Low-cost GelSight with UV Markings: Feature Extraction of Objects Using AlexNet and Optical Flow without 3D Image Reconstruction

Alexander C. Abad[1,2], Anuradha Ranasinghe[1]

***Abstract*— GelSight sensor has been used to study microgeometry of objects since 2009 in tactile sensing applications. Elastomer, reflective coating, lighting, and camera were the main challenges of making a GelSight sensor within a short period. The recent addition of permanent markers to the GelSight was a new era in shear/slip studies. In our previous studies, we introduced Ultraviolet (UV) ink and UV LEDs as a new form of marker and lighting respectively. UV ink markers are invisible using ordinary LED but can be made visible using UV LED. Currently, recognition of objects or surface textures using GelSight sensor is done using fusion of camera-only images and GelSight captured images with permanent markings. Those images are fed to Convolutional Neural Networks (CNN) to classify objects. However, our novel approach in using low-cost GelSight sensor with UV markings, the 3D height map to 2D image conversion, and the additional non-Gelsight captured images for training the CNN can be eliminated. AlexNet and optical flow algorithm have been used for feature recognition of five coins without UV markings and shear/slip of the coin in GelSight with UV markings respectively. Our results on confusion matrix show that, on average coin recognition can reach 93.4% without UV markings using AlexNet. Therefore, our novel method of using GelSight with UV markings would be useful to recognize full/partial object, shear/slip, and force applied to the objects without any 3D image reconstruction.**

I. Introduction

GelSight sensor is a decade old technology invented by Johnson and Adelson [1] that has proven its worth in the world of haptics and tactile sensing applications. It evolved from the bulky cubic box structure with a side length of 30-cm [1] to a portable configuration made of acrylic tube (3-in. diameter, 8-in. long) presented in [2]–[4]. A miniaturized cubic fingertip GelSight sensor with a 3-cm side length was presented in [5] This fingertip GelSight sensor was later enhanced using better lighting and casing as presented in [6]. The latest iteration on GelSight sensor physical structure was introduced in [7] known as the GelSlim and was further improved in GelSlim 2.0 with a more robust design, parametrically adjustable, and better illumination [8].

GelSight sensor has four basic components according to Jia et al. [2]: 1) clear elastomeric slab with a reflective coating on one side, 2) transparent glass or acrylic plate support for the slab, 3) uniform and controlled lighting usually provided by Light Emitting Diodes (LED), and 4) camera or webcam at the back of the supporting plate to capture the impressed image on the slab [1], [9]. Current GelSight elastomers are created in the laboratory by using thermoplastic elastomer (TPE) which requires an oven to melt in a mold or silicones made by two separate liquid parts that form a firm gel when mixed [10]. Three major challenges in creating a clear elastomer are the long curing time of about six or seven hours [10], quality consistency [11], and the formation of air bubbles within a gel that needs vacuum pump for degassing [10]–[13]. Aside from these challenges, GelSight sensor elastomer can be easily damaged during contact-rich manipulation tasks such as grasping [14]. Long hours of curing time and complex process related to making clear elastomer slab can be skipped using commercial off-the-shelf (COTS) clear silicone cosmetic sponge [15] as shown in Fig. 1.

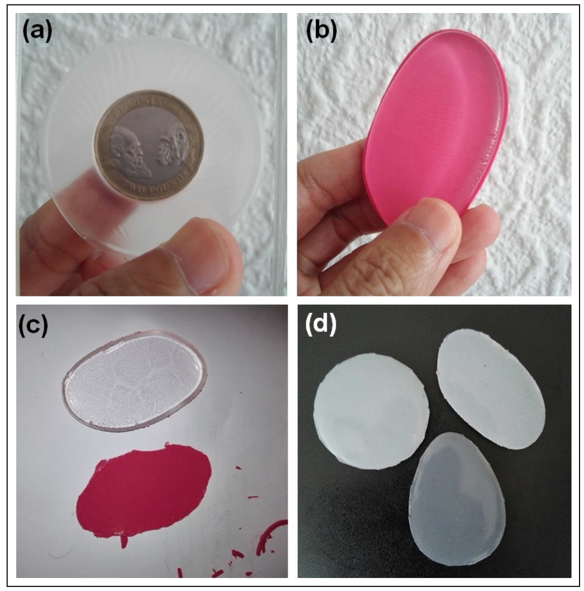

Fig. 1: Commercially available silicone cosmetic sponge: (a) Transparent silicone sponge: (b) silicone sponge with pink cushion, (c) pink cushion can be easily removed by cutting the edges of the sponge, and d) silicon sponges in different shapes and sizes painted with a reflective coating on one side.

[1] Alex, and Anuradha are with the School of Mathematics, Computer Science and Engineering, Faculty of Science, Liverpool Hope University Hope Park — Liverpool L16 9JD. UK. abada@hope.ac.uk; dissana@hope.ac.uk

[2] Alex is also with the ECE Department, Gokongwei College of Engineering, De La Salle University, Manila, Philippines alexander.abad@dlsu.edu.ph

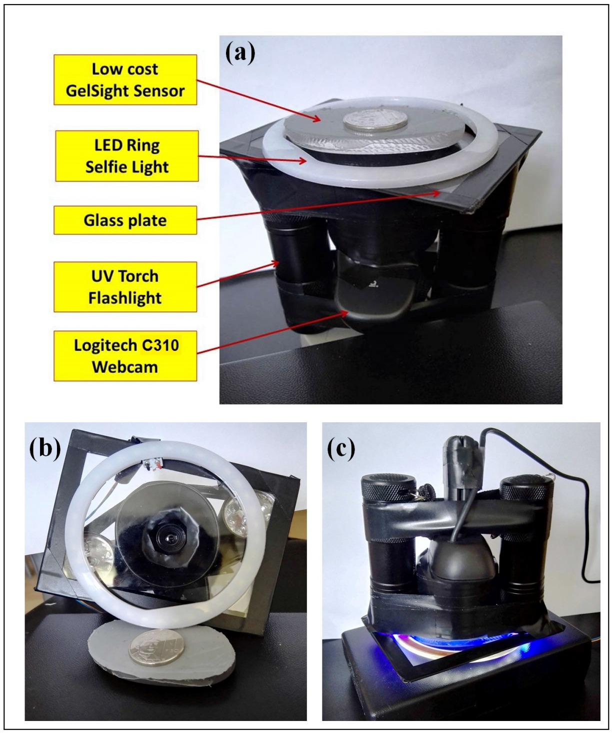

Fig. 2: GelSight prototype 1 with coin sample on top: (a) It is composed of the low cost GelSight with white selfie ring LEDs. This ring LED has three levels of brightness. UV torch flashlights are used to illuminate the UV markings. GelSight sensor is supported by clear glass and a webcam is on other side of the glass with a distance of 2 inches, (b) Front view of the prototype, and (c) Prototype 1 is pressed down on the coin sample with White LEDs and UV lights.

Current GelSight sensors can be divided into two categories: with and without permanent grid dots or markers. GelSight sensor used in the measurement of surface texture [1] and microgeometry [9], lump detection [2], and tactile mapping and localization [16] do not use grid dots while GelSight sensor used in the measurement of shear and slip [6], [7], [17]–[19] used the permanent markers in the elastomer. The use of permanent markers in the GelSight sensor was first introduced by Yuan et al. [10].

It was reported by Li and Adelson in [4] that surface textures can be sensed and recognized using the portable GelSight sensor presented in [9]. The actual GelSight images they got are 3D height maps. They proposed a multi-scale local binary pattern (MLBP) algorithm and have devised a simple yet effective texture recognition system that can correctly categorized materials with high accuracy. But in the process, they converted the GelSight 3D height maps to 2D gray images by using brightness levels to represent the height information. According to Li and Adelson, while there is a clear distinction between 2D visual textures such as those in the Outex databases and the 3D surface textures in

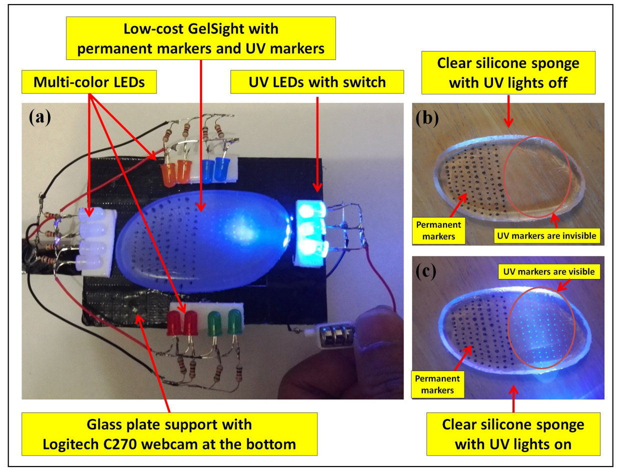

Fig. 3: GelSight prototype 2: (a) The sensor was inverted to show that UV markers can be seen when the UV LEDS are on, (b) clear silicone sponge with UV lights off making the UV markers invisible, and (c) clear silicone sponge with UV lights on showing the UV markers.

GelSight, the basic principle of texture classification remains the same [4].

GelSight sensor with permanent markers can be used to measure microgeometry through photometric stereo algorithm and measure slip through the tracking of permanent markers [6], [17]. But the introduction of permanent markers in the reflective coating of GelSight might obscure some important image features that might be helpful for object recognition through 2D image processing such as textile type recognition based on weave patterns.

Permanent markers might be treated as noise that negatively affects some important 2D image features especially if these markers are bigger than the image features [17]. This issue can be observed in the images presented in [20]–[22] where the GelSight sensor with permanent markers was used in cloth or textile characterization. Moreover, increasing the density of markers affects the capability of the GelSight sensor to measure contact surfaces height map [18].

In our recent work, we presented a new type of GelSight markers using ultraviolet (UV) ink that can be made visible or invisible by switching on or off the UV light [15]. In one grip or in one press of GelSight sensor, we can recognize object through 2D image feature extraction and study shear and slip without changing the sensor. We demonstrate this by using the GelSight sensor to recognize five different coins One Peso old (1PHO), One Peso new (1PHN), One Pound UK (1UK), Five Peso (5PH), and Ten Peso (10PH) using Convolutional Neural Network (CNN) named AlexNet [23]. As UK coins images is limited to a same image, we have used one coin (one pound) from UK and four coins (one peso old, one peso new, five peso, and ten peso) from the Philippines. By simply turning on the UV light, UV markers can be tracked using optical flow algorithm that

Fig. 4: Five coin samples with different faces are used to test the coin recognition algorithm: (a) One Peso old (1PHO), (b) One Peso new (1PHN), (c) One Pound UK (1UK), (d) Five Peso (5PH), and (e) Ten Peso (10PH)

shows patterns for shear or slip in the form of flow vector arrows.

This paper is structured as follows: experimental setups are discussed in section II, evaluation of results in section III followed by conclusion and recommendation in section IV.

II. Experimental Setups

Two experimental setups using low-cost GelSight sensor made from COTS silicone sponges are shown in Fig. 2 and Fig. 3. Detailed construction of prototype 2 has been discussed in our previous studies [15]. Prototype 1 is similar to prototype 2 in terms of the basic construction materials. Details on the construction materials and some differences between the two prototypes are as follows:

A. Elastomer slab with reflective coating and UV marking

Both prototypes used the same commercially available silicone sponge as their elastomer slab. Peeled silicone sponge (please see Fig. 1c) was marked with UV dots using COTS UV pen [24] before painted with a reflective coating from Smooth-On Inc. [25]. To create a gray color similar to aluminum, we mixed white and black pigments of Silc Pig™ [26]. Then, we diluted the Psycho Paint® with pigment using Novocs™ Matte [27] and used an airbrush to spray the mixture on the silicone sponge as shown in Fig. 1d.

B. Lighting

White ring LED selfie light used in mobile phones was mounted in prototype 1 as shown in Fig. 2a. This lighting provided the uniform and controlled lighting in the elastomeric slab. Prototype 1 used only white light like the GelSlim [7] which used two neutral white, high-powered, and surface-mount LEDs (OSLON SSL 80) on each side of the finger. All the other GelSight sensor structures have used multicolored lighting. In order to make the UV markers visible in prototype 1, two UV torch flashlights were attached on the sides of the webcam as shown in Fig. 2c.

On the other hand, multi-color LEDs positioned at different locations ready for photometric stereo technique were mounted on prototype 2 as shown in Fig. 3. According to Yuan [10], there are two ways to get differentiated illumination needed for 3D image reconstruction: 1) switching different LEDs positioned at different locations and take separate pictures of the same scene, and 2) using multi-color LEDs simultaneously and take a single picture; reflection of different color LEDs can be known by taking different channels of the color image. Aside from multi-color LEDs, UV LEDs were also used in prototype 2 as shown in Fig. 3. UV LEDs can be switched on to show the presence of UV markings in the reflective coating.

C. Camera

Prototype 1 used Logitech C310 which has 5 megapixel (MP) resolution while prototype 2 used Logitech C270 which has only 3 MP resolution [28]. Although it has been stated in Logitech website that both webcams have fixed focus with the help of [29], we managed to adjust the focus manually. We obtained a clear image even at 1.5-in. distance from the camera using Logitech C270. Prototype 1 has a focus distance of 2-in. to provide a wider field of view compared to prototype 2.

D. Software

We used two software platforms: MATLAB 2019 (The MathWorks Inc.) on which AlexNet [23] was used for coin recognition, and Python 3.6 with the OpenCV library for optical flow algorithm [30].

1) Coin Recognition:

According to [23], AlexNet is a convolutional neural network that is trained on more than a million images from the ImageNet database. The network is 8 layers deep and it could be used to classify images into 1000 object categories such as keyboard, mouse, pencil, and many animals. As a result, the network has learned rich feature representations for a wide range of images. The network has an image input size of 227x227. This will enable AlexNet to perform classification on new image collections.

In this study, five coin samples with different faces as shown in Fig. 4 were used to test the coin recognition algorithm. We captured 500 images for each coin using our GelSight sensor prototypes 1 and 2 as shown in Fig. 2

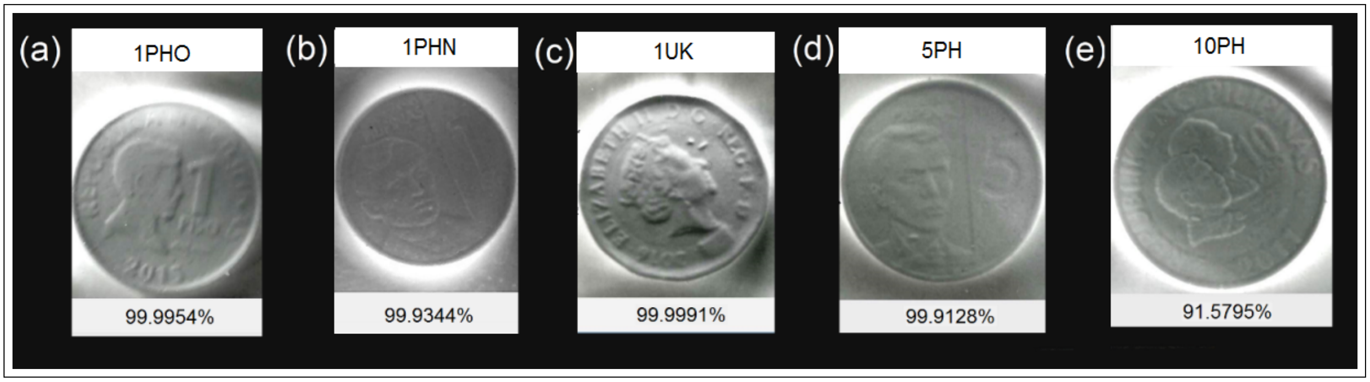

Fig. 5: Results using prototype 1: Results from coin recognition: (a) One Peso old (1PHO), (b) One Peso new (1PHN), (c) One Pound UK (1UK), (d) Five Peso (5PH), and (e) Ten Peso (10PH). Percent (%) probability for classification is shown below on every coin image.

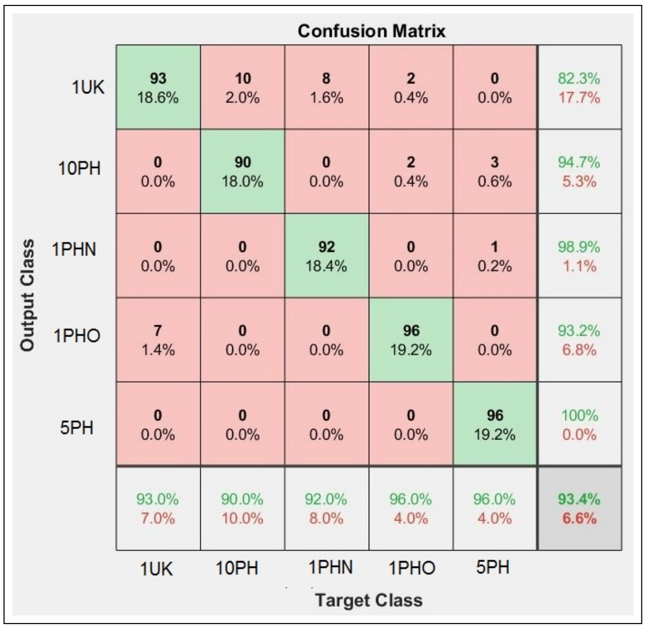

Fig. 6: Confusion matrix for five coins shown in Fig. 4 recognition using AlexNet. Here feature extraction was done without UV markings

and Fig. 3 respectively. Captured data were used to re-train AlexNet to classify five coins.

2) Slip and Shear Visualization using Optical Flow:

After using GelSight sensor for coin recognition, we turned on the UV markers by turning on the UV LEDs. We tracked the UV markers using the optical flow algorithm discussed in [30]. We also used blob detection [31] to detect the markers and morphological image processing then we applied Lucas-Kanade [32], [33] method optical flow algorithm. According to Yuan et al. [18], the displacement field can be derived by measuring the displacement of the markers. Moreover, the displacement of the markers is obtained by comparing the positions of the markers in different frames. The displacement field of the GelSight sensor can be visualized using vector arrows indicating magnitude and direction of force inferred from the makers' displacement.

III. Evaluation of Results

In this paper, we present GelSight sensor with UV markings. We present our results from prototype 1 and prototype 2. GelSight prototype 1 was used for full feature extraction of the coins. GelSight prototype 2 was used to feature extraction of a partial image of the coin.

1) Prototype 1:

Results from coin recognition using AlexNet without UV markings are shown in Fig. 5. Prototype 1 has a wider field of view capable of capturing the whole coin with a diameter of 3 cm. On the other hand, prototype 2 has only a capture area of 2 cm x 2 cm.

Feature extraction has been done using prototype 1. We managed to extract features and recognize five coins with (93.4%) mean accuracy. However, when two faces are presented on the coin, accuracy of recognition went down to 90% as shown in confusion matrix in Fig. 6. AlexNet in CNN has been treated as an algorithm to extract features. We relied on black-white 2D images on coin recognition. Therefore, the authors argued that object recognition in GelSight can be done without 3D image reconstruction in previous studies [6], [16], [17]. This simple mechanical filter without any electronics, objects recognition can be achieved. Therefore, the morphology of objects can be studied using only a GelSight embedded with optics without using any 3D image reconstructions.

2) Prototype 2:

Prototype 2 was used to test whether our novel GelSight with UV markings can be used to recognize partial image of objects. The results of prototype 2 are shown in Fig. 7. Partial image of One Pound (UK) can still be correctly classified with 85.1718% probability as shown in Fig. 8a.

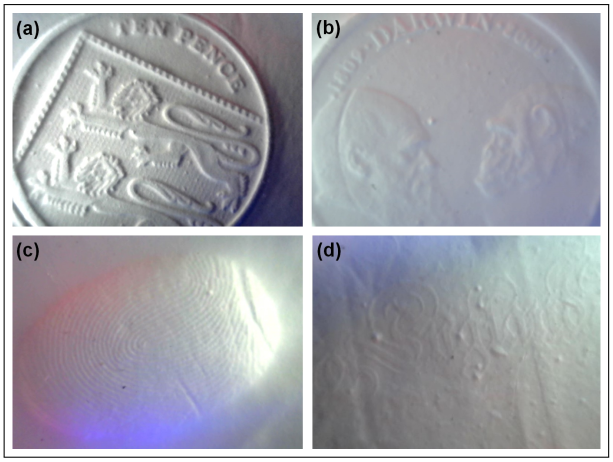

Fig. 7: Results using prototype 2: (a) ten pence (10pUK) coin marking, (b) two pound (2UK) marking with the face of Darwin, (c) fingerprint marking, and (d) Banknote marking.

We introduced in our previous studies [15] UV ink as a new form of GelSight marking. UV ink markings are invisible to ordinary LEDs. We used UV LEDs to see the UV markings. When we want to study shear and slip, we need markers to track the deformation in the reflective coating. Instead of the black and permanent markers used by Yuan et al. [10], [18], UV markers were used in this study. UV markers can be seen using UV light as shown in Fig. 3c and Fig. 8b. When we want to study texture and microgeometry, we do not need the markers. We turned off the UV light and the UV markers became invisible. The result was like the typical image produced by GelSight sensor as shown in Fig. 8a. When we want to study shear and slip, we need to track the UV markers with algorithms such as optical flow.

Aside from the partial coin recognition, prototype 2 was used to study slip/shear and force from the object using an optical flow algorithm. Our novel UV markers have been taken into account how to make an optical flow vector. The results showed that optical flow vector could be used to infer slip/shear, magnitude, and direction of the applied force to the coin pressed towards the elastomer as shown in Fig. 8c and Fig. 8d. The greater the force applied to the coin, the longer the length of the arrow in the direction of the applied force. Moreover, a torque or rotational force can also be tracked and visualized. UV makers' displacement field of the fingertip twisting the elastomer in anticlockwise and clockwise direction are shown in Fig. 8e and Fig. 8f respectively. Detailed analysis on how to analyze shear and slip based on GelSight sensor markers' displacement field has been reported by Yuan et al. [18]. Moreover, inverse Finite Element Method (iFEM), a numerical method to reconstruct the contact force distribution based on marker displacements has been proposed by Ma et al. in [8].

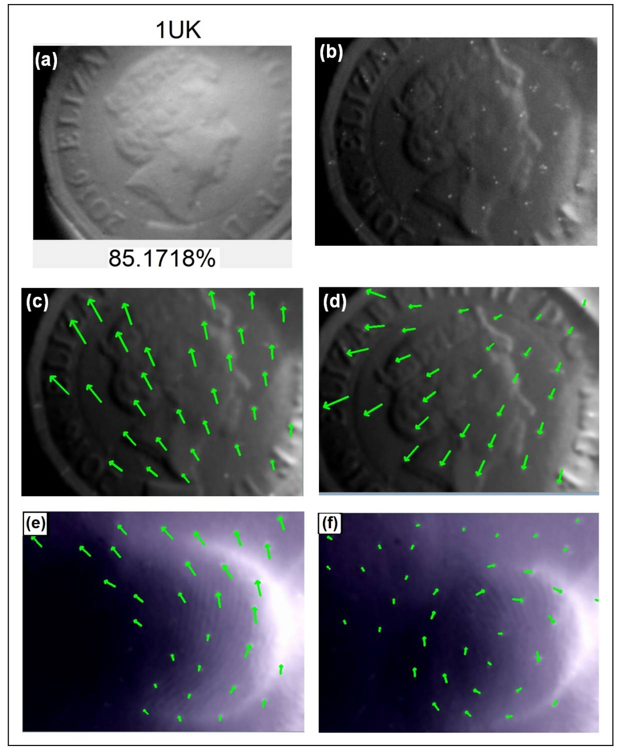

Fig. 8: Results using Prototype 2: a) Partial coin recognition with 85.1718% probability classification, b) UV markers are lit up using UV light, c) UV markers are tracked using optical flow algorithm and the flow vectors shown are in upward direction, (d) with downward optical flow vectors. The optical flow vectors represent the movement of how the coin was pushed on the GelSight sensor. (e) UV markers are detected by optical flow algorithm with on object. The direction of fingertip twisting is shown by a swirl in counterclockwise, and (f) The direction of fingertip is clockwise direction.

IV. Conclusion and Recommendation

In this study, we presented two prototypes that use low-cost GelSight with UV markings made from COTS cosmetic silicone sponge. In creating our prototypes, we skipped the degassing process in creating clear silicone slab and the long hours of curing time. We demonstrated using our prototypes coin recognition using full and partial coin images without 3D image reconstruction or permanent markings. Moreover, we used UV markings to visualize slip, shear, and applied force in the form of flow arrow vectors generated by optical flow algorithm. Switching the UV light, UV markers would become visible. To the best of our knowledge, this is the first to present the use of UV markers to study slip/shear and applied force from object on GelSight. Therefore, we claim in this study, we can do object recognition and slip/shear analysis without 3D image reconstruction using in-house low-cost GelSight sensor with UV markings and optical flow algorithm. We will bring this idea forward to study how to embed low-cost GelSight with UV markings in telerobotics.

This would be useful in many applications, in particular quality testing of material like a piece of fabric or paper, virtual surgery, and remote sensing.

ACKNOWLEDGMENT

The authors would like to thank: Liverpool Hope University, De La Salle University - Manila, and DOST-ERDT for helping us in this study.

REFERENCES

[1] M. K. Johnson and E. Adelson, "Retrographic sensing for the measurement of surface texture and shape," in Computer Vision and Pattern Recognition (CVPR), 2009 IEEE Conference on. IEEE, 2009, pp. 1070-–1077.

[2] X. Jia, R. Li, M. A. Srinivasan, and E. H. Adelson, "Lump detection with a gelsight sensor," in World Haptics Conference (WHC), 2013. IEEE, 2013, pp. 175—179.

[3] M. K. Johnson, F. Cole, A. Raj, and E. H. Adelson, "Microgeometry capture using an elastomeric sensor," in TOG, vol. 30, no. 4. ACM, 2011, p. 46.

[4] R. Li and E. Adelson, "Sensing and recognizing surface textures using a gelsight sensor," in Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 2013, pp. 1241-–1247.

[5] R. Li, R. Platt, W. Yuan, A. ten Pas, N. Roscup, M. A. Srinivasan, and E. Adelson, "Localization and manipulation of small parts using gelsight tactile sensing," in Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on. IEEE, 2014, pp. 3988–3993.

[6] S. Dong, W. Yuan, and E. Adelson, "Improved GelSight tactile sensor for measuring geometry and slip," IROS, 2017.

[7] E. Donlon, S. Dong, M. Liu, J. Li, E. Adelson, A. Rodriguez, "GelSlim: A High-Resolution, Compact, Robust, and Calibrated Tactile-sensing Finger," IROS 2018: 1927–1934.

[8] D. Ma, E. Donlon, S. Dong, A. Rodriguez, "Dense Tactile Force Estimation using GelSlim and inverse FEM," 2019 International Conference on Robotics and Automation (ICRA) Palais des congres de Montreal, Montreal, Canada, May 20-24, 2019, pp. 5418-5424.

[9] M. K. Johnson, F. Cole, A. Raj, and E. H. Adelson, "Microgeometry capture using an elastomeric sensor," in TOG, vol. 30, no. 4. ACM, 2011, p. 46.

[10] W. Yuan, "Tactile measurement with a gelsight sensor," Master's thesis, MIT, Cambridge, MA, USA, 2014.

[11] R. Li, "Touching Is Believing: Sensing and Analyzing Touch Information with GelSight," Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2015.

[12] W. Li, J. Konstantinova, Y. Noh, A. Alomainy, K. Althoefer, "Camera-based force and tactile sensor." Towards Autonomous Robotic Systems: 19th Annual Conference, TAROS 2018, Bristol, UK July 25-27, 2018, Proceedings. Vol. 10965 LNAI, pp. 438–450.

[13] Available online: https://www.smooth-on.com/support/faq/198/ (accessed on 13 March 2019).

[14] K. Takahashi, J. Tan, "Deep Visuo-Tactile Learning: Estimation of Tactile Properties from Images," 2019 International Conference on Robotics and Automation (ICRA) Palais des congres de Montreal, Montreal, Canada, May 20-24, 2019, pp. 8951-8957.

[15] A. C. Abad, D. Reid, A. Ranasinghe, "Pilot Study: Low Cost GelSight Sensor," Workshop on ViTac: Integrating Vision and Touch for Multimodal and Cross-modal Perception, ICRA 2019 ViTac Workshop Accepted paper, http://wordpress.csc.liv.ac.uk/smartlab/icra-2019-vitac-workshop-accepted-papers/

[16] M. Bauza, O. Canal and A. Rodriguez, "Tactile Mapping and Localization from High-Resolution Tactile Imprints," 2019 International Conference on Robotics and Automation (ICRA) Palais des congres de Montreal, Montreal, Canada, May 20-24, 2019, pp. 3811-3817.

[17] W. Yuan, S. Dong, and E. H. Adelson, "GelSight: High resolution robot tactile sensors for estimating geometry and force," Sensors, vol. 17, no. 12, p. 2762, 2017.

[18] W. Yuan, R. Li, M. A. Srinivasan, and E. H. Adelson, "Measurement of shear and slip with a gelsight tactile sensor," in Robotics and Automation (ICRA), 2015 IEEE International Conference on. IEEE, 2015, pp. 304—311.

[19] J. Li, S. Dong, E. Adelson, "Slip Detection with Combined Tactile and Visual Information," ICRA 2018: 7772-7777, arXiv:1802.10153.

[20] W. Yuan, Y. Mo, S. Wang, E. H. Adelson, "Active Clothing Material Perception Using Tactile Sensing and Deep Learning," ICRA 2018: 1–8.

[21] S. Luo, W. Yuan, E. Adelson, A. Cohn and R. Fuentes, "ViTac: Feature Sharing between Vision and Tactile Sensing for Cloth Texture Recognition", IEEE International Conference on Robotics and Automation (ICRA), 2018.

[22] J. Lee, D. Bollegala, S. Luo, " "Touching to See" and "Seeing to Feel": Robotic Cross-modal Sensory Data Generation for Visual-Tactile Perception," 2019 International Conference on Robotics and Automation (ICRA) Palais des congres de Montreal, Montreal, Canada, May 20-24, 2019, pp. 4276-4282.

[23] "AlexNet", https://ww2.mathworks.cn/help/deeplearning/ref/alexnet.html (accessed on 12 September 2019)

[24] "Kids Spy Pen Invisible Ink & UV Light Write & Read Secret Messages Cheap Gift," Available online: https://www.ebay.co.uk/i/201080338369?chn=ps&var=500259631132 (accessed on 13 March 2019)

[25] Available online: https://www.smooth-on.com/products/psycho-paint/ (accessed on 09 September 2019)

[26] Available online: https://www.smooth-on.com/products/silc-pig/ (accessed on 09 September 2019)

[27] Available online: https://www.smooth-on.com/products/novocs/ (accessed on 09 September 2019)

[28] Available online: https://kagoo.co.uk/webcams/compare/logitech-c270-vs-logitech-c310(accessed on 09 September 2019)

[29] Logitech c270 focus adjustment, Available online: https://www.youtube.com/watch?v=v-gYgBeiOVI (accessed on 13 March 2019)

[30] Optical Flow, Available online: https://docs.opencv.org/3.4/d4/dee/tutorial_optical_flow.html(accessed on 09 September 2019)

[31] Blob Detection, Available online: https://www.learnopencv.com/blob-detection-using-opencv-python-c/(accessed on 09 September 2019)

[32] B. D. Lucas, T. Kanade, "An iterative image registration technique with an application to stereo vision," In IJCAI, volume 81, pages 674-679, 1981.

[33] S. Baker, I. Matthews, "Lucas-kanade 20 years on: A unifying framework," International journal of computer vision, 56(3):221-255, 2004.