Real-time Friction Estimation for Grip Force Control

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***Abstract*— In this abstract, we present for the first time a fully-instrumented version of our PapillArray tactile sensor concept, which can sense grip force, object weight, and incipient slip and friction, all in real-time. We demonstrate the real-time estimation of friction and measurement of 3D force from PapillArray sensors mounted on each finger of a two-finger gripper, combined with a closed-loop grip-force control algorithm that dynamically applies a near-optimal grip force to avoid dropping objects of varying weight and friction. Lifting a number of bespoke and household items, using a 20% safety margin on the target grip force, the actual grip force applied was only 9-30 % greater than that required to avoid slip. Future work will focus on increasing the number and density of pillars, and incorporating real-time torque measurement into the grip force feedback control.**

I. INTRODUCTION

A. Tactile sensors that sense incipient slip and/or friction

The vast majority of tactile sensors lack any friction-sensing capability. The majority of existing tactile sensors focus on determining (predominantly) normal forces and (occasionally) tangential forces at the contact interface. While these quantities are important, they alone provide insufficient information to successfully perform precision (i.e., two-fingered) grasping and manipulation.

The critical information which they do not measure relates to other properties (i.e., the coefficients of static (μ_s) and dynamic friction) and interactions (incipient/partial and overt/complete slip) at the interface between the gripper fingers and the object being manipulated. μ_s is a key parameter that influences the minimum grip (i.e., normal to the gripper fingers) force required to hold an object of a specific weight (generating forces tangential to the gripper fingers). In certain grip poses, if μ_s is accurately estimated and the tangential forces can also be measured, then the grip force can be adjusted to securely hold the object.

B. Innovation

Our group previously published a tactile sensing concept to estimate μ_s from incipient slip occurring on one or more silicone pillars in an array called the PapillArray [1]; an early prototype of this sensor was presented at the ViTac 2018 workshop in Brisbane, demonstrating a novel optical sensing technique that uses a *camera obscura* mechanism [2].

Now, in this paper, we further miniaturize the design presented in [1] and instrument each of the nine silicone pillars using the optical technique presented in [2]. Furthermore, we demonstrate the real-time operation of two PapillArray sensors in a range of simple lifting tasks, 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 emphasize, never before has a sensor been able to detect incipient slip and accurately measure normal and tangential forces at the location of slip to estimate μ_s.

II. METHODS

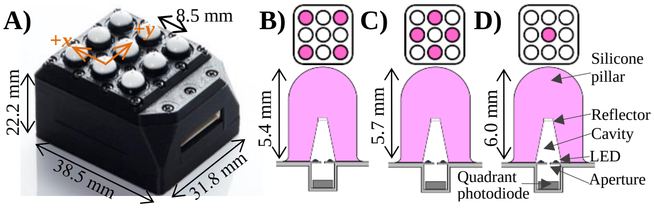

Figure 1. A) Photograph of a PapillArray sensor, and dimensions of the B) corner (shortest) pillars C) middle-height pillars, and D) central (tallest) pillar. For all pillars, the pillar outer diameter is 6 mm, the diameter of the base of the conical cavity is 4 mm, the reflector diameter is 2 mm, the aperture diameter is 0.8 mm, the reflector to aperture distance is 3.5 mm. and distance from the aperture to the top of quadrant photodiode is 2.0 mm.

A. PapillArray sensor

The design concept of the PapillArray sensor is described in [1]. 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 encourages each of the pillars to experience a different normal force (resulting in a different traction). When a tangential force is also applied, this distributes approximately uniformly across the pillars, meaning the ratio of tangential-to-normal force experienced by each pillar is different. As the tangential force increases, the first pillar whose tangential-to-normal force ratio exceeds μ_s will slip. As the tangential force increases further, the next pillar whose tangential-to-normal force ratio exceeds μ_s will slip next, and so on, until the last pillar slips (resulting in overt/gross slip of the object against the sensor). The new miniaturized PapillArray sensor is shown in Fig. 1A with the pillar dimensions Fig. 1B-D.

The instrumentation of the PapillArray pillars is described in [2]. Briefly, for each pillar of the PapillArray sensor, a *camera obscura* 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 molded inside the silicone pillar (Fig. 1D). 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 four measurements of

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light incident on each of the four photodiode quadrants are used to infer 3D displacement and 3D force, using two independent calibration mappings. Each of the eighteen pillars in the two PapillArray sensors was calibrated as described in [2]; full details on this calibration step can be found in our ICRA 2021 paper [3].

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

A real-time algorithm analyses the tangential velocity of all pillars on a PapillArray sensor. When the velocity of a pillar drops below that of a reference pillar, it is deemed to have slipped and the ratio of tangential-to-normal force acting on that pillar at the moment of slip was taken as the current estimate of μ_s for that sensor. The minimum μ_s of the most recent estimate from each of the two sensors is used.

C. *Two-finger gripper*

The two-finger gripper was a modified 2F-140 (Robotiq, Quebec, Canada). The motor of the gripper was replaced with a stepper motor (NEMA 17, 1.8° step angle). A PapillArray sensor was mounted on each finger of the gripper (Fig. 2).

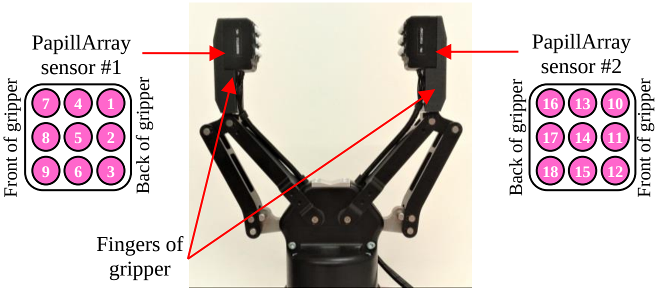

Figure 2. Modified Robotiq 2F-140 gripper two-finger gripper with a PapillArray sensor mounted on each finger. Pillar labels (1-18) also shown.

D. *Grip-force controller*

A PID controller moved the two-fingered gripper to minimize the error between the measured grip force (sum for normal forces on a sensor) and the estimated grip force required to avoid slip on the sensor measuring the lowest friction (estimated using tangential forces on sensor and estimated friction, assuming Coulomb friction law). See [3].

E. *Experimental protocol*

The gripper was mounted on a vertical linear stage (T8x4 lead screw, 300 mm stroke) actuated using a stepper motor (NEMA 17, 1.8° step angle) – see Fig. 3. The vertical stage lifts the gripper/object up 10 mm with a velocity of 10 mm.s^{-1} and acceleration of 50 mm.s^{-2}, then holds for 5 s. Grip success is defined by how far the object slips relative to the gripper in the 5 s duration at the end of the lift, resulting in three grip success categories: success; slow slip, and; failure.

A custom object with replaceable surfaces and adjustable weights, and a number of everyday household objects were lifted (see Fig. 3).

III. RESULTS

In all lifting experiments, the dynamic grip force was shown to be near-optimal (i.e., near minimal without invoking object slip) when compared to applying a predetermined fixed grip force. Using a 20% safety margin on the target grip force, the actual grip force applied was only 9-30 % greater than that required to avoid slip. Full results can be found in [3].

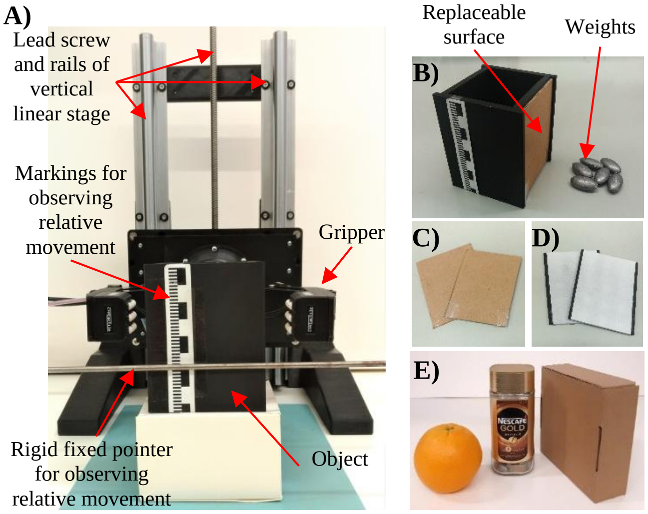

Figure 3. A) Experimental test rig. Vertical linear stage lifts the gripper up 10 mm. B) The object with replaceable surfaces and adjustable weight, C) lubricated paper surface, D) cardboard surfaces, and E) household items.

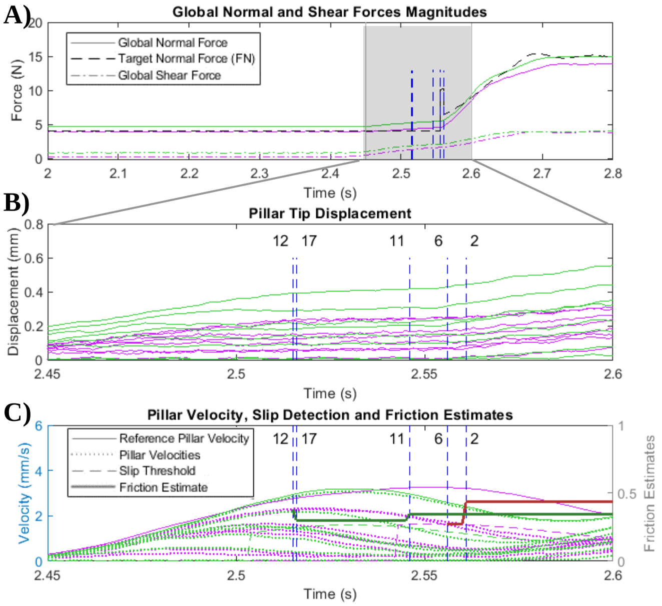

Figure 4. Example lifting task with dynamic grip-force control. Heavy custom-made object (788 g, ~7.73 N) with lubricated paper (low friction) surface: A) global shear and normal force magnitudes, B) tangential pillar displacements for shaded region in A), and C) tangential pillar velocities, slip detection and friction estimates for shaded region in A). Green lines for PapillArray #1 and purple lines for PapillArray #2. Vertical dashed lines indicate pillar slip detection (numbers indicate pillar label, as per Fig. 2).

REFERENCES

[1] H. Khamis, R. I. Albero, M. Salerno, A. S. Idil, A. Loizou, and S. J. Redmond, "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.

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[3] H. Khamis, B. Xia, and S. J. Redmond, "Real-time Friction Estimation for Grip Force Control," presented at the 2021 IEEE International Conference on Robotics and Automation (ICRA), Xi'an, China, 30 May - 5 June, 2021 (in press, accepted 28/02/2021).