inverted image of the reflector disk is projected onto a quadrant photodiode (i.e., four photodiodes in a segmented configuration). The projected image of the disk appears as a spot of light; the shape, position, and area of the projected light spot depend primarily on the 3D orientation and XYZ displacement of the reflector disk. The measured light incident on each of the four photodiode quadrants are used to infer 3D displacement and 3D force, using two independent calibration mappings.

Each pillar of the PapillArray sensor was calibrated as described in [8]. Briefly, this involved applying pre-defined patterns of deflection to each pillar individually using an XYZ stage. Deflection of the pillars in 3D was verified using point tracking applied to a simultaneously recorded video of the external pillar tips (and stage Z position), and 3D forces acting on the pillar were verified against the signals from a 3D force/torque sensor. Two distinct multivariate polynomial regression models (2<sup>nd</sup> order) were trained (using MATLAB R2018a, Mathworks, Natick, MA, USA) using the training data set: (i) four photodiode outputs mapped to the three XYZ displacement coordinates, and; (ii) four photodiode outputs mapped to three orthogonal force vector components.

### B. Real-time slip detection and friction estimation

When the pillars are loaded with a tangential force, they are deflected away from their unloaded positions. While a pillar is stuck (not slipping) against an object and the tangential force increases, this shear deflection also increases at the same rate as the object. When the pillar slips, it ceases to deflect at the same rate as the object. Here, a pillar that is in contact ( $> 0.25$  N normal force) during the initial contact phase was detected to have slipped when the magnitude of its tangential velocity first drops below 70% of the tangential

velocity of the pillar under the greatest normal force; this velocity threshold percentage will trade off slip detection robustness against slip detection latency.

When a pillar was detected to have slipped, the ratio of tangential-to-normal force acting on that pillar at the moment of slip was taken as the current estimate of  $\mu_s$ ; any previous estimates of  $\mu_s$  are discarded and replaced by this most recent estimate.

The two calibration mapping models (3D displacement and 3D force) and the incipient slip detection and friction estimation algorithms were implemented in Java, running in real-time on a PC, with the four quadrant photodiode signals being streamed through a serial port.

### C. Two-finger gripper

The two-finger gripper was custom made of two opposing linear stages (T8x2 lead screw, 60mm stroke) actuated using stepper motors (NEMA 17, 1.8° step angle). Mounting brackets, frames and the gripper fingers were 3D printed in PLA thermoplastic using an Ultimaker 3 printer (Ultimaker B.V., Geldermalsen, Netherlands). A functional PapillArray sensor was mounted on one finger of the gripper, and a physically identical but non-functional PapillArray sensor was mounted on the other finger. The gripper is shown in Fig. 1B with the PapillArray sensors mounted on the fingertips.

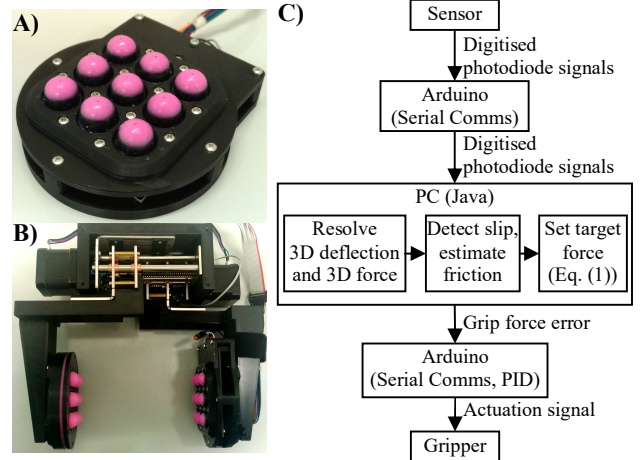


Figure 1. A) Photograph of PapillArray sensor, B) photograph of two-finger gripper, and C) block diagram of gripper system with real-time friction- and load-dependent dynamic grip force control.

### D. Grip-force control

A microcontroller (Due; Arduino, Italy) streamed the digitized photodiode signals to a PC where the 3D deflection and 3D forces were resolved, incipient slip was detected, and the target grip force was calculated (described below) using the abovementioned Java application. The target grip force was sent from the PC to a second microcontroller which performed PID control to actuate the motors of the two-finger gripper in order to achieve the target grip force. A block diagram of the system is illustrated in Fig. 1C.

### E. Experimental protocol

The gripper was mounted on a vertical linear stage (Fig. 2). After the gripper makes initial contact with the object to

be lifted, the linear stage moves upwards a total of 20 mm (the lifted position) with a velocity of  $2.5 \text{ mm.s}^{-1}$ . The vertical stage remains at the lifted position for 5 s and the relative movement between the object and the gripper are observed visually with the aid of markings on the bottle and a rigid pointer on the gripper; the lift is considered successful if the object has not slipped (object move downwards less than 0.5 mm with respect to the gripper) during this time; if the object has slipped between 0.5 and 5 mm during this time, then the result is considered to be very slow gross slip, and the lift is considered unsuccessful if the object has slipped by more than 5 mm with respect to the gripper during this time.

The objects that were lifted were a partially-filled or full water bottle (1 L total capacity) wrapped in lubricated (Unilube; Griffon, Netherlands) paper (low friction) or a plastic label (high friction); i.e., two weights, two surface materials; total of four objects). Each object was lifted five times for each grip-force control strategy investigated (one dynamic grip-force control strategy, and five fixed grip-force control strategies) which are described below.

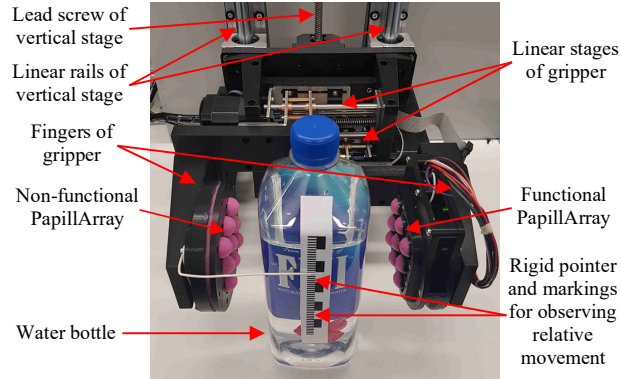


Figure 2. Photograph of experimental test rig. The gripper closes and achieves a target grip force on the bottle. The vertical stage then lifts the gripper and bottle up 20 mm. During the lifting phase, the PapillArray will detect slip of one or more of its nine pillars, and from the forces on these slipping pillars estimate the friction, which is subsequently used to set a target grip force which is sufficient to secure the grasp on the water bottle.

#### Dynamic grip force control

The grasp is initiated such that at least two pillars of the PapillArray sensor make contact with the object (target grip force of 5 N). The vertical stage then lifts the gripper. During the lifting phase, following the first pillar slip detection, the target grip force is dynamically set according to:

$$F_N = \max(5, 1.2 \times (F_T / \mu_{EST})), \quad (1)$$

where  $F_N$  is the target grip force,  $F_T$  is the magnitude of the global load force which is determined by summing the tangential forces on each pillar, and  $\mu_{EST}$  is the current estimate of friction based on the tangential-to-normal force ratio magnitude for the most recent pillar to slip. A minimum target grip force of 5 N is maintained to prevent pillars from losing contact with the object.

#### Fixed grip force control

Five different fixed grip-force values were tested: 5, 7.5, 10, 12.5, and 15 N. This protocol was the same as the dynamic grip force control, except that the target grip force remained constant throughout the initial contact and lifting phases.

### III. RESULTS

An example of the outputs of the PapillArray sensor during the lifting task with dynamic grip-force control while lifting a full water bottle with a lubricated paper surface is shown in Fig. 3A and B, and lifting a partially-filled water bottle with a plastic surface is shown in Fig. 3C and D. During both trials, the bottle was successfully lifted. Different friction estimates were obtained for the two different object surfaces and different tangential forces were measured for the different object weights, resulting in a different target grip force in each case. Note, reference friction measurements were not made, so the accuracy of these friction estimates have not been validated here.

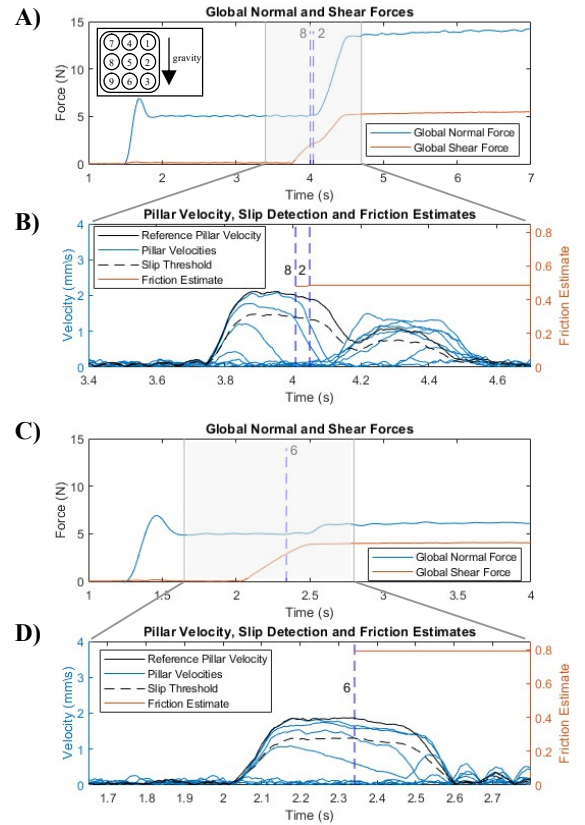


Figure 3. Example sensor output during lifting task with dynamic grip-force control. Full bottle with lubricated paper surface: A) global shear and normal force, and B) pillar velocities, slip detection and friction estimates for shaded region in A). Partially-filled bottle with plastic surface: C) global shear and normal force, and D) pillar velocities, slip detection and friction estimates for shaded region in C). Vertical dashed lines indicate pillar slip detection (numbers indicate pillar label, as per inset in A)).

The results of all 120 lifting trials (2 weight conditions  $\times$  2 surfaces  $\times$  5 repetitions  $\times$  (dynamic grip force + 5  $\times$  fixed grip force)) are shown in Table I. Using the friction and load-dependent dynamic grip force (determined using the PapillArray sensor outputs) always resulted in a successful lift, and the final grip force used during these trials was always near-optimal; that is, the dynamically-determined target grip force had a magnitude between the largest fixed grip force that resulted in a very slow gross slip and the smallest fixed grip force where lifting was successful for the same weight and surface condition.

TABLE I. RESULTS OF LIFTING EXPERIMENTS USING DYNAMIC GRIP FORCE CONTROL (INCLUDING MEAN  $\pm$  SD OF FINAL  $F_N$  AND  $\mu_{EST}$ ) AND FIXED GRIP FORCE CONTROL.

| Surface          | Bottle weight            | Dynamic grip force                                    | Fixed grip force |       |      |        |      |
|------------------|--------------------------|-------------------------------------------------------|------------------|-------|------|--------|------|
|                  |                          |                                                       | 5 N              | 7.5 N | 10 N | 12.5 N | 15 N |
| Plastic          | Partially-filled (680 g) | $F_N = 6.0 \pm 0.1$ N<br>$\mu_{EST} = 0.81 \pm 0.03$  | ✓✓✓✓✓            | ✓✓✓   | ✓✓✓  | ✓✓✓    | ✓✓✓  |
|                  | Full (930 g)             | $F_N = 8.7 \pm 0.6$ N<br>$\mu_{EST} = 0.69 \pm 0.03$  | ✗✗✗              | ✓✓✓   | ✓✓✓  | ✓✓✓    | ✓✓✓  |
| Lubricated paper | Partially-filled (840 g) | $F_N = 11.4 \pm 0.5$ N<br>$\mu_{EST} = 0.48 \pm 0.02$ | ✗✗✗              | ✗✗✗   | ✓✓✓  | ✓✓✓    | ✓✓✓  |
|                  | Full (1000 g)            | $F_N = 13.4 \pm 0.0$ N<br>$\mu_{EST} = 0.49 \pm 0.01$ | ✗✗✗              | ✗✗✗   | ✗✗✗  | ✓✓✓    | ✓✓✓  |

✓ = successful lift (< 0.5 mm slip in 5 seconds); ~ = very slow gross slip (between 0.5 and 5 mm of slip in 5 seconds); and ✗ = unsuccessful lift (> 5 mm slip in 5 seconds)

#### IV. DISCUSSION

Besides the PapillArray sensor, there are currently no resoundingly successful tactile sensors that can detect incipient slip and also measure friction without requiring gross slip to occur [6]. Perhaps the most successful of the incipient slip sensors is the GelSight/GelSlim sensor family [9, 10]. A transparent elastomer skin is patterned so the sensor's surface movements can be tracked using video. This allows the measurement of relative displacement of different regions of the contact area. These sensors can reliably detect incipient slip [11], but cannot estimate friction so as to suggest an appropriate grip force; in [11], the grip is simply increased in 10 N increments whenever incipient slip is detected. More recently, inverse finite element modelling has enabled force distribution estimates from gel displacements, which could facilitate friction estimation from incipient slip [12]. The gel and patterning used in these sensors have also shown limited long-term durability [10]. A similar sensor is described in [13], whereby a camera tracks the overlap and color mixing of colored markers in two layers of elastomer for measuring the distributed 3D motion of a surface, but these displacements have not yet been resolved to measure local force or subsequently estimate friction. Furthermore, these camera-based systems have inherent limitations with respect to sampling frequency (limited by camera frame rate) and the minimum size of the sensor (limited by camera focal length and/or depth of field).

A number of incipient slip sensors [9, 14-18] have been integrated into the fingers of robotic grippers to demonstrate their utility in grip stabilization. However, none of these have provided quantitative results with respect to the ability of the sensor to optimise the target grip force [6]. In this work, this quantitative analysis has been performed using the PapillArray sensor [7, 8]. The utility of the PapillArray sensor as a real-time 3D force, incipient slip detection and friction estimation sensor has been demonstrated in a simple lifting task with objects of multiple weights and surface materials; the dynamic friction- and load-dependent grip-force control, achieved using the PapillArray sensor signals, was shown to apply a near-optimal grip force irrespective of the weight and friction of the object, unlike applying a fixed, pre-determined grip force. Future work will focus on incorporating real-time torque measurement into the grip force feedback control so objects can be grasped off-center.

This will significantly advance the state-of-the-art in artificial tactile sensing and bring us closer to robotic dexterity.

#### REFERENCES

- [1] Vallbo, Å. B. and Johansson, R.: Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. *Human Neurobiology*, vol. 3, pp. 3-14, 1984.
- [2] Jenmalm, P., Birznieks, I., Goodwin, A. W., and Johansson, R. S.: Influence of object shape on responses of human tactile afferents under conditions characteristic of manipulation. *European Journal of Neuroscience*, vol. 18, pp. 164-176, 2003.
- [3] Khamis, H., Redmond, S. J., Macefield, V., and Birznieks, I., "Classification of texture and frictional condition at initial contact by tactile afferent responses," in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, 2014, pp. 460-468.
- [4] Johansson, R. S. and Westling, G.: Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research*, vol. 56, pp. 550-564, 1984.
- [5] Tiwana, M. I., Redmond, S. J., and Lovell, N. H.: A review of tactile sensing technologies with applications in biomedical engineering. *Sensors and Actuators A: Physical*, vol. 179, pp. 17-31, 2012.
- [6] Chen, W., Khamis, H., Birznieks, I., Lepora, N. F., and Redmond, S. J.: Tactile Sensors for Friction Estimation and Incipient Slip Detection – Towards Dexterous Robotic Manipulation: A Review. *IEEE Sensors Journal*, pp. 1-1, 2018.
- [7] Khamis, H., Albero, R. I., Salerno, M., Idil, A. S., Loizou, A., and Redmond, S. J.: PapillArray: An incipient slip sensor for dexterous robotic or prosthetic manipulation—Design and prototype validation. *Sensors and Actuators A: Physical*, vol. 270, pp. 195-204, 2018.
- [8] Khamis, H., Xia, B., and Redmond, S. J.: A novel optical 3D force and displacement sensor—Towards instrumenting the PapillArray tactile sensor. *Sensors and Actuators A: Physical*, vol. 291, pp. 174-187, 2019.
- [9] Yuan, W., Li, R., Srinivasan, M. A., and Adelson, E. H., "Measurement of shear and slip with a GelSight tactile sensor," in *Proceedings of IEEE International Conference on Robotics and Automation*, 2015, pp. 304-311.
- [10] Donlon, E., Dong, S., Liu, M., Li, J., Adelson, E., and Rodriguez, A., "GelSlim: A High-Resolution, Compact, Robust, and Calibrated Tactile-sensing Finger," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2018, pp. 1927-1934.
- [11] Dong, S., Ma, D., Donlon, E., and Rodriguez, A., "Maintaining Grasps within Slipping Bounds by Monitoring Incipient Slip," in *2019 International Conference on Robotics and Automation (ICRA)*, 2019, pp. 3818-3824.
- [12] Ma, D., Donlon, E., Dong, S., and Rodriguez, A., "Dense Tactile Force Estimation using GelSlim and inverse FEM," in *2019 International Conference on Robotics and Automation (ICRA)*, 2019, pp. 5418-5424.
- [13] Lin, X. and Wiertelowski, M.: Sensing the Frictional State of a Robotic Skin via Subtractive Color Mixing. *IEEE Robotics and Automation Letters*, vol. 4, pp. 2386-2392, 2019.
- [14] Maeno, T., Hiromitsu, S., and Kawai, T., "Control of grasping force by detecting stick/slip distribution at the curved surface of an elastic finger," in *Proceedings of IEEE International Conference on Robotics and Automation*, 2000, pp. 3895-3900.
- [15] Ueda, J., Ikeda, A., and Ogasawara, T.: Grip-force control of an elastic object by vision-based slip-margin feedback during the incipient slip. *IEEE Transactions on Robotics*, vol. 21, pp. 1139-1147, 2005.
- [16] Watanabe, N. and Obinata, G., "Grip force control based on the degree of slippage using optical tactile sensor," in *Proceedings of International Symposium on Micro-NanoMechatronics and Human Science*, 2007, pp. 466-471.
- [17] Shirafuji, S. and Hosoda, K.: Detection and prevention of slip using sensors with different properties embedded in elastic artificial skin on the basis of previous experience. *Robotics and Autonomous Systems*, vol. 62, pp. 46-52, 2014.
- [18] Dong, S., Yuan, W., and Adelson, E. H., "Improved gelsight tactile sensor for measuring geometry and slip," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 137-144.