

Title

A novel optical 3D force and displacement sensor – Towards instrumenting the PapillArray friction-based tactile sensor

Authors and Affiliations

Heba Khamis¹, Benjamin Xia¹, Stephen J. Redmond^{1,2}

¹ Graduate School of Biomedical Engineering, UNSW Australia

² School of Electrical and Electronic Engineering, UCD, Dublin, Ireland

Corresponding Author

Name: Heba Khamis

Email: h.khamis@unsw.edu.au

Abstract

As robots move into unstructured environments, tactile sensing will become an essential capability of any robotic gripper attempting to engage in dexterous object manipulation. Sensing the frictional properties of the sensor-object interface (along with contact forces and torques) is essential for determining the minimum grip force required to securely grasp an object; however, most existing artificial tactile sensors are incapable of sensing the property of friction. In previous work, a design was presented for a grip security sensor – the PapillArray – which consists of an array of independent silicone pillars with different uncompressed heights, inspired by the papillae in the skin of the human finger pad. It was shown that tracking the relative deflections of the pillar tips can be used to detect incipient slip; and when incipient slip is detected, measuring the 3D force on the pillar provides an estimate of the coefficient of static friction. In a continuation of this work, here we present a method of instrumenting the movement and forces experienced by the pillars of the PapillArray. A novel pinhole camera design is implemented whereby deformation of the pillar results in both movement and change in area of a spot of light, projected onto a quadrant photodiode. The four quadrant photodiode signals are mapped to true 3D displacement and force using multivariate regression. The accuracy of the mapping's position and force estimates are validated using both video-tracking of the pillar tip and measurements made with a 3D force sensor, respectively, when stimulating the pillar with a spiral XY displacement pattern at various Z compressions. The overall displacement estimation error (mean $\pm$ SD) in the X, Y and Z axes was 0.012 ± 0.077 mm, 0.041 ± 0.074 mm and 0.010 ± 0.023 mm, respectively, for a full-scale deflection of 10.0 mm in X and Y, and 3.25 mm in Z. The overall force estimate error (mean $\pm$ SD) was 0.002 ± 0.045 N, -0.007 ± 0.049 N and 0.073 ± 0.118 N, for full-scale force of approximately 4 N in X and Y and 11 N in Z, respectively. The sensitivity of the pillar to vibration (between 100 and 1000 Hz) was also tested, as this may help to detect incipient slip events. The pillar can detect vibration up to 1000 Hz for a vibration displacement amplitude as small as $0.35 \mu\text{m}$. This technique can be used to instrument all pillars in the PapillArray sensor, thereby facilitating incipient slip detection and friction measurement. Such a sensor would be of particular benefit in a robotic gripping application where it is important to apply only the grip force required to prevent slip of the object of interest, both to reduce the energy usage of the gripping system and to avoid damaging the gripped object.

Keywords

Sensor; tactile; grip; slip; friction; grip security

1. Introduction

Humans can handle and manipulate objects with ease. Thousands of mechanoreceptors embedded in the hairless skin of the hand can detect vibration, pressure, and skin stretch [1], and information about object shape [2], texture, and even friction [3]. This feat of tactile sensing is an essential element underpinning our ability to perform dexterous manipulation. While the sophistication of robotic/prosthetic gripping systems continues to advance, they still fall far short of achieving a dexterity comparable to that of humans. One major limitation of these systems is a lack of adequate tactile sensing in the gripper fingers; required feedback for grip-force control.

Most tactile sensor designs focus on determining the normal forces at the contact interface [4]; a subset of these also consider tangential/shear forces. However, other tactile parameters are also important for dexterous manipulation, including the coefficient of static friction (μ_s) and the occurrence and extent of incipient slip (an event where part of the area of the sensor in contact with the object slips, usually near the periphery of the contact area). The μ_s of the contact interface helps to determine the minimum grip (normal) force required to hold an object of a specific (apparent) weight (tangential force). In certain grip poses, if the μ_s is known and the normal and tangential force are measured, then the normal force can be adjusted so the object is held securely. One approach which makes use of frictional information involves detecting incipient slip and subsequently adjusting the grip force, akin to the adaptive motor response of humans during precision grip [5]; although it is not understood whether humans explicitly estimate the coefficient of friction or implicitly utilise this friction information by adjusting the grip to arresting the slip.

A recent review discusses tactile sensors which aim to measure friction or detect incipient slip [6]. Of those sensors attempting to measure friction, a number of significant limitations are highlighted, including: the use of transduction mechanisms (e.g., vibration, acceleration) which, if they are the only transducers available, are unlikely to be practicable during autonomous robotic control due to interference from robot/gripper vibration and gross movement; being restricted to use on objects with only planar surfaces, and; having a severely limited output range. Regarding incipient slip sensors, most overlook one or more important factors which make the detection of incipient slip practicable [6], such as the need to allow different regions of the gripper-object interface to move independently, and the importance of measuring relative displacement of regions of the contact area, rather than detecting the vibration/acceleration caused when incipient slip occurs.

A promising incipient slip and friction sensor under development by our research group is the PapillArray sensor [7]. This design concept aims to detect incipient slip while the grip is still secured, enabling grip force adjustment before total loss of grip is experienced. The PapillArray sensor is comprised of an array of independent silicone pillars with different uncompressed heights (**Figure 1**). This design addresses some of the shortcomings of previous incipient slip sensors [6], namely: (i) it allows different regions (i.e., here, different pillars) of the sensor to move and slip independently; (ii) the different pillar heights promote a non-uniform pressure distribution across the array of pillars when gripping an object, encouraging slip on the peripheral pillars first where the local grip force (and hence traction) is smallest. The ability of the PapillArray design concept to estimate friction was recently described by our group [7]; however, the instrumentation to measure the displacement of and force on each pillar in the array had not yet been developed. In this work, we present a novel technique to instrument the individual pillars of the PapillArray sensor, such that 3D pillar

displacement and 3D force can be measured for each pillar in real-time, enabling the detection of the moment when a pillar slips, and subsequent estimation of the coefficient of static friction between each slipped pillar and the surface of the object with which it is in contact, taken as the tangential-to-normal force ratio at the time of the slip event.

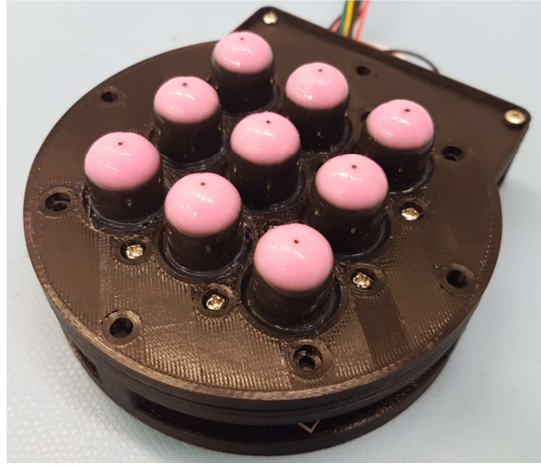


Figure 1. Photo of the PapillArray sensor array – an array of independent silicone pillars with different uncompressed heights. In the prototype pictured here, the centre pillar is the tallest and the four corner pillars are the shortest. In a proof-of-principle demonstration, estimating forces on the peripheral pillars when they slip against an object surface allows the coefficient of friction to be estimated [7].

2. Methods

2.1 Instrumenting the 3D displacement and force experienced by a PapillArray pillar

The instrumentation proposed here for measuring the 3D displacement and 3D force experienced by each pillar of the PapillArray [7] sensor is based on the principal of a pinhole camera, whereby light from a source passing through a small hole projects an inverted image onto a surface below. A pinhole camera is created by making a pinhole aperture on a printed circuit board at the base of the silicone PapillArray pillar, and embedding a diffuse reflector disk at the end of a cavity which is moulded inside the silicone PapillArray pillar (**Figure 2A**). The diffuse reflector is illuminated by two light-emitting diodes (LEDs) mounted on the PCB, either side of the pinhole aperture (**Figure 2C**). Below the aperture, the inverted image of the reflector disk is projected onto a quadrant photodiode (i.e., four separate photodiodes in a segmented configuration). The projected image of the disk appears as a spot of light (**Figure 2D**); the shape, position, and area of the projected light spot depend primarily on the 3D orientation, XY displacement, and Z displacement of the reflector disk, respectively.

By measuring the relative magnitudes of the four diode photocurrents, it is possible to infer the XY position of the light spot, and hence the XY position of centre of the reflector disk. Furthermore, if the distance between the reflector and the aperture decreases, both the area and average intensity of the projected light spot image are expected to increase, and thus the distance between the reflector disk and the aperture can be inferred (assuming a constant emitted light intensity from the LEDs).

2.2 Prototype design and fabrication of a single instrumented pillar

For the prototype presented in this paper, a single pillar was fabricated with an arbitrary height of 20 mm and diameter of 15 mm, with a hemispherical tip. The internal cavity of the

pillar consists of a truncated cone with a height of 8 mm, base diameter of 8 mm and upper diameter of 3 mm. The fabrication process can be broadly divided into two parts: (i) pillar assembly (the silicone pillars, sensor housing, and mounting hardware), and; (ii) photoelectronic (illumination LEDs and quadrant photodiode) and interface circuit manufacture. These are described in the following subsections.

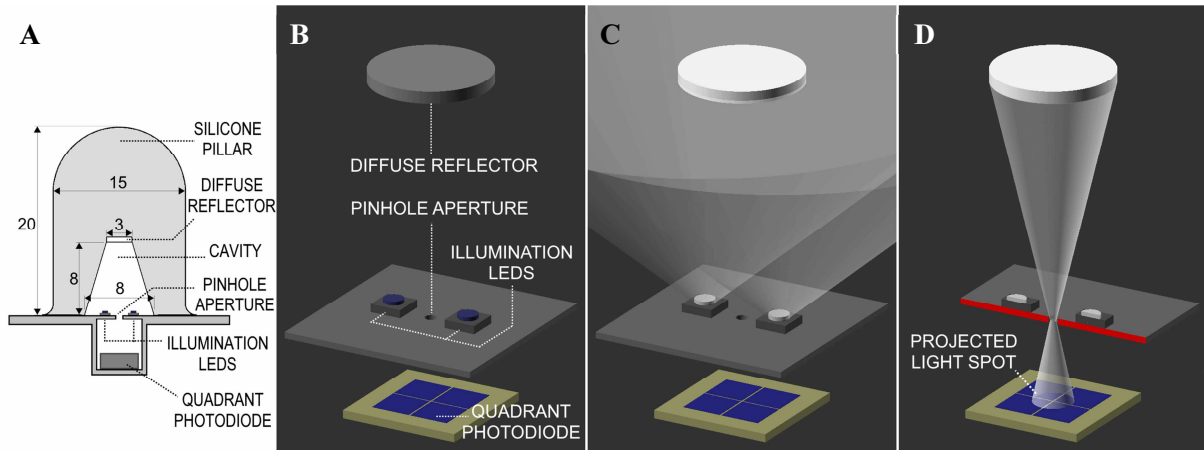


Figure 2. Principle of instrumentation of a single pillar of the PapillArray sensor array. **A)** Cross-section of a pillar of the PapillArray, showing the moulded silicone pillar and cavity, the diffuse reflector, LEDs, pinhole aperture, and photodiode sensor. The sides of the cavity are blackened to maximise the proportion of light reflected from the diffuse reflector. Dimensions shown in mm. **B)** 3D rendered illustration of reflector, LEDs, pinhole aperture, and quadrant photodiode sensor. **C)** Infrared LEDs flood the truncated-conical pillar cavity with light causing the diffuse reflector at the top of the cavity to behave as a light source. **D)** Light from the reflector passes through the aperture and a light spot is projected across a four quadrants of a quadrant photodiode below.

2.2.1 Pillar assembly

Two 3D-printed moulds were used to fabricate the silicone pillar. The lower mould (**Figure 3A**) forms the outer structure of the pillar, and was 3D printed in ABSplus® thermoplastic using a Statasys Mojo printer (Stratasys, MN, USA). To smooth the 3D-printed layer lines, the mould was placed inverted on top of a glass cup (diameter 90 mm) of acetone heated in a bath of hot (~80 °C) water for 15 minutes, creating a sealed chamber for acetone vapour to build up in contact with the mould surface. The upper mould forms the internal pillar cavity and external pillar displacement tracking dot, and was 3D printed in PLA thermoplastic using an Ultimaker 3 printer (Ultimaker B.V., Geldermalsen, Netherlands).

The pillar was moulded from a two-component skin-safe silicone (PinkySil; Barnes Products, Sydney, Australia). In order to create a tracking dot to later measure XY pillar displacement, the upper mould was first fitted with a narrow needle-like tip (**Figure 3B**). The hemispherical end of the mould (corresponding to the pillar tip) is then filled with undyed (pink) silicone and allowed to cure, and the upper mould was removed. A second batch of silicone was prepared with black dye added, to absorb light inside the cavity, maximising the proportion of light reflected from the diffuse reflector. The upper mould was then fitted with a truncated conical tip (**Figure 3C**) and the black silicone mixture was poured and left to cure, completing the pillar structure. **Figure 3D** shows the upper mould fitted to the lower mould, with the poured black-dyed silicone, and **Figure 3E** shows the cured single pillar.

The reflector, a disk of diameter 3 mm and thickness 0.6 mm, was 3D printed in white PLA plastic and was secured to the top of the pillar cavity using E41 Silicone Adhesive (Barnes

Products, Sydney, Australia). The prototype housing was 3D printed in PLA plastic and consists of an upper and lower plate with the silicone pillar structure sandwiched between (**Figure 3F**). The pinhole aperture was drilled into the lower plate with a 1mm drill-bit.

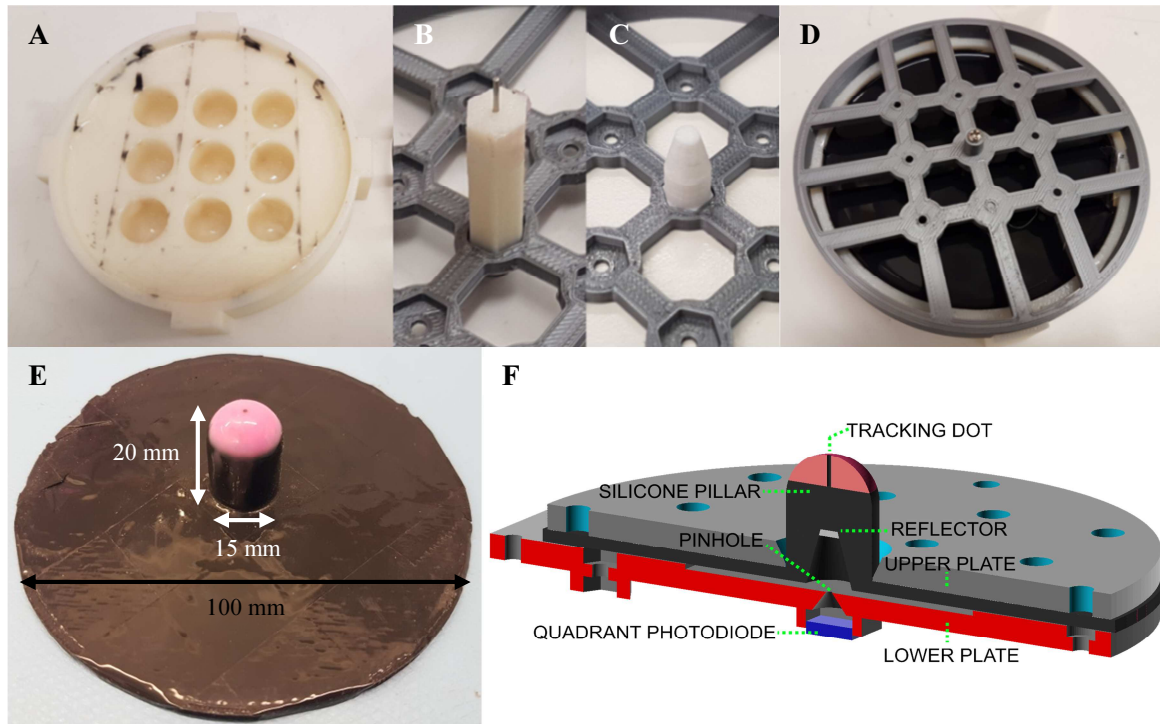


Figure 3. Fabrication of pillar assembly. **A)** Lower mould for a 9-pillar PapillArray – to mould a single pillar, all but the central hole were covered with tape. **B)** Upper mould with needle-like protrusion for creating a channel through the pink hemisphere, into which the black-dyed silicone tracking dot will be poured. **C)** Upper mould with cavity insert. **D)** Upper mould attached to lower mould after pouring of black dyed silicone, **E)** Final silicone pillar. **F)** Cross-sectional drawing of pillar between upper and lower plates of sensor housing.

2.2.2 Electronics

Cavity illumination was provided by a pair of infrared LEDs (VSMY1850; Vishay Semiconductors, Malvern, PA, USA) soldered to a PCB either side of the pinhole aperture at the base of the pillar cavity. The LEDs could be pulsed with a programmable duty cycle to minimise power consumption and heat generation when not being sampled.

The quadrant photodiode (OPR5911; TT Electronics, Woking, England) consisting of four common-cathode photodiodes in a square tile arrangement. Each photodiode was operated in photovoltaic mode with photocurrents amplified using a quad op-amp (TLV9064IDR; Texas Instruments, Dallas, TX, USA) at a gain of $1\text{V}/\mu\text{A}$. The amplifier output was sampled with a 12-bit analog-to-digital converter (MAX11632; Texas Instruments, Dallas, TX, USA) with a reference voltage of 4.096 V, resulting in a 1 mV resolution, corresponding to 1 nA of photocurrent or $1.38\text{ mW}/\text{m}^2$ irradiance per step. An internal 16-sample averaging filter was enabled on the analog-to-digital converter to reduce noise. The components were assembled on a PCB and interfaced with an external microcontroller for data acquisition (described below).

2.3 Displacement and force mapping

2.3.1 Test rig

An XYZ-stage consisting of three translation stages (M-605.1DD; Physik Instrumente GmbH & Co. KG, Karlsruhe, Germany) was used to bring a transparent acrylic test surface into contact with the PapillArray pillar and then move the surface to a prescribed set of positions. A 3D force/torque sensor (Mini40, SI-80-4 calibration; ATI Industrial Automation, Apex, NC, USA) was mounted between the pillar and a support frame (**Figure 4B**). A digital camera (Hero 6; GoPro, CA, USA) with a +10 diopter macro lens (GoPro Macro Lens; Polar Pro, CA, USA) was secured approximately 100 mm below the pillar tip.

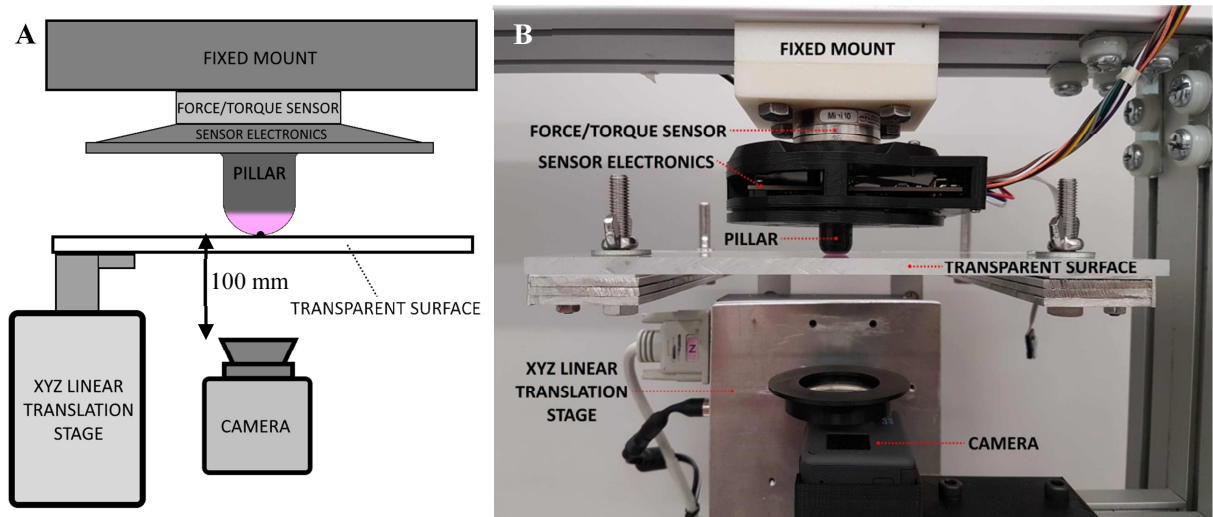


Figure 4. Test rig for displacement and force mapping. **A)** Illustration and **B)** photo showing camera, XYZ linear translational stage, transparent surface, pillar, sensor electronics, force/torque sensor and fixed mount.

2.3.2 Experimental protocol

The XYZ stage was programmed to visit a set of 3D positions. Two movement patterns were used: (i) a ‘spoke’ pattern, consisting of 24 evenly-spaced radial lines of length 12.4 mm (**Figure 5A**), and: (ii) a ‘spiral’ pattern, consisting of an octagonal spiral with lines spaced 2 mm apart and maximum radius of 12.4 mm (**Figure 5B**). Each linear movement was carried out at a velocity of 5 mm/s with a pause of 0.8 s between movements. Each pattern is repeated at multiple pillar compressions (Z displacement), giving an approximately uniform sampling of 3D space.

A training dataset was captured to generate a mapping from photodiode output voltages to measured displacement and force, and a test dataset captured to evaluate the accuracy of this mapping. The training dataset was generated with a spoke and spiral pattern, with Z displacement ranging from 0.5 mm to 3.5 mm, in 0.5 mm intervals. A test dataset for validating the mapping was generated with a spiral pattern with a narrower Z displacement range of 0.75 mm to 3.25 mm, in 0.5 mm intervals.

To synchronise the data, a synchronisation signal (generated by the XYZ stage control software) was used to pulse an external LED, which is within the view field of the digital camera, at the start and end of each stimulation pattern performed at each Z displacement. During XYZ stage operation, a microcontroller (Due; Arduino, Italy) was used to simultaneously sample the PapillArray digital photodiode signals, the XYZ-stage position digital outputs, and the synchronisation signal. The sampled data was sent from the Arduino, via a serial interface, to a logging program on a laptop computer. The force sensor data was simultaneously logged by the same program through a second serial interface. The data was

sampled at 100 Hz. In order to later validate the XY displacement of the pillar, video of the PapillArray pillar in contact with the transparent acrylic surface was captured with the digital camera in MP4 format with 1920×1080 pixel resolution at 59.94 frames per second (fps).

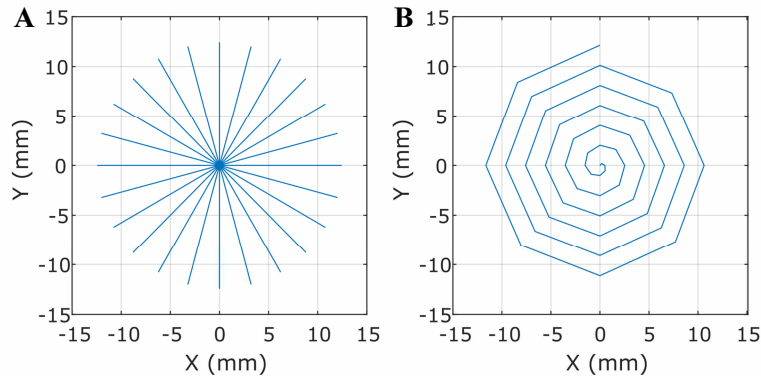


Figure 5. XY stage movement for displacement and force mapping. **A)** Spoke and **B)** spiral stimulation pattern. These patterns were repeated for each Z displacement, ranging from 0.5 mm to 3.5 mm, in 0.5 mm intervals.

2.3.3 Data processing

2.3.3.1 Pre-processing and data fusion

Synchronisation of the video data and the computer-logged data (3D force, XYZ stage position including synchronisation signal, and four photodiode signals) was required. The video frames containing the rising and falling edges of the LED brightness were manually annotated and used to synchronise the video stream with the recorded synchronisation signal from the XYZ stage; hence, the video-tracking data is synchronised with all data sampled by the Arduino (see above). The PapillArray / XYZ stage / ATI data were then resampled (with linear interpolation) to match the sample times of the video-tracking data.

2.3.3.2 Video processing

The synchronised videos were processed in MATLAB (R2018a, Mathworks, Natick, MA, USA) to extract the position of the tracking dot. Camera calibration was performed using the MATLAB Camera Calibration App. The camera parameters were used to undo lens distortion in each video frame. Each frame was then first passed through a brightness threshold filter and a convex hull was applied to the output to isolate the large pink hemispherical pillar tip region. Within this region, a second brightness threshold filter was applied to extract the darker pixels containing the small black tracking dot. Finally, the centroid of the darker pixels was calculated as the pillar tip position. An example of the steps involved in processing a single frame of video is shown in **Figure 6**.

2.3.3.3 Sensor modelling

Multivariate polynomial regression (5th order) was applied (using MATLAB) to the four photodiode signals captured during the creation of the spoke- and spiral-patterned training data (i.e., with Z displacements ranging from 0.5 mm to 3.5 mm, in 0.5 mm increments) in order to model two distinct mappings: (i) four photodiode outputs mapped to the three XYZ displacement coordinates, and; (ii) four photodiode outputs mapped to three orthogonal force vector components. The total number of data samples used to train the regression models which approximate each mapping was 61,222 (1,021 s of data sampled at 59.94 Hz). These

two mapping models were then used to estimate the 3D displacement and 3D force using the four quadrant photodiode signals from the test data (the spiral pattern with Z displacement ranging from 0.75 to 3.25 mm, in 0.5 mm steps – distinct from the training set data) as the input to each mapping model. The total number of data samples in the test set was 28,144 (469 s of data sampled at 59.94 Hz).

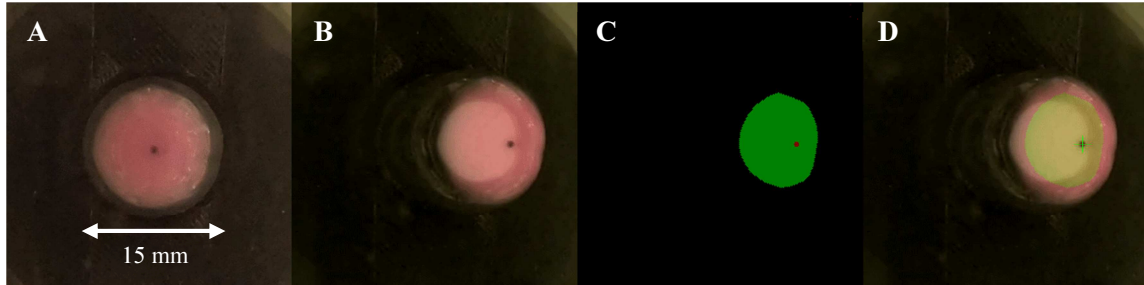


Figure 6. Image processing for pillar tip tracking. **A)** Raw image – pillar in its resting position, not in contact with transparent platform. **B)** Raw image – pillar compressed by transparent platform and shear force applied, deforming it toward the right of the image. **C)** Pillar tip region isolation (green) and tracking dot isolation (red •). **D)** final tracked pillar tip position (green +).

2.4 Vibration

The experiment described above involves slow changing displacements of, and forces on, the pillar tip. However, it is also of interest to observe the pillar response to high-frequency stimuli and its ability to detect such vibrations.

2.4.1 Test rig

A modal shaker (M20 SignalForce; Data Physics, San Jose, CA, USA) was used to vibrate the pillar. For vibration along the pillar X and Y axes, the shaker was brought into contact with the pillar at a location approximately two-thirds of the pillar height up from the base, and oriented such that the oscillation of the shaker would cause the pillar to deflect predominantly along the respective axis. For Z vibration, the shaker was brought into contact with the pillar tip, and oriented such that the shaker's axis of oscillation was predominantly aligned with the Z axis of the pillar. A laser displacement sensor (optoNCDT 2200; Micro-Epsilon, Ortenburg, Germany) and 45° cone were arranged such that the laser measured the displacement of the shaker probe along the axis of vibration. The arrangement of the pillar, shaker, laser displacement sensor, and cone for measuring vibration along the X axis of the pillar are shown in **Figure 7**.

2.4.2 Test procedure

Ten frequencies were tested ranging from 100 Hz to 1000 Hz in 100 Hz increments. At each frequency the shaker was programmed to deliver the oscillations at five different amplitude levels. Finally, the shaker was positioned such that the axis of the oscillation aligned with each of the pillar axes, respectively. In total, 150 tests were performed (i.e., 10 frequencies $\times$ 5 displacement amplitudes $\times$ 3 spatial axes), with each test lasting 3 s. Both the laser displacement sensor and raw photodiode signals were captured with a 16-bit data acquisition system (Power1401; CED, Cambridge, UK) at a sampling frequency of 17.9 kHz. Note that this is a different data acquisition system to that used for sampling photodiode signals for the displacement and force mapping; this was necessary for the vibration testing in order to sample the data with a higher resolution and sampling frequency.

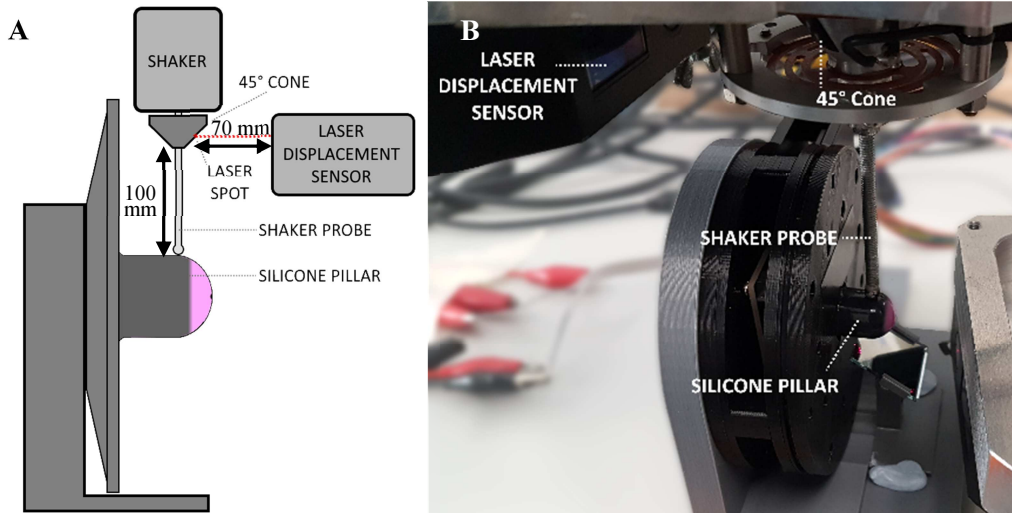


Figure 7. Test rig for vibration testing. **A)** Illustration and **B)** photo showing the pillar, the shaker and probe, 45° cone, and laser displacement sensor for vibration testing along the X axis of the pillar.

2.4.3 Data processing

The XYZ displacement mapping (described earlier) was applied to the four photodiode quadrant readings (with a 16-sample moving average applied during data acquisition) to estimate the 3D displacement of the pillar tip. This was compared with the displacement of the shaker, as determined by the laser displacement sensor. Welch's periodogram (with 1 second window, 50% overlap, and a Hamming window), was used to estimate the power spectral density (PSD) of the 3D displacement estimates and the true shaker position in order to quantify the frequency response of the pillar and its pinhole-camera-based instrumentation.

3. Results

3.1. Displacement and force

A typical recording of the four quadrant photodiode signals with respect to time is shown in **Figure 8A**, for the spiral stimulation pattern at 3.25 mm Z displacement. Also shown are the corresponding actual and estimated 3D displacements (**Figure 8B**) and 3D forces (**Figure 8C**), with respect to time. Finally, the X displacement is shown with respect to Y displacement (**Figure 8D**), and the X forces are shown with respect to the corresponding Y forces (**Figure 8E**), using the spiral stimulation pattern here for illustration purposes. Note that the true X and Y displacement of the pillar (from video-tracking position; **Figure 8D**) does not exactly match the X and Y displacement of the stage (**Figure 5B**); when the XY stage changes direction, the stage is stationary for 0.8 s, which, at large displacements, results in the pillar contracting towards the origin (due to relaxation of the silicone).

The 3D displacement and 3D force estimate errors for the test dataset (spiral pattern at Z displacements of 0.75 to 3.25 mm, in 0.5 mm increments) are summarised in **Table 1**. The X, Y, and Z displacement estimation error is on the order of tens of μm . The X and Y force estimation error is on the order of tens of mN, whereas the Z force estimation error is an order of magnitude larger. Also presented in **Table 1** are the R^2 values of the test dataset for the estimated and actual X, Y and Z displacement and force. The R^2 for displacement and force estimates in all three axes were greater than 0.9985.

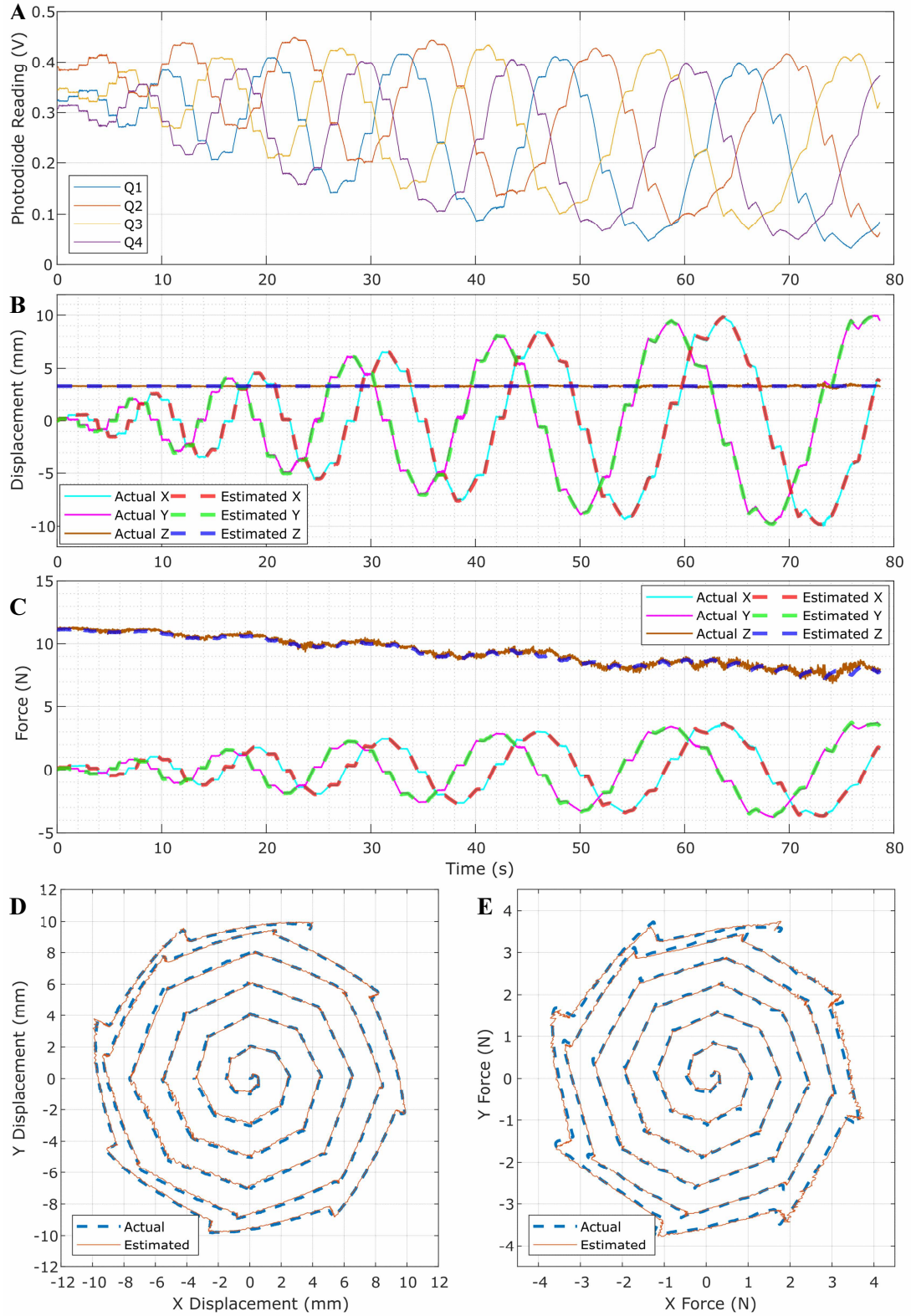


Figure 8. Displacement and force mapping for spiral stimulation pattern at Z displacement of 3.25 mm. **A)** Raw quadrant photodiode outputs. **B)** Actual and estimated 3D displacement. **C)** Actual and estimated 3D force. **D)** Actual and estimated X and Y displacement. **E)** Actual and estimated X and Y force.

In order to visualise the distribution of the test dataset estimation errors across the range of stimuli, and the dependence of this error on the displacement or force applied, the actual XY displacements were binned into 1 mm bins and boxplots of the X, Y, and Z displacement

estimation errors were generated (**Figure 9A**). The X, Y, and Z displacement estimation errors were also plotted against the actual Z displacement (**Figure 9B**). Similarly, the X, Y, and Z force estimation errors were plotted against the binned (0.5 N bins) actual XY force (**Figure 10A**), and the X, Y, and Z force estimation errors plotted against the binned (1 N bins) actual Z force (**Figure 10B**).

Table 1. Overall mean, standard deviation (SD) and maximum (test dataset) estimate error for 3D displacement and 3D force, and R^2 value between the (test dataset) estimated and actual 3D displacement and 3D force.

Axis	Displacement				Force			
	Estimate Error (mm)			R^2	Estimate Error (N)			R^2
	Mean	SD	Maximum		Mean	SD	Maximum	
X	0.012	0.077	0.443	0.99963	0.002	0.045	0.211	0.99917
Y	0.041	0.074	0.599	0.99969	-0.007	0.049	0.198	0.99912
Z	0.010	0.032	0.432	0.99864	0.073	0.118	1.435	0.99927

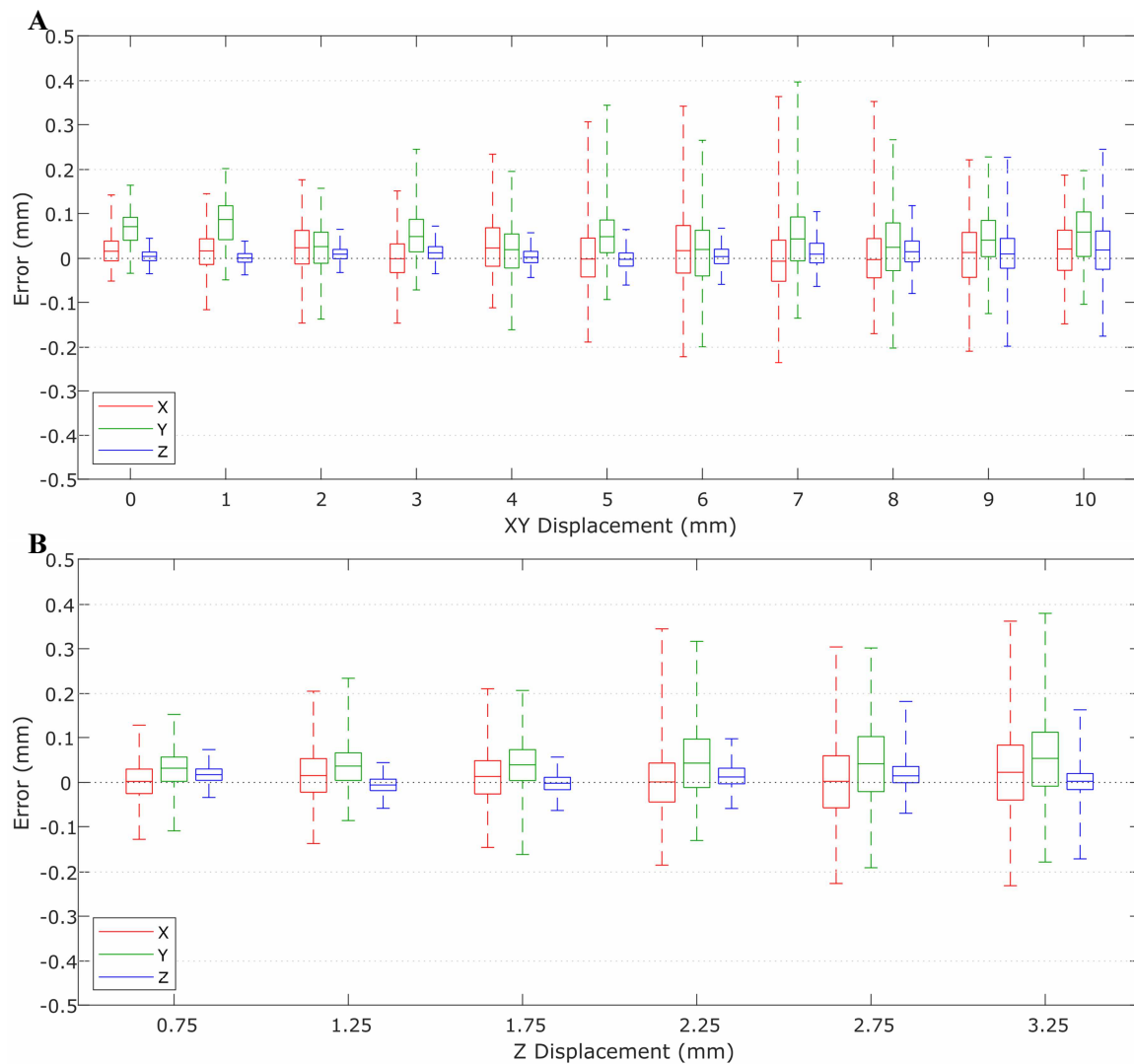


Figure 9. X, Y, and Z displacement estimation error as a function of: **A)** XY displacement binned into 1 mm wide bins (mean $\pm$ SD and minimum number of data points in each bin is 2558 ± 1404 and 463, respectively), and; **B)** Z displacement binned into 0.5 mm wide bins (mean $\pm$ SD and minimum number of data points in each bin is 4693 ± 15 and 4678, respectively). Extremities of boxes are 25th and 75th percentiles and whiskers extend to 0.5th and 99.5th percentile (i.e., whiskers show 99% of data).

The Z displacement estimation error is somewhat dependent on the magnitude of displacement in XY (larger error for larger displacements; for absolute Z force error vs. true

XY force, Pearson correlation coefficient $R = 0.371$), the X displacement estimation error less so ($R = 0.154$), and interestingly, the Y displacement estimation error does not appear to be correlated to with the magnitude of displacement in XY ($R = 0.044$). The X and Y displacement estimation error are dependent on the Z displacement ($R = 0.294$ and 0.299 , respectively); however, the Z displacement estimation error is less dependent on the Z displacement magnitude ($R = 0.172$). Interestingly, the X and Y force estimation error does not appear to be dependent on the magnitude of XY or Z force applied (for absolute X and Y force error vs. true XY force, Pearson correlation coefficient $R = 0.046$ and -0.033 , respectively, and for absolute X and Y force error vs. true Z force, $R = 0.033$ and 0.055 , respectively); however, the Z force estimation error does show some dependence on the magnitude of XY and Z force applied (for absolute Z force error vs. true XY force, $R = 0.230$, and for absolute Z force error vs. true Z force, $R = 0.244$).

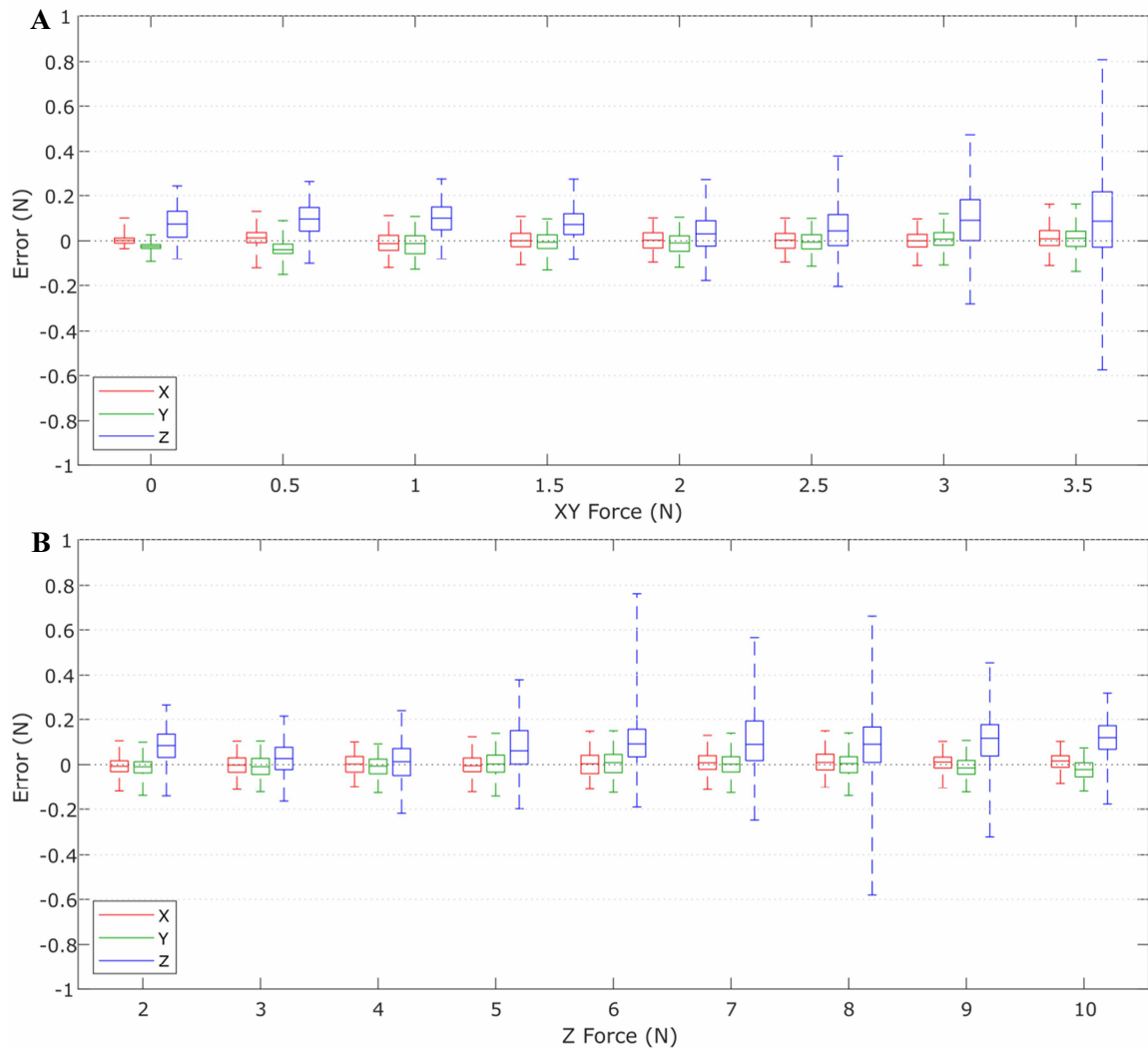


Figure 10. X, Y and Z force estimate error as a function of **A)** XY force binned into 0.5 N wide bins (mean $\pm$ SD and minimum number of data points in each bin is 3488, 1683, 432), and **B)** Z force binned into 1 N wide bins (mean $\pm$ SD and minimum number of data points in each bin is 2550 $\pm$ 1143, 809). Extremities of boxes are 25th and 75th percentiles and whiskers extend to 0.5th and 99.5th percentile (i.e., whiskers show 99% of data).

3.2. Vibration

A typical recording of the shaker displacement and the corresponding 3D displacement estimates with respect to time is shown in **Figure 11A**, for vibration along the X axis at a

frequency of 200 Hz and a vibration amplitude of $\sim 8 \mu\text{m}$. Also shown are the corresponding PSDs for the shaker displacement and estimated X, Y, and Z displacements (**Figure 11B**). It can be seen that the sinusoidal shape of the shaker displacement is matched predominantly in the displacement estimates of the axis of stimulation (i.e., X axis) and that this corresponds to a large peak ($13 \mu\text{m}/\sqrt{\text{Hz}}$) at 200 Hz in the PSD of the X displacement. Note that the displacement amplitude estimated in the X axis does not match the shaker displacement amplitude as measured by the laser displacement sensor, since in the X and Y axis vibration experiments the shaker contacts the pillar at a point about two-thirds of the way up the pillar from its base, one-third of a pillar height away from the pillar tip, however, the mapping estimates the displacement of the pillar tip. A smaller peak in the PSDs of the orthogonal axes (peaks of 1.8 and $1.3 \mu\text{m}/\sqrt{\text{Hz}}$ in the Y and Z axes, respectively) can also be seen at the stimulation frequency (200 Hz). No other significant peaks can be seen at any other frequencies; this behaviour was similar at all frequencies and/or amplitudes tested.

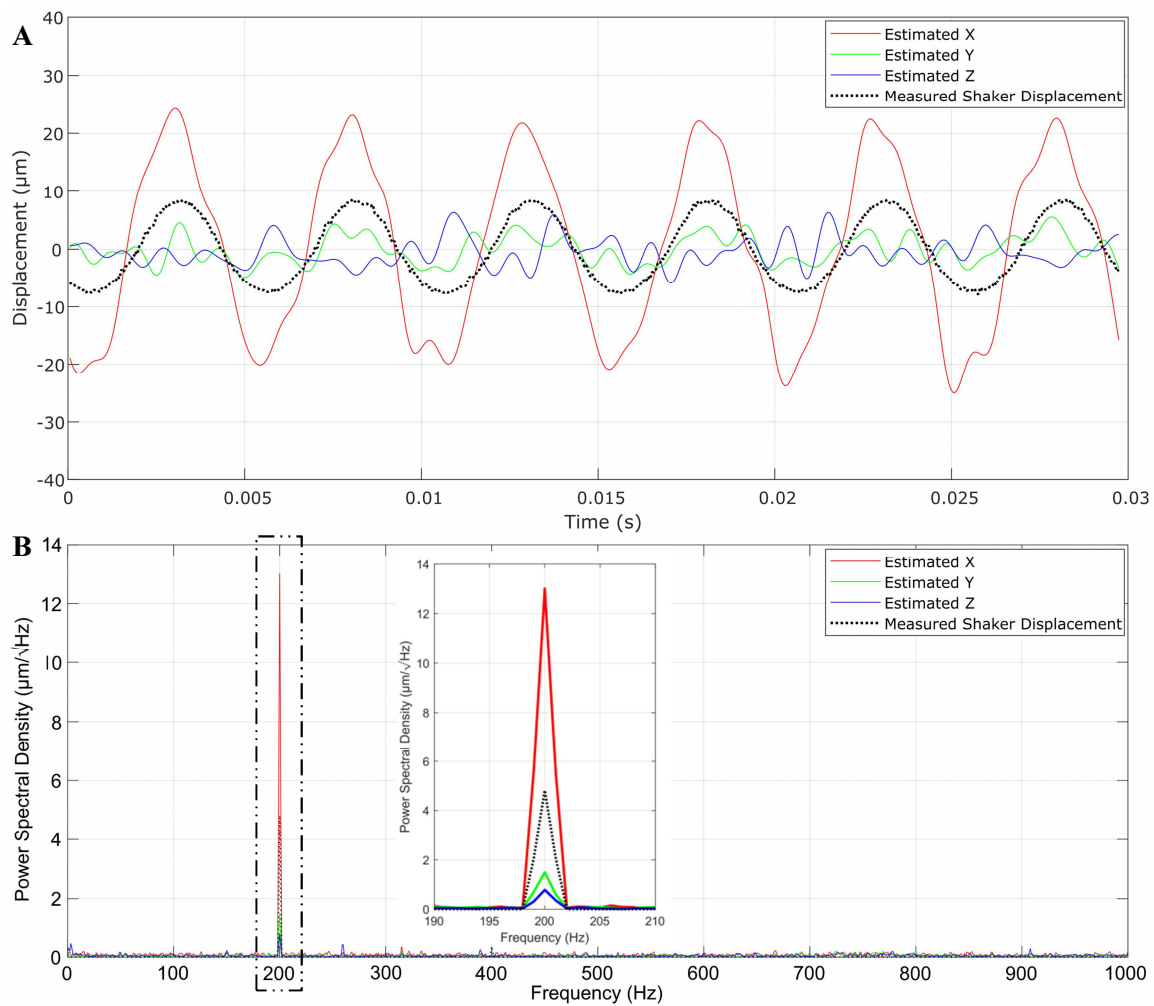


Figure 11. Response to vibration in the X axis at 200 Hz and shaker displacement amplitude of $\sim 8 \mu\text{m}$. **A)** 3D displacement estimate and shaker displacement. **B)** Corresponding power spectral density with inset showing a dominant peak on the X axis at 200 Hz.

The peak amplitude of the PSD of the X, Y, and Z displacement estimates at the stimulation frequency in all three axes for all 150 vibration trials (stimulation along 3 axes $\times$ 10 frequencies $\times$ 5 vibration amplitudes) are shown in **Figure 12**. Also shown are the corresponding PSD peak amplitudes for the shaker displacement at these same frequencies, and the PSD noise floor ($0.2 \mu\text{m}/\sqrt{\text{Hz}}$). Note again, for vibration in the X and Y axes, the

shaker displacement is not the same as the pillar tip displacement, since the shaker stimulates a point approximately two-thirds of the way up the pillar; and while the Z deformation is applied at the tip, in some frequency bands, the mechanics of the silicone do not transfer this vibration to the reflector. In general, for all experiments, the shaker vibration amplitude decreases with increasing frequency; this is a limitation of the shaker.

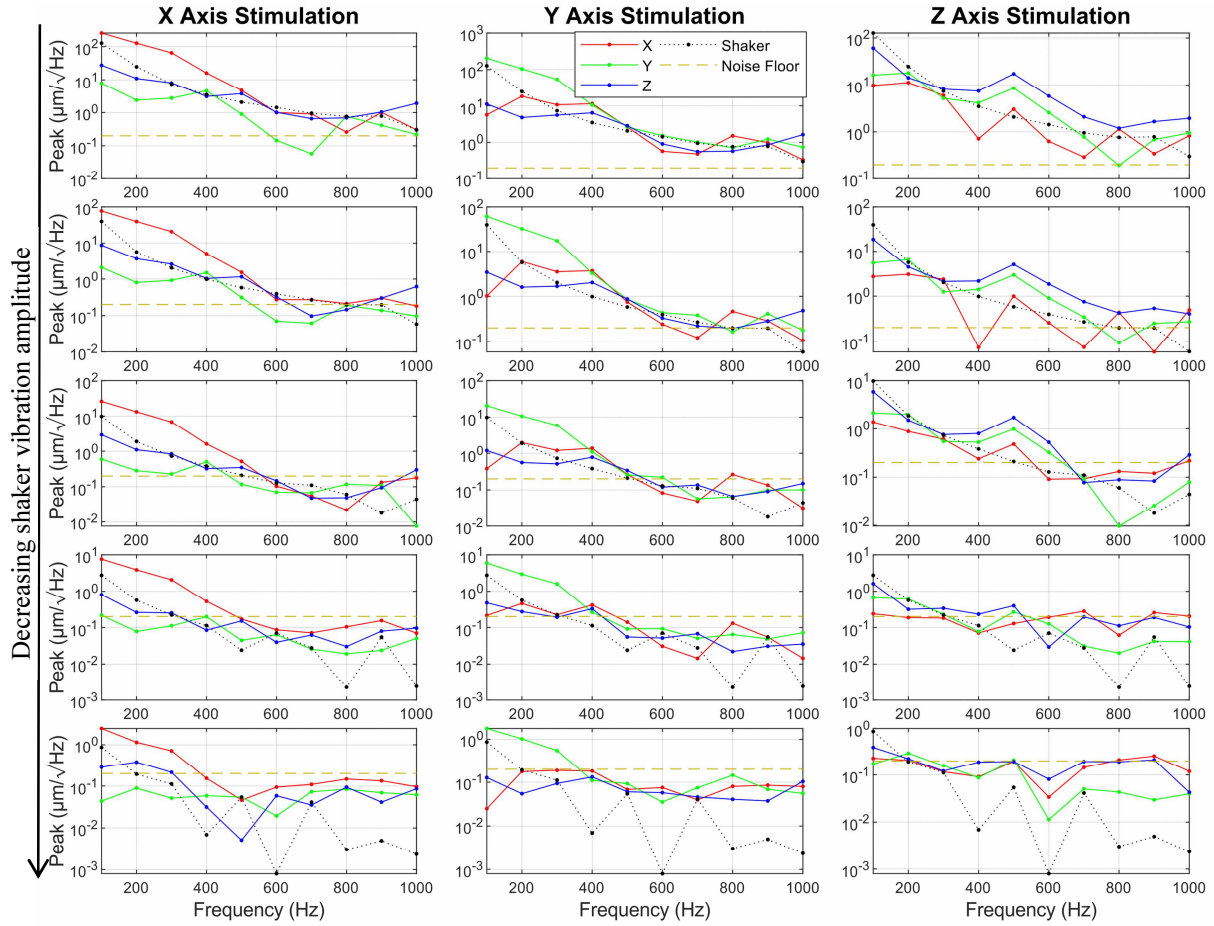


Figure 12. PSD peak amplitude at all stimulation frequencies for vibration stimulation. Left to right: X, Y, and Z stimulation axis (i.e., the direction the pillar was shaken in). Top to bottom: decreasing vibration amplitude.

Each plot shows: the PSD peak amplitude at all stimulation frequencies, generated using the X, Y, and Z displacement estimates output from the mapping; the PSD peak amplitude at the corresponding frequencies for the shaker displacement, and; the PSD amplitude of the noise floor ($0.2 \mu\text{m}/\sqrt{\text{Hz}}$).

Stimulation in the X and Y axis generally results in a large peak in the PSD of the X and Y displacement, respectively, (compared to orthogonal axes) particularly at larger vibration amplitudes. However, stimulation in the Z axis results in a large peak in the PSD of all three axes. This could be due to the difficulty in ensuring that the shaker is actually producing a vibration predominantly along the Z axis. It can also be seen in all subplots that when the shaker vibration gives a peak PSD amplitude of greater than $\sim 0.2 \mu\text{m}/\sqrt{\text{Hz}}$ (which corresponds to a vibration amplitude of $\sim 0.35 \mu\text{m}$), the peak PSD amplitude of the displacement estimate along the axis of stimulation is consistently above the noise floor, at all stimulation frequencies, indicating that the frequency sensitivity is at least up to 1000 Hz at a vibration amplitude as small as $\sim 3.5 \mu\text{m}$.

4. Discussion

4.1. Summary

4.1.1 Summary of design concept

In this work, a novel method has been presented to instrument the displacement and force experienced by a silicone pillar. This single pillar is intended to serve as one component in a larger tactile sensing array, similar to the PapillArray sensor previously presented by our group [7]. The proposed design makes novel use of the pinhole camera concept, whereby deformation of the pillar results in both the movement and change in area of the image of a diffuse reflector disk (i.e., a spot of light) which is projected through the pinhole and onto a quadrant photodiode. The four quadrant photodiode current signals are mapped to true 3D displacement and force using multivariate regression.

4.1.2 Summary of results

The accuracy of the regression displacement and force mappings were validated using both video-tracking of the pillar tip displacement and force measurements made with a 3D force sensor, respectively. The overall displacement estimation error (mean $\pm$ SD) in the X, Y, and Z axes was 0.012 ± 0.077 mm, 0.041 ± 0.074 mm and 0.010 ± 0.023 mm, respectively, for a full-scale deflection of 10.0 mm in X and Y, and 3.25 mm in Z. The overall force estimation error (mean $\pm$ SD) was 0.002 ± 0.045 N, -0.007 ± 0.049 N and 0.073 ± 0.118 N, for full-scale force of approximately 4 N in X and Y and 11 N in Z, respectively. The sensitivity of the pillar to vibration (between 100 and 1000 Hz) was also tested, as this may help to detect incipient slip events. The pillar can detect vibration up to 1000 Hz for a vibration displacement amplitude as small as $0.35 \mu\text{m}$.

4.2 Design advantages

The sensor pillar is compliant, yet does not require the use of flexible electronics which can considerably increase the complexity of the manufacturing process [8]. Thus, it can be manufactured at its current scale using proven low-cost techniques. In fact, no electronic components are used in the moulded silicone structure which sits above the PCB on which the LEDs are mounted, allowing the PCB and silicone parts to be manufactured independently. It is still conceivable, however, that the LEDs, pinhole, and quadrant photodiodes could be placed on a flexible/stretchable substrate, allowing the backplane of the sensor to deform and be subsequently fixed to non-planar geometries (e.g. gripper fingers).

The optical transduction method has a very large bandwidth and resolution, with a sensitivity to displacements as small as $0.35 \mu\text{m}$ up to 1 kHz. Such a large response bandwidth is not typically achieved using other transduction approaches [9]. While piezoresistive methods, (e.g., strain gauges) can have very high bandwidth, they are mechanically fragile unless mounted on a robust backplane, which ultimately limits their range of movement, making them unsuitable for use in compliant tactile sensors undergoing extensive 3D deformation. Piezoresistive elastomers overcome the issues of fragility and restricted movement, but can suffer from hysteresis due to the relaxation time constant of the elastomer material, which ultimately limits the bandwidth of the response; we certainly expect this to also be a factor limiting the high-frequency response of the silicone-pillar design presented here. Piezoelectric transduction (e.g., polyvinylidene fluoride plastic) is excellent for detecting high-frequency vibration, but cannot sense static force or displacement, and hence must be combined with some other transduction mechanism to achieve a full bandwidth response. Capacitive transduction elements have a good frequency response, sensing both static and

dynamic displacement/force, but suffer from interference from stray capacitance and require moderately complicated excitation and measurement circuitry. Methods using pressure sensing of vibration in fluids lacks spatial resolution; the BioTac sensor has only one vibration channel for the entire sensor [10]. Such approaches also require the entrapment of gas or fluid and hence are at risk of leaking. Magnetic sensing methods, such as the distributed tri-axial tactile sensors from Xela Robotics [11], are prone to interference from ferromagnetic materials, magnets and DC field motors. The pinhole camera transduction mechanism is robust against electromagnetic interference, such as stray capacitances, and static or time-varying magnetic fields; ambient light interference can also be rejected by pulsing the LEDs. Compared to these commonly-used alternative transduction techniques, optical sensing of displacement/force is a competitive approach.

The proposed pinhole camera design approach can implicitly measure localised force and displacement in 3D. This functionality is very often absent from tactile sensor designs presented in the literature. In other approaches, 3D sensing tends to be achieved indirectly through the creation of a “force localising protrusion” in the sensor skin, which converts normal forces to tensile forces, or shear forces to normal forces, so that an arrangement of several sensing elements can decompose the forces or displacements experienced [8]. However, this is a more explicit approach, with the design of individual transduction elements and the design of the force localising protrusion arrangement divorced from one another, which may result in an overall poorer spatial resolution due to an effective loss of sensing array density.

4.3 Mapping process and optimisation/customisation

The multivariate regression mapping used here to convert the quadrant photodiode signals to 3D displacement and 3D force estimates was intended only to provide a proof-of-concept demonstration that this information can be extracted from the raw photodiode outputs with reasonable accuracy. More computationally-efficient and/or more accurate mapping models may exist. For example, it is possible that a model which gives greater consideration to the geometry and physics of the sensor arrangement (geometry of the cavity, reflector, pinhole aperture; reflectivity of all internal surfaces; photodiode size, shape and placement; refraction) might achieve a more accurate mapping. Similarly, parameterising the pillar mechanics (external geometry, cavity geometry, silicone elasticity, shore hardness) in a physically-realistic model may improve the inference of 3D force. Conversely, it is likely that the geometry of the pinhole camera and pillar, and the properties of the pillar material can be optimised, perhaps per intended application, to improve the range and accuracy of the displacement and force estimates. Optimisation of the properties of the pillar material may also be required to improve the durability of the sensor, or the pillar tip may need to be covered/coated with a more durable material, since this will be the point of contact with manipulated objects and hence will likely be the site experiencing most wear and tear.

It is important to note the limitations of the sensor design and regression mapping models presented in this paper. In all experiments, the transparent acrylic test surface was oriented parallel to the upper/lower plates of the sensor (see **Figure 4**). The regression models attempt to map the 3D force/displacement at the tracking dot by collecting light from the diffuse reflector, which of course is dependent on the position and orientation of the reflector. It is obvious that there is no unique one-to-one relationship between the deformation of the outer surface of the silicone pillar and the position and orientation of the reflector contained within it. This means that the regression mapping models derived may demonstrate lesser accuracy

when the pillar is contacted at some other angle or by a non-planar surface. This issue could be mitigated by moving the reflector closer to the tip, or by using a less compliant silicone (or other material) to manufacture the pillar, but with the consequence of a reduced light intensity arriving at the photodiode. Unfortunately, exploring the potential influence of these effects on sensor accuracy is not trivial with the apparatus used herein, but will be explored as part of our future work.

4.4 Miniaturisation

In the context of robotic gripping, miniaturisation of the individual sensing elements of a tactile sensor is required in order to achieve a similar spatial resolution to the human finger pad (spacing of approximately 1mm) and thus enabling improved dexterity. The design presented here can certainly be reduced in size while using the same electronics. Efforts to further miniaturisation of an array of pillars could make use of: a photodetector array, such as CMOS photodiode array, to replace the proposed array of discrete quadrant photodiode components; LED displays (punctured with pinholes) to replace the discrete LEDs for cavity illumination; more sophisticated additive manufacturing techniques to fabricate the silicone pillar array (with a cavity and reflector in each pillar). Encouragingly, there have also been impressive reports of flexible and stretchable LED [12-15] and photodetector arrays [16-18], which could be used to make the PapillArray backplane flexible and/or stretchable, moving away from the current rigid PCB backplane.

4.5 Discussion of related work

4.5.1 Other uses of the pinhole camera concept

A similar principle to the pinhole camera concept has been used in sun sensors [19]. Sun sensors are commonly used on satellites to orient them with respect to the sun. In an analog sun sensor, what is collimated light from the sun travels through a pinhole makes a spot on a photodetector array. However, this approach only intends to infer the sun's direction based on the XY coordinate of the light spot on the photodetector array. Because the sun subtends an arc of only approximately 32 minutes on the sky (a little over half a degree), the area of the spot is very small on the photodetector and thus a high-density array is required to track the centroid of this spot.

However, the use of a relatively large diffuse reflector in this paper results in a beam of light emitted from the pinhole subtending angle (when the sensor pillar is undeformed) of $2 \tan^{-1}(1.5/8) \approx 21.24^\circ$, illuminating the quadrant photodiode. The advantage of this large subtended angle is that the projected light spot overlaps with all four quadrants of the photodiode, allowing the XYZ location of the reflected (and by proxy the pillar tip) to be inferred from the absolute and relative light intensities measured on only four photodiode quadrants, rather than requiring a large-pixel-count photodetector array.

4.5.2 Optical sensors using reflected, scattered, or light to infer displacement of force

There are a number of related works which use closely-related transduction approaches, injecting light into a sensing component and inferring force or deformation of the tactile sensor surface by analysing the light collected at a detector.

The commercially-available Optoforce force sensor emits light from the centre of a hemispherical shell and then collects the light reflecting from inside this shell using three or more photodiodes [20]. Transparent filler materials of varying refractive indices are used to provide resistance to buckling and to partly focus the light onto the detectors. This approach requires the photodiodes to be placed around the light source in the same plane, limiting how small the sensor area can be made; the pinhole camera approach here places the quadrant photodiode beneath the PCB layer containing the LEDs, minimising the footprint. It has not been reported whether the Optoforce sensor can undergo large shear displacement and reliably estimate this displacement, for the purposes of allowing and detecting incipient slip.

A similar approach to the Optoforce was used by Persichetti *et al.* [21] to measure pressure, illuminating one end of a long silicone channel and measuring how the received light intensity changes when the applied pressure alters the geometry of the channel. A related approach is taken by Ramuz *et al.* using a polydimethylsiloxane waveguide [22]. These approaches cannot detect XY deformation.

Rossiter & Mukai [23, 24], and Kampmann & Frank [25], transmitted light through a semi-opaque foam and collected it at a photodiode. The increasing density of the foam as it is compressed both attenuates transmitted light and increases backscattered light. Since these approaches are based on absorption and scattering of light, they cannot distinguish the direction of the applied force or displacement, rather measuring compression in the foam material.

Xie *et al.* [26] used a very similar concept to that proposed here, injecting light up through an optic fibre into a cavity, reflecting off two 45° mirrors, and collecting the light as it returns down the cavity with another optic fibre. The mirrors are mounted on a flexible material and allowed to move up and down under a normal force, effectively shortening the path length of the light when pressed down; more light is collected at the detector when the path length is shorter, as the beam has diverged less. However, again, the design cannot detect XY movement required to detect slip or estimate friction.

Koike *et al.* [27] reflect light off the underside of the sensor surface and collected it with a photodiode. Deformation of the sensor surface alters the intensity of light collected at the photodiode. In a related configuration, they capture an image of the reflected light on a diffuser sheet, and this image is then recorded by a camera. Again, the limitation of this method is that it cannot determine if there has been any XY deformation of the surface, nor has it been shown that forces can be inferred.

We also briefly mention a number of designs based on received light after transmission through an optic fibre, either due to bending (light loss [28-30]) or stretch (Bragg diffraction [31]). The approach these methods use is quite different than what is described in this paper, and all these methods can only sense pressure as presented.

4.5.3 Camera-based methods

Despite the inspiring technologies deployed in flexible and stretchable e-skins [8], some of the most impressive tactile sensors to date use camera-based imaging of the movement of the back of the sensor surface [32-38]. Begej's method senses pressure using frustrated total internal reflection [32]. Both the TacTip [33, 39] and GelSight/GelSlim sensors [34-36, 40] use a camera to track the displacement of pins or markers on the elastomer surface of the

sensor and hence detect gross slip or incipient slip. The GelSight sensor uses photometric stereo imaging (illuminating the back of the sensor skin with different colored light from different angles) to estimate 3D displacement, and from this 3D force and emergent parameters, such as torque and incipient slip, can be inferred. These methods have outstanding spatial resolution. However, the use of a camera makes it challenging to develop a compact design due to the need to maintain focus; this issue motivated the design of the mirrored GelSlim sensor. The relatively low frame rate means these sensors cannot detect high-frequency vibration without use of more advanced imaging techniques. And finally, there is likely a large computational burden associated with multiple-point-tracking in the resulting images/video. The proposed optically-instrumented pillar has advantages over the above camera-based approaches: only four signals per pillar, rather than millions of pixels from a camera image; no need for image tracking; a relatively simple mapping between sensor output and displacement/force; very high frequency response (up to 1000 Hz); a lower profile as image focusing is not necessary.

4.6 What must be sensed to estimate friction?

In the literature, a number of different transduction techniques – resistive, inductive, piezoelectric, and optical – have been employed for measuring force and vibration, and these signals have then been analysed to estimate friction or detect incipient slip [6]. As of yet, there are very few resoundingly successful tactile sensor designs which can detect incipient slip well, and none which robustly estimate friction. Those sensor designs which aim to estimate friction on initial contact with an object are typically large, and also surrender the ability to reassess the friction while the grasping task is on-going; should the friction change after the contact is established, this change will go undetected, risking the object being dropped. Those methods which are based on incipient slip often use vibration sensing to detect incipient slip events; this approach is prone to vibration interference from robotic motors and is further confounded by vibrations caused by contact between the sensor and object, or object and environment, during manipulation. It appears that humans use a combination of vibration, pressure, and stretch at the skin-object interface in order to detect incipient slip [41], so we are certainly motivated to sense shear deformation of the sensor where it interfaces with the object using tactile sensors. However, to go further and estimate friction, if that is the approach one wishes to take to inform a grip force control system, localised 3D force measurement at the location(s) where incipient slip occurs is also required.

Therefore, we propose that the desired functionality of a tactile sensor which has the ability to robustly measure friction includes the following: (i) must establish a traction/pressure differential over the contact area, so that incipient slip is encouraged on parts of the contact area while the remainder of the contact area remains firmly stuck; (ii) for incipient slip to be possible, the sensor must be allowed to stretch or experience shear deformation at the contact interface; (iii) must be able to sense localised vibration to facilitate incipient slip detection, especially for compliant object surfaces (incipient slip is possibly detectable for rigid objects based solely on shear deformation); (iv) must be able to sense localised 3D forces so that the coefficient of static friction can be estimated when and where incipient slip occurs.

The sensor design presented in this paper, using a silicone pillar, diffuse reflector, pinhole, and quadrant photodiode, will facilitate the design of a sensor array which achieves the design specifications outlined above for a tactile sensor which can detect incipient slip and subsequently estimate friction from the local forces at the time and place of the slip event. This will be the focus of our future work on this topic.

5. Conclusions and future work

In this work, a novel method has been validated for instrumenting a silicone pillar such that 3D displacement, 3D force, and vibration of the pillar tip can be measured. This optical method of sensing displacement and force may find numerous future applications in tactile sensing and beyond; however, the primary motivation for developing this technique here was as a means of instrumenting the PapillArray tactile sensor [7]. Measuring the deflection and force from an array of such pillars which constitute the PapillArray sensor can enable the measurement of global forces, torques, and possibly object surface shape. Furthermore, the detection of incipient slip, and concurrent measurement of the forces on each pillar when it slips, can be used to estimate the coefficient of static friction without complete loss of grip occurring. Friction and force feedback to an autonomous robotic gripper allows the grip force to be optimised to avoid dropping a grasped object.

Our future work will focus on miniaturising and arraying these pillars, and demonstrating whether this design concept can sense incipient slip and friction in real-time, in addition to global forces and torques. Such an achievement will significantly advance the state-of-the-art in artificial tactile sensing and bring us closer to dexterous robotic manipulation.

Acknowledgements

We thank A/Prof Ingvars Birznieks (UNSW Sydney) and Mr Kevin Ng (UNSW Sydney) for their assistance with the vibration testing. This work was supported by the Office of Naval Research (US Department of the Navy)/ Navy and Marine Corps Science and Technology [grant number GRANT12395989] and in part by an Australian Research Council Future Fellowships Grant [grant number FT130100858].

References

- [1] Å. B. Vallbo and R. Johansson, "Properties of cutaneous mechanoreceptors in the human hand related to touch sensation," *Human Neurobiology*, vol. 3, pp. 3-14, 1984.
- [2] P. Jenmalm, I. Birznieks, A. W. Goodwin, and R. S. Johansson, "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] H. Khamis, S. J. Redmond, V. Macefield, and I. Birznieks, "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] M. I. Tiwana, S. J. Redmond, and N. H. Lovell, "A review of tactile sensing technologies with applications in biomedical engineering," *Sensors and Actuators A: Physical*, vol. 179, pp. 17-31, 2012.
- [5] R. S. Johansson and G. Westling, "Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip," *Experimental Brain Research*, vol. 66, pp. 141-154, 1987.
- [6] W. Chen, H. Khamis, I. Birznieks, N. F. Lepora, and S. J. Redmond, "Tactile Sensors for Friction Estimation and Incipient Slip Detection – Towards Dexterous Robotic Manipulation: A Review," *IEEE Sensors Journal*, pp. 1-1, 2018.
- [7] 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.
- [8] M. L. Hammock, A. Chortos, B. C. K. Tee, J. B. H. Tok, and Z. Bao, "25th Anniversary Article: The Evolution of Electronic Skin (E-Skin): A Brief History, Design Considerations, and Recent Progress," *Advanced Materials*, vol. 25, pp. 5997-6038, 2013.
- [9] Z. Kappassov, J.-A. Corrales, and V. Perdereau, "Tactile sensing in dexterous robot hands — Review," *Robotics and Autonomous Systems*, vol. 74, pp. 195-220, 2015.

- [10] J. A. Fishel and G. E. Loeb, "Sensing tactile microvibrations with the BioTac — Comparison with human sensitivity," in *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2012, pp. 1122-1127.
- [11] T. P. Tomo, S. Somlor, A. Schmitz, S. Hashimoto, S. Sugano, and L. Jamone, "Development of a hall-effect based skin sensor," in *2015 IEEE SENSORS*, 2015, pp. 1-4.
- [12] Z. Yu, X. Niu, Z. Liu, and Q. Pei, "Intrinsically Stretchable Polymer Light-Emitting Devices Using Carbon Nanotube-Polymer Composite Electrodes," *Advanced Materials*, vol. 23, pp. 3989-3994, 2011.
- [13] T. Sekitani, H. Nakajima, H. Maeda, T. Fukushima, T. Aida, K. Hata, and T. Someya, "Stretchable active-matrix organic light-emitting diode display using printable elastic conductors," *Nature Materials*, vol. 8, p. 494, 2009.
- [14] R.-H. Kim, D.-H. Kim, J. Xiao, B. H. Kim, S.-I. Park, B. Panilaitis, R. Ghaffari, J. Yao, M. Li, Z. Liu, V. Malyarchuk, D. G. Kim, A.-P. Le, R. G. Nuzzo, D. L. Kaplan, F. G. Omenetto, Y. Huang, Z. Kang, and J. A. Rogers, "Waterproof AlInGaP optoelectronics on stretchable substrates with applications in biomedicine and robotics," *Nature Materials*, vol. 9, p. 929, 2010.
- [15] S.-I. Park, Y. Xiong, R.-H. Kim, P. Elvikis, M. Meitl, D.-H. Kim, J. Wu, J. Yoon, C.-J. Yu, Z. Liu, Y. Huang, K.-c. Hwang, P. Ferreira, X. Li, K. Choquette, and J. A. Rogers, "Printed Assemblies of Inorganic Light-Emitting Diodes for Deformable and Semitransparent Displays," *Science*, vol. 325, p. 977, 2009.
- [16] I. Jung, G. Shin, V. Malyarchuk, J. S. Ha, and J. A. Rogers, "Paraboloid electronic eye cameras using deformable arrays of photodetectors in hexagonal mesh layouts," *Applied Physics Letters*, vol. 96, p. 021110, 2010.
- [17] C. Wang, D. Hwang, Z. Yu, K. Takei, J. Park, T. Chen, B. Ma, and A. Javey, "User-interactive electronic skin for instantaneous pressure visualization," *Nature Materials*, vol. 12, p. 899, 2013.
- [18] H. C. Ko, M. P. Stoykovich, J. Song, V. Malyarchuk, W. M. Choi, C.-J. Yu, J. B. Geddes Iii, J. Xiao, S. Wang, Y. Huang, and J. A. Rogers, "A hemispherical electronic eye camera based on compressible silicon optoelectronics," *Nature*, vol. 454, p. 748, 2008.
- [19] Adcole. (2018, 15 November 2018). *Analog Sun Sensors*. Available: <https://www.adcole.com/aerospace/analog-sun-sensors/>
- [20] Á. S. Tar, G. G. Cserey, and J. Veres, "Sensor device," USA Patent US9513178B2, 2016.
- [21] A. Persichetti, F. Vecchi, and M. C. Carrozza, "Optoelectronic-Based Flexible Contact Sensor for Prosthetic Hand Application," in *2007 IEEE 10th International Conference on Rehabilitation Robotics*, 2007, pp. 415-420.
- [22] M. Ramuz, B. C. K. Tee, J. B. H. Tok, and Z. Bao, "Transparent, Optical, Pressure-Sensitive Artificial Skin for Large-Area Stretchable Electronics," *Advanced Materials*, vol. 24, pp. 3223-3227, 2012.
- [23] J. Rossiter and T. Mukai, "A novel tactile sensor using a matrix of LEDs operating in both photoemitter and photodetector modes," in *SENSORS, 2005 IEEE*, 2005, pp. 994-997.
- [24] J. Rossiter and T. Mukai, "An LED-based Tactile Sensor for Multi-sensing over Large Areas," in *SENSORS, 2006 IEEE*, 2006, pp. 835-838.
- [25] P. Kampmann and F. Kirchner, "Integration of Fiber-Optic Sensor Arrays into a Multi-Modal Tactile Sensor Processing System for Robotic End-Effectors," *Sensors*, vol. 14, 2014.
- [26] H. Xie, A. Jiang, H. A. Wurdemann, H. Liu, L. D. Seneviratne, and K. Althoefer, "Magnetic Resonance-Compatible Tactile Force Sensor Using Fiber Optics and Vision Sensor," *IEEE Sensors Journal*, vol. 14, pp. 829-838, 2014.
- [27] M. Koike, S. Saga, T. Okatani, and K. Deguchi, "Sensing method of total-internal-reflection-based tactile sensor," in *2011 IEEE World Haptics Conference*, 2011, pp. 615-619.
- [28] R. Ahmadi, M. Packirisamy, J. Dargahi, and R. Cecere, "Discretely Loaded Beam-Type Optical Fiber Tactile Sensor for Tissue Manipulation and Palpation in Minimally Invasive Robotic Surgery," *IEEE Sensors Journal*, vol. 12, pp. 22-32, 2012.
- [29] J.-S. Heo, K.-Y. Kim, and J.-J. Lee, "Development of a Distributed Force Detectable Artificial Skin Using Microbending Optical Fiber Sensors," *Journal of Intelligent Material Systems and Structures*, vol. 20, pp. 2029-2036, 2009.
- [30] M. Rothmaier, P. M. Luong, and F. Clemens, "Textile Pressure Sensor Made of Flexible Plastic Optical Fibers," *Sensors*, vol. 8, 2008.
- [31] J.-S. Heo, J.-H. Chung, and J.-J. Lee, "Tactile sensor arrays using fiber Bragg grating sensors," *Sensors and Actuators A: Physical*, vol. 126, pp. 312-327, 2006.
- [32] S. Begej, "Planar and finger-shaped optical tactile sensors for robotic applications," *IEEE Journal on Robotics and Automation*, vol. 4, pp. 472-484, 1988.
- [33] J. W. James, N. Pestell, and N. F. Lepora, "Slip detection with an optical tactile sensor," *IEEE Robotics and Automation Letters*, 2018.

- [34] W. Yuan, R. Li, M. A. Srinivasan, and E. H. Adelson, "Measurement of shear and slip with a GelSight tactile sensor," in *Proceedings of IEEE International Conference on Robotics and Automation*, 2015, pp. 304-311.
- [35] S. Dong, W. Yuan, and E. Adelson, "Improved GelSight tactile sensor for measuring geometry and slip," *arXiv preprint arXiv:1708.00922*, 2017.
- [36] E. Donlon, S. Dong, M. Liu, J. Li, E. Adelson, and A. Rodriguez, "GelSlim: A high-resolution, compact, robust, and calibrated tactile-sensing finger," *arXiv preprint arXiv:1803.00628*, 2018.
- [37] Y. Yamada, T. Morizono, Y. Umetani, and H. Takahashi, "Highly soft viscoelastic robot skin with a contact object-location-sensing capability," *IEEE Transactions on Industrial Electronics*, vol. 52, pp. 960-968, 2005.
- [38] H. Yussuf, M. Ohka, H. Suzuki, and N. Morisawa, "Tactile Sensing-based Control System for Dexterous Robot Manipulation," in *Advances in Computational Algorithms and Data Analysis*, S.-I. Ao, B. Rieger, and S.-S. Chen, Eds., ed Dordrecht: Springer Netherlands, 2009, pp. 199-213.
- [39] N. F. Lepora and B. Ward-Cherrier, "Superresolution with an optical tactile sensor," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2015, pp. 2686-2691.
- [40] W. Yuan, S. Dong, and E. H. Adelson, "GelSight: High-Resolution Robot Tactile Sensors for Estimating Geometry and Force," *Sensors (Basel, Switzerland)*, vol. 17, p. 2762, 2017.
- [41] A. Barrea, B. P. Delhay, P. Lefèvre, and J.-L. Thonnard, "Perception of partial slips under tangential loading of the fingertip," *Scientific Reports*, vol. 8, p. 7032, 2018.