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Recent Trends in Human Motion Detection Technology and Flexible/stretchable Physical Sensors: A Review

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Abstract

Human body motion detection is important in several industry sectors, such as entertainment, healthcare, rehabilitation, and so on. In this paper, we first discuss commercial human motion detection technologies (optical markers, MEMS acceleration sensors, infrared imaging, etc.) and then explain recent advances in the development of flexible and stretchable strain sensors for human motion detection. In particular, flexible and stretchable strain sensors that are fabricated using carbon nanotubes, silver nanowires, graphene, and other materials are reviewed.

Keywords: human motion detection, stretchable sensor, flexible sensor, strain sensor, nanomaterials

1. INTRODUCTION

Entertainment, healthcare, social welfare, and safety are important areas in current research. In these areas, the development of advanced fusion hybrid systems with innovative functions that combine the latest electronics, materials, and mechanical technologies is actively being pursued. In addition, a system capable of integrating various sensors, having new cognitive functions, and enabling bidirectional feedback, is being developed. In particular, human motion detection technology recognizes the user's movements; records, analyzes, and diagnoses them; and provides feedback to the user as needed. This technology is attracting great attention, and a large market is being formed.

In the field of entertainment (specifically, the gaming and movie industries), active use of sensors is being developed. The Nintendo Wii game console, launched in 2006, integrates a variety of sensors, including MEMS accelerometers, gyroscopes, and infrared sensors, which collect data as the game console in manipulated through the user's body movements; the introduction of the Wii led to a new paradigm in the video game market. In 3D animated movies, 3D motion capture systems have been used to realize a lively and realistic computer graphic effect.

In the healthcare field, gait analysis is used to analyze the gait of elderly individuals and patients to detect gait disorders, diagnose the underlying causes, monitor disease progression, and to guide treatment. In addition, proper drug therapy can be provided by monitoring the behavior of patients with mental illness in real time and reading important patterns. Human motion detection technology is also used to analyze the behavior of physicians in surgical and emergency situations, and it can be used as a training tool for medical practice.

In the fields of social welfare and safety, assistive devices are developed and implemented based on pattern recognition in data gathered through behavior monitoring of persons with disabilities. In addition, a variety of technologies are being developed, including safety measures to protect workers from dangers. In addition, wearable fitness monitoring gadgets, which enable users to exercise effectively by monitoring the amount of exercise performed and the correct exercise patterns during running, weight training, and yoga, are becoming popular in the market.

Human body motion detection methods include optical marker image analysis using cameras, depth monitoring of objects using infrared sensors, object recognition by an electric field change, acceleration and angular velocity measurement using MEMS accelerometers and gyroscopes, joint motion measurement using an articulated structure by mechanical or optical sensors. In this paper, we first discuss commercial human motion detection technologies, and then explain human motion detection technology using flexible electronic devices, which are currently

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being actively developed. In particular, flexible strain sensors using carbon nanotubes, silver nanowires, graphene, and other materials will be discussed in detail.

2. HUMAN MOTION DETECTION TECHNOLOGY

2.1 Optical marker tracking

In this approach, the motions of several optical markers attached to the user's body are simultaneously measured by several cameras to track the user's posture and motion [1]. Typically, a spherical object coated with a reflective film with a diameter of a few millimeters, or a marker with an infrared LED attached are utilized, and their images are captured by 4 to 32 CCD cameras simultaneously with a sampling rate of 30 to 1000 fps. The cameras are installed in previously calculated positions and directions, and two-dimensional coordinate values a re obtained from the images photographed by the respective cameras. Then, three-dimensional coordinates of the marker are calculated by combining the two-dimensional coordinate values of the respective images. After that, the skeletal structure motion model of the subject is extracted through various stages of signal processing. This method is the most accurate and precise human motion monitoring system, and it is the most widely used method to generate realistic characters in 3D animated movies, action games, and so forth. However, expensive equipment is required, and measurement is only possible in a specific space equipped with a multi-photographing apparatus, so portability and maneuverability with this method are low.

2.2 Infrared imaging

In this approach, the reflection of infrared rays by an object is used. As a representative infrared imaging platform, Microsoft's Kinect sensor system is based on measuring the time-of-flight of infrared light reflected from an object to determine its position in a three-dimensional space [2]. Infrared rays scattered in a point pattern in a three-dimensional space are reflected by an object and then detected by an infrared CMOS sensor. Time-of-flight differs depending on the distance of the object, so depth information on the three-dimensional space can be obtained. Subsequently, the depth information obtained from the infrared CMOS sensor is matched to the visible light color video image information obtained by an RGB camera. The Kinect system can acquire and analyze up to four human joint movements and body shapes at the same time. It offers excellent performance for the real-time detection of precise operation despite its low price. However, the system is usually installed in front of a TV or PC; it is not small or light enough to be wearable.

2.3 Electric field change measurement

The human body can act as a ground electrode in an electric field. Therefore, the electric field changes according to the motion of the human body, and human body motion can be sensed by measuring the electric field. Microchip's GestIC is an example of a body motion sensor platform based on this method [3]. It is mainly used to detect hand movements, and it uses one transmission (Tx) electrode and four receiver (Rx) electrodes. The distortion of the electric field depends on the three-dimensional position of the human hand, and this can be calculated using the system's four receiver electrodes. The system is relatively small, inexpensive, and convenient to use; however, it is not able to precisely distinguish fine and varied movements, such as the movements of individual finger joints.

2.4 MEMS accelerometer /gyroscope

It is possible to detect human body motion using a 3-axis accelerometer and a 3-axis gyroscope manufactured by a MEMS process. Using an accelerometer, acceleration in the axial directions (x, y, z) can be measured. Using a gyroscope, angular velocity in (θ,φ,ψ) can be measured [4]. A MEMS accelerometer has a miniature silicon oscillator that can operate as a mass-spring system in a vacuum package, and when acceleration is applied, the oscillator is displaced by inertia. At the same time, the capacitance between the movable electrode and the fixed electrode changes. The MEMS gyroscope measures the change in capacitance as a result of the oscillator vibrating at a frequency of several tens of kilohertz and receiving a Coriolis force due to the external angular velocity. Errors of the MEMS accelerometer and gyroscope can be accumulated in the integration process, and the reliability of the position value can be low. To prevent this, it is necessary to calibrate the data from time to time using magnetic field sensors.

2.5 Mechanical/optical measurement of joint rotation angle

The oldest human motion analysis method is to measure the rotational angle of human joints using a mechanical and optical goniometer. A light and robust articulated structure is mounted on human body to measure the rotation angle of the joint [5]. The simplest sensor is a potentiometer whose resistance varies with the rotation angle. Also, there is a fiber-optic goniometer that measures the change in the amount of light propagating as the optical fiber bends.

3. HUMAN MOTION DETECTION TECHNOLOGY USING STRETCHABLE SENSOR MATERIAL

A conventional human motion detection system using a MEMS accelerometer / gyroscope and articulation–rotation measurement was described in the previous section. It is expensive and requires the user to wear somewhat stiff devices to provide signal connections. Also, the user may feel uncomfortable due to the lack of flexibility. In recent years, flexible and stretchable sensors have been actively developed to measure the mechanical strain of an object to overcome these issues. Although most of these technologies are still in the laboratory stage of development, they are expected to be commercialized soon. In this section, we will discuss flexible and stretchable strain sensors and human motion detection technology based on them.

The most basic principle of the human motion detection method using strain sensors is the strain change on the skin caused by the movement of the human joint [6]. When a stretch tension sensor is attached in the direction with the maximum tensile strain, it can measure the rotation angle of the joint. It should be noted that the maximum strain of skin on the human body is $\varepsilon \sim 50\%$ at the knee when it is bent to a maximum angle of 155°. Typical metal thin-film-based strain sensors can be used for strains up to 5%. Therefore, to measure the skin strain caused by human motion, a flexible strain sensor should be used. To realize this, strain sensors based on a composite material composed of conductive nanomaterials (nanoparticles, nanowires, nanotubes, graphene, etc.) and a rubber material (elastomer) have been developed.

3.1 Measurement methods: resistance change vs. capacitance change

Electrical strain sensors are largely based on two principles, namely, changes in resistance and capacitance. In the case of resistance change, the microstructure of the nanomaterial thin film changes the electron flow path as a result of tensile strain. In the case of nanomaterial-based thin films, complex phenomena occur, such as disconnection between single nanomaterials, crack propagation on thin films, and changes in tunneling currents, and this results in great strain sensitivity. A more detailed description of each mechanism is given below.

(1) Disconnection mechanism: Metal nanowires, graphene, and carbon nanotube (CNT) thin film comprise a complex connection network (network percolation) of thousands of single materials. When tensile strain is applied, the overlapping areas between single materials decrease. This phenomenon has been applied in strain sensors based on graphene [7], nanowires [8], and other materials.

(2) Crack growth mechanism: When a thin film of metal nanoparticles or CNTs [9] is applied to a stretchable material, such as rubber, by a solution process, there are many initial microcracks. These microcracks are enlarged by the external tensile stress, and they interfere with the current flow. When the tension is released, the cracks are closed again by the elasticity of the substrate, and the original conductivity is restored. This phenomenon has been clearly observed in silver nanoparticle films coated on a PDMS substrate, and it was found that the strain sensitivity was greatly increased.

(3) Tunneling current change mechanism: Metal nanowires and metal nanoparticles synthesized by a solution process often have a thin organic coating on the surface. Even if thermal sintering is performed after printing, an organic coating film partially remains. These insulating organic coatings allow tunneling current to flow when they are very thin. The tunneling current depends largely on the nature and thickness of the insulating film between two electrodes, and a current can flow within a cut-off distance. For example, the threshold is 0.58 nm for a silver nanowire–PDMS–silver nanowire combination [10], while it is 1.8 nm for a CNT–epoxy–CNT combination [11].

3.2 Performance index

Stretchability, sensitivity (gauge factor), linearity, hysteresis, and response speed are the main indicators that determine the performance of stretchable strain sensors. They are explained in detail below.

(1) Stretchability: It is the maximum tensile strain that allows the original electrical properties to be restored when the sensor returns to the relaxed state after tensile application. Generally, tensile sensors based on nanoparticles or graphene films have relatively low stretchability due to

cracking or brittleness of the material (ε <20%). Metal nanowire–elastic polymer composites show higher stretchability (ε <70%). However, CNT–elastic polymer composites have shown even higher stretchability (ε <500%).

(2) Sensitivity: It refers to the relative change in electrical characteristics (resistance or capacitance) versus unit tensile strain. It is also called the "gauge factor" (GF). Generally, CNT networks show a low gauge factor (GF <2) because the complex twisted nature of the nanotubes results in small changes in the electrical properties in response to external tensile strain. In contrast, graphene thin-film-based tensile sensors have large cracks due to the brittle nature of the graphene material; thus, they show much larger changes in electrical resistance under tensile strain.

(3) Linearity: A sensor with good linearity can reliably produce sensor signals even without rigorous calibration over a wide range of tensile strain. In general, electric-resistance-type sensors are less linear than capacitance-type sensors. In resistance-type sensors, as the tensile strain increases, the electrical connection of the sensing material network breaks more rapidly, and cracks propagate faster. In the case of capacitive sensor, the change in the electrical capacitance shows a linear response in a relatively large region due to the elasticity of the polymer dielectric material.

(4) Response speed: Due to the viscoelasticity of the stretchable polymer substrate, it does not respond instantaneously to fast pulling input and exhibits a slow transient response. It reacts like a secondary mass-spring-damper system due to the viscoelastic properties of the elastomeric polymer. Ninety-percent response times ($T_{90\%}$) of 100 to 200 ms have been reported for silver nanowire–PDMS, graphene–PDMS, and silver nanowire–Ecoflex composites.

3.3 Electrode and substrate materials

Conductive nanomaterials used in stretchable strain sensors include metal nanoparticles, carbon black, CNTs, metal nanowires, and graphene. For flexible substrates, flexible polymer materials, such as PDMS, Ecoflex, and polyurethane, are generally used. The conductive nanomaterial is dispersed in a solution to form a nanomaterial ink, followed by vacuum infiltration, spray coating, inkjet printing, pattern transfer, drop coating, and solution mixing to produce a composite material. More detailed explanations are given below.

(1) Silver nanowire electrode–PDMS substrate [8]: Silver nanowire synthesized by a solution process is dispersed in a solvent, and it is drop coated onto a polyimide substrate to form a silver nanowire percolation network. When the PDMS precursor is poured onto it, curing is performed, and a sensor in which a thin film of silver nanowire–PDMS composite material is formed on the PDMS substrate. An additional PDMS layer is further coated on the sensor thin film to form a sandwich-type structure, and it is possible to realize a strain sensor having high stretchability (~ 70%) and sensitivity (gauge factor ~ 10).

(2) Graphene electrode–PDMS substrate [12]: A graphene thin film is synthesized on a catalytic metal thin film by a vapor deposition process (CVD), and then transferred using a PDMS stamp or by spray coating to form a graphene electrode. The electrical connection between the innumerable graphene flakes changes according to the tensile strain of the substrate, which is measured in terms of electrical resistance. Generally, it has very high sensitivity (gauge factor ~ 100) but it has low stretchability due to the brittleness of graphene film.

(3) Carbon nanotube (CNT) electrode–Ecoflex substrate [13]: CNT powder synthesized by vapor deposition is dispersed in a solution and sprayed to form a thin film on a polyimide substrate. The Ecoflex solution is poured and cured. In the case of CNTs, the electrode material itself is flexible and the nanotubes have a complex twisted structure, unlike metal nanowires. The stretchability of the sensor is more than 500% because of the very high elasticity of Ecoflex. However, due to the twisted shape of the CNTs, the change in electrical resistance due to tensile strain is small (gauge factor: 1 to 2.5).

(4) ZnO nanowire–polystyrene nanofiber [14]: Polystyrene nanofiber bundles are fabricated using an electrospinning process. After that, nanofiber bundles are immersed in a ZnO nanoparticle solution and coated with seed, and then hydrothermal synthesis is performed to synthesize ZnO nanowire on the polystyrene nanofiber bundles to form a PS nanofiber core–ZnO nanowire branch structure. When external tensile force is applied, changes in the resistance of many junctions between ZnO nanowires appear as changes in resistance.

4. HUMAN MOTION DETECTION APPLICATION EXAMPLE

The stretchable strain sensors can be easily attached to human skin or clothes, and have excellent sensitivity and stretchability. Therefore, they are used in various human motion detection areas. In particular, it has been reported that flexible and lightweight sensors can adhere well to the curved surface of the skin, allowing the user to move without inconvenience, and it is possible to detect minute movements, such as wrist pulses. A few examples are presented below.

(1) Smart glove system [8]: In this system, multiple strain sensors are attached to a multi-channel measurement system, and acquired sensor signals are processed through signal filtering and amplification circuits. Then, the smart glove system transmits data to a PC through a Zigbee wireless communication module. When a user wears the smart glove and moves his or her fingers, the system can measure the bending of each finger and control the avatar fingers in the virtual space. This system can be used as a master device to control a slave robot in a remote place.

(2) Multiaxial skin strain detection system [13]: It is possible to measure the strain in three axial directions at the same time by printing CNT sensors in three axial directions. It has been shown that the axial strains (εx, εy) and shear strain (γxy) in x and y directions on human skin can be estimated simultaneously. This type of system can be used to monitor the swelling, relaxation, and movement of the abdomen, elbow, and ankle during respiration.

(3) Blood pressure measurement system [15]: A capacitance-type strain sensor, fabricated by putting a PEDOT:PSS electrode on silicon rubber film, is used to measure blood pressure. The diameter of the blood vessel varies by up to 10% due to the blood pressure changing in the range of 80 to 120 mmHg. The developed sensor showed a fast response time of 50 ms in the range of 0 to 200 mmHg, so vessel diameter changes can be measured in real time.

(4) Motion sensing system [16]: A capacitance-type strain sensor is fabricated by inserting a PDMS insulator between silver nanowire electrode patterns. It is possible to monitor human body movements in real time by measuring the contraction and relaxation of the skin surface of the knee during various types of exercise, such as walking, running, and jumping.

(5) Pulse measurement system [10]: An electric resistance-type pressure sensor is developed in which the contact area between two electrodes changes according to the pressure applied by interposing nanopillar array electrodes coated with metal thin film. Very fine pressure (minimum ~ 3 Pa) can be measured, and a bandwidth of about 10 Hz allows pulse measurement.

As seen in the abovementioned examples, most flexible and wearable strain sensors still remain at the level of basic concept verification and performance demonstration in the laboratory. Commercialization requires much improvement in terms of reliability and reproducibility. However, new sensors are developed that can achieve superior performance (for example, high sensitivity, stretchability) that commercial sensors cannot provide as well as low power consumption and price competitiveness, they will be commercially successful in various industries, such as healthcare, sports, social welfare, and safety in the future.

5. CONCLUSIONS

In this paper, the importance of human motion detection in various industries was discussed, and then, a review of human motion detection technology using stretchable strain sensor was presented in detail. Flexible and stretchable strain sensors allow direct attachment to human skin or clothing. They have the advantage of low power consumption and are capable of measuring minute forces and movements more precisely than conventional sensors. Although human motion detection technology is still in the early stages of technology maturity, it is expected that the potential market growth and the wide range of possible applications will lead to the rapid development of related technologies and commercialization in the future.

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