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Design and Application of Three-component Force Sensor Principle and Structural Progress

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Three-component force sensors are capable of simultaneously detecting force or moment components in three directions in space, and are widely used in robotics, industrial automation, medical equipment, and sports technology. This article focuses on resistive-strain, capacitive, and piezoelectric three-component force sensors. Among them, the resistance strain type three-component force sensor has the characteristics of high precision, small creep and low manufacturing cost, so it is the most widely used in practice. The elastomer structure of combined and integral three-component force transducers is also distinguished and summarized. At present, the research and improvement work of this kind of sensor by scholars at home and abroad mainly focuses on reducing interdimensional coupling, improving sensitivity, reducing measurement error and reducing nonlinear error, so as to improve the actual performance. This paper also analyzes the performance of three-component force sensors in specific applications such as manipulator

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grasping and plantar force sensing. Finally, combined with the research and application status of three-component force sensors, the future development trend of the three-component force sensor is prospected, indicating that this technology will play an important role in more fields and is expected to develop in a more precise and intelligent direction.

Keywords: Three-component force transducer; elastomer structure; flexible tactile sensors; manipulator; plantar force perception.

1. INTRODUCTION

Three-component force sensor is also called three-dimensional force sensor, as an important component that can sense mechanical information in multiple directions in three-dimensional space in real time, is widely used in modern industry, scientific research and daily life, such as automobile collision test, industrial automation, engineering measurement (Li, 2011), robot mechanical perception (Song et al., 2013) and surgery. In recent years, with the rapid development of robot intelligence and automation, many fields need sensors with high sensitivity and small structure size. For intelligent equipment, accurate force information perception is very important, because the accuracy of measurement is directly related to the accuracy of equipment perception and control (Wang, 2015), so higher requirements are put forward for the accuracy and structure of sensors.

This paper mainly summarizes the measuring principle of three-component force sensor and its research status in elastic structure design, and deeply introduces the application scenarios of this kind of sensor. Based on the existing research progress, the future development trend of three-component force sensor is prospected.

2. MEASUREMENT PRINCIPLE OF THREE-COMPONENT FORCE SENSOR

With the development of micromachining technology, the research of three-component force sensors has developed rapidly at home and abroad, and three-component force sensors based on different working principles have been introduced one after another, such as resistance strain type (Zhou & Ren, 2011), capacitance type (Viry et al., 2014) and piezoelectric type (Lee et al., 2019). The measurement method based on the principle of resistance strain is one of the earliest developed technologies, which is not only highly mature, but also the most widely used method at present (Sun, 2016).

2.1 Resistance Strain Type

The resistance strain type three-component force sensor is a sensor that uses the resistance strain effect to measure the external force/torque. The basic principle is that when a force or torque is applied to the elastic body, the strain gauge attached to it will deform correspondingly, resulting in a slight change in the length and cross-sectional area of the resistance wire inside the strain gauge, which in turn causes a change in the resistance value. By using the Wheatstone bridge circuit, these resistance changes will be converted into measurable voltage signals for output, and the amplitude of the voltage signals directly reflects the magnitude of the force or torque. Qin Chong of Henan University of Science and Technology (Qin, 2023) designed a flexible three-dimensional force tactile sensor based on resistance strain, which has high sensitivity, and can reach 1.8V/N in X and Y axes, and within 3.1V/N in Z axis. This sensor can be applied to real-time detection of tangential force and normal force in dexterous hands. Yu Zhiwei of Nanjing University of Aeronautics and Astronautics and others (Yu et al., 2012) developed a small resistance strain type three-dimensional force sensor. By adopting a new elastic body structure, opening a slot in its upper layer and sticking the resistance strain gauge on the side of the elastic body, this design can effectively eliminate the coupling effect between the dimensions, thus meeting the application requirements of micro-robots and small-scale measurement. As shown in Fig. 1, it can be used to detect three-dimensional forces in space.

2.2 Capacitance

Capacitive three-component force sensor is a sensor that uses capacitance effect to measure force/torque. The basic principle is that when force/torque acts on elastic body, it will cause capacitance change. By measuring this capacitance change, the value of external force can be obtained. Lee et al. (2008) put forward a capacitive sensor for detecting three-dimensional

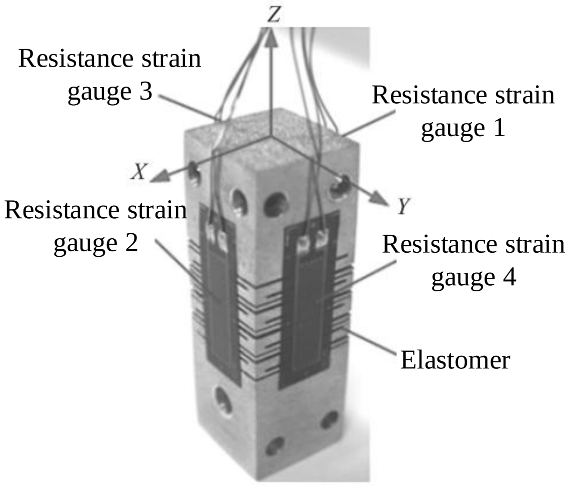


Fig. 1. Structural diagram of three-dimensional force sensor (Yu et al., 2012)

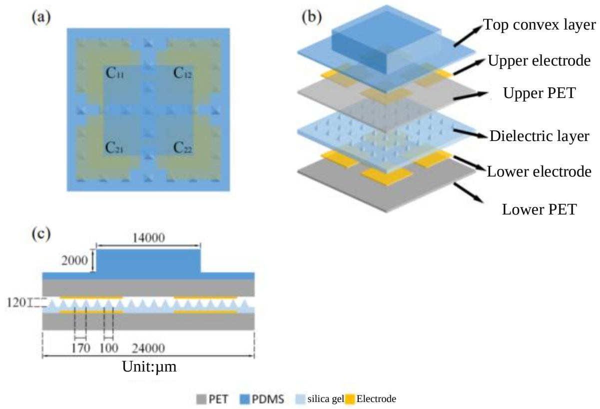


Fig. 2. Capacitive flexible three-dimensional force tactile sensor: (a) top view, (b) layered schematic diagram and (c) cross-sectional view. (Xu, 2022)

force. When external force is applied, the distance between the electrode plates of the output induction unit changes, which will produce signal output, and then the external force can be detected. Zhao Ningjuan, xidian university (Zhao, 2023) designed a highly sensitive ionic capacitive flexible three-dimensional force tactile sensor, which not only has the ability to detect normal and tangential forces, but also has an ultra-fast force response time of 3ms and a long-term fatigue resistance under 8000 cycles, so it has shown high application value in health monitoring, rehabilitation and other fields. Xu Taipu (Xu, 2022) of Jiangsu University has developed a capacitive flexible three-dimensional force tactile sensor. As shown in Fig. 2, this sensor has the advantages of fast response (<60ms) and good cycle stability. It provides important scientific value for intelligent wear, human-computer interaction and humanoid robot.

2.3 Piezoelectric Type

Piezoelectric three-component force sensor is a sensor that uses piezoelectric effect to measure force/torque. The basic principle is that under the action of force or torque, piezoelectric material will produce charge, which will lead to the change of output voltage signal. By measuring this voltage signal, the value of force/torque can be reflected. A new flexible piezoelectric sensor array has been developed by Yu Ping (2016) of Zhejiang University. The sensor shows good linearity, relatively low coupling effect, high repeatability and acceptable frequency response in the range of 5–400 Hz, and is suitable for detecting normal and shear loads. In addition, the sensor array can be easily integrated into the curved surface, which makes it show significant advantages in the applications of robotics and prosthetic hands. Zhang Yanfang of South China

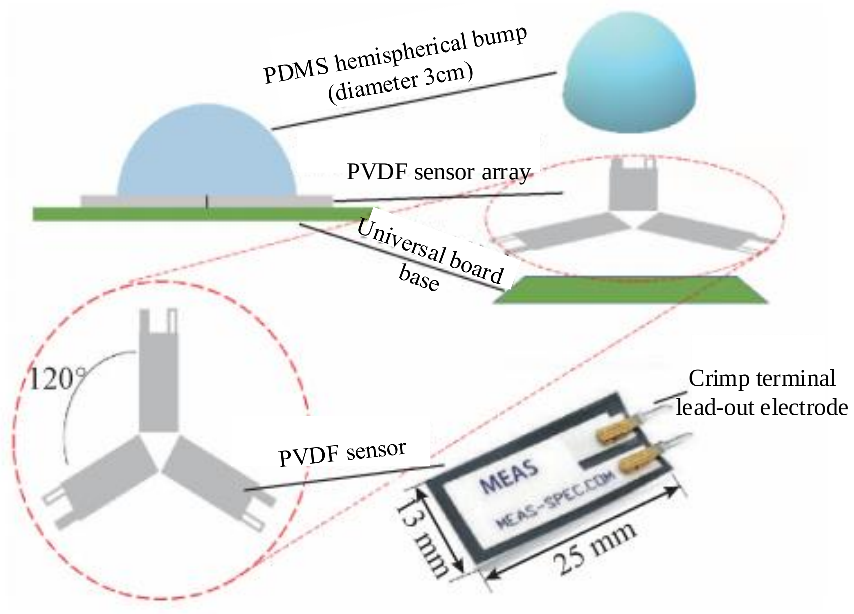


Fig. 3. Structural diagram of PVDF sensor (Zhang, Liu, & Xu, 2021)

University of Technology and others (Zhang, Liu, & Xu, 2021) put forward a three-dimensional force sensor based on PVDF piezoelectric film. As shown in Fig. 3, compared with the traditional four prism structure, this sensor can maintain higher sensitivity and smaller error, and reduce the cost by reducing one piezoelectric sensing unit. Zhang Chunyan of Taiyuan University of Technology and others (Zhang et al., 2023) developed a piezoelectric three-dimensional force sensor, which has excellent directional resolution, normal sensitivity and high linearity, and can feed back information in real time to distinguish different surface roughness and force directions. These characteristics make it possible to become a self-powered wearable device in future human-computer interaction or personalized identification applications.

Compared with capacitive and piezoelectric three-component force sensors, the resistance strain type three-component force sensor has the advantages of high precision, small creep, small nonlinear and hysteresis errors and low manufacturing cost, and can compensate the zero balance, sensitivity and zero temperature influence of the sensor, but the sensitivity and stiffness are mutually restricted, resulting in low dynamic response. Capacitive three-component force sensor has the advantages of good temperature stability, large pressure range, high sensitivity and low hysteresis, but it will be affected by parasitic capacitance in the surrounding environment, so it is rarely used in practice. Piezoelectric three-component force sensor has the advantages of high natural frequency and good dynamic performance, but compared with resistance strain three-component force sensor, its manufacturing cost is high and it is not suitable for measuring static force. Compared with capacitive three-component force sensor, it is easily affected by environmental temperature and humidity and has high noise.

3. ELASTOMER STRUCTURE DESIGN OF THREE-COMPONENT FORCE SENSOR

According to whether the elastomer structure of the three-component force sensor is integrated, it can be divided into two types: integral elastomer and combined elastomer. The design of elastomer will directly affect the dynamic performance, coupling degree between dimensions, sensitivity and measurement accuracy of the sensor (Cao et al., 2020). Therefore, the core of developing a new multi-dimensional force sensor is to propose a unique and reasonable elastic structure design.

3.1 Structural Design of Integral Elastomer

Integral elastomer structure refers to that in the manufacturing process, the elastic element and other parts of the sensor (such as the base or connector) are made by single piece of material or one-time molding. Because of its integrated design, this structure has the advantages of simplicity, good reliability and high precision. Qin Yuanlin of Shanghai Institute of Aerospace Precision Machinery (Qin et al., 2024) designed a small three-dimensional force sensor elastomer, which belongs to cantilever double-hole parallel beam elastomer structure. This elastomer structure is suitable for small-size and high-precision stress measurement tasks. By adjusting the thickness and width of the double-hole parallel beam, its range can be flexibly controlled, which makes it show excellent applicability. Luo Xunhuang of Wuhan University of Science and Technology and others (Luo et al., 2022) put forward an integral elastic structure with simple structure, and attached strain gauges on the side walls between structural holes. Compared with the existing strain-type multi-dimensional force sensor, this design has significantly improved the coupling error between dimensions. As shown in Fig. 4, the measurement accuracy is high, the maximum error occurs when the force Fz acts, and the inter-dimensional coupling interference is 0.8775%.

3.2 Structural Design of Combined Elastomer

The combined elastic structure means that the elastic element of the sensor and other components are manufactured independently, and then combined into a complete sensor by bonding and bolting. Because the components are manufactured separately, this structure is easy to maintain and has good adaptability and flexibility. Yang Wei (Yang, 2019) of Yanshan University put forward a kind of rigid-flexible hybrid large deformation parallel three-dimensional force sensor, as shown in Fig. 5, which integrates the concept of rigid-flexible hybrid design into multi-dimensional force sensing technology, and adopts a new type of mobile parallel mechanism with stable force transmission characteristics to optimize the design of force sensing elements. This innovative idea not only effectively improves the sensitivity and operational reliability of the system, but also significantly improves the structural stability and

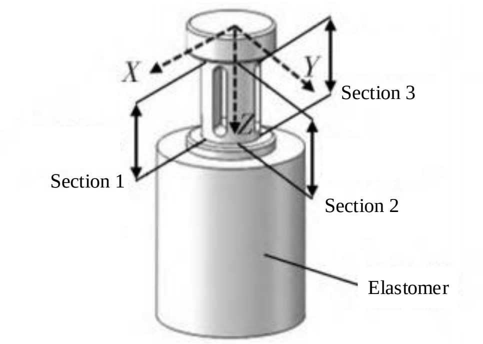


Fig. 4. Structural diagram of integrated three-dimensional force sensor (Luo et al., 2022)

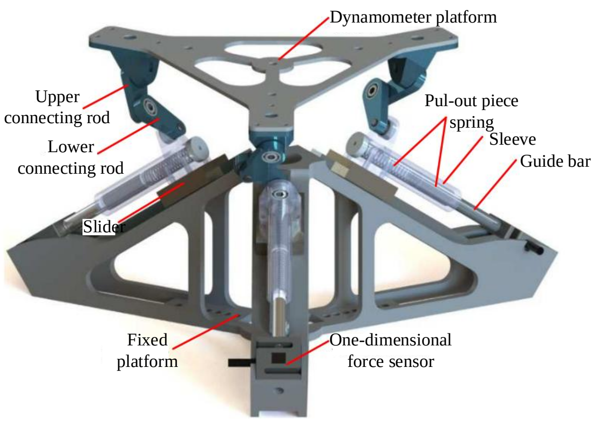
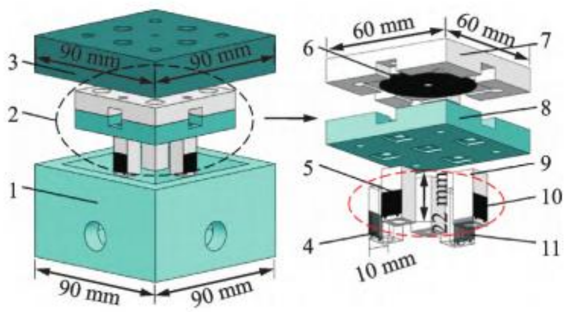


Fig. 5. Structure diagram of rigid-flexible hybrid large deformation parallel three-dimensional force sensor (Yang, 2019)



1- shell; 2- elastomer region; 3- upper cover; No. 4-2 piezoelectric film; 5-1 piezoelectric film; 6-Z piezoelectric film; 7- Upper cover plate; 8- Lower cover plate;9- Column group; 10-4 piezoelectric film; 11-3 Piezoelectric film.

Fig. 6. Three-dimensional structure diagram of combined three-dimensional force sensor (Zhao et al., 2023)

dynamic response. Through the application of this mechanism, the system can still maintain excellent performance consistency and measurement accuracy in the face of complex and changeable working environment and load conditions, which provides a solid technical support for high-precision force control tasks.

Zhao Peng of Jinan University and others (Zhao et al., 2023) designed a combined self-decoupling piezoelectric thin film three-dimensional force sensor, and the diamond-shaped structure of columns has the ability to offset the coupling between dimensions. As shown in Fig. 6, it has the characteristics of high sensitivity and high natural frequency. The nonlinear errors in all three directions are less than 0.2%, and the coupling error between dimensions is less than 1.2%. The sensor has shown extremely important application value in the cold heading forming of high-precision bearing steel balls and transient strong impact scenes.

In the above literature, no matter in the research of integral elastic structure or combined elastic structure, a lot of work and continuous improvement of domestic and foreign scholars mainly focus on reducing the coupling effect between dimensions, improving the sensitivity of structures, reducing measurement errors and restraining nonlinear errors. The optimization of these key technical indexes aims to further improve the accuracy and stability of sensors or actuators under complex working conditions, so as to enhance their adaptability and use value in practical application scenarios such as industrial detection, robot sensing and precision assembly. At the same time, the related research has gradually expanded to the direction of lightweight structure, simplified manufacturing process and multi-functional integration, which has promoted the transformation of elastomer design from experience-driven to theoretical guidance.

4. APPLICATION SCENARIO OF THREE-COMPONENT FORCE SENSOR

Three-component force sensor plays an indispensable role in key fields such as intelligence, automation and human-computer interaction, and its application range extends from the control of manipulator accurately grasping objects to the action analysis and optimization in physical training, and even the fine monitoring of patients' rehabilitation process in clinical medicine. This kind of sensor not only improves the operation accuracy and intelligence level of robot technology, but also provides scientific basis for athletes' technical improvement, and promotes the development of personalized treatment scheme and the accuracy of curative effect evaluation in the medical field.

4.1 Manipulator Grasping

Manipulators (also known as robot end effectors) are designed to simulate the functions of human hands and arms, and can pick up, carry and place various types of objects. In order to accurately control the grasping force and grasping position, a variety of sensors are usually installed on the manipulator, which can help adjust the grasping force and sense whether the manipulator has successfully contacted and grasped the object. Mao Leidong of Hefei

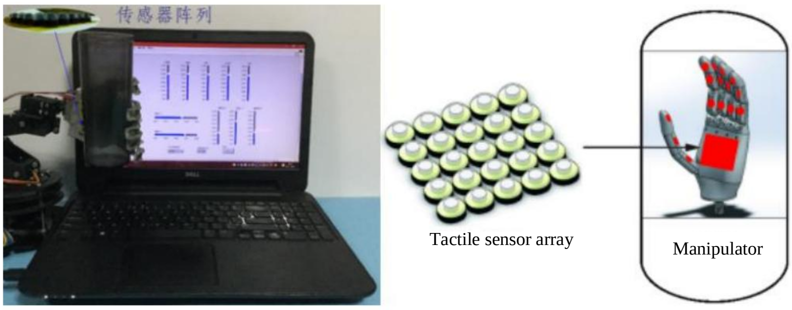


Fig. 7. Schematic diagram of robot hand grasping (Mao, 2018)

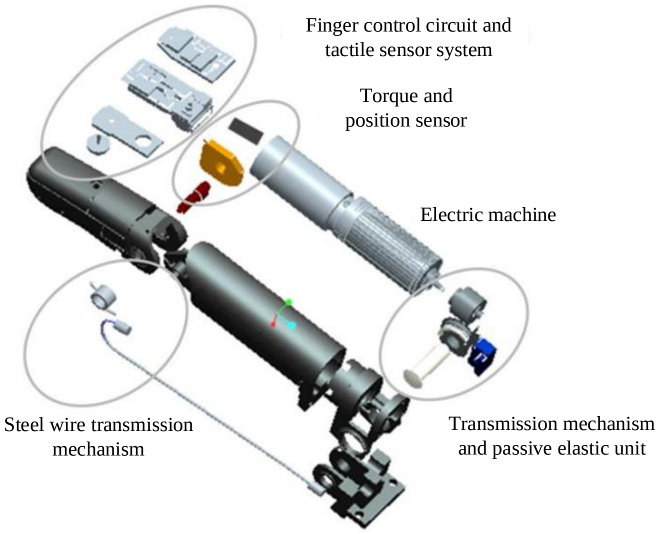


Fig. 8. Structure diagram of humanoid artificial finger (Zhang, 2014)

University of Technology (Mao, 2018) applied the flexible tactile three-dimensional force sensor to the palm of a robot to grasp and perceive objects. As shown in Fig. 7, the soft grasping strategy based on tactile system was studied, and the grasping state was identified by support vector machine, with the recognition accuracy as high as 94.8%.

Zhang Ting (Zhang, 2014) of Harbin Institute of Technology studied the dynamic grasping of the three-dimensional force tactile sensor of humanoid artificial finger. As shown in Fig. 8, through a dynamic grasping control method based on tactile sensor information feedback, the operational performance of the artificial hand was improved, and the research focused on the adaptive impedance force tracking control of the artificial hand, aiming at balancing the flexibility of contact and the accuracy of grasping force control. The experimental results show that the impedance force tracking control method can follow the expected grasping force with high accuracy and ensure the compliance of contact, which lays the foundation for the research of dynamic grasping control.

4.2 Plantar Force Perception

The perception and measurement of plantar force can analyze the force distribution between the foot and the ground, and provide important data support for clinical medicine and sports training. Wu Jiaqi (Wu, 2023) of Fujian Institute of Engineering has designed a plantar three-dimensional force sensor based on the improvement of the traditional cross beam structure, as shown in Fig. 9, which can realize the real-time display and storage of plantar force information. The experimental calibration shows that the sensor has small static error and high sensitivity. By analyzing the pressure distribution on the sole of the foot, it can be used to diagnose gait abnormalities, such as flat feet and high arch feet.

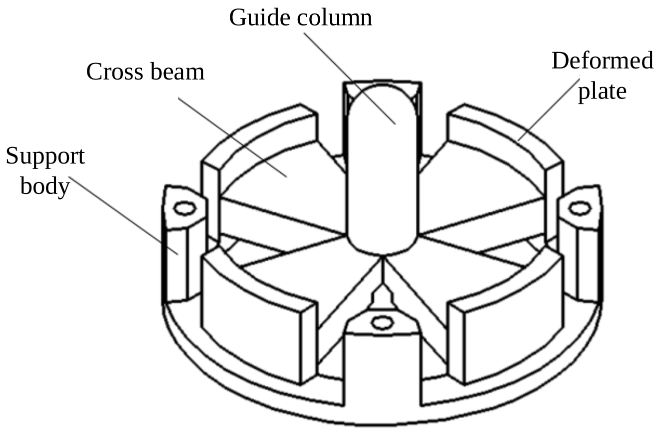


Fig. 9. Structure diagram of plantar three-dimensional force sensor (Wu, 2023)

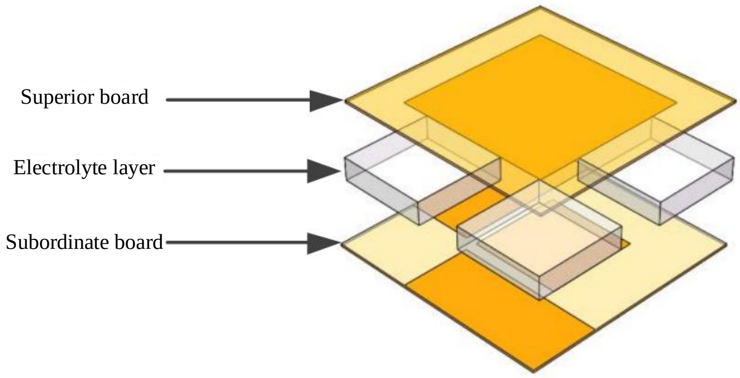


Fig. 10. Structure diagram of parallel plate capacitance three-dimensional force sensor (Zhang, 2018)

Xue Hongwei of Huazhong University of Science and Technology (Xue, 2023) developed a flexible three-dimensional force sensor based on magnetic field. Aiming at the problems of low dimension, poor environmental adaptability and insufficient wearability of traditional force sensors, the corresponding solutions were put forward, and they were applied to human balance control and rehabilitation process guidance, which provided technical support for the development of wearable devices and human motion measurement. Xidian university Zhang Feng (2018) studied a flexible sensor for three-dimensional force of parallel plate capacitance, as shown in Fig. 10, which can realize long-term and long-distance real-time measurement of three-dimensional interface stress of sole, and has the advantages of high sensitivity, flexibility and portability. By monitoring the data of plantar force distribution in athletes' daily training, we can find out the factors that may lead to injuries and intervene in advance.

5. DEVELOPMENT TREND OF THREE-COMPONENT FORCE SENSOR

5.1 Integration and Miniaturization

With the progress of microelectronics and materials science, the three-component force sensor is developing towards smaller volume and lighter weight. This trend is conducive to the integrated application of sensors, especially in space-limited occasions, such as micro-robots or wearable devices. The miniaturized three-component force sensor can be embedded in the end effector of the robot, so that it can perform fine operations in a narrow space, such as minimally invasive surgery or precision assembly tasks in the medical field. Miniaturized sensors have low production and manufacturing costs, and can improve economic benefits in large-scale production and manufacturing.

5.2 Measurement Accuracy and Durability

The three-component force sensor with high measurement accuracy can capture the tiny force change more accurately. In the precision manufacturing industry, it can be ensured that the force applied in the machining process is kept within an ideal range, thus improving the quality of products and reducing the rejection rate. In the aerospace field, it can be used to monitor various forces borne by aircraft during high-speed flight, thus improving the safety of aircraft. Durability is the key factor when the three-component force sensor adapts to harsh working environment. More durable materials and optimized manufacturing process can ensure the sensor to work normally in deep sea exploration, aerospace exploration and extreme environment.

5.3 Intelligentize

With the development of Internet of Things technology, the process of sensor intelligence is accelerating. Sensors are no longer simple data acquisition devices, but they have been able to conduct preliminary data processing and analysis. This data fusion ability enables the sensor to combine the collected information with the data of other sensors, and then only transmit useful data, which improves the efficiency and response speed of the whole system, and also enhances the intelligent level of the system, providing users with more refined services and management. With the continuous progress of technology, the application scope of smart sensors will continue to expand and become an important force to promote the development of various industries.

6. CONCLUSION

This paper introduces a three-component force sensor based on three different measuring principles: resistance strain type, capacitance type and piezoelectric type. Among them, the resistance strain type three-component force sensor is favored because of its wide application and the highest technical maturity. In this paper, the structural characteristics of integral and combined elastic body of three-component force sensor are summarized, and the application examples of this kind of sensor in manipulator grasping, plantar force sensing and other fields are discussed. These examples not only show the application results of the existing technology, but also provide valuable reference for the future development of three-component force sensor suitable for special environment. Finally, based on the current application status of the three-component force sensor, the paper looks forward to its future development trend. It is predicted that with the continuous innovation of technology and the growth of market demand, the three-component force sensor will play a key role in more industries and promote the development of related technologies in the direction of higher precision, smaller size, lower power consumption and higher intelligence.

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 writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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