Flexible Tactile Sensors in Electronic Skins

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Abstract. With the rapid development of robot technology, robot is widely used in daily life. According to different functions, the new generation of robots can be classified into social robots, medical robots, auxiliary robots and humanoid robots. Compared with traditional human-controlled industrial robots, these new-generation robots have the characteristics of close interaction, so it is particularly important to have a safe and accurate interaction system, and the tactile sensor has become the key to achieve this function. Tactile sensors can mimic human skin, and they can express temperature, humidity, force and other senses in a digital way, so that the robot can perform tasks completely and accurately in the process of interacting with the external environment. Flexible tactile sensors have the advantages of flexibility, light weight, versatility and affordability and have possible applications in wearable electronics and artificial intelligence. Therefore, more and more researchers began to study tactile sensors. This review gives an overview of advanced flexible tactile sensors, which focuses on the working principle, new materials and application prospect of three mainstream flexible tactile devices, namely piezoelectric sensor, conductive sensor and resistive tactile sensor. Finally, possible routes, future tendency and new opportunities are presented.

Keywords: Flexible tactile sensor, electronic skins, mimic human skin, digital sensors, versatility.

1. Introduction

A large amount of efforts have been made to integrate tactile sensing capabilities into intelligent robotic systems by equipping such systems with tactile sensors that resemble human skin, as sensory information with a variety of modalities could improve the accuracy of robot interaction with unstructured environments [1]. The creation of flexible tactile sensors with high sensitivity and superb flexibility is now possibly thanks to recent advancements in manufacturing techniques and advanced materials. According to their operating principles, flexible touch sensors can be classified as piezoresistive, capacitive, and piezoelectric sensors [2-4]. Recent developments in structural engineering, novel material development, and existing physical principles all contribute to the benefits of tactile sensing technology.

Tactile sensors can mimic human skin, artificial tactile sensors are devices designed to detect external stimuli and convert them into signals that can be measured or recorded. Tactile sensors, which are in physical contact and resemble human skin, may sense pressure, tension, temperature, and even humidity. In contrast to "rigid", "flexible" means that the tactile sensor has the characteristics similar to human skin, has the flexibility of being malleable and bendable, can adapt to any shape of the carrier, and is conducive to measuring the force information on the surface of the object and sensing the nature and characteristics of the target object. High flexibility and sensitivity, enormous stretch, ultra-conformal, low cost, and vast-area manufacture are characteristics of flexible tactile sensors. Particularly, some flexible tactile sensors with high-performance electrodes and sophisticated sensing materials perform superior sensing to that of human skin. Because of their superior qualities, touch sensors are successful in tracking human activities, providing personal healthcare, artificial intelligence and other fields. At present, flexible tactile sensors can be classified into many types. This paper reviews the latest development of flexible tactile sensors, piezoelectric sensor, capacitive sensor and piezoresistive sensor are highlighted.

2. Piezoresistive Flexible Sensor

2.1. Piezoresistive Sensing Principles

Lord Kelvin first discovered piezoresistivity dates in 1856 [5]. With the exploration of the piezoresistive effect in silicon (Si) and germanium (Ge) in 1954, the creation of piezoresistive devices advanced [6]. Piezoresistive effect refers to that when the force is applied to the silicon crystal,deformation causes the scattering of carriers from one energy valley to another,which causes the change of carriers' mobility and the average amount of carriers in longitudinal and transverse directions,so as to change the resistivity of silicon. The functional relationship between the change of silicon resistance and the external stress is shown in Formula (1):

$$\frac{\Delta R}{R} = (1+2\nu)\ \ \varepsilon + \frac{\Delta\rho}{\rho} \tag{1}$$

Where R is the resistance of the material, ρ is the resistivity, v is Poisson's ratio, ε is the stress on the material.

Flexible piezoresistive tactile sensors also use silicon crystals as sensitive materials but choose a more flexible substrate which is different from traditional piezoresistive sensors so that it has better deformation ability.

2.2. Materials in Flexble Piezoresistive Tactile Sensors

Flexible piezoresistive tactile sensors are composed of substrate material and active material.Flexible piezoresistive is insulating so it should carry active material which is conductive.

2.2.1 Flexible substrate material

Substrate material is the frame of piezoresistive sensor, which impacts greatly on the quantity of flexible pressure sensor and determines the flexibility of resistive tactile sensor to a great extent where low Young's modulus is expected. Different polymers have been used in substrate, such as polydimethylsiloxane (PDMS), polyethylene terephthalate (PET), polyacrylate (PEA), hydrogels (polyvinyl alcohol (PVA), polyacrylamide (PAM)), etc. [7].

PDMS are widely used as substrate materials due to their high tensile properties, biocompatibility and good toughness. Bang et al. designed a flexible stress sensor based on piezoresistive nanocomposites to describe human pressure sensing capabilities. Using graphene as a conductive filler and PDMS as substrate, the pressure sensor has a wide pressure detection range of 100 Pa-1020kpa [8]. Rinaldi et al. examined a new lightweight piezoresistive sensor based on PDMS polymers in a foam structure coated with multi-layer graphene nanoplatelets for applications requiring high sensitivity, such as wearable medical systems and human-machine interface devices [9].

2.2.2 Active material

Active materials can be roughly divided into metal-based materials, carbon nanocomposites, conductive polymer materials, etc. Metal-based materials are mainly gold, silver, copper, nickel and other materials; Carbon nanocomposites where carbon nanotubes, graphite and graphene are commonly used. Conductive polymers are also often used in conductive layers of piezoresistive flexible tactile sensors, such as polyaniline (PANI) and ionic hydrogels.

Metal-based materials have long been used as sensitive materials because of their excellent conductivity. Metal-based materials have large Young's modulus. In order to meet the requirements of flexibility, researchers will change the size and shape of metal particles and make them into micron or nano level, so as to prepare various piezoresistive flexible tactile sensors. Zhu et al. made use of electrohydrodynamics (EHD) printing technology to prepare AgNPs pressure sensors, which have high electrical conductivity and good mechanical properties [10].

2.3. Future Development

Piezoresistive tactile sensors have made great progress and shown protential application in electronic skin after decades of development. However, it still has a lot of space for exploring. Due to the rapid development of intelligent robots, resistive tactile sensors gradually show great potential in machine sensing systems. In addition, the robot's self-learning and environmental adaptability can be improved with tactile sensors so that it can operate in extremely harsh environments, and play a significant role in manufacturing, service, medical, military and other industries. At the same time, the electronic skin with piezoresistive tactile sensors can also be explored in the direction of multi-function, self-healing, self-cleaning, etc. to achieve similar perception and tactile performance with human skin so that the robot can better adapt to the complex environment and is valuable in the field of bionic robots, medical care and other fields.

3. Capacitive Flexible Pressure Sensor

3.1. Principle

Capacitive pressure sensors, featuring high sensitivity, low power consumption, rapid response and simple structure, have got great success in electronic products such as touch screens, trackpads and biometric devices. Thanks to the development of flexible tactile sensing system, the function of capacitive stress sensors is optimized and its application scope is also expanding to intelligent robotics, healthcare, wearable devices and other fields. The sensing mechanism of capacitive sensors is the principle of parallel plate capacitors in response to the applied strain through changes in capacitance. The calculation of capacitance (C) is given by the formula (2):

$$C = \varepsilon_0 \varepsilon_r A/d \tag{2}$$

where ε_0 is the dielectric constant, where A is the overlapped area of the two plates, d is the separation between the plates, and ε_r is the relative static dielectric constant of the dielectric layer between the plates. Three variables in this equation—ε_r, A, and d—are pressure-sensitive. Among them, d and A are the most susceptible to outside influences. It is usual practice to estimate normal forces using the variation of d.

3.2. Common Materials in Capacitive Flexible Stress Sensors

For capacitive flexible pressure sensor, the selection of electrode material and dielectric layer material directly affects its initial capacitance, sensitivity and other properties. Therefore, it is necessary to understand common property of these materials when designing capacitive sensors and then select appropriate materials and carry out structural design according to the needs of the sensor. The characteristics of electrode materials and dielectric materials for sensors are briefly introduced below.

3.2.1 Electrode material

Carbon materials such as graphene and carbon nanotubes (CNTs) are widely used as electrode materials in capacitive flexible stress sensors thanks to their excellent electrical conductivity and flexibility. Among them, carbon nanotubes are used in many electrode materials for the reason of mature manufacture technology which enables them to be mass-produced. The research of carbon nanotubes as electrode materials has made some progress, but with the deepening of the research, people paid great attention to CNT composites. In recent years, it has become a hot research field to combine CNT with conductive polymer, metal oxide, graphene and other polar binary materials [11]. Panasenko et al. deposited polyaniline (PANI) on CNT thin film by electrochemical deposition method to prepare CNT/PANI composite material. The capacitance of this material is 3 times larger than pure CNT electrode material [12]. Lai et al. synthesized CNT/NiO composite materials by hydrothermal method, enabling NiO to grow on the surface of CNT and providing high capacitance through the reduction reaction of flower cultivation [13].

3.2.2 dielectric material

Polymer dielectric materials are widely used in electrostatic capacitors for their high charge-discharge rate, high breakdown field strength and self-healing properties. Among them, Polydimethylsiloxane (PDMS) is a non-toxic and chemically stable silicon-based organic polymer. Due to the characteristics of low preparation cost, simple preparation, good light transmittance and strong biocompatibility, PDMS material is not only often used as the dielectric material of capacitive stress sensors, but also widely used in other flexible sensors.

PET (terephthalate) is a kind of thermoplastic polymer resins. PET has excellent electrical insulation properties, so it can be used as insulation material for capacitive sensors. PET is less affected by temperature and has good heat resistance, so it can be used for the preparation of electrical parts. PET not only has good light transmittance, but also has good mechanical properties.

PI (polyimide) is a polymer of imide monomers. The film made of PI material has excellent mechanical properties, not only high tensile strength and creep resistance, but also radiation resistance, high temperature resistance, and high insulation characteristics. It is a common material for the preparation of flexible sensors.

Silicone rubber is a kind of synthetic rubber, with bending resistance, high temperature resistance, oxidation resistance, strong electrical insulation characteristics. Today, as one of the most common elastic materials, silicone rubber has a wide range of applications in construction, electronics, aviation and medical [14].

3.3. Future Direction

Miniaturization and lightweight capacitors are urgently required with the development of high-power and small-sized electronic devices and energy systems. This increases the need for capacitors to operate steadily over an extended period of time in high electric fields and temperatures. The dielectric materials of high temperature polymer capacitors are setting off a wave. There is a tendency to study high temperature polymer dielectric materials in the future [15].

4. Flexible Piezoelectric Tactile Sensor

4.1. Principle

Flexible Piezoelectric tactile sensors works according to the piezoelectric effect. They can convert mechanical signals into electrical signals with the advantages of simple structure, stable performance, high precision, and fast response and can be widely used in various complex curved surface structures. The difference between the piezoelectric tactile sensor and the former two is that the piezoelectric material has a piezoelectric effect. When it is under pressure, the surfaces of the material will generate positive and negative electric charges, and the amount of charge is positively related to the force on the material. Force, pressure, acceleration, temperature and other quantities can be measured by converting the acquired data into electric charges [16].

There is a dielectric material within which there are chaotically arranged crystals, which have positive and negative charges. When the dielectric is deformed by an external force of compression or stretching, the chaotically arranged crystals inside will deflect, and the positive and negative charges will move toward the surface of the dielectric relative to each other, thus creating electrodes. After the load is removed, the charge on the surface of the dielectric returns to the state before the movement, and the surface of the dielectric is no longer charged, which called positive piezoelectric effect which reflects the process by which the dielectric converts mechanical energy into electrical energy, and this effect can be used to monitor the deformation of the structure. When the dielectric material is placed in an electric field, the dielectric is subjected to the electric field, and the chaotically arranged crystals are gradually arranged in an orderly manner, and the dielectric is deformed macroscopically. After removing the external electric field, the crystals inside the dielectric return to the state of chaotic arrangement, and the deformation disappears which called inverse piezoelectric effect. The inverse piezoelectric effect reflects the ability of a certain dielectric to change electrical energy into mechanical energy. Using this ability, the dielectric can be made into a signal generator or signal receiver to sense signal changes in different states, thereby achieving the purpose of detecting damage [17].

4.2. Piezoelectric Sensor Material Selection

In the current research on piezoelectric materials, it can be divided into three types according to their chemical composition: organic piezoelectric materials, inorganic piezoelectric materials and composite piezoelectric materials. A good piezoelectric material can not only make the sensor more sensitive, but also avoid errors. Density, Poisson's ratio, Young's modulus, and relative permittivity of piezoelectric materials are all key factors affecting piezoelectric sensors. Therefore, it is necessary to comprehensively consider the effectiveness, stability and economy in the selection of materials.

4.2.1 Organic piezoelectric materials

The organic material generally adopts polyvinylidene fluoride (PVDF). This kind of film material is characterized by high flexibility and light weight, and it has good applications in fields that require certain flexibility such as personal wear, and it also has good piezoelectric and pyroelectric properties. The maximum temperature that can be used is 150°C. PDMS (polydimethylsiloxane) has excellent viscoelasticity and flexibility, simple preparation, good biocompatibility, low cost and good thermal stability, etc. It is also the first choice for piezoelectric materials. PDMS is a non-toxic, transparent and stable polymer material with low manufacturing cost and simple manufacturing process. These advantages make PDMS widely used in the field of tactile sensors.

4.2.2 Inorganic piezoelectric materials

Inorganic piezoelectric materials are widely used piezoelectric materials at present. Generally divided into piezoelectric single crystal and piezoelectric ceramics.

Quartz crystal

The Curie temperature point of quartz crystal is 500℃, when its temperature is below 500℃, its piezoelectric coefficient varys very slightly; But when its temperature is higher than 575 ℃, it no longer has piezoelectric properties. It is commonly used in standard sensors or dynamometer, thanks to its higher strength and stable piezoelectric properties.

$LiNbO_3$ crystal

Lithium niobate is one of the most widely used new inorganic materials at present. Its chemical formula is $LiNbO_3$, which is a negative crystal , the polarized lithium niobate crystal is a material with piezoelectric, ferroelectric, photoelectric, nonlinear optics properties, which is widely used in the manufacture of piezoelectric tactile sensors.

Piezoelectric ceramics

Barium Titanate ($BaTiO_3$) is the earliest material used as piezoelectric ceramics. Lead Zirconate Titanate (PZT) is the most widely used piezoelectric ceramics. Its Curie temperature is about 300 ℃. It can be used as a signal generator and also be used as a signal receiver. Piezoelectric ceramics have many advantages. It is very sensitive to the vibration of the structure, has a fast response speed, can work at a higher frequency, and can accurately and quickly identify small damages inside the structure; the cost of making piezoelectric ceramics is very low; low operating threshold, and extremely high practicability.

4.2.3 Composite piezoelectric materials

At present, there have been some composite materials combining PDMS and PZT, but there are problems of high cost and low yield. In addition, there are cement-based composite piezoelectric materials, crystalline polymers or amorphous polymers mixed with ferroelectric ceramics, concretebased composite piezoelectric materials, etc. They are relatively indestructible and can be made into underwater acoustic transducers [17].

4.3. Application Prospects

The application prospects of piezoelectric tactile receptors in electronic skin are very broad. In 2020, J. He et al. used PZT and other materials to prepare high-sensitivity electronic skin. Firstly, PZT nanofibers were prepared by electrospinning, and mixed with PDMS to fabricate the piezoelectric layer [18]. PZT nanofibers obtained higher aspect ratio after electrospinning, and PZT itself has a higher piezoelectric constant than PVDF, so that the composite film made has high sensitivity and electromechanical conversion coefficient. In the durability test, it has good stability through 1600 tests. Electronic skin is limited by the existing preparation technology, etc., and the unit density of thin film devices is still low. In 2020, Y.M. Liu et al. proposed a method for preparing a large-scale high-throughput tactile sensor array [19]. The PZT tactile sensor array prepared by this method has high resolution, which can simplify data acquisition and reduce costs. During preparation, PZT powder and PDMS are first mixed, then stirred and ground, then film cast, and finally screen-printed on a flexible circuit to prepare an electronic skin with a 4×4 array in order to make the electronic skin more flexible. It adopts a serpentine interconnection layout. The density of the sensor can reach 25/cm^2, and it exhibits the characteristics of high resolution and high accuracy in various hand motion and pressure sensing scenarios.

5. Conclusion

After decades of development, flexible tactile sensors have made great progress and show promising applications on electronic skins. Researchers have conducted various researches on flexible tactile sensor materials, and this article has repeatedly mentioned the potential of PDMS and its composite materials for flexible tactile sensors. However, it is still difficult to integrate flexible tactile sensors into electronic skin, and there are still many problems in its development and research. First of all, the current resistive flexible tactile sensor is still difficult to achieve both high flexibility and high sensitivity. Although some sensors have achieved high sensitivity in a low working range, they cannot be extended to a higher working range. Perceptual performance is limited. Secondly, flexible tactile sensors are difficult to cut and splice, and large-area coverage is still difficult. Although the performance of the sensing unit has been greatly improved, its scalability is not good, and it cannot adapt to arbitrary tailoring and splicing under different carrier conditions. Thirdly, the manufacturing process of electronic skin is relatively complicated, and the high cost also limits its mass production capacity. In addition, the array scale of the sensing unit is large, the signal reading circuit is too complicated, and the sampling rate is low, so the real-time performance cannot be guaranteed. Finally, the high power consumption of electronic skin and the lack of intelligent algorithms are also the problems that limit its development. High consumption on the circuit means high requirements for electric energy, and high-density tactile images also means that special intelligent algorithms are required to realize intelligent recognition and perception of tactile objects. Due to the rapid development of intelligent robots and the popularity of mobile smart devices, flexible tactile sensors have gradually shown great potential for application in machine tactile perception systems and flexible human-computer interaction networks. In addition, the blessing of the tactile perception system can improve the robot's self-learning and environmental adaptability, and has the function of operating in extremely harsh environments, and it will play a greater role in manufacturing, service, medical, military and other industries. At the same time, in addition to high flexibility and high sensitivity, the electronic skin integrated with flexible tactile sensors can also develop in the direction of multi-function, anti-interference, self-healing, self-cleaning, etc., to achieve a comprehensive perception that is more similar to human skin The tactile performance enables the robot to better adapt to the external complex environment.

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