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Development of a low-cost Gelsight Sensor for surface geometry extraction and detecting the direction of motion of an object

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1. ABSTRACT

The observation of the geometry of an object and its direction of motion is important in robotics to localize and manipulate objects accurately. Typically, this can be achieved only by using a camera. However, the gathered information on the geometry and motion of objects is limited to the 2D space in this approach. Instead of using this approach, a new approach is proposed in this work to observe the geometry and direction of motion of objects using recently developed high-resolution tactile sensor technology known as Gelsight. In this approach, gathered geometry information is not limited to 2D space, and its depth information is indicated by the deformation of the contact surface. In this research, a Gelsight sensor was made using inexpensive materials, and the geometry of small objects was observed. Moreover, code-wise generated dot patterns were used to track the motion of objects. According to the results of this work, the geometry of small objects can be captured with 66.67% accuracy using the developed low-cost Gelsight sensor and computer vision algorithms. Furthermore, the results show the possibility of using code-wise generated dot patterns as markers to track the direction of motion of objects.

Keywords: Gelsight, 3D Reconstruction, Photometric Stereo, Computer Vision, Optical flow.

2. INTRODUCTION

Accurate observation of geometry and motion of objects is needed to localize and manipulate objects in robotics. Although the geometry and motion of objects can be directly observed using a camera, most of the time it has missed some important properties such as depth information. Hence, this research explores a high-resolution tactile sensing-based method to observe the geometry and motion of objects. In contrast to the camera-based direct observing method, this work follows an approach which is used tactile sensors to obtain accurate geometry and motion information. The main challenge of this research is getting depth visualization of the object. The key component in this approach is the Gelsight sensor [1]. The Gelsight sensor is a high-resolution tactile sensor that was introduced by Ted Adelson’s research group (MIT, USA) [1]. It mainly consists of three components as shown in figure 1. (1) A block of transparent elastomer with metallic paint on the bottom side acting as the contact surface of the sensor, (2) LEDs illuminating the elastomer (3) a camera capturing the deformation of the elastomer.

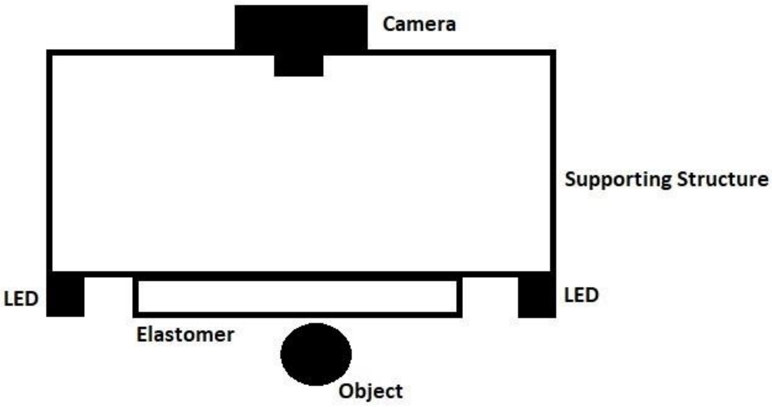

Figure 1: Basic components of the Gelsight sensor.

The previous work on the Gelsight sensor mainly used two different materials to construct the elastomer of the Gelsight sensor. The first material is Thermoplastic Elastomer (TPE) [1]. However, the physical properties of TPE decrease greatly with the increase in temperature hence its application is limited. The second material is Silicone [2]. Typically it comes in a liquid form in two parts. These two parts are mixed with some ratio in the moulding process. The major problem in this approach is the formation of air bubbles in this mixture. The elimination of air bubbles is challenging and it takes significant time. To skip this degassing process and curing time alternative materials have been tested [3,4].

Gelsight sensor technology was introduced as a 2.5D (visual perception) scanner for acquiring the surface texture and shape of small objects [1]. The authors in [1] used the Photometric stereo algorithm[5,6,7] to reconstruct the surface. This algorithm uses a series of images taken from a stationary camera focusing on a scene under different illumination directions to reconstruct the surface in 3D space [8,9]. There are previous methods such as photogrammetry [10] that can be used to generate basic shapes in 3D space. However, generating highly detailed 3D shapes using these techniques is challenging because of the sensitivity of photogrammetry to the textural properties of the surface. Gelsight sensor technology extended to capture microscopic domain geometry by improving sensor materials, illumination design, and reconstruction algorithms [11,12]. The capability of using Gelsight sensors in the medical sector has been tested [13]. According to the authors in [13], the sensor could detect a 2 mm lump at a depth of 5 mm in soft media.

Recently, this sensor technology has been extended to a new research area that measures shear and slip [2,12]. The authors in [2] put permanent markers on the elastomer to track the displacement of markers. Then they used the optical flow algorithm [14] to the displacement of markers. However, this permanent marker technique is hard to use in a setup which is used to observe both 3D shape and direction of motion because permanent markers are not needed to construct 3D shapes. Hence, the design of markers has evolved from permanent markers [2] to UV markers [4]. However, these two approaches can be challenging when the distance between markers wanted to be changed because they are located in fixed positions.

Recently, a mathematical model was developed to estimate object hardness with a Gelsight sensor [15]. Furthermore, this sensor widely is used in robotics by improving the physical structure of this sensor nowadays [16,17].

In conclusion, the Gelsight sensor gives image results of the geometrical data according to the deformation of the contact surface of the sensor [11]. Image processing techniques and optical flow algorithms is used on the image results of the Gelsight sensor to observe the geometry and motion of objects in this work. Moreover, a photometric stereo algorithm is used to reconstruct the 3D geometry of the surface of a contacting object in this work.

This paper discusses how to observe the geometry and motion of objects using Gelsight sensor technology. First discusses how to make a Gelsight sensor using inexpensive materials, then goes on to evaluate the performance of a developed low-budget Gelsight sensor by observing the geometry and motion of the contacting object.

3. METHOD

3.1 Experimental Setup

In this research work, a low-cost commercially available silicone sponge was used as the elastomer. One side of the silicone sponge was painted with reflective (metallic) paint to avoid background interfering lights. The background lights were strictly controlled to obtain accurate colour calibration by the sensor. The four sides of the clear elastomer (silicone sponge) were illuminated simultaneously using a Light-emitting diode (LED) array. The clear elastomer gel was placed on top of a clear glass box with the dimension of 6.4 cm (width) x 8.9 cm (length) x 3.8 cm (height). The glass box was used as the supporting structure for clear elastomer gel. All sides of the glass box, excluding the top and bottom, were covered to control the background lights. To capture the deformation of the elastomer a camera was placed at the back of the supporting structure. In this research project, the Logitech C270 HD webcam was used as the camera. The focus length of the webcam was adjusted to 3.8 cm.

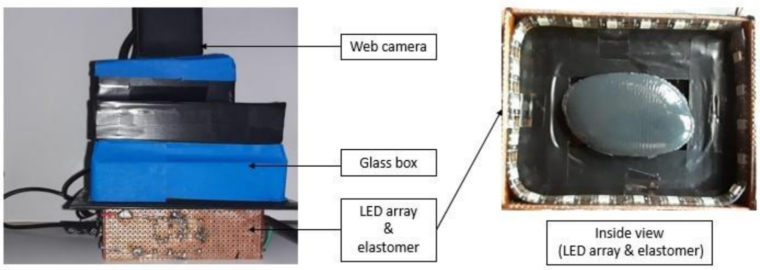

Figure 2: The developed Gelsight sensor and its major components.

The working principle of the Gelsight sensor can be illustrated using figure 3. The one-side coated elastomer acts as a contact surface of the sensor (figure 3(a)). When an object is pressed against the contact surface, it deforms according to the 2D geometry of the object. The deformation is captured by the camera (figure 3(b)).

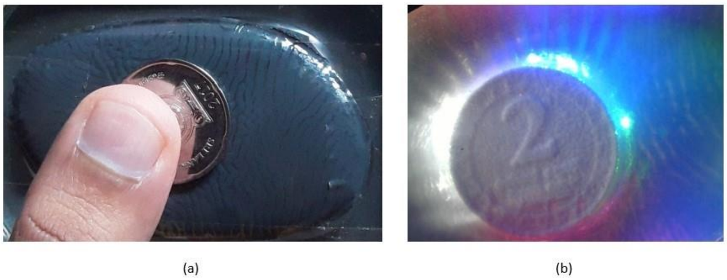

Figure 3: Operational principle of the Gelsight sensor. 3(a) Coated layer of the elastomer acts as a contact surface of the sensor. 3(b) Contact surface deforms according to the 2D geometry of an object. Then the deformation can be captured by the camera which is situated at the back of the contact surface.

3.2 2D Geometry Extraction

An algorithm was developed to extract the 2D geometry of objects using image processing techniques. Firstly, an RGB image of the object was captured using the Gelsight sensor by pressing the object against the sensing surface of the Gelsight sensor. The RGB image was converted to the Grayscale image to reduce computational requirements and processing time. After converting the RGB image to a *grayscale image*, a *low pass filter* (i.e. Gaussian filter) was applied to reduce noise in the image. After that *edge detection* techniques were applied. Then the morphological image processing techniques (i.e. dilate operator) were applied to identify the edges of the object. Morphological reconstruction techniques were used to process images furthermore. Finally, the region of interest was automatically cropped down from the background by identifying the object area.

The main steps in the 2D geometry observation algorithm can be summarized using the following flow diagram.

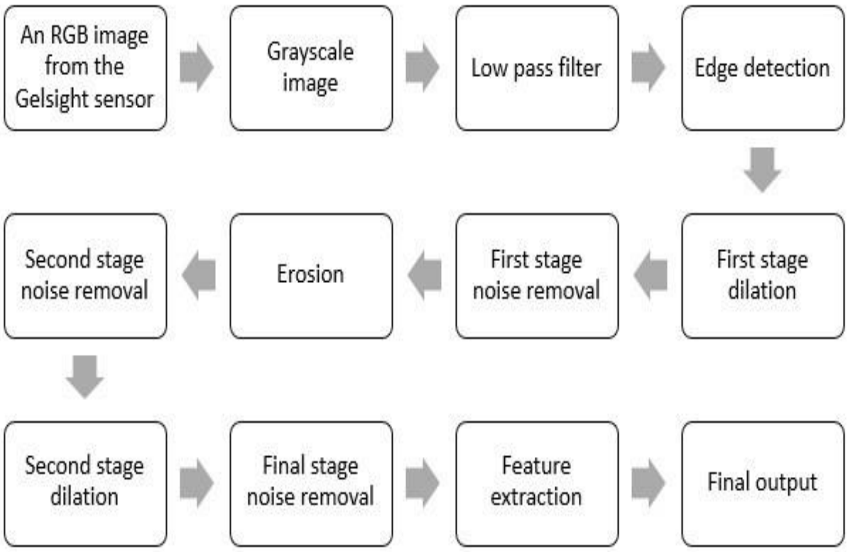

Figure 4: Stages of 2D geometry observation algorithm.

3.3 Tracking the Direction of Motion

The elastomer was modified to observe the direction of motion of objects. This was accomplished by adding markers between the thin paint layer and the top surface of the elastomer. At the initial stage of this research work, the permanent markers method [2] was used. However, two difficulties were faced in this approach. (1) The dot pattern was soluble in the paint. Hence the dot pattern gets faded. (2) The dot patterns were too large in the camera view because the focal length was adjusted to 1.5 inches in the experimental setup. Hence the motion of the elastomer and object became negligibly small compared to the dots. Due to these difficulties, markers (dot patterns) were generated using an algorithm. Then an algorithm was developed based on the Lucas Kande algorithm [18] to track the displacement of dot patterns.

3.4 3D Reconstruction

An open-source algorithm [19] was used to reconstruct object shapes 3D space. Firstly, freely available datasets [20] were tested to observe the accuracy of the algorithm. After that, a new data set was created using the Gelsight sensor. For our case, an object was pressed against the elastomer and the six different images of the deformation of the elastomer were captured by varying the direction of the LED lights. Finally, captured images were input to the Photometric stereo algorithm to obtain the albedo and 3D map of the object.

The main steps in the Photometric stereo algorithm can be summarized using the following flow diagram.

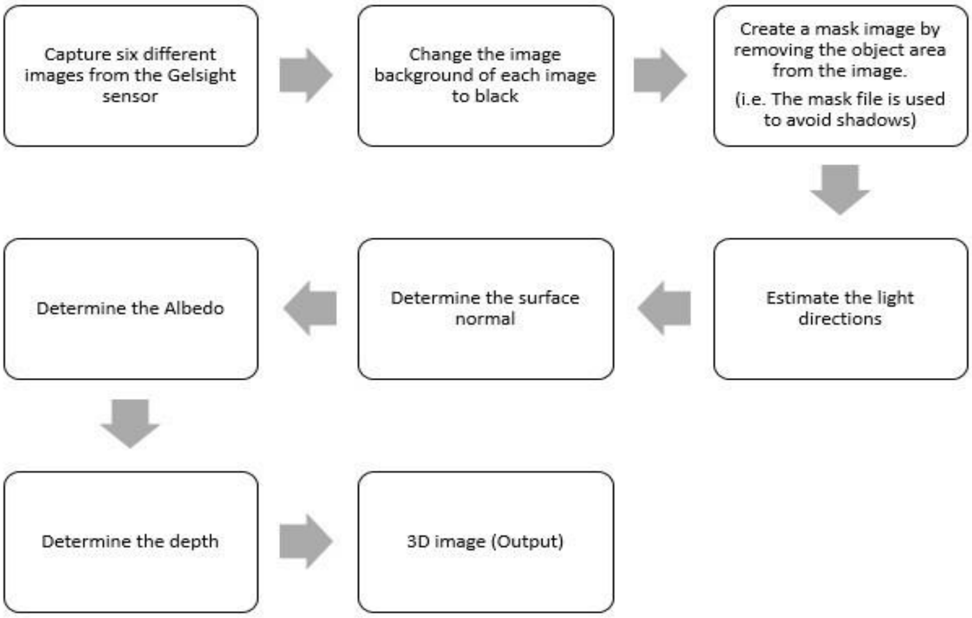

Figure 5: Stages of Photometric stereo algorithm.

4. RESULTS AND DISCUSSION

4.1 2D Geometry Extraction

Figures 6(a), 6(b) and 6(c) show the Gelsight view of several objects. A two rupee coin and a USB cable were captured using the developed Gelsight sensor to determine the capabilities of the sensor.

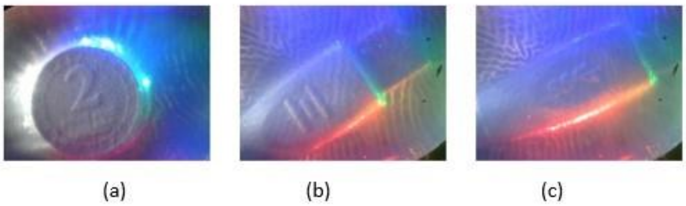

Figure 6: The deformation of the elastomer can be captured by the camera as the Gelsight view. (a) The Gelsight view of a two rupee coin (b) The Gelsight view 1 of a USB cable. (c) The Gelsight view 2 of a USB cable.

The captured 2D geometry was further analyzed using image processing techniques to verify the accuracy of the sensor. Different coins were captured by the sensor to evaluate the accuracy of the sensor. According to the results, the sensor can capture 2D geometry with 66.67% accuracy. As a consequence of the missing point on the edge (figure 7), the 2D geometry observation algorithm could not be able to detect the edge of the object clearly at some coins. However, this obtained accuracy can also be a consequence of the issues in the lighting condition and the elasticity of the elastomer. Furthermore, the dependency of accuracy concerning the lighting condition was tested. For that intensity of LEDs was varied using PWM (pulse with modulation). According to the results, the maximum accuracy of the algorithm was observed at 20% duty cycle.

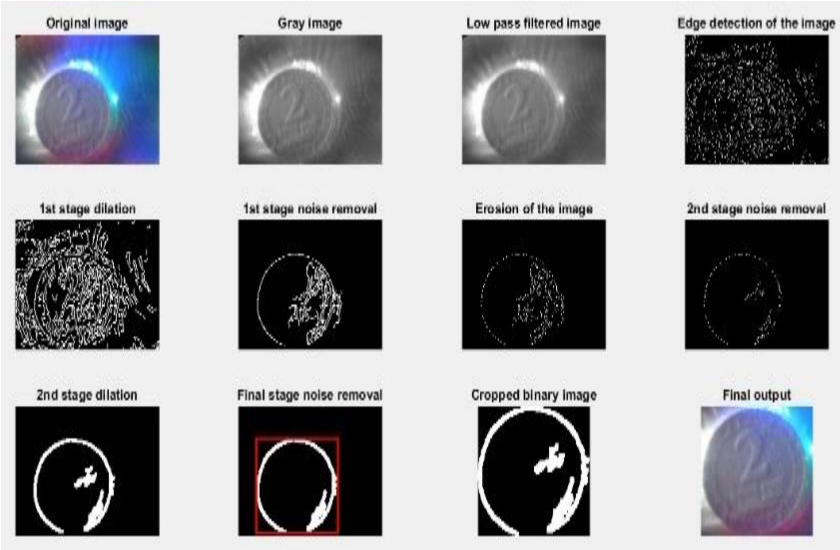

Figure 7: Main steps of the image processing based object detection

4.2 3D Reconstruction

The Gelsight view of objects were tried to reconstruct in in 3D space using Photometric stereo techniques (figure 8). Firstly, a coin was pressed against the elastomer and the six different images of the deformation of the elastomer were captured by varying the direction of the LED lights (figure 8: input images 1-6). Then the mask file was created by converting an input image to binary format (figure 8: Mask image). Six different input images and the mask file were used as the input of the 3D reconstruction algorithm. Although the basic shape was reconstructed in 3D space (figure 8: 3D view 1-3), the textures on the coins couldn’t be reconstructed in the 3D image in this work. The problems in contact surfaces such as less elasticity, oval shape, and low-quality reflective paint can be considered as the possible reasons for that.

Figure 8: Here, a new dataset has been produced using the Gelsight sensor. Then the 3D map has been obtained using the newly created data set.

4.3 Tracking the Direction of Motion

In this study, the direction of motion of objects was observed by tracking the displacement of code-wise generated dot patterns. Figure 9(a) and 9(b) show the linear and rotational motion which was tracked by the Lucas Kande optical flow algorithm [18]. The direction of motion is represented by the arrow vectors generated by the algorithm. The results suggest that the Gelsight sensor can be used to track the motion of objects with the help of code wise generated dot patterns.

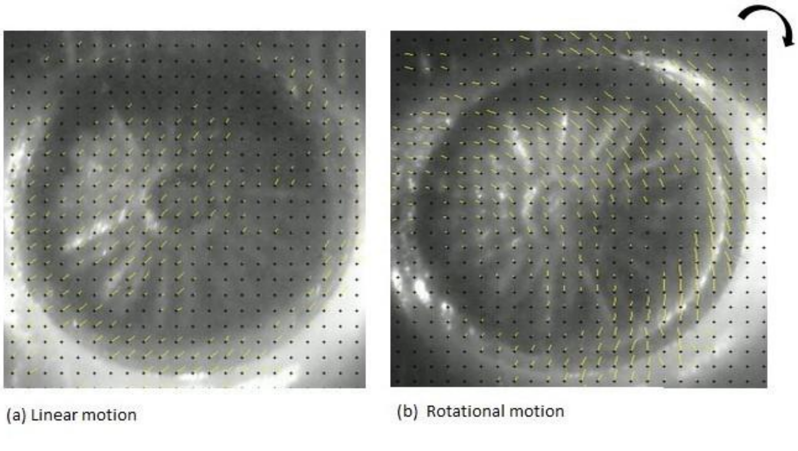

Figure 9: shows the results of observation of the direction of motion using the Gelsight sensor. The optical flow vectors represent the direction of motion.

In the previous studies [2,4] permanent or UV makers were used on the sensor to track the motion direction of the object. However, in this work, computer generated markers were used to track the direction of motion which is an advantage over the manual printed markers.

5. CONCLUSION

The Gelsight sensor is a novel method used to capture the geometrical and physical features of an object. In this research work, a Gelsight sensor was produced using inexpensive materials. According to the results of this research work, the produced low-cost Gelsight sensor was successfully used to capture the geometry of small objects and the direction of motion of an object. However, the performance of the sensor has to improve furthermore by enhancing the elastic properties of the elastomer, identifying a better-reflecting coating for the elastomer, and providing a better lighting condition.

6. ACKNOWLEDGEMENT

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