Original Research Article

Research status and trend of three-dimensional force sensor

ABSTRACT

The sensor can simultaneously detect the force value information of three dimensions in the three-dimensional space. With the progress of science and technology and the development of the Internet, the sensor is widely used in many fields such as medical rehabilitation and aerospace. The three-dimensional force sensor based on the measuring principle of resistance strain gauge, capacitance type and piezoelectric type is introduced. Because of its advantages of high precision, mature technology and wide measuring range, the three-dimensional force sensor becomes the most mature kind of sensor. At present, the main goal of the elastomer design of the sensor is to improve the measurement accuracy of the sensor and reduce the coupling error between dimensions. Finally, the development trend of the three-dimensional force sensor is prospected based on the research and application status of the three-dimensional force sensor.

Keywords:Three-dimensional forcesensor; Elastomer structure; Resistance strain formula;Force perception;Sensor applicationf

1. INTRODUCTION

The three-dimensional force sensor can perceive the three-dimensional force perception information in the six-dimensional space, with representative perceptive *Fx*/*Fy*/*Fz*, *Fx/Fy*/*Mz* and *Mx*/*My*/*Fz*. With the progress of science and technology, intelligent and autonomous robot control requires sensors to provide accurate force value information for work interaction. Three-dimensional force sensors are widely used in medical rehabilitation [1-2], aerospace [3-5] and other fields, such as aircraft wind tunnel detection, vehicle collision detection and mechanical parts quality detection. The development of sensors has always affected the development of intelligent manufacturing and intelligent equipment, so the current research of sensors is very important.

The sensor is mainly composed of elastomer unit, signal acquisition card, calibration system and so on. In this paper, the measurement principle of three-dimensional force sensor, elastomer structure design and other aspects of the current research content are summarized, and its application scenario is analyzed, and finally combined with the current research status of three-dimensional force sensor, the future development prospect of three-dimensional force sensor is prospected.

2. MEASUREMENT PRINCIPLE OF THREE-DIMENSIONAL FORCE SENSOR

According to the measurement principle, it can be divided into piezoelectric type, capacitive type, inductance type, resistance type and other types, among which the most widely used is the resistance sensor, and the most common resistance sensor is the force sensor.

2.1Resistance strain formula

Resistance strain gauge Three-dimensional force sensor mainly uses resistance strain effect to measure external force. The principle is to paste the resistance strain gauge on the sensor elastomer and carry out Wheatstone bridge construction. When the elastic body is deformed after the sensor is stressed, the resistance strain gauge resistance changes due to the deformation, and the resistance signal is converted into the voltage signal output through the Wheatstone bridge. It is characterized by adaptability to a variety of harsh environments and is suitable for both static and dynamic detection. YanzhiZhaoproposed a three-dimensional force sensor with rigid and flexible parallel, which can be used for positioning and attitude adjustment of the platform. Manbokhong[6] proposed a three-dimensional force sensor in series. Strain gauges were pasted on three hinges to sense the force value. The sensor was used in the field of medical rehabilitation.

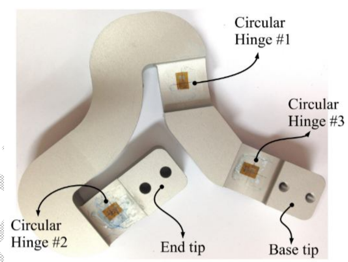

Fig1Proposed compliant structure for the three-axis F/T sensor.[6]

2.2 Capacitive

The flexible Three-dimensional force sensor converts the external load signal into capacitance signal, and the acquisition circuit converts capacitance change into electrical signal output sensor. The capacitor sensor is mainly composed of the upper and lower two layers of electrode plates and the dielectric layer in the middle. When the sensor is subjected to external load, the dielectric layer will produce corresponding deformation, resulting in the change of the relative position between the upper and lower two layers of electrode plates, and the capacitance will change accordingly, thus transforming the change of external force into a change of capacitance. Capacitive Three-dimensional force sensor is widely used in electronic field because of its high temperature resistance, good dynamic response stability, high sensitivity, simple structure and flexible application.

Ying Huangdesigned a capacitive haptic sensor with a multi-electrode structure on the same plane, as shown in Figure 2. By compressing the composite dielectric layer to affect the electric field distribution and change the capacitance, the three-dimensional force can be detected in the 0-10 N range, and the normal and tangential sensitivity can reach 0.0095, 0.0053 and 0.0060 N^{-1}, respectively. The sensor adopts the structure of the same electrode. Compared with the traditional parallel plate capacitor structure, the wiring is more convenient, which is conducive to the array of the sensor, and is also more suitable for curved surface loading [7]. Liang Guanhao[8] proposed a flexible capacitive haptic sensor array with truncated PDMS pyramid array as the medium layer The sensor array consists of 4 × 4 sensor units, each of which is composed of four planar capacitors. The sensor has high sensitivity for the measurement of normal force and tangential force, and the sensitivity of x axis, y axis and z axis are 58.3%/N, 57.4%/N and 67.2%/N, respectively, but its measurement range is small and the process is more complicated.

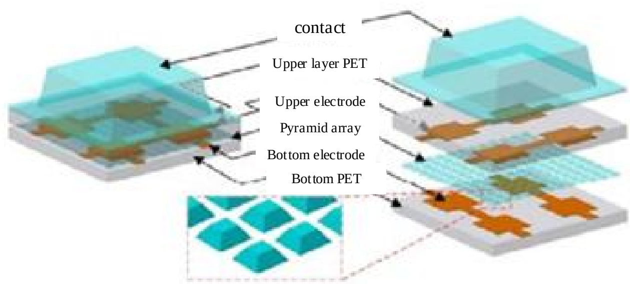

Fig2 Flexible capacitive haptic sensor array based on truncated PDMS pyramid[7]

2.3 Piezoelectric

Piezoelectric three-dimensional force sensor through the piezoelectric effect to detect the force value, piezoelectric material deformation, under the action of internal electron polarization, the two relative surfaces of the material respectively appear positive and negative charges, deformation recovery after the charge disappears, the phenomenon is called the piezoelectric effect, piezoelectric tactile sensor is through the piezoelectric effect of piezoelectric materials to feedback external information. At present, the commonly used piezoelectric materials include piezoelectric ceramics, quartz crystals and PVDF (polyvinylidene fluoride).Pan Qi have proposed a haptic sensor for three-dimensional force robots based on PVDF.

As shown in Figure 3. The sensor pastes PVDF piezoelectric film on the four sides of the four-edge platform. When the contact surface of the prism is subjected to different forces in different directions, the pressure on each film on the side wall is also different, resulting in different amounts of positive and negative charges. By measuring the electrical signal, the information of the loaded three-dimensional force can be reflected [9].Liu et al., Zhejiang University, proposed a novel fingertip piezoelectric tactile sensor array capable of recognizing roughness information. Four tactile units were arranged as a 2 × 2 matrix to form a tactile sensor array. The sensor has good flexibility and repeatability, and can identify seven stimuli of multiple spatial cycles at different scanning speeds, with a recognition rate of up to 99.93%[10].

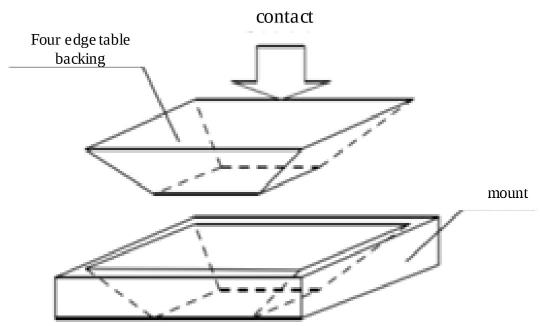

Fig3 Sensor head structure design [9]

3. THREE-DIMENSIONAL FORCE SENSOR ELASTOMER DESIGN

The core unit of a three-dimensional force sensor is an elastic body, which plays a key role in the sensitivity and dimensional coupling of the sensor [11]. The structure of elastomer is divided into one type and combined type.

3.1COMBINED STRUCTURE DESIGN

The combined sensor is the sensor that is processed separately by the elastomer and then assembled. The combined sensor is easy to process, and different structures can be obtained through different combination methods. Gong Haibin et al. [12] proposed a three-dimensional force measuring platform based on four parallel three-dimensional force sensors for the measurement of high-speed train bogie parameters, as shown in Figure 4. Zhao Yanzhi et al. [13] proposed an overconstrained planar parallel three-dimensional force sensor. Six single-dimension force sensors were combined in parallel to measure the force. The measurement accuracy of the sensor was 2.56% for radial force, 0.92% for torque, 2.56% for class I error, and 2.29% for maximum class II error. If a single elastomer of the combined sensor is deformed and damaged, it can be reprocessed to make one, and the secondary calibration of the subsequent sensor can be avoided after direct replacement.

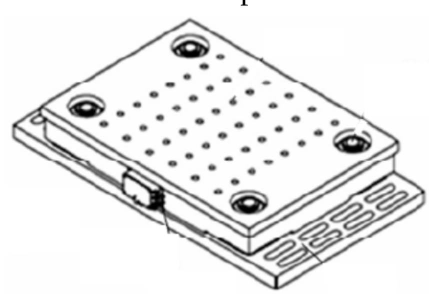

Fig4 Large range force measuring platform [12]

3.2 INTEGRATED STRUCTURE DESIGN

The integrated sensor elastomer is processed by removing a whole material, and the integrated sensor does not need to be installed, and there is no friction and no gap between the elastomers. Qin Yuanyuan [14] proposed an elastomer design of a small three-dimensional force sensor, as shown in Figure5. The cantilever beam and double-hole parallel beams of the cantilever beam were designed. The results show that the elastomer has high accuracy, strong anti-lateral load bias ability and object understanding coupling ability, which can ensure the measurement accuracy of the small three-dimensional force sensor. Luo Xunhuang[15] proposed a simple strain-type three-dimensional force sensor. Compared with the current strain-type multi-dimensional force sensor, the developed strain-type three-dimensional force sensor has a great improvement in the inter-dimensional coupling error, the maximum error occurs when the force *Fz* acts, and the inter-dimensional interference is only 0.8775%.From the above literature analysis, it can be concluded that the main purpose of scholars' research on the elastomer of the current three-dimensional force sensor is to improve the sensitivity of the sensor, reduce the coupling between dimensions, and thus improve the measurement accuracy.

Three-dimensional force sensor is widely used in medical rehabilitation, aircraft wind tunnel test, collision detection and other fields play an important role, accurately provide force value information, can also be applied to Three-dimensional turning force detection.

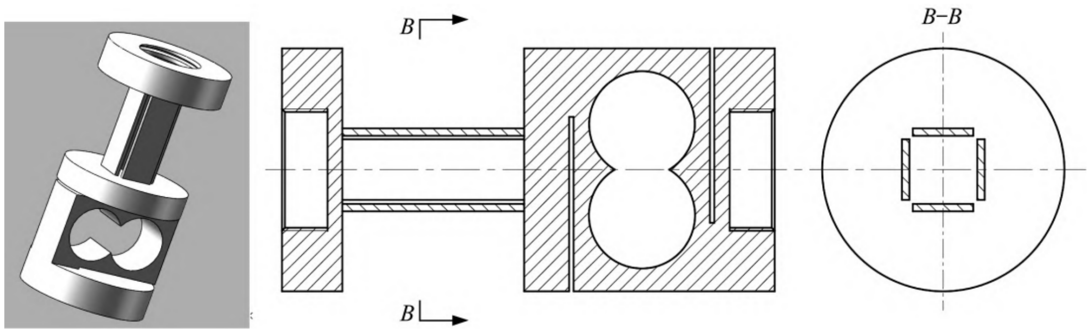

Fig5 Cantilever type double hole parallel beam elastic structure[14]

4.THREE-DIMENSIONAL FORCE SENSOR SCENARIO APPLICATION

4.1 MEDICAL REHABILITATION TEST

Sensors are already playing a key role in the medical industry, According to the requirements of pulmonary interventional surgery, Liu Yanhong et al[15] from Zhengzhou University designed a segmented fiber grating three-dimensional force sensor to provide accurate and real-time end-force feedback for flexible robots. The transverse force sensitivity coefficients were 431.3 pm/N and 517.6 pm/N, the axial force sensitivity coefficients were 153.5 pm/N, and the root-mean-square errors were 0.026, 0.025 and 0.041 N, respectively. Luo Wei [16] designed and implemented a 6-DOF upper limb exoskeleton rehabilitation system based on direct force control, which can realize multiple modes such as active, passive, resistance and exercise prescription. The system can continuously monitor the contact force during exercise and help avoid sports injuries. The closed-loop sensorimotor training can be formed when the brain-computer interface is combined with functional electrical stimulation technology, which provides a new research tool for the clinical application of upper limb exoskeleton rehabilitation system.

4.2 Turning force detection

Zhang Jun [17] from developed an integral piezoelectric three-way turning dynamometer with double elastic ring structure in view of the measurement requirements of three-dimensional dynamic turning force and the shortcomings of the tool bar type and platform type piezoelectric dynamometer. Han Lili [18] designed a piezoelectric three-way drilling force measuring instrument using only four piezoelectric quartz chips to simultaneously measure the torque, radial force and axial force generated in the drilling process, in order to overcome the shortcomings of the previous piezoelectric three-way drilling force measuring instrument which used more quartz chips, so the assembly process was very high, the debugging was difficult, and the manufacturing cost was high.

4.3 Crash Test

Collision detection can be used in vehicle collision detection or robot arm collision detection, etc. Lin Yizhong[19] proposed an intelligent collision sensor with the characteristics of "inertial force detection electromagnetic force servo" to solve the problem of low sensitivity of end collision detection of industrial robots. Chen Haichu[20] designed a three-dimensional anti-collision force sensor, which can use one input to realize the collision force test in the three directions of x, y and z. When used in 6-D.O.F series welding robot ends, it can not only protect the robot itself, but also install on the end effector of other equipment to protect the equipment

5. Development trend of Three-dimensional force sensor

5.1 Miniaturization

The development of sensor miniaturization is a hot spot of current research, the sensor application field has been developed to the cardiovascular and other small space field, at the same time the design of the sensor needs to adapt to this small space, but at the same time the performance of the sensor can not be reduced, but need to improve. Therefore, the design of sensors with high sensitivity, simple structure and small size is one of the current research hotspots.

5.2 Intelligence

The development of sensor intelligence is the focus of current research. The intelligence of the sensor can better realize the detection of precise force. And it can conduct independent analysis and decision after force value detection. At the same time, it can adjust its own performance in different environments and maintain high precision measurement.

5.3 High-performance decoupling

The sensor needs to be decoupled after the design is completed. Some sensors can eliminate the impact of dimensional coupling through their own structure, but some sensors still need to be decoupled through software algorithms, such as least square method, neural network, extreme learning machine and genetic algorithm. Aiming at how to improve the decoupling speed of software algorithm, it is necessary for scholars to study the decoupling algorithm with fast speed and high precision.

6 Conclusion

This paper introduces the three-dimensional force sensor based on the measuring principle of resistance strain gauge, capacitance type, piezoelectric type, etc. At present, resistance strain gauge three-dimensional force sensor is widely used and relatively mature. The characteristics of combined and integrated elastomer structure of Three-dimensional force sensor are summarized. The application of Three-dimensional force sensor in medical rehabilitation, turning force detection and collision detection is introduced. It has important reference significance for developing Three-dimensional force sensor in special environment. Finally, combined with the application status of Three-dimensional force sensor, the development trend of Three-dimensional force sensor is prospected.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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