Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

A novel tactile sensor based on structured light

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***Abstract*—In this paper, we have developed a tactile sensor based on the working principle of structured light. It solves the problem that structured light systems are highly susceptible to ambient light and require frequent calibration. And the structural light principle is applied to the robot operation process, that the robot can acquire the three-dimensional structure information of the object during the operation process, without worrying that the robot will block the camera and affect the reconstruction effect during the robot operation. The main components of the tactile sensor are two cameras, a transparent elastomer, and an adhesion layer pattern. In the experiment, we used the sensor to reconstruct a roman column model in three dimensions, in which the adhesion layer pattern is a structured light pattern coded by the spatial coding method. The results show that the tactile sensor developed in this paper can be used for three-dimensional reconstruction of contact objects with good results. The 3D reconstruction accuracy of the sensor designed in this paper is 0.4mm.**

***Index Terms*—tactile sensor; structure light; three-dimensional reconstruction; pattern codification**

I. Introduction

Structured light (SL) is a set of system structures consisting of projectors and cameras. It usually projects a certain pattern of structured light onto the object surface and the three-dimensional information of the object is obtained by processing the offset distance of the structured light captured by the camera. Structured light technology is considered to be one of the most reliable techniques for recovering the object surface [1], with advantages such as high precision and high resolution. This technology has been applied in many fields, such as automatic grinding robot [2], probe calibration [3], weld robot [4], etc. And Sagawa et al. [5] used a one-shot scanning method based on structured light technology to reconstruct the 3D shape of the object in each frame of the high frame rate video, that is, the three-dimensional structures during the motion of the object were obtained. It is well known that the three-dimensional structure of an object during motion can not only reflect the structure and surface texture, but also reflect some internal properties of the object, such as softness and roughness. These properties make the robot to understand objects more deeply, which can improve the intelligence level and manipulation success rate of robots. In order to make the robot acquire the three-dimensional structure information of the object during the manipulation, we try to apply the structured light system to the robot operating system. However, structured light systems are highly susceptible to ambient light and the robot is likely to block cameras in structured light systems during operation. Therefore, this paper explores a novel tactile sensor based on the working principle of structured light.

An experiment with object manipulation by Volunteers whose hand were anesthetized (deactivated their tactile receptors), demonstrated the importance of human tactile perception in successful grab and manipulation [6]. Similarly, the ability of a robot to sense object property information in an environment is a key factor affecting the manipulation performance. And the most efficient way to get object properties is based on tactile sensors. At present, according to the implementation principle, the tactile sensors can be divided into: piezoresistive [7], capacitive [8], piezoelectric [9], quantum tunnel [10]], optical [12]. And the advantages and disadvantages of these tactile sensors are compared in detail in [13]. Some of them are good at measuring the force of the object [14], or are apt to obtain the texture [15] and other information. However, there is no tactile sensor that can output a highly precision three-dimensional structure of an object, which not only covers the texture and shape of the object, but also includes richer object attribute information such as softness and hardness.

In order to enable the tactile sensor to acquire the three-dimensional structural information of the object and improve the existing limitations of the structured light, a tactile sensor based on structured light is developed in this paper. The tactile sensor belongs to an optical tactile sensor and is a sensor that acquires tactile information using cameras. In this paper, we have made the following contributions

- A new type of tactile sensor was developed to integrate the structured light system into a closed structure measuring 40*34*30.
- The tactile sensor can use any spatial coding in the structured light system by simply replacing the attachment layer pattern of the tactile sensor.
- The tactile sensor enables the structured light system to be applied to the haptic field for the first time, and the reconstruction accuracy of the contact object is 95%, which is getting better as the adhesion layer process is improved.

In the next section, we will introduce the working principle of our tactile sensors, and describe in detail the structure and preparation of the adhesion layer. The section 3 illustrates the method that the tactile sensor obtains the three-dimensional structure of the object based on the pattern prepared in the

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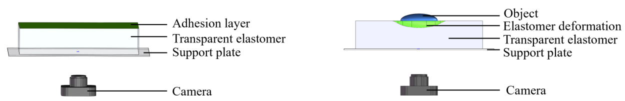

Fig. 1. The working principle of optical tactile sensors

section 2. The section 4 gives the three-dimensional structure of the object output by the tactile sensor. Finally, the section 5 summarizes the effects of the tactile sensor and discusses future work.

II. Tactile Sensor

A. The Working Principle

The optical tactile sensor acquires tactile information of the contact object by processing the deformed image of the elastic body captured by the camera. And the elastic body can display information such as texture [10], temperature [16] or three-dimensional force [11] of the contact object according to its deformation characteristics and the anti-reflection property of the adhesion layer on the elastomer surface, as shown in Fig. 1 Such tactile sensors have been applied to sliding detection [17], three-dimensional force measurement [18], object recognition [17], etc. On the other hand, the structured light technology works by obtaining the three-dimensional structural information of the object based on the spatial relationship between the camera and the projector and the deformation information of the projected pattern. Generally, the optical axis of the camera and the central axis of the projection of the projector have an angular difference, which is one of the important factors for solving the three-dimensional structural information of the object. The pattern projected by the projector is mainly used to match the marker points in the 3D reconstruction process of the object. And the coding methods mainly include time method and space method. The pattern encoded by the temporal encoding method is typically a sequence of lines or points that varies over time (requires multiple patterns); whereas a pattern encoded by a spatial method typically requires only one pattern, and the arrangement of the points in the pattern has a spatial relationship.

The tactile sensor developed in this paper combines the working characteristics of optical tactile sensors and structured light systems. We prepared the projection pattern in the structured light system as an adhesion layer pattern on the surface of the elastomer in the optical tactile sensor. According to the spatial relationship between the two cameras and the transparent elastic body, the three-dimensional structure of the contact object is reconstructed based on the pattern information of the adhesion layer. It is worth noting that the projection pattern can only use the pattern encoded by the spatial encoding method due to device limitations.

B. Structure

The structure of the tactile sensor is shown in Fig. 3. The main components are the shell, cameras, the support plate,

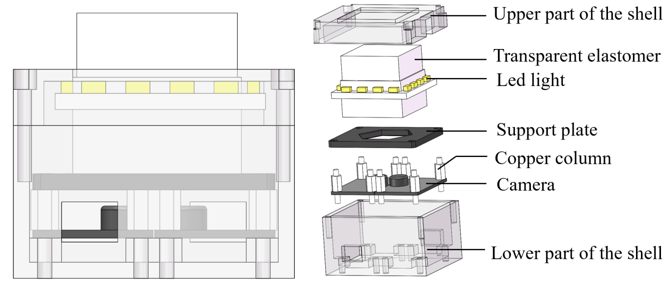

Fig. 2. The structure diagram of our tactile sensor

the transparent elastic body, and the LED light board. Among them, two cameras are placed horizontally, and the side where the lens is located is attached. The copper column is used to fix cameras, lower parts of the shell and the support plate to keep them stable. The Led light panel surrounds the transparent elastomer to provide a uniform, stable source of light for the camera to capture the image of the elastomeric surface. Last but not the least, the center of the two cameras is collinear with the center of the support plate and the center of the transparent elastomer. Therefore, the areas of the transparent elastomer that the two cameras can capture are equal in theory.

C. The Preparation of Adhesion Layer

The adhesion layer is on the upper surface of the transparent elastomer, which determines the perceived performance of the tactile sensor. At present, the existing adhesion layers of such tactile sensors are: metal silver powder layer [17], metallic copper sputter layer [12], thermochromic layer [16]. The two metal layers are sensitive to the texture of the object, while the thermochromic layer can be used to sense the temperature and texture of objects. The adhesion layer prepared in this paper is used to match the marked points in the images taken by the two cameras, and the pattern of the adhesion layer can be selected from any pattern, which encoded by the spatial encoding method. The preparation materials are pigments and silicone oils, the tools are mask and squeegee, and the preparation technique is screen printing technology. Silicone oil is a material that is excellent in adhesion to transparent elastomers. The mask board can be designed and machining according to the pattern selected.

The flow chart of the preparation of the adhesion layer is shown in Fig. 1, and the steps are as follows:

- Design and machining the mask board according to the selected pattern;

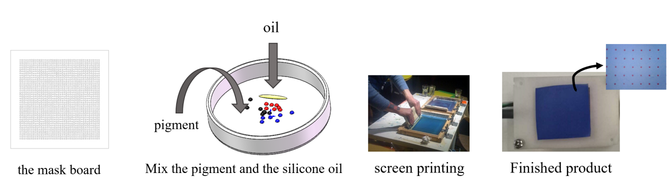

Fig. 3. The flow chart of the preparation of the adhesion layer.

- Mix the pigment and the silicone oil in a ratio of 5:1 and stirring uniformly; (multiple colors should be prepared separately)
- Prepared by screen printing technology

III. METHODOLOGY

Structured light techniques can be divided, according to different methods of encoding the projected pattern, into three categories [20]: direct coding, time-varying, and spatial neighborhood. The methods based on the time-varying strategy are easy to be implemented and can achieve the highest accuracy and a good resolution [21]. The major drawback to these patterns is the difficulty to solve dynamic scenes because several patterns must be projected precisely. Patterns coded directly offer a great spatial resolution but are unstable to noise and light variations. The spatial neighborhood codification strategies are attractive for low-cost systems because the 3D reconstruction could be obtained form just a single pattern carried all the codes [19], [22]. More importantly, the last method can deal with dynamic scenes.

For our application, considering the low cost, little size and dynamic scenes of the developed tactile sensor, we adopt the spatial neighborhood method for pattern codification.

A. Pattern Encoding

M-array, also called pseudorandom array, technique is one category of the spatial neighborhood techniques, which is a two-dimensional encoding method. By definition, an M-array is an $r \times v$ matrix over with element from an alphabet of k symbols and every possible sub-matrix $m \times n$ appears exactly once [23].

In order to verify the performance of the tactile sensor, we choose a simple pattern similar to the pattern proposed by Albitar et al. [22]. The codeword w_{ij} can be expressed by (1).

$$w_{ij} = \{x_{i-1,j-1}, x_{i-1,j}, \cdots, x_{i,j}, \cdots, x_{i+1,j}, x_{i+1,j+1}\}, \tag{1}$$

where, $2 <= i <= m-1$, $2 <= j <= n-1$ and $x_{i,j}$ is the digit number taken from the alphabet $P = \{0, 1, 2\}$.

The pattern matrix M ($m \times n$) based on M-array designed in this paper respects the unique conditions that all the codewords (3×3 window) of the pattern is uniqueness, as explained in (2). Here, W is a set which consists of all the codewords in the pattern matrix:

$$W = \left\{ w_{i,j} \middle| \begin{array}{c} w_{ij} \neq w_{kl}, (i,j) \neq (k,l) \\ 2 \leq i \leq m-1, 2 \leq k \leq m-1 \\ 2 \leq j \leq n-1, 2 \leq l \leq n-1 \end{array} \right\} \tag{2}$$

The uniqueness condition is applied to similarly the correspondence problem of stereo vision, which is also the property of M-array technology. Then we choose the monochromatic light as the pattern used in the tactile sensor. Then to simplify the segmentation stage and matching stage of the decoding process, we choose three simple geometrical shapes: line, triangle, and circle to associate with three symbols in the alphabet (0: line, 1: triangle, 2: circle), as shown in Fig. 5 (graph on the right). Fig. 4 shows the matrix M encoded in this paper, with the size of (42×42). Fig. 5 shows the pattern image represented by geometrical shapes (graph on the left).

0	1	0	0	0	1	0	1	1	2	1	1	1	2	1	1	0	2	1	1	2	0	1	1	1	0	0	2	1	1	1	0	1	1	2	1	2	2	0	1	1	0
2	2	1	1	2	1	0	2	2	1	1	0	1	1	1	2	0	2	0	0	2	1	2	1	1	2	1	0	0	2	2	2	1	1	1	2	0	1	0	0	1	0
1	1	0	0	2	0	2	2	2	0	1	0	0	2	0	0	2	2	1	1	1	1	0	0	2	1	1	2	1	0	1	0	2	0	1	2	2	2	0	2	1	0
2	1	0	2	1	2	1	0	2	0	0	1	2	2	1	1	2	0	2	0	1	2	2	2	2	0	0	2	2	2	2	1	2	0	2	0	0	1	1	2	0	1
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0	0	0	1	0	1	1	0	1	2	1	0	0	2	0	2	2	0	2	1	0	0	2	1	2	2	0	0	0	0	2	1	2	0	2	2	1	0	0	0	1	0

Fig. 4. The matrix M encoded in this paper.

B. Segmentation and Decoding

The detection of the correspondences between two images captured from stereo cameras is one of the most important steps in 3-D reconstruction[Dual pseudorandom array technique for error]. In the pattern decoding precess, the codeword of each pattern symbol in both captured images should be accurately determined to solve the correspondences.

The decoding process is divided into three stages in this paper: segmentation, symbol identification, and matching codewords. In the segmentation stage, captured images are converted to a gray image. Then adaptive threshold algorithm is applied to transform the gray image to a binary image according to the formulae:

$$dst(x,y) = \begin{cases} maxValue & \text{if } src(x,y) > T(x,y) \\ 0 & \text{otherwise} \end{cases}. \tag{3}$$

Here $T(x,y)$ is an adaptive threshold calculated individually at each pixel. Then morphological transformations are applied to remove noise. We use erosion filter to shrink all the segments in the binary image and dilation filter to expand the segments smoothly, as explained in (4) and (5) respectively.

$$dst(x,y) = \min_{(x',y'):element(x',y') \neq 0} src(x+x', y+y') \tag{4}$$

$$dst(x,y) = \max_{(x',y'):element(x',y') \neq 0} src(x+x', y+y') \tag{5}$$

To identify the codewords represented by geometrical shapes, we detect all contours of the binary image and obtain all the positions of the points that make up this contours.

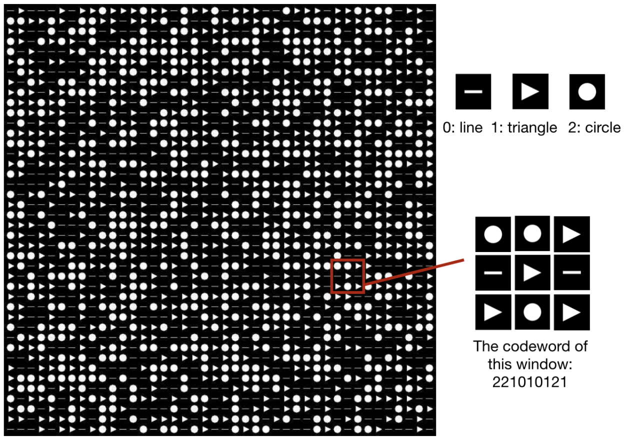

Fig. 5. The pattern resolution encoded in this paper.

Then very big contours or very small contours is abandoned by comparing the size of each contour and the average size of all contours. Then the centroid $(\bar{x}, \bar{y})$ of every contour is calculated by the image moments, as explained in (6):

$$\bar{x} = \frac{m_{1,0}}{m_{0,0}}, \quad \bar{y} = \frac{m_{0,1}}{m_{0,0}}, \tag{6}$$

where $m_{i,j}$ is calculated by:

$$m_{i,j} = \sum_{x,y} x^i y^i f(x, y). \tag{7}$$

Fig. 6 shows the process of extracting the grid points (centroids) of the pattern. Here, Fig. 6(a) is the captured image, Fig. 6(b) is the symbol contours extracted from the captured image. Fig. 6(c) show the the grid points of these contours.

C. Classifying the Detected Symbols

The purpose of getting the grid of each symbol is to determine the coordinate and geometry category of each symbol. However, due to the size of symbol (about $0.5mm \times 0.5mm$), uneven illumination, surface discontinuities and deformation of objects and so on, the geometrical shapes in the captured images are usually blurred and distorted as shown in Fig. 7. Thus, it is difficult to detect the symbols classification accurately. Then we use the convolutional neural networks (CNNs) based on the Lenet-5 [24], which is well-known for its efficient solution for handwritten digit recognition problem. The input layer designed in this paper is RGB images with the size of (18×18), as shown in Fig. 7. The output layer is three predict values between 0 and 1 representing the possibility of three categories (line, triangle, circle). The datasets are collected from the captured images with different illumination and objects. Fig. 8 shows the flow chat of the decoding process.

IV. Experiment Results And Discussion

In the experiment, the tactile system is composed of two wild filed cameras with a resolution of 640×480 pixels, and a focus of $3.35mm$, which are calibrated by the method proposed by Zhang [25]. The distance of two symbols in the adhesion layer is $0.5mm$, the working distance is about $15mm$ and the measurement area is about $5mm \times 15mm$. To test the 3D reconstruction capability of a designed tactile sensor, we use the bowling model as the testing object (Fig. 9(a)), and the 3D reconstruct result is shown in Fig. 9(b) and Fig. 9(c). It can be seen from the Experimental results that by combining the tactile sensor with the structured light technology, the perception of the 3D structure of the measured object can be realized. Then the 3D reconstruction accuracy is 0.4mm.

V. Conclution

We have designed a new tactile sensor that combines the advantages of a structured light system and an optical tactile sensor for the first time. It can sense the 3D structure of the contact objects. Besides, embedding the structured light technology the designed tactile sensor could solve many problems the convolutional structured light technique encountered, such as the sensitivity to color, immovability of the structured light device, etc. The tactile sensor can use any spatial coding in the structured light system by simply replacing the attachment layer pattern of the tactile sensor.

As future work, we are going to improve the performance of the tactile sensor. The tactile sensor in this paper is the first-generation device. We are planning to design the next device to enhance the 3D reconstruction stability of the sensor, and enable the sensor to sense the stiffness of the objects.

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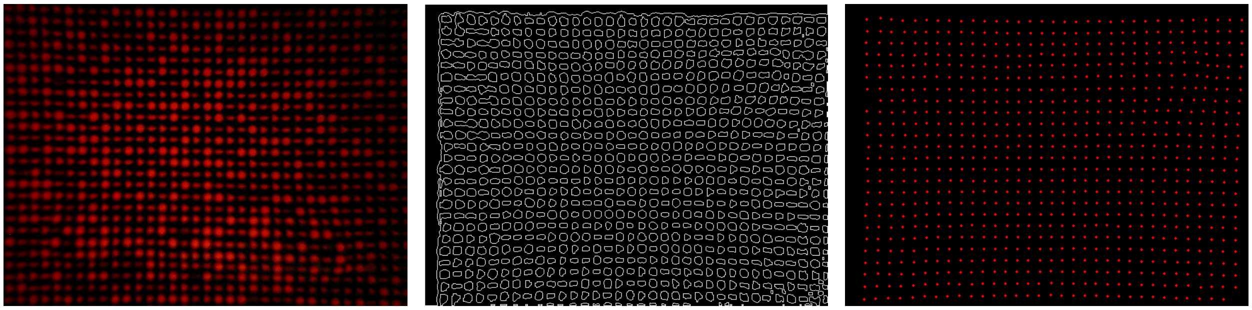

(a) (b) (c)

Fig. 6. Square grid points extraction process: (a) captured image; (b) contour detection result; (c) extracted the grid points of previous contours

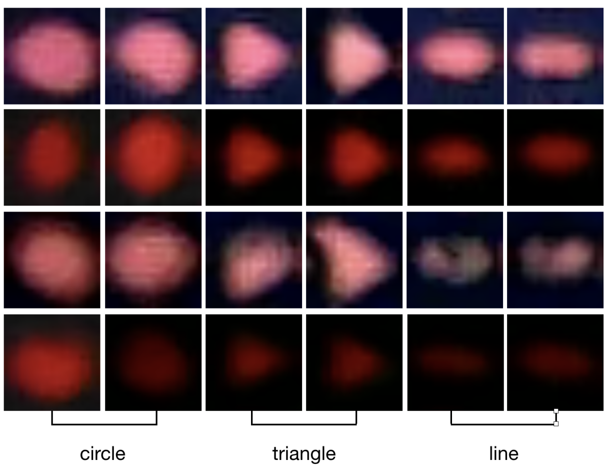

Fig. 7. The pattern are blurred and distorted due to the uneven illumination, noise, or deformation.

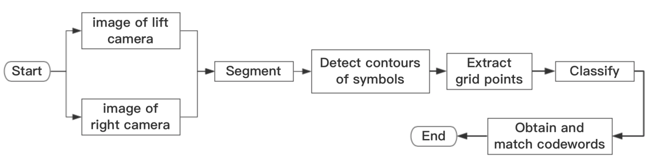

Fig. 8. The flow chat of the decoding process.

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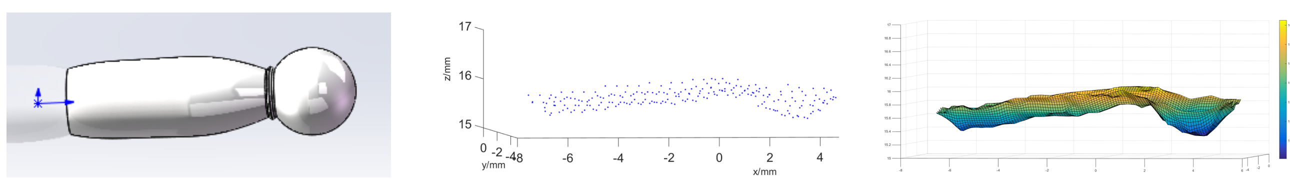

(a) (b) (c)

Fig. 9. Model and the 3D reconstruction result: (a) Bowling model; (b) The reconstructed 3D point cloud model; (c) The reconstructed 3D model of object.