Design and Optimization of Fiber Optic Grating Pressure Sensing Array

Honglin Liu¹, Tongyang Feng², Guan Lu¹*

¹School of Mechanical Engineering, Nantong University, Nantong, Jiangsu, 226000, China
²School of Mechanical Engineering, Nantong University, Nantong, Jiangsu, 226000, China
*Corresponding author’s e-mail: luguan@ntu.edu.cn

Abstract. Aiming at the haptic problem of robot hand pressure, this paper studies a fiber grating tactile sensor array. Using polydimethylsiloxane (PDMS) package, and the finite element simulation of the package body to obtain internal strain. Aiming at the strain field distribution when the robot hand is gripping, the design of preliminary sensor array and finite element analysis are carried out, and the improved particle swarm algorithm is used to further optimize the measurement points. It provides a theoretical basis for the subsequent construction of the measurement points of the FBG tactile sensor array detection system.

1. Introduction

Tactile perception is one of the most important functions of intelligent robots. When robots often need to complete many complex operations in daily life, the tactile sensing plays a very important role. Compared with traditional tactile sensors, flexible tactile sensors are physically closer to the shape, tactile sensation and softness of human skin, enabling robots to realize flexible tactile perception[1]. However, most of the tactile sensing elements are rigid sensing elements and do not have flexibility. The flexibility of the sensor and the limitation of the tactile rigid elements have certain problems, and there are problems such as electromagnetic interference, which affect the measurement results. In recent years, with the development of fiber optic sensing technology, fiber Bragg grating (FBG) has been widely used in the field of sensing[2]. Due to its small size, simple structure, flexibility, embedding in materials, easy packaging, and resistance to electromagnetic interference, FBG has been used as a new type of flexible tactile sensing element by scholars at home and abroad[3].

Since the development time of FBG technology is not long, the sensor array based on FBG has also been continuously researched and developed. At the present stage, most of the electric finger sensors used in robotic finger pressure tactile sensor arrays are used[4]. The domestic and foreign researches of robotic finger pressure tactile sensor arrays based on fiber grating are in the initial stage, and there are few related reports[5]. As the demand for tactile interfaces becomes higher and higher in daily work and life. The study of FBG tactile sensor arrays is urgently needed.

2. The design of tactile sensor array

2.1. FBG tactile sensing principle

The fiber Bragg grating is a phase grating formed in the fiber core by using the interaction between the
core germanium ion and the external photons. When a broadband light wave passes through the fiber grating, reflection and transmission phenomena will occur due to the difference in refractive index. Among them, the incident light that meets the Bragg reflection condition will be reflected, and the transmission light transmission spectrum will have a concave peak. It reflects light of a specific wavelength[6].

The change in the center wavelength of the fiber grating caused by external force $F$ can be expressed as formula (1):

$$\Delta \lambda = \frac{F}{E} \frac{1}{S} (1 - P_t) \lambda_0$$

As can be seen from the above formula, under constant temperature conditions, when a longitudinal load is applied to the fiber grating, the center wavelength of the grating will change accordingly. By building a fiber grating sensor array to detect the rate of change of the center wavelength of the grating, the robot can grasp tactile perception of grip pressure[7].

2.2. The design of FBG' tactile sensor array
The FBG tactile sensor array designed in this paper is packaged in PDMS, which requires finite element analysis of PDMS materials. During the simulation of the elastic body, the lower surface of the elastic body is fixedly constrained and cannot move in the vertical direction (Z direction), but can freely expand and contract in the horizontal direction (X direction) and (Y direction). Apply vertical downward pressure on the upper surface of the sensor to obtain the strain of the sensor. According to the actual manipulator size, the elastic body size is set to $9\text{mm} \times 7\text{mm} \times 4\text{mm}$.

2.2.1. Research on the depth of fiber embedding
A uniform load of 2N is applied to the center of the upper surface of the elastomer, and the loading area is $1\text{cm}^2$. The strain change of the fiber at different embedding depths is obtained, as shown in Figure 1. When the embedding depth of the optical fiber is 1 mm from the upper surface, the strain value of the grating at this time is the largest and it is within the strain sensitive range of the grating. Therefore, an embedding method with a fiber embedding depth of 1 mm is selected to improve the sensitivity of the sensor.

![Figure 1. Strain diagram of optical fiber at different embedding depths](image)

2.2.2. Sensor array design based on strain field
When sensing this non-large area and non-uniform force area when the robot grips, it only needs to sense the force of a particular part. If the dense equidistant distribution method is not used to meet the miniaturization requirements of the robot sensor, it will also cause a waste of resources. Therefore, the sensor array is designed for the strain field distribution during the gripping action of the robot. Taking the middle finger as an example, the driving load of 0.1Mpa is applied to the three segments of the middle finger to obtain the strain field distribution of the model.
Based on the above conclusion, it is designed that the depth of the embedded optical fiber is 1mm. Therefore, the strain field of the 1mm section of the elastic body on the three-section phalanx of the middle finger is analyzed, and the distribution position of the measuring points of the sensor array is preliminary designed. As shown in Figure 2, the strain field distributions of the upper, middle and lower phalanx from left and right are in the strain sensitive range of the grating.

According to Figure 3, it can be seen that the lower part of the cross-section is a strain-sensitive area. At this time, the arrangement of measuring points in this area can improve the accuracy and sensitivity of the sensor array. Due to the 1.5mm length limitation of the grating, it will do not arrange measurement points at a distance of 1.5mm from the edge of the elastic body. The strain field presents a symmetrical distribution pattern and is initially designed as two strain-sensitive areas, and 60 nodes are taken in this area.

3. Single finger measurement point optimization based on improved particle swarm optimization

3.1. Improved particle swarm optimization algorithm based on simulated annealing and genetic algorithm

In the gripping process of the manipulator, there is uneven strain distribution on the knuckle surface. Therefore, the use of different combinations of nodes as the measuring point combination is the key to the sensor array's identification of the stressed state[8]. The traditional measurement point selection is usually to choose a measurement point with good linearity, low hysteresis, high sensitivity, good unity and no redundancy. However, this selection method needs to be familiar with structural stress and have rich engineering experience[9]. With the increasing complexity of mechanical structures and the improvement of measurement requirements, this method is more cumbersome[10].

However, in the search process of the algorithm, the particles find the current optimal position, and other particles will quickly move closer to it. If the current optimal position is the local best, the algorithm can easily fall into the local optimal, and the phenomenon of premature convergence occurs[11]. Therefore, this paper introduces the genetic algorithm and simulated annealing ideas into the particle swarm optimization algorithm to improve the premature problem of the particle swarm optimization algorithm in order to obtain a better combination of measuring points[12].
algorithm flow chart is shown in Figure 4.

3.2. Single finger measuring point optimization simulation experiment

According to the above algorithm flow, Matlab is used to optimize the measuring points, and the results of when the target measuring points are selected to be 2 or 3 are compared and analyzed. The measuring point combination and the percentage error of the force state and the program running time are shown in Table 1.

Table 1. Optimization results of measuring points with 2 or 3 target measuring points

| Target measuring points | 2     | 3  |
|-------------------------|-------|----|
| Measuring point combination | 24, 84 | 14, 55, 114 |
| Percentage error (%)    | 2.15  | 1.95 |
| Time (s)                | 45    | 65  |

It can be seen from Table 1 that when the number of target measurement points is 2 or 3, the percent recognition error of the force state is not much different. The sensor array design with 2 measuring points as shown by the red node in the left picture. Through the improved particle swarm optimization algorithm, the three-segment phalanx of the middle finger is optimized for measuring points. The arrangement of the measuring points is shown in Figure 5. The percentage error of the force state recognition under this combination of points is the smallest, so the number of measuring points can be measured for the middle finger. It is a combination of 6 measuring points.
4. Conclusion

Aiming at the problem of pressure tactile perception when robot fingers are gripped, the initial selection of measurement points is based on the strain field distribution when robot fingers are gripped. After that, genetic algorithm and simulated annealing are added to the particle swarm algorithm to prevent the algorithm from falling into local optimum and premature convergence phenomenon. The improved particle swarm optimization algorithm was used to further optimize the measuring points, and the percent error of the force state recognition was used as the judging standard for the measuring point arrangement. The single-finger optimal measuring point combination was designed to provide the subsequent design of the FBG tactile sensor array sensing system. Based on the theoretical basis, it meets the requirements of miniaturization and accuracy of robot finger measurement points.

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