An Elastomer-based Flexible Optical Force and Tactile Sensor

Wanlin Li[1], Jelizaveta Konstantinova[1], Yohan Noh[2], Zixiang Ma[3], Akram Alomainy[3],
Kaspar Althoefer[1]

***Abstract*— Tactile and force sensing devices that are capable to interactively explore the external environment have attracted a lot of research interest. Optical-based tactile sensors are becoming popular because they do not suffer from electromagnetic interference and because improved signal processing techniques enable intelligent sensor data classification. However, there is still no implementation of a sensor that measures both force and tactile information concurrently in an efficient manner in terms of material efficiency. In this research, we present a novel design for an elastomer-based tactile and force sensing device that senses both information within one elastomer. In addition, the tactile information is measured in the form of pressure distribution from the surface of objects. The proposed sensor has a soft and compliant design employing an opaque elastomer. The optical sensing method is used to measure both force and tactile information simultaneously based on the deformation of the reflective elastomer structure and a flexure structure. Here, we present the fabrication and development principles of the overall sensor. The experimental evaluation shows that the prototype is capable of sensing normal forces up to 70 N with an error of 6.6%.**

I. INTRODUCTION

Robotic research on dexterous manipulation is an important element in the development of robotic devices. Many tactile sensing devices [1] are developed to imitate human behavior to manipulate complex task. Since human hands have an extremely powerful preceptory system that can detect various tactile stimuli with the feedback of the contact from the fingers, tactile perception became an important aspect in robot sensing as it is used to convey information about the interaction of the physical body with the external world [2] [3] [4]. Moreover, the development of force and torque sensors is also an important aspect when creating flexible robot structures [5]. Such sensors are required to provide a means to measure forces and tactile information exerted on the body of a robotic structure during dexterous manipulation and navigation. Force and tactile information can be used to determine important mechanical properties of the target object, such as stiffness, shape, friction and geometry and texture of the surface. This information is essential for robot manipulation when providing feedback to the controller.

In past decades, most researchers have focused their efforts on vision due to the availability of well-designed computer vision systems and techniques [6]. Optical-based tactile and force sensors have become a topic of great interest due to today's availability of enhanced signal processing techniques and immunity from electromagnetic interference. A number of optical tactile sensors [7] [8] [9] that use soft materials as the sensing medium are being developed. Elastomeric materials provide compliance to the sensing devices, giving them an ability to conform to curved or irregular surfaces [10]. A compliant sensor is useful for manipulation such as grasping and object handling, with the acquired force and tactile information enhancing the grasping performance [11] [12]. For instance, the GelSight tactile sensor is a soft sensor that has the unique characteristic of being able to capture the geometry of the contact surface. Another device, TacTip sensor is composed of a silicone outer skin with internal nodule pins that enable the detection of edges and texture. These tactile sensors perceive contact pressure with high spatial resolution. However, the issue is that they cannot effectively measure the applied force magnitude, and can cope with maximum normal forces of approximately 30 N [13].

(a) (b)

Figure 1. The design of the elastomer-based flexible optical force and tactile sensor: a) manufactured prototype, and b) the design structure.

[1] Wanlin Li, Jelizaveta Konstantinova and Kaspar Althoefer are with the Centre for Advanced Robotics @ Queen Mary (ARQ), Queen Mary University of London, Mile End Road, London, E1 4NS, United Kingdom (phone: +44 (0)20 7882 3419; e-mail: k.althoefer@qmul.ac.uk).

[2] Yohan Noh is with Centre for Robotics Research (CoRe), King's College London, Strand, London, WC2R 2LS, United Kingdom (e-mail: yohan.noh@kcl.ac.uk).

[3] Zixiang Ma and Akram Alomainy are with the School of Electronic Engineering and Computer Science (EECS), Queen Mary University of London, Mile End Road, London, E1 4NS, United Kingdom (e-mail: a.alomainy@qmul.ac.uk).

In our previous work, we have proposed a force and tactile sensor that also uses a transparent elastomer to measure force information, as well as to record the contact surface pattern [14]. However, the pressure distribution from the tactile information of the irregular shape of an object in contact was not measured in our previous design. In this paper, we propose an optical-based force and tactile sensor design that uses a reflective soft opaque elastomer together with a flexible force sensitive structure (flexure) to obtain both normal force information and spatial pressure distribution simultaneously. The concept of measuring force information and tactile information in one sensor can be useful when connecting to a robot arm as an end-effector to provide feedback information. Our sensing device is easy to manufacture, and benefits from a wide measuring range of normal force. Moreover, the device is immune to electromagnetic interference, as it uses an elastomeric material, a 3D printed structure and a camera which is situated remotely, away from the sensing area.

We present the design and development process of the proposed sensor in Section II. Calibration and experimental evaluation processes are presented in Section III. Conclusions are drawn in Section IV.

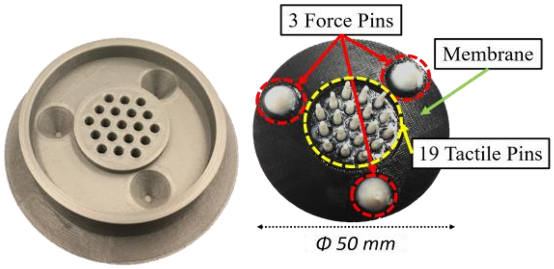
II. SENSOR DESIGN AND DEVELOPMENT

The overall design of the proposed optical-based force and tactile sensor is shown in Figure 1. The proposed sensor is composed of the following main components. The soft and flexible elastomer structure (1) is a core part of the sensor used to measure normal force as well as tactile information in the form of spatial pressure distribution. The elastomer is positioned on the 3D printed part – which is the flexure in our design (2) [15]. The flexure is acting like a spring mechanism due to an integrated cantilever structure (3) and is used for support and stabilization of the elastomer structure. In addition, it enables the required displacement for normal force measurements. A CCD camera (4) is used to capture the deformations of the elastomer, then converted to force and tactile information. In addition, a LED array (5) acts as an internal light source to sufficiently illuminate the elastomer via the light plate (6) for effective image capturing. The assembly of the sensor is completed with a top cap (7) to fix the elastomer, and a base part (8) to hold the structure together. The plastic components of the sensor are fabricated from ABS material using a 3D printer FDM360mc from Stratasys.

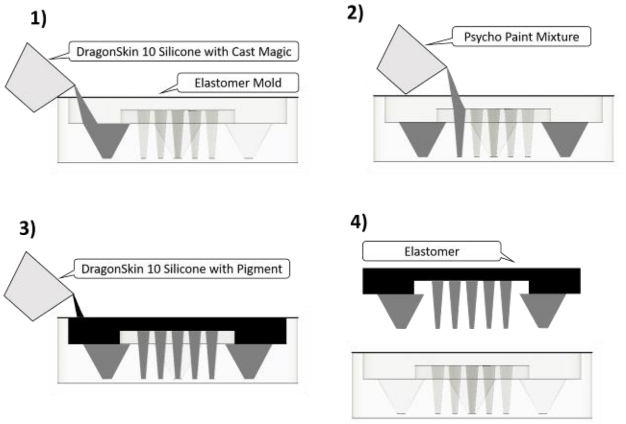
A. Design and Fabrication of Elastomer Structure

Soft, flexible elastomers are an important part of the sensor design. In our research, we use a special opaque and reflective elastomer material as the interface between the sensor and the environment to be measured. The elastomer structure is made of silicones of different types to distinguish between tactile and force information. Figure 2 (a) and (b) shows the produced elastomer structure together with its 3D-printed mold. Figure 2 (c) shows the fabrication process of the elastomer structure. The elastomer structure is composed of three parts, as it is shown in Figure 2 (b). Force pins are used to measure normal force information; tactile pins measure tactile information in the form of spatial pressure distribution, and a membrane is used as the medium for interaction with the environment. The elastomer structure is positioned on a 5 mm thickness transparent supporting plate made from an acrylics sheet (Figure 3 (a), (b)).

1) Pins for Normal Force Measurement. Three gray reflective conical pins are used to measure the normal force. Each pin has a height of 8 mm, a diameter of 11 mm at the base, and a diameter of 2 mm at the tip. The smaller surface of the pins is in contact with the acrylic support plate when at rest. The pins deform and are pushed towards the plate when an external force is exerted onto the sensor. The deformation capturing principle is further explained in Section II.B.



(a) Mold for the elastomer (b) Manufactured elastomer



(c) Fabrication of the elastomer

Figure 2. Elastomer description and its fabrication process.

TABLE I. ELASTOMER MATERIAL PROPERTIES

Property	**Silicone Material**	
	DragonSkin 10	***Psycho Paint***
Mix Ratio By Volume	1A:1B	1A:1B
Elongation at Break	1,000%	1,000%
Color	Translucent	Translucent
Shore Hardness	10 A	Not Given
Specific Gravity	1.07 g/cc	1.07 g/cc

We use silicone (DragonSkin10, Smooth-On, Inc.*)* with an addition of reflective powder (Cast Magic Silver Bullet, Smooth-On, Inc.*)* to fabricate the force pins (Figure 2 (c) 1). The reflective properties are required for efficient image capturing. The silicone material properties are shown in Table I. The silicone is prepared and mixed with a powder with a weight ratio of 50:1. Further on, the mixture is put into a conditioning planetary mixer (THINKY ARE-250) for mixing and degassing. Then we pour the resultant silicone mixture into the three conical holes of the mold. The curing process of force pins takes 5 hours.

2) Pins for Tactile Information. The tactile information is measured by nineteen gray reflective conical pins - The resultant output is presented in the form of spatial distributed pressure information. Each conical pin has a height of 11 mm, a diameter of 3 mm at the base, and a diameter of 1.25 mm at its tip. The pins are arranged in a honeycomb pattern underneath the membrane. The nineteen pins can be treated as a tactile sensing array with a spatial resolution of 5 mm × 5 mm. All pins are in contact with the acrylic supporting plate at the rest status and will deform when an external object is in contact with the elastomer membrane.

The measurement principle of tactile information is similar to the TacTip sensor [13], described in Section I. The TacTip sensor obtains tactile information from white circular markers on raised pins. However, the markers are not made from the reflective material, and they remain the same size for different pressure levels. In contrast, in our device, the pin deformation and the resultant diameter of the contact area with an acrylic supporting plate depends on the magnitude of the applied force. Therefore, we can capture different irregular 3D shapes and patterns observing the displacement of the silicone pins.

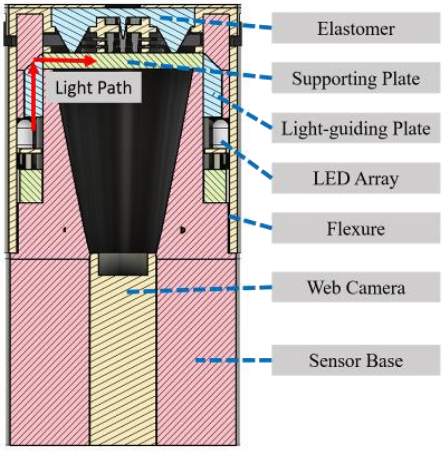
We use platinum color silicone (Psycho Paint, Smooth-On, Inc.) with an addition of reflective powder (Cast Magic Silver Bullet, Smooth-On, Inc.) to produce the tactile pins. The material properties of the used silicone are described in Table I. The fabrication process is similar to the creation of the force pins, and shown in Figure 2 (c) 2). Toluene (thinning agent) is added to the mixture to reduce the viscosity and to facilitate the pouring of silicone into the small holes of the mold.

3) Contact Membrane. The membrane is a touch interface in contact with the external environment; its making is the final step in the manufacturing of the elastomer structure. The membrane is fabricated from black silicone to block any interference from external light. The silicone (DragonSkin10, Smooth-On, Inc.) is mixed with black pigment (Silc Pig Black, Smooth-On, Inc.) at a ratio of 100:1. The mixture is degassed and poured into the mold to cure for 5 hours (Figures 2 (c) 3) and 4)).

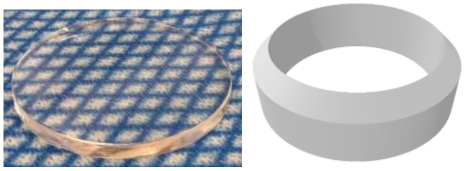
B. Illumination and Image Capture

Another key aspect in the sensing process is the way the elastomeric structure is illuminated. The illumination is implemented using an LED array in a closed environment, and the device is required for good quality image capturing. The array contains twelve white LEDs with an outer diameter of 5 mm and 30-degrees viewing angle. As shown in Figure 3 (a), the LED array is positioned inside the closed structure of the sensor. To ensure light guidance towards the elastomer structure, the light-guiding plate was designed and 3D printed with Veroclear material (Figure 3 (c)). It is a hollow structure with a 45°-edge at the top. The light travels through the light-guiding plate and is reflected from the top surface towards the center of the sensor – i.e. towards the transparent acrylic supporting plate. Thus, the reflective elastomer is illuminated as shown in Figure 3 (a). A USB camera (Microsoft LifeCam Studio), with a resolution of 640×480 pixels and a frame rate of 30 fps, is placed inside the sensor to capture the visible area of the elastomeric structure.

Once the sensor is switched on, the light information is transferred from the light source to the unloaded sensing element (elastomer structure) and then to the camera. The raw images are received by the camera, Figure 4 (a). As shown in the flowchart of Figure 5, the input image is converted to a grayscale format. Further on, it is split into four regions – one for tactile pins (200 × 200 pixels), and three for each of the force pins (80 × 80 pixels). To process tactile information, the tactile region is divided into 19 parts in a honeycomb pattern, each hexagon representing one sensing element. As a next step, the grayscale image is converted into a binary image, as shown in Figure 4 (b). For visualization purposes, a numeric display is used to show the force magnitude value for each pin. The magnitude is calculated from the quantity of black and white pixels in each region for force measurement, and in each hexagon for the tactile information. Once a force is applied, the pins are pushed towards the supporting plate and the pin contact area increases. Hence, the corresponding sensing area receives more activated pixels in the camera image, Figures 4 (c), (d). This sensing approach is a straightforward way to visualize the change of applied pressure and its distribution. The relationship between the number of activated pixels and applied force can be used to calibrate the sensor and measure force and tactile information. A mathematical model defines the change of contact area for both tactile and force pins. Additionally, we visualize the distribution of tactile information using a grayscale pressure colormap on a user interface.



(a) Schematic design of the proposed sensor



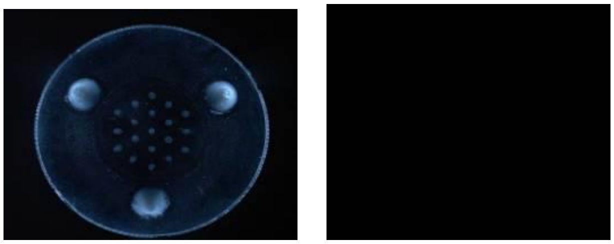
(b) Acrylic supporting plate (c) 3D view of light-guiding plate

Figure 3. Proposed force and tactile sensor illumination system.

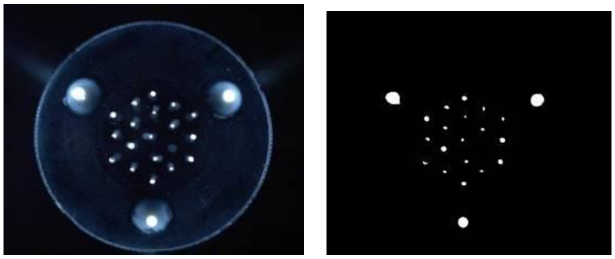
III. SENSOR CALIBRATION AND EVALUATION

A. Sensor Calibration for Normal Force

Calibration is required for accurate measurement of normal force in Z-direction. The aim of the calibration process is to obtain a relationship between the output, in the form of activated pixels of the three force pins shown in Figure 2(b), and normal forces. A set of weights, from 10 N to 70 N with increments of 5 N, is evenly applied on a plate above the the sensor as the normal forces, as it is shown in Figure 6. The sensor saturates after the maximum force of 70 N is applied. The test is repeated by ten times for each weight and the relationship between the applied force and the average number of activated pixels for each force pin is shown in Figure 7. A linear curve is fitted to each response, and the coefficients of the linear fitting curves ($y=Ax + B$) are shown in Table II. However, Pin 1 and Pin 3 don't really give a good linear response because of the fabrication error of both the elastomer and shell which are shown in Figure 1 (1) and (2) since the surface of the shell is not perfect aligned to the elastomer surface and the three force pins in Figure 2 (b) are not at the exact same heights.



(a) Unloaded camera image (b) Unloaded post-processed image



(c) Loaded camera image (d) Loaded post-processed image

Figure 4. Camera view and viewer tool illustrating the deformation of the reflective elastomer.

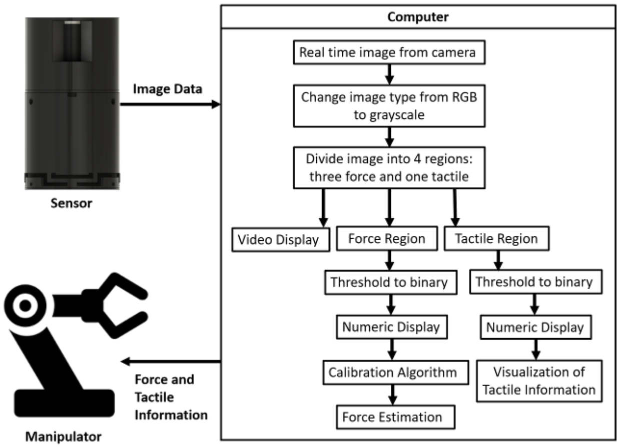


Figure 5. Flowchart of the proposed light intensity to force and tactile information sensing system. The system acquires the input video in 30 frame per second and all the image computations can be processed in real-time.

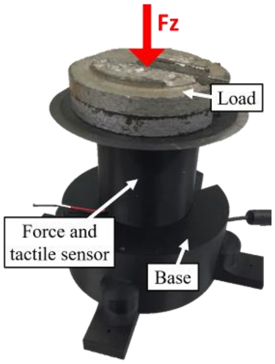


Figure 6. Experimental set up for the calibration of normal force *Fz*.

TABLE II. COEFFICIENT OF LINEAR FITTING CURVE

Sensor Element Number	Coefficients	
	A	***B***
1	9.764	-60.7
2	6.379	61.3
3	7.233	-162.3

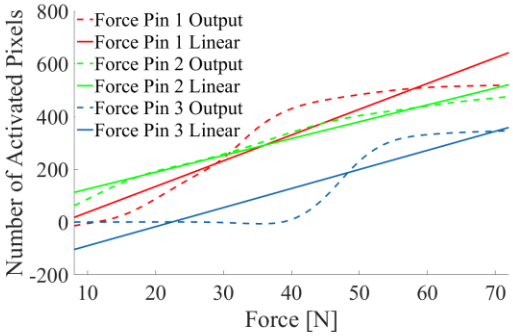


Figure 7. Characteristic curves of output activated pixels of force-element of the elastomer and its linear fitting.

Multiple Linear Regression (MLR) is applied to find the relationship between the number of activated pixels for each force pin. We assume that they are three independent variables, namely s_1, s_2, s_3, and the normal force F_z is the dependent variable. The obtained calibration curves are used to generate a 3×1 calibration matrix K. This matrix converts three numbers of activated pixels to one physical value of the normal force. By applying MLR, the matrix K is calculated as follows:

$$[k_1 \quad k_2 \quad k_3] \times \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = [F_z] \qquad (1)$$

$$K = [-0.0081 \quad 0.1375 \quad 0.0260] \qquad (2)$$

As shown above, the estimated normal force F_z can be obtained by multiplying the calculated calibration matrix with the sensor activated pixels s_1, s_2 and s_3.

B. Evaluation of Normal Force

To evaluate the performance of the calibration method, weights are used to gradually apply the increasing step-like force on the sensor. Figure 8 shows the sensor response for the weights ranging from 10 N to 70 N at increments of 5 N. We repeat the test for ten times and the maximum error between the estimated and the ground-truth normal force values does not exceed 6.6%, and the root mean square error (RMSE) is 2.25 N.

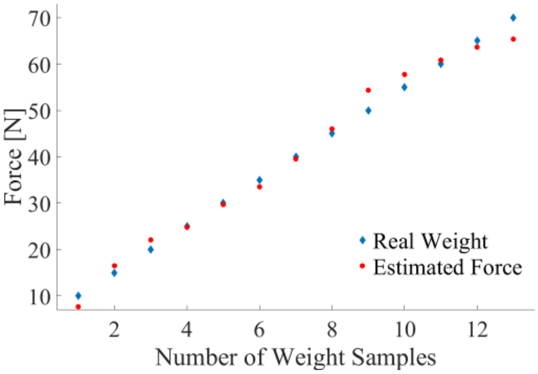


Figure 8. Static response of the sensor using weights for loading.

C. Visualization of Tactile Information

As described above, the pressure distribution is displayed using the information from the activated pixels of the tactile pins. Figure 9 shows the testing tools for tactile sensing and Figure 10 shows a user interface for the display of the tactile information. The grayscale pressure colormap is updated when an object comes into contact with the elastomer membrane. The magnitude of the pressure colormap is calculated using the maximum applied pressure (number of activated pixels) as a reference. Therefore, when no force is applied, the initial color is dark gray for all sections as the default value (Figure 10 (a)). To evaluate the tactile response, several shapes were tested. Firstly, we touch the side of the membrane with a sharp pin with 2 mm in diameter, and the result is shown in Figure 10 (b). It can be seen, that the color magnitude of the pressure colormap is updated, with white color indicating no contact, and black corresponding to the highest pressure magnitude. The second tested shape is an edge with the width of 1.5 mm. It was pressed at the center of the membrane. The result is shown in Figure 10 (c). Finally, pressure was applied onto the whole membrane surface. For this purpose, a finger was used in order to observe the irregular distribution of the pressure, the result is shown in Figure 10 (d).

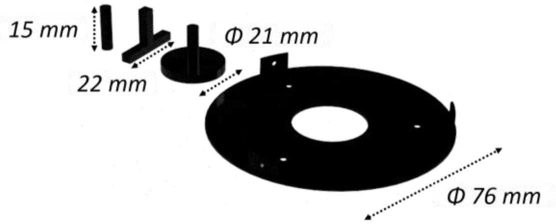
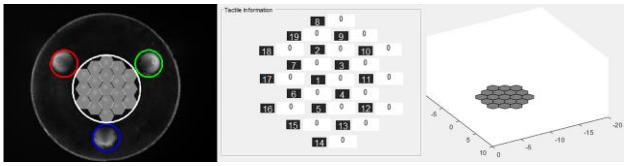
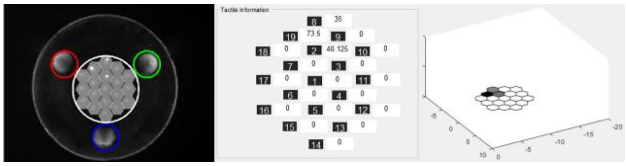


Figure 9. Three tools for tactile informtion tests with the reference of a sensor cap, one edge detection is tested by the left tool, section detection is tested by the middle tool and non-uniform detection is tested by the right tool which has a non-uniform surface at the bottom.


Tactile Information

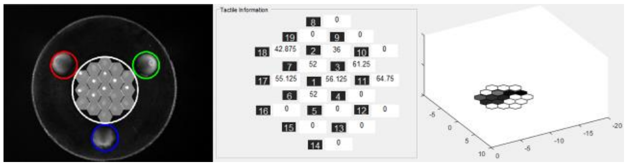
8	0
19	0
9	0
18	0
2	0
10	0
7	0
3	0
17	0
1	0
11	0
6	0
4	0
16	0
5	0
12	0
15	0
13	0
14	0

(a) No pressure is applied to the membrane.


Tactile Information

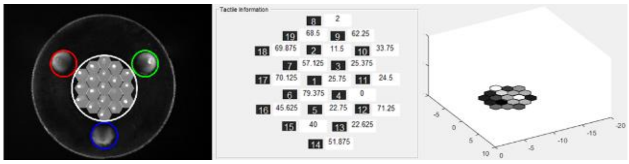
8	35
19	73.5
9	0
18	0
2	40.125
10	0
7	0
3	0
17	0
1	0
11	0
6	0
4	0
16	0
5	0
12	0
15	0
13	0
14	0

(b) Applying pressure at one edge of the membrane.


Tactile Information

8	0
19	0
9	0
18	42.875
2	36
10	0
7	52
3	61.25
17	55.125
1	56.125
11	64.75
6	52
4	0
16	0
5	0
12	0
15	0
13	0
14	0

(c) Applying pressure to the section of the membrane.


Tactile Information

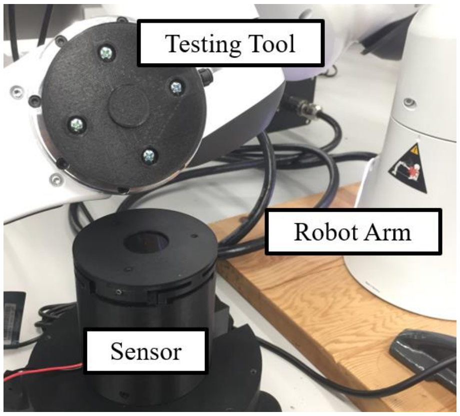
8	2
19	68.5
9	62.25
18	69.875
2	11.5
10	33.75
7	57.125
3	25.375
17	70.125
1	25.75
11	24.5
6	79.375
4	0
16	45.625
5	22.75
12	71.25
15	40
13	22.625
14	51.875

(d) Applying non-uniform pressure to the whole membrane.

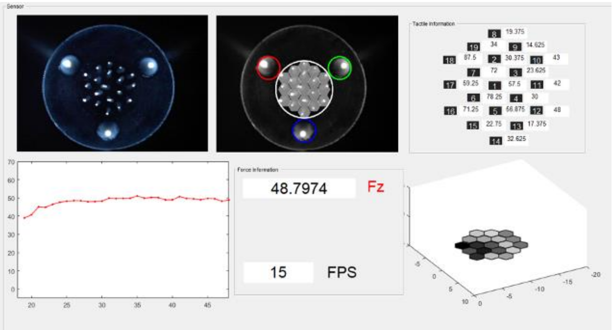
Figure 10. User display of the tactile information: different types of applied pressure. The left plots in (a) (b) (c) (d) are the post-processing images of the input videos. Three force pins are highlighted with red, green and blue circles. The white circle in the middle indicates 19 tactile pins which are allocated in a honeycomb arrangement. The middle plots indicate the areas of activated pixels (using Matlab function bwarea()) of each 19 tactile pins seperately. The right plots show the visulizations of the tactile information in form of pressure distributtion.

D. Simultaneous Force and Tactile Sensing

In this additional experiment, our sensor is used to measure real-time force and tactile information by attaching a flat surfaced object to the end-effector of Franka Emika Panda robot arm, as it is shown in Figure 11 (a). A normal force of 50 N was continuously applied to the membrane of the sensor via a Franka Emika Panda robot arm. In this experiment, our sensor has demonstrated its ability to measure the continuous and stable normal force over time, as well as to visualize the pressure distribution applied to the elastomer membrane.



(a) Experimental test set-up. A 3d printed object is attached on a Franka Emika Panda robot arm and then exerted on the top of the sensor.



8 19.375
19 34
9 14.625
18 87.5
2 30.375
10 43
7 72
3 23.625
17 59.25
1 57.5
11 42
6 78.25
4 30
16 71.25
5 56.875
12 48
15 22.75
13 17.375
14 32.625

48.7974 Fz

15 FPS

(b) User interface illustrating the sensor can measure the realtime normal force and the pressure distribution (tactile information) simutanously.

Figure 11. A scene of measureing both force information and tactile information using 3D printed object attached on a robot arm and the corresponding live user interface display.

IV. DISCUSSION AND CONCLUSION

In this paper, we propose a novel design of a prototype of force and tactile sensor using a soft structure made form elastomeric material shaped into reflective pins to sense both force and tactile information. The fabrication procedure uses different types of silicone materials and other required components are presented. The experimental results demonstrate that the sensor can measure real-time normal forces over a range from 0N to 70 N. The pressure distribution can be visualized at the same time. In the proposed configuration, the sensor can only measure force along one dimension. However, theoretically a 3×3 calibration matrix can be calculated for the measurement of additional two moments in lateral directions, *Mx* and *My*, depending on the three-degree of freedom of the shell design. We intend to build a customized calibration device using a commercial force sensor, as well as to apply deep learning methods for calibration. In future work, we plan to improve and formally assess the sensor characteristics (such as error, crosstalk, hysteresis). We also plan to provide feedback control to the robot arm by connecting the sensor data together with the Franka Emika Panda robot arm.

ACKNOWLEDGMENT

This work was supported in part by the EPSRC National Centre for Nuclear Robotics project (EP/R02572X/1), the Innovate UK WormBot project (104059) and the Innovate UK project iGrasp (103676).

REFERENCES

[1] H. Yousef, M. Boukallel and K. Althoefer. Tactile sensing for dexterous in-hand manipulation in ro-botics—A review. In Sensors and Actuators A: physical, 167(2): 171-187, 2011.

[2] J. Konstantinova, A. Stilli and K. Althoefer. Fingertip Fiber Optical Tactile Array with Two-Level Spring Structure. In Sensors 17(10), 2337, 2017.

[3] A. Yamaguchi and C. Atkeson. Implementing tactile behaviors using FingerVision. In 2017 IEEE-RAS 17th International Conference on Humanoid Robotics (Humanoids), pp. 241-248, 2017.

[4] C. Oddo, L. Beccai, G. Muscolo, and M. Carrozza. A biomimetic MEMS-based tactile sensor array with fingerprints integrated in a robotic fingertip for artificial roughness encoding. In IEEE International Conference on Robotics and Biomimetics, 2009.

[5] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker. Soft robotics: Biological inspiration, state of the art, and future research. In Appl. Bionics Biomech., vol. 5, pp. 99 - 117, 2008.

[6] G. Metta, and P. Fitzpatrick. Early integration of vision and manipulation. In Adaptive Behavior, 2003, 11(2): 109–128.

[7] M. Ohka, Y. Mitsuya, I. Higashioka and H. Kabeshita. An experimental optical three-axis tactile sensor for micro-robots. In Robotica 23, 457-465, 2005.

[8] W. Yuan, R. Li, M.A. Srinivasan and E.H. Adelson. Measurement of shear and slip with a GelSight tactile sensor. In 2017 IEEE International Conference on Robotics and Automa-tion (ICRA), pp. 304-311, 2015.

[9] L. Cramphorn, J. loyd and N.F. Lepora, Voronoi Features for Tactile Sensing: Direct Inference of Pressure, Shear, and Contact Locations. In 2018 IEEE International Conference on Robotics and Automation (ICRA), pp. 2752-2757, 2018.

[10] G. Obinata, T. Kurashima, and N. Moriyama. Vision-based tactile sensor using transparent elastic fingertip for dexterous handling. In International Symposium on Robotics, volume 36, page 32, 2005.

[11] H Xie, A Jiang, L Seneviratne and K Althoefer. Pixel-based optical fiber tactile force sensor for robot manipulation. In Proceedings of the 2012 IEEE Sensors, pp. 1-4, 2012.

[12] J.W. James, N. Pestell and N.F. Lepora, Slip detection with a biomimetic tactile sensor. In IEEE Robotics and Automation Letters, pp. 3340-3346, 2018.

[13] B. Winstone, G. Griffiths, T. Pipe and J. Rossiter. TACTIP—Tactile fingertip device texture analysis through optical tracking of skin features. In Biomimetic Biohybrid Systems, pp. 323-334, 2013.

[14] W Li, J. Konstantinova, Y. Noh, A. Alomainly and K. Althoefer. Camera-based force and tactile sensor. In Annual Conference Towards Autonomous Robotic Systems (TAROS), pp. 438-450. 2018.

[15] Y. Noh, J. Bimbo, S. Sareh, H. Wurdemann, J. Fras, D. S. Chathuranga, H. Liu, J. Housden, K. Althoefer and K. Rhode. Multi-axis force/torque sensor based on simply-supported beam and optoelectronics. In Sensors 2016, vol. 16, no. 11, p.1936, 2016.