Flexible Pressure Sensor Arrays

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Contributor: Yanhao Duan, Shixue He, Jian Wu, Benlong Su, Youshan Wang

Flexible pressure sensors that can maintain their pressure sensing ability with arbitrary deformation play an essential role in a wide range of applications, such as aerospace, prosthetics, robotics, healthcare, human–machine interfaces, and electronic skin. Flexible pressure sensor arrays can visualize touch actions, track motion trajectories, and map pressure distribution in real time with high pressure sensitivity and high resolution.

Keywords: flexible sensing ; pressure sensors ; sensor arrays

1. Introduction

One of the most observable variables, pressure, is defined as the ratio of force to the area across which it is exerted, resulting in surface spatial deformation or performance variation . The Earth's gravity and physical contact contribute to the generation of pressure. Pressure sensors that can translate pressure signals into matching electrical impulses can detect pressure . Flexible pressure sensors provide several benefits over rigid sensors . Compared with conventional rigid sensors, flexible pressure sensors can withstand different deformations, such as compression, bending, tension, and even twisting, and can conform to curvilinear and even deformable surfaces Flexible pressure sensors may be produced by turning the substrate into a flexible form and employing organic and nanomaterials rather than the traditional inorganic semiconductor materials. For decades, the tremendous progress in flexible and stretchable substrates, deformable electrodes, novel durable materials, and novel processing technologies has made a huge contribution to the advancement of flexible pressure sensors. These flexible pressure sensors have distinct advantages, such as low cost, exceptional flexibility, great stretchability, and compatibility with large-area processing processes. Recently, a few novel flexible sensors have been reported to have features such as light weight, high flexibility, and fast response, which indicates an extraordinary potential for use in aerospace, prosthetics, robotics, healthcare, human–machine interfaces (HMIs), and electronic skin.

With the development of cyber–physical systems, the Internet of Things (IoT), and cloud computing, the concept of intelligent manufacturing has rapidly evolved . Manufacturing systems in the intelligent manufacturing age may monitor physical processes and make intelligent choices through real-time communication and collaboration with humans, machines, sensors, and so on.

The rapid advancement of manufacturing systems has raised the bar for flexible pressure sensor arrays, requiring high performance, high resolution, flexibility, and low weight. With breakthroughs in artificial intelligence and computing power, intelligent systems have developed rapidly , necessitating a greater demand for flexible sensor arrays that can collect real-time data and transmit them to a cloud server for analysis using big data and artificial intelligence. Flexible pressure sensor arrays can visualize touch actions, track motion trajectories, and map pressure distribution in real time with high pressure sensitivity and high resolution. Therefore, there is a strong demand for flexible pressure sensor arrays with high resolution and sensitivity in order to fulfill the requirement of intelligent manufacturing, allowing issues to be solved and adaptive choices to be made on time. To broaden the detection range, improve the sensitivity, and realize the visualization of pressure imaging, enormous efforts have been applied to sensor arrays with different transduction mechanisms.

Now, the main task and problem faced by pressure sensors are those of improving their performance. High performance means that the performance parameters of the sensor are developed in continuous improvement, including high sensitivity, wide detection range, self-powered operation, high resolution, and low crosstalk. The use of new materials and the proposal of new structures have significantly improved the sensitivity and detection range of pressure sensors. High-resolution pressure sensors exceeding human skin have been achieved due to the piezo-phototronic effect and nanomaterials. To achieve the needs of self-powered operation, pressure sensors based on the piezoelectric effect and triboelectric effect have come into being. The problem of crosstalk can be addressed by rationally designing the sensor structure. However, the current achievements are still limited, and the performances of pressure sensors are expected to be further improved.

2. Transduction Mechanisms of Flexible Pressure Sensor Arrays

Flexible pressure sensors can convert external pressure stimuli into electrical signals. Traditional transduction mechanisms, such as piezoresistivity, capacitance, piezoelectricity, and triboelectricity, are widely used in flexible pressure sensor arrays.

2.1. Piezoresistivity

Piezoresistive pressure sensors work on the principle of converting an external pressure stimulus applied to the device into a recordable change in resistance. This effect is called the piezoresistive effect. $R = \rho\, L/A$ (ρ is the material's resistivity, L is the length, and A is the area). The L and A parameters change with the material's deformation, which leads to a variation of the resistance value.

2.2. Capacitance

The capacitive pressure sensor is a sensor whose capacitance changes under external pressure stimulation. The equation for the capacitance is $C=A\varepsilon_0\varepsilon r/d$.

where A is the overlapping area, d is the separation gap, ε_0 is the permittivity of a vacuum, and εr is the relative static permittivity of the dielectric. During an external loading on capacitive pressure sensors, the capacitance of the sensors changes due to alterations in one or all of the variables.

2.3. Piezoelectricity

Wang and Song first fabricated a piezoelectric nanogenerator (PENG) based on zinc oxide nanowires in 2006[1]. Piezoelectricity is another transduction method for pressure sensing. Flexible piezoelectric pressure sensors can convert mechanical stimuli into electrical signals. The piezoelectric effect refers to electric charge production due to the occurrence of electrical dipole moments from mechanical force with a non-centrosymmetric crystal structure.

2.4. Triboelectricity

Triboelectric nanogenerators (TENGs) have recently gained much attention due to their exceptional performance in energy harvesting and signal induction. Furthermore, TENGs have recently sparked much curiosity, ever since Wang et al. identified the first one in 2012[2]. The principle of TENGs is based on the coupling effect of electrification and electrostatic induction. Electron transition between the atoms/molecules happens with a strong electron cloud overlap (or wave function overlap) between the two atoms/molecules in the repulsive region owing to the reduced interatomic potential barrier[3].

3. application of Flexible Pressure Sensor Arrays

3.1. Human–Machine Interface

A Human–machine interface (HMI) is a new technology that can transfer information between humans and electronic devices. Recently, advancements in the IoT and artificial intelligence have put forward new requirements for HMIs, such as flexibility, portability, etc. And HMI can help achieve the goal of harmonious coexistence and efficient collaboration between humans and the digitalized world[4][5]. Pressure sensor arrays are a significant part of an HMI, and recent advances in HMIs have been achieved by using flexible pressure sensor arrays.

A vital application of flexible pressure sensor arrays in HMIs is spatial pressure distribution monitoring and real-time trajectory mapping. For example, Xu et al. proposed a 3D human–machine interaction by combining electrooculography and a 4 × 4 capacitive pressure sensor array [6]. The signals of the EOG were used for convenient contactless 2D (XY-axis) interaction, and the signals of the pressure sensor array were used for complex 2D movement control and Z-axis control in the 3D interaction.

Motivated by the regular use of human hands for daily interaction, smart gloves are predicted to replace conventional HMIs, such as keyboards, joysticks, etc. [7]. Smart gloves are also an important applications of HMIs. For instance, Sundaram et al. demonstrated a tactile glove that was assembled with piezoresistive pressure sensor arrays on a knitted glove [8]. A deep convolutional neural network and a scalable tactile glove were combined to reveal the mechanics of how humans grasp objects. The tactile glove could record tactile videos and detect normal forces ; more importantly, the tactile glove's cost was low.

Niu et al. fabricated a 5 × 5 capacitive pressure sensor array with a spatial-pressure differentiation ability [9]. The sensor array could distinguish objects with the shapes of “U”, “J”, and “N”. A numeric keypad in braille was proposed by combining it with the capacitive pressure sensor array . Moreover, the braille could be decoded through the braille numeric keypad when an artificial fingertip touched the braille. Combined with a TENG and a field-effect synaptic transistor, a 28 × 28 sensor array with a high sensitivity of 0.192 kPa^{-1} in the range of 1 to 5 kPa and 0.007 kPa^{-1} in the range of 5 to 20 kPa was presented [10]. This device could realize handwritten images that were visualized in real time in addition to subsequent real-time neuromorphic computing.

3.2. Healthcare

Significant advances in wearable technologies are revolutionizing our lives by integrating flexible pressure sensor arrays onto our bodies to monitor our health and help us pursue comfortable lives. A flexible sensor can collect signals from the human body and transfer the data to a computer, so this technology can be used for diagnosis, observation, and sharing .

Pedobarography can be used for the biomechanical analysis of gait recognition and posture [11]. Flexible pressure sensor arrays can detect the pressure between the plantar surface of a foot and the floor. This is meaningful for wearable biosensors, sports injury detection, and early diagnosis.

By using PENGs serving as a sensor array, an insole plantar pressure mapping system was proposed [12]. This device could achieve self-powered operation, and the pressure signal was transferred to a smartphone for real-time foot pressure monitoring. An intelligent insole system that could realize static and dynamic plantar pressure mapping was proposed by Tao et al. [13]. This intelligent insole system is composed of capacitive pressure sensors and a data acquisition system with a wireless transmitter and a PC terminal. This device could detect static and dynamic pressure on the sole of the foot with different motions, such as different standing postures, yoga asana, walking straight , etc. This device is beneficial in the restoration of healthy and normal posture.

An intelligent toilet was demonstrated by using 10 textile-based triboelectric sensors to compose the toilet seat[14] . According to the triboelectric pressure sensor arrays, user identification and records of the entire seating time could be achieved, which is more private than the previous approach. The device can monitor a user’s health.

Implantable electronics are widely used in personalized health monitoring and precision therapies because of the development of biomedicine. Flexible pressure sensor arrays can also be used in implantable electronics . For example, Wang et al. fabricated a pressure sensor array to monitor dynamically moving organs [15]. In order to solve the problem of direct contact mapping of dynamic and fast-moving organs, a flexible pressure sensor array was attached to the surface of the right ventricle of a rabbit . The electrophysiological mapping of the beating heart illustrated the potential of sensing arrays for implantable applications.

3.3. Aerospace

Morphing aircraft with intelligent variability and adaptability have become a research hotspot because they have a deformable structure to improve their aerodynamic performance [16]. So, it is crucial to accurately measure the parameter of such an aircraft’s structures and external environment. Recently, there have been more and more demands to apply flexible pressure sensor arrays in curved aircraft structures. For example, to measure the pressure in wind-flow surroundings, a range-programmable capacitive pressure sensor array was demonstrated by Xiong et al. [17]. The sensing range of the capacitive array could be changed by changing the reference pressure. The capacitive sensor array was tested on an airfoil NACA0012 in a wind tunnel. It could detect the positive and negative stress, which was time-dynamic and space-distributed on curved surfaces .

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