Original Research Article

Advances and Current Applications of Two-Dimensional Force Sensors

ABSTRACT

Multidimensional force sensors, serving as critical components of intelligent devices, have attracted considerable attention for their widespread applications across automated manufacturing, aerospace engineering, and medical technologies.The careful selection of suitable multidimensional force sensors tailored to specific force measurement scenarios is of paramount importance. Notably, two-dimensional force sensors, which enable the simultaneous detection of planar two-dimensional force components, have emerged as a prominent research focus with the ongoing expansion of low-dimensional force measurement applications.This study seeks to provide a comprehensive review of advancements in two-dimensional force sensors. Initially, it presents an in-depth analysis of the sensing mechanisms, dimensions, materials, and measurement ranges of these sensors, culminating in the identification of optimal application scenarios for each type.Furthermore, the elastomer, a pivotal determinant of sensor measurement performance, is systematically examined in terms of its configuration designs. This review also explores the applications of two-dimensional force sensors in intelligent manufacturing, aerospace, biomedical engineering, and human-computer interaction.Lastly, this paper evaluates the current state of applications to pinpoint critical technological challenges and offers insights into the future trajectories of two-dimensional force sensor development.

Keywords:Two-dimensional force sensors; Sensing principle; Structural configuration design;Practical application scenarios

1. Introduction

With the rapid advancements in technology, the integration of digitalization and intelligent systems across diverse industries has accelerated, positioning force sensors as a pivotal sensing technology with extensive applications in automated manufacturing, aerospace engineering, and healthcare.The growing demand for high-precision force measurement in these domains has catalyzed the advancement of multidimensional force sensor research, ushering it into a new era.

The expanding variety of low-dimensional force measurement scenarios has significantly amplified the market demand for two-dimensional force sensors.In micro-manipulation domains, including MEMS[1](Micro-Electro-Mechanical Systems), micromanufacturing[2], biomedicine[3], and cellular operations[4], real-time force feedback is essential for constructing control systems that guarantee the accurate handling of micro-components and prevent damage to delicate elements.Furthermore, in macroscopic operation domains like grinding[5], parts polishing[6], and human-robot collaboration[7], the integration of high-performance force sensors at actuator endpoints is imperative. These sensors empower actuators to perceive real-time force information during tasks and autonomously adapt based on operational conditions, thereby fulfilling the demands of precise operations.

In numerous low-dimensional application scenarios, the elastomer of two-dimensional force sensors can effectively constrain non-essential degrees of freedom, focusing exclusively on the deformation induced by the measured load components. Such a design facilitates highly precise and minimally coupled force measurements.Moreover, the advancement and deployment of two-dimensional force sensors can significantly mitigate resource and cost inefficiencies that arise from employing multidimensional force sensors for low-dimensional measurements.This study seeks to deliver a thorough review of the advancements in two-dimensional force sensors.Initially, it delves into the detailed sensing mechanisms of two-dimensional force sensors, examining variations in size, material, and measurement range among different sensor types, and subsequently analyzes their respective application scenarios.To investigate the evolution of structural configurations in two-dimensional force sensors, the study systematically reviews methods employing flexible mechanism design.Subsequently, drawing from practical application cases, the elastomer properties of two-dimensional force sensors are thoroughly examined, emphasizing their pivotal influence on sensor measurement performance.Lastly, this study addresses prevailing technological challenges and outlines prospective development trajectories for two-dimensional force sensors, with the aim of offering valuable guidance for the design of high-performance sensors.It fills the gap in the literature of existing two-dimensional force sensors.

2. The Sensing Principles of Two-Dimensional Force Sensors

As illustrated in Figure 1, the force sensor operates by converting the force signal acting on the elastomer into an electrical signal. The critical step in this process involves accurately capturing the deformation of the flexible element induced by the applied load.

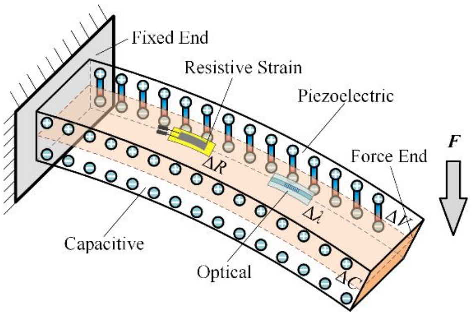

Figure1Deformation of the flexible unit under external load application

Equation (1) defines the correlation between the stiffness $\boldsymbol{K}$ of the deformed structure and its corresponding deformation $\boldsymbol{x}$.

$$\boldsymbol{F} = \boldsymbol{K}\boldsymbol{x} \tag{1}$$

In the equation, $\boldsymbol{K} \in \mathbf{R}^{2\times 2}$ denotes the stiffness matrix of the orthogonal two-dimensional force sensor, with its values being determined by the type and dimensional parameters of the elastomer's flexible units.

Orthogonal two-dimensional force sensors can be classified into resistive, capacitive, piezoelectric, and optical types, depending on their respective detection principles. The differences in these principles result in distinct sensor characteristics and their suitability for various application scenarios.

2.1Resistive strain gauge type

Resistive force sensors operate by detecting changes in the resistance of metallic strain gauges under the influence of external forces. These resistance variations are subsequently converted into output voltage signals using a measurement bridge, enabling precise determination of the applied force.Serving as the core sensing element in resistive force sensors, strain gauges exhibit an excellent linear relationship between resistance changes and external forces, thus ensuring superior measurement accuracy and sensitivity.

High-hardness aluminum alloys or alloy steels are commonly employed as materials for the elastomers of resistive sensors, endowing them with a wide measurement range and exceptional stability.Resistive sensors are characterized by compact structures, simplified measurement circuitry, and robust anti-interference performance, enabling their extensive application in robotics, mechanical load testing, industrial automation, aerospace, and medical rehabilitation.However, resistive force sensors are limited by signal instability, bio-incompatibility, and challenges in miniaturization, primarily due to the size constraints of metallic strain gauges.These drawbacks significantly restrict their applicability in high-frequency dynamic force measurement, biological sensing, and micro-scale detection devices.

2.2 Capacitive sensing type

The core sensing element of a capacitive force sensor is a parallel-plate capacitor.As illustrated in Figure 1, deformation in the flexible unit caused by the applied load leads to a variation in the distance between the plates, thereby inducing a change in capacitance, which is used to quantify the magnitude of the applied load.

Capacitive force sensors are distinguished by their high sensitivity, excelling in the detection of minute forces. This characteristic renders them highly suitable for static force measurement applications, particularly in laboratories and precision instrumentation.Nevertheless, their relatively poor mechanical stability renders them vulnerable to external shocks and vibrations, thereby restricting their effectiveness in challenging environmental conditions.To counteract the influence of electromagnetic interference on measurement accuracy, these sensors often require sophisticated signal processing circuitry, which contributes to elevated overall costs.

2.3 Piezoelectric sensing type

The operational principle of piezoelectric sensors is rooted in the piezoelectric effect exhibited by specific dielectric materials.Under external loading, deformation in these materials induces internal polarization, resulting in the transfer of opposite charges to the material's surfaces. A charge amplifier then facilitates the conversion of these charges into readily measurable voltage signals.Piezoelectric sensors are typically constructed from piezoelectric materials, including ceramics, single crystals, or polymer composites.These materials generate electrical charges in response to applied mechanical forces and are characterized by outstanding mechanical strength and durability.

Piezoelectric force sensors boast a wide detection range, exceptional sensitivity, and rapid response times, making them well-suited for high-frequency force measurement applications.Consequently, they are extensively employed in dynamic force measurement scenarios, including impact and vibration analysis. Despite being among the most promising sensing elements, piezoelectric components face several limitations, including challenges in stacking piezoelectric wafers, incapacity to sustain static force measurements over prolonged durations, and high sensitivity to loading orientations. Improper installation or unevenly distributed loads can induce measurement inaccuracies, thereby limiting their applicability in specific scenarios.

2.4Optical sensing type

The fiber Bragg grating force sensor operates by measuring the variation in the refractive index of the optical fiber, induced by deformation of the flexible unit under applied force, to detect external loads.In contrast to force sensors that rely on electromagnetic-sensitive components, the sensing element of the fiber Bragg grating force sensor is an optical fiber material with photosensitive properties, using broadband light as the transmission medium.As a result, it offers unique advantages, including excellent resistance to electromagnetic interference, non-electrical detection, chemical stability, and biocompatibility.Furthermore, the optical fiber enables distributed measurements, which facilitate the miniaturization of the sensor, thereby making it highly applicable in the medical rehabilitation field.

2.5Comparative Analysis

By summarizing the measurement principles of various force sensor types, the differences in size, material composition, and measurement range across different sensor categories are highlighted.Resistive sensors provide greater stability and accuracy for industrial automation, while capacitive sensors are more sensitive and therefore better suited for static measurement in laboratory environments. In addition, piezoelectric sensors are used in dynamic applications, such as impact testing. Optical sensors in biomedical applications have more stable biocompatibility, and the unique advantages of each technology can be combined with different application scenarios.To provide guidance on selecting the most suitable sensor type for specific application scenarios, Table 1 presents a comparative analysis of the key characteristics of the force sensors described above.

Table 1 Comparative Analysis of Two-Dimensional Force Sensor Types and Their Key Characteristics

Sensor Type	Response Time	Key Characteristics	Application Scenarios
Resistive Strain	Moderate	High Precision, Wide Measurement Range, Excellent Stability	Robotics and Industrial Automation
Capacitive	Relatively Fast	High Sensitivity, Fast Response	Static Force Measurement in Precision Instruments
Piezoelectric	Relatively Fast	Durability, Fast Response, Requires Precise Installation	Vibration and Shock Testing
Optical	Moderate	Electromagnetic Interference Resistance, Biocompatibility, Miniaturization	Biomedical

3. Configuration Design of Two-Dimensional Force Sensors

As one of the key technologies in force sensor design, the configuration of the elastomer significantly impacts factors such as sensor sensitivity, linearity, stability, dynamic response, and durability.Therefore, a rational approach to elastomer configuration design is crucial for improving the performance of multi-dimensional force sensors.Research into structural innovations in two-dimensional force sensors is continually progressing. Classifying existing force sensors from the perspective of flexible mechanisms aids in understanding the current state of the field.

Flexible beam units, as the most fundamental flexible elements, offer advantages such as high linearity, simple structure, and low manufacturing cost, making them widely used in elastomer configuration design.Cappelleri et al. [8] proposed three types of two-dimensional vision-based force sensors, all with identical structural designs, as shown in Figure 2(a). The elastomer is a compliant mechanism with decoupling stiffness, composed of a rigid probe and flexible beams.Thanh-Vinh et al. [9] proposed a MEMS-based two-axis force sensor, as shown in Figure 2(b). The elastomer configuration consists of a central pillar and four elongated flexible beams in parallel, which generate high strain during measurement tasks.Quist et al. [10] proposed a two-dimensional force sensor for measuring tactile contact within the millinewton range, as shown in Figure 2(c). The elastomer consists of a circular cross-section cantilever beam, strain gauges, and a rigid base, with a Wheatstone half-bridge circuit used for outputting the voltage signal.The two strain gauges are vertically arranged at the base of the same cantilever beam, which effectively enhances measurement sensitivity, ensuring high resolution even within the microforce range.Sun et al. [11] proposed a two-dimensional force sensor based on fiber Bragg gratings, as shown in Figure 2(d). The elastomer configuration is a parallel cross-beam spoke structure, which facilitates integration into robotic wrists for two-dimensional force measurement.Wei et al. [12] proposed a piezoresistive two-dimensional force sensor for micro-assembly, capable of detecting the contact position and grasping force of micro-objects on a gripping surface. As shown in Figure 2(e), the elastomer consists of an L-shaped beam and a deeply deflected contact plate used for executing grasping tasks, detecting local interaction forces through the deformation of the flexible beams.The above elastomer configurations indicate that using flexible beam structures helps improve sensor performance metrics such as sensitivity and accuracy. However, simple series or parallel configurations have poor decoupling performance, making precise force decoupling challenging.

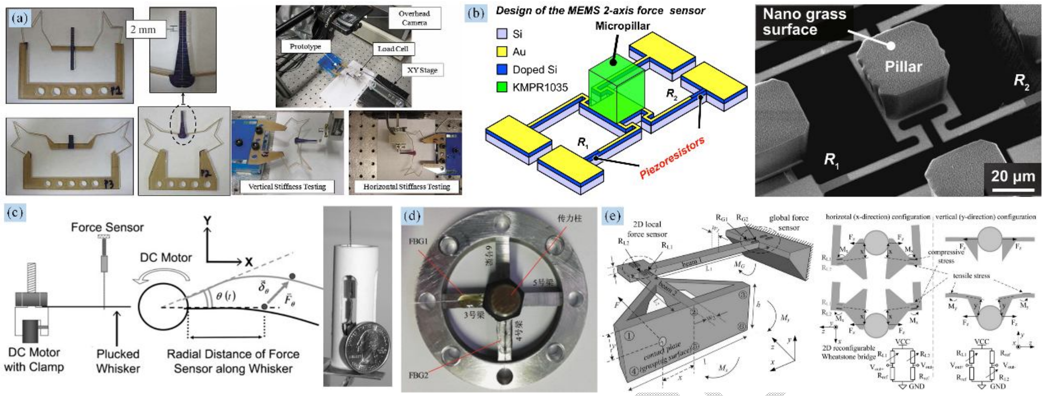

Figure2 Elastomer of Two-Dimensional Force Sensor Using Flexible Beam Units：(a)Cappelleri[8](2010)；(b) Thanh-Vinh[9](2015)；(c) Quist[10](2008)；(d) Sun[11](2020)；(e) Wei[12](2009)

In addition to flexible beam units, the four-bar mechanism, which generates only translational motion under external force with minimal displacement and no rotation, can significantly improve the measurement accuracy of the sensor.Under the same external force, the bridge amplification mechanism can enlarge the deformation of the mechanism, thereby improving the resolution of the force sensor.Therefore, these two fundamental compliant mechanisms are commonly employed in the elastomer configuration design of two-dimensional force sensors.Shen et al. [13] proposed a novel two-dimensional piezoelectric force sensor for micro-operation applications, as shown in Figure 3(a). The elastomer consists of two one-dimensional force measurement units connected in series, both using a parallel beam structure, offering advantages such as high stiffness, high sensitivity, and decoupling of force measurements.Similarly, Xu et al. [14] proposed a position and grasping/interaction force sensing technology integrated with micro-grippers. The designed two-dimensional force sensor uses a parallelogram mechanism and MCPFs as the main sensing elements, as shown in Figure 3(b).Buttafuoco et al. [15] designed a force sensor for 2-degree-of-freedom haptic applications based on a specific elastic framework, as shown in Figure 3(c). The elastomer consists of two flexible structures that bend around the same axis, significantly reducing inter-dimensional coupling.

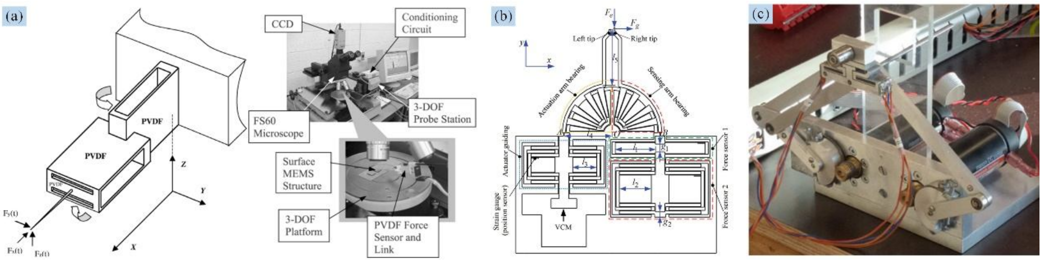

Figure3 Elastomer of Two-Dimensional Force Sensor Using Fundamental Compliant Mechanisms:(a)Shen[13](2004)；(b) Xu[14] (2015)；(c) Buttafuoco[15] (2014)

By combining simple compliant mechanisms such as flexible beams, parallel four-bar mechanisms, and bridge amplification mechanisms in series or parallel, complex compliant mechanisms can be obtained for the elastomer of two-dimensional force sensors.Unlike simple compliant mechanisms, complex compliant mechanisms can better suppress deformation in non-measured dimensions, while the measurement structure exhibits greater structural strength, stability, and improved deformation capability.Xu et al. [16] proposed a micro-gripper integrated with an electrostatic actuator and a capacitive force sensor, capable of alternately measuring grasping forces on two axes and environmental interaction forces, as shown in Figure 4(a).Yang et al. [17] proposed a novel micro-electromechanical system (MEMS) micro-gripper, whose left arm is driven by a lever amplification mechanism.Through this structure, the displacement of the electrostatic actuator is transmitted and amplified at the tip of the gripper; the right arm of the gripper is designed to use a capacitive sensor to detect the grasping force and interaction force, as shown in Figure 4(b).The compliant mechanisms offer advantages such as compact structure, mechanical decoupling, and high accuracy, providing typical cases for the design of novel force sensors.

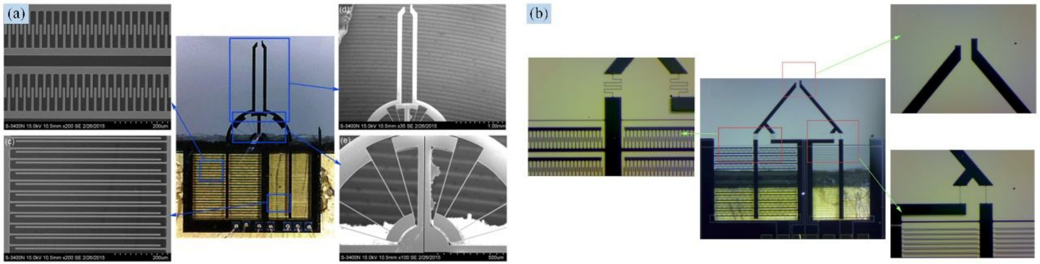

Figure4Elastomer of Two-Dimensional Force Sensor Using Complex Compliant Mechanisms:(a) Xu[16] (2015)；(b) Yang[17] (2017)

Additionally, Song et al. [18] proposed a miniature octagonal ring two-dimensional force sensor, as shown in Figure 5(a). Its elastomer features a simple octagonal ring structure and integrates an overload protection function, offering advantages such as high sensitivity and high strength.Zhu et al. [19] proposed a micro two-dimensional force sensor based on an E-type circular diaphragm elastomer, designed to meet the real-time and accurate measurement requirements for axial pressure and radial shear forces in fracture trauma cross-sections.However, these elastomer structures are highly dependent on the designer's experience and creativity, offering limited assistance in the development of new sensors and the exploration of sensor configuration design methods.Pang et al. [20] proposed a strain-based two-dimensional force sensor for long jump testing, as shown in Figure 5(b). Its elastomer features an I-shaped structure with a T-beam force-sensitive unit. The normal force is measured using a full-bridge circuit (R1~R4), while the horizontal force is measured with a half-bridge circuit (R5 and R6). When the normal force is misaligned, causing the sensor to experience a bending moment, the deformation pattern will mirror that of the horizontal force, leading to significant inter-dimensional coupling, which can negatively impact the sensor's measurement accuracy.

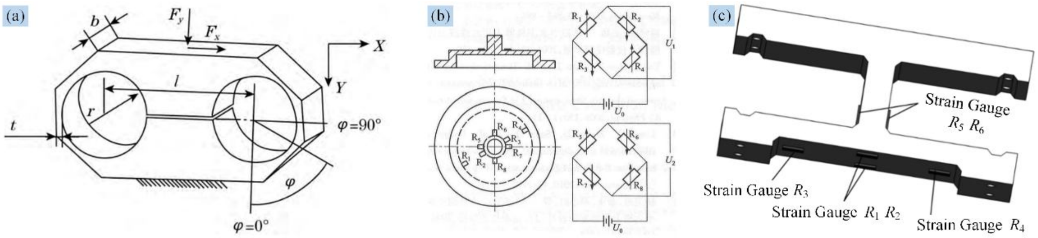

Figure5Other Elastomers for Two-Dimensional Force Sensors:(a)Song[18](2018)；(b) Zhu[19] (2014)；(c) Pang[20] (2020)

4. Applications of Two-Dimensional Force Sensors

In numerous modern intelligent systems, sensors capable of providing more comprehensive force load component information play a crucial role.Compared to the combination of uniaxial tensile sensors for two-dimensional force measurement, the main advantage of two-dimensional force sensors lies in their ability to simultaneously detect the two-dimensional force load components in a plane, and their ease of integration into intelligent systems. By analyzing the signals from individual sensor units, precise force measurement can be achieved.They have demonstrated remarkable performance in fields such as intelligent robotics, healthcare systems, and wearable devices, providing strong technical support for achieving smarter interactive experiences.

4.1 Intelligent Robotics

In the field of robotic force sensing, Chen et al. [21] proposed a flexible biaxial gripper driven by two piezoelectric actuators, as shown in Figure 6(a). The design features an asymmetric structure that can be divided into two parts, incorporating a dual-hole force measurement module, enabling two-degree-of-freedom grasping and rotational operations with two-dimensional force sensing capabilities.Takeshita et al. [22] proposed a promising shear force sensor, as shown in Figure 6(b). This compact sensor can be embedded within the fingers of a robotic hand, enabling the decoupling of measurements for biaxial shear forces and the detection of slip phenomena.As shown in Figure 6(c), Song et al. [23] addressed the challenge of dexterous and compliant grasping of soft or brittle objects by integrating an octagonal ring two-dimensional force sensor into a robotic actuator, enabling sensitive force perception capabilities like those of the human hand during grasping tasks.

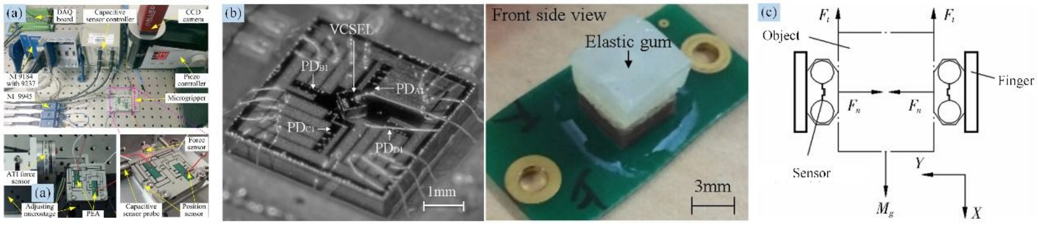

Figure6Intelligent Robot Field:(a)Chen[21] (2017)；(b) Takeshita[22] (2016)；(b) Song[23] (2018)

4.2 Healthcare Systems

In the field of healthcare, Zarrin et al. [24] proposed a sterilizable needle-driven gripper, as shown in Figure 7(a), which utilizes fiber Bragg grating to measure axial and gripping forces.Performance evaluation results indicate that the two-degree-of-freedom gripper is capable of measuring gripping and axial forces, with measurement accuracies of 0.27N and 0.3N, respectively.As shown in Figures 7(b) and 7(c), Akinyemi et al. [25] and Shi et al. [26] respectively proposed prototypes of a 2D distal force sensor using 3D printing based on fiber Bragg grating, offering excellent force and temperature decoupling capabilities, as well as high resolution. These sensors are designed to measure the contact forces between medical instruments and blood vessels during robot-assisted heart surgeries.

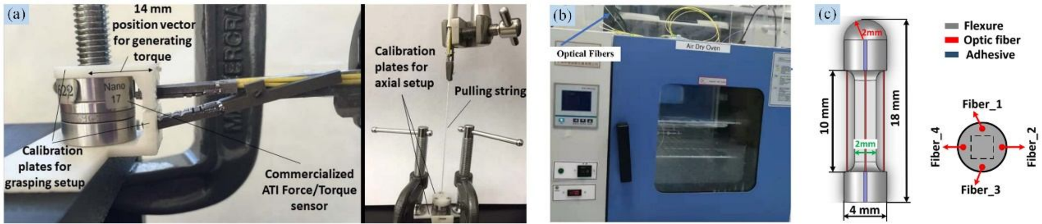

Figure7Medical Health Field:(a) Zarrin [24] (2018)；(b) Akinyemi[25] (2021)；(c) Shi[26] (2017)

4.3 Wearable Devices

In the field of wearable devices, Kim et al. [27] proposed the design process of a mechanically decoupled two-dimensional force sensor (M2D), aimed at developing a wearable ground reaction force (GRF) sensing system.As shown in Figure 8(a), by introducing a mechanical decoupling structure, the number and thickness of the sensors were reduced, enabling seamless integration into the shoe sole for detecting tactile force information.In the field of force sensing at the robotic foot, it is essential to integrate a tactile sensing system into the foot design to establish a real-time feedback mechanism during movement.As shown in Figure 8(b), Schulze et al. [28] designed a low-cost two-axis force sensor for precise GRF measurement. Unlike other decoupled elastic bodies, the sensor's angle was optimized to effectively utilize crosstalk, simplifying the mechanical design and enhancing system integration.As shown in Figure 8(c), Ananthanarayanan et al. [29] designed a two-degree-of-freedom foot force sensor for high-speed running quadrupeds, incorporating a lightweight, durable, and compact magnetic field sensing system. To mitigate the impact of strain gauge creep on measurement accuracy under dynamic forces, the sensor utilizes the deformation characteristics of the elastic body material and embedded magnets, with a miniature Hall effect sensor array to measure the magnet's position and infer the applied force.

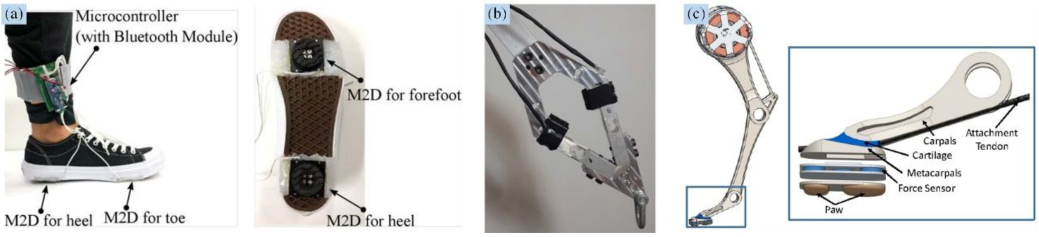

Figure8Wearable DevicesField:(a)Kim [27] (2019)；(b) Schulze[28] (2021)；(c) Ananthanarayanan[29] (2012)

4.4 Industrial Applications

In industrial applications, the contact characteristics between tires and the road surface significantly influence vehicle dynamics and handling stability.To accurately estimate the frictional force between the tire and the road surface under dynamic conditions, Zhang et al. [30] designed an embedded flexible local force sensor, as shown in Figure 9(a). The sensor is embedded at a specific angle to capture multi-directional local friction forces, and its measurements are interpreted through a mathematical model to extract the local contact friction force, offering excellent sensitivity and resolution.Chen et al. [31] developed a tire-road force sensing and estimation scheme based on embedded flexible force sensors. As shown in Figure 9(b), the tire tread is cut longitudinally and transversely along the centerline, and the sensor membrane is folded and embedded. The first row attaches to the inner surface of the tread to measure the normal load, while the embedded rows measure the internal forces of the tread. Experimental results show that this sensor accurately measures friction characteristics in the slip region.

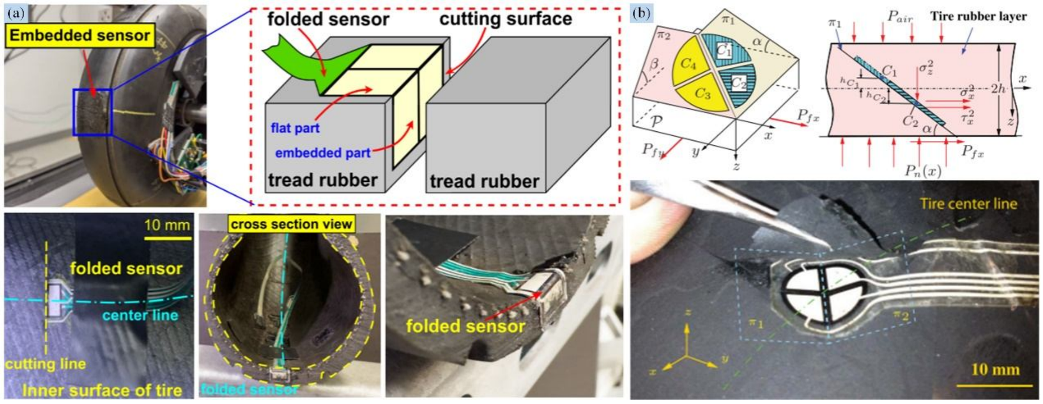

Figure9Industrial ApplicationsField：(a) Zhang [30] (2013)；(b) Chen [31] (2023)

4.5 Large-scale Force Measurement

In the field of large-scale force measurement, Yingri et al. [32] designed a novel bidirectional shear force sensor, as shown in Figure 10(a). Its structure separates the shear force measurement component from the vertical load-bearing component, enabling accurate friction force measurement under high compression forces. This design addresses the limitation of conventional shear force sensors, which are not suitable for measuring friction in structural compression-shear tests.As shown in

Figure 10(b), Zhang et al. [33] designed a multi-branch orthogonal compliant vector force measurement system for rocket engine and high-thrust aircraft engine tests in the aerospace field. The branching configuration of this system provides valuable reference for the design of large-load vector force measurement systems.

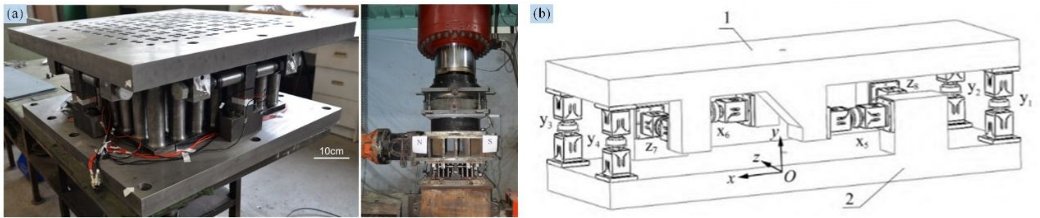

Figure10Large-scale Force Measurement：(a)Yingri [32] (2022)；(b) Zhang[33] (2024)

5. Key technical problems of two-dimensional force sensor

Driven by the increasing demand for 2D force sensing in various application domains, fueled by advancements in intelligence and digitization, 2D force sensors have undergone extensive research in recent years, leading to substantial progress in areas such as configuration design, performance enhancement, and application diversification.Nonetheless, despite these advancements, significant challenges remain as they transition towards industrialization.Nonetheless, despite these advancements, significant challenges remain as they transition towards industrialization.

5.1 Configuration Design

The elastomer, as the core component of orthogonal 2D force sensors, is designed to meet the force measurement range and characteristics required by various application scenarios.During material selection, the fundamental mechanical properties of the materials are thoroughly considered to ensure the sensor’s high sensitivity, resolution, and rigidity.Selecting an appropriate shape is crucial for enhancing the performance of the sensor. When optimizing the structure, the determination of dimensional parameters must comprehensively consider their impact on sensitivity, stress distribution uniformity, and other performance metrics.Inadequate dimensional design may lead to stress concentration, affecting the sensor's linearity, repeatability, and potentially damaging the elastomer.During the manufacturing process, feasibility and production costs are also essential factors that must be considered in the elastomer configuration design.For modular structures, appropriate interfaces and space must be reserved for the installation of other components to ensure the overall stability and reliability of the system.Therefore, to address diverse application requirements, a systematic configuration design approach should be employed for material selection, structural optimization, and manufacturing of 2D force sensors.

5.2 Theoretical Model

With the continuous innovation of elastomer configurations, the absence of theoretical models due to the diversification and complexity of flexible elements has resulted in the reliance on experience and trial-and-error methods for elastomer structure design. This makes it challenging to accurately predict the impact of various structural shapes and dimensions on force measurement performance, thus hindering the determination of the optimal structure.Furthermore, establishing the mapping relationship between outputs through analysis software and experimental data fitting not only incurs significant time and financial costs but is also subject to errors and uncertainties, which further complicate the process.Simultaneously, the lack of a theoretical model complicates the calculation of performance metrics, making it impossible to theoretically compute key parameters such as sensitivity and linearity during the design phase, and thus challenging to evaluate whether the sensor meets application requirements in advance.The performance variations of the sensor under different operating environments and conditions cannot be accurately predicted, nor can effective compensatory measures be taken in advance. As a result, the sensor's performance becomes unstable in practical applications, severely limiting its performance improvement and application expansion.

5.3 High-precision Measurement

The elastomer structure of orthogonal 2D force sensors is prone to measurement errors due to factors such as material inhomogeneity, manufacturing tolerances, and the performance discrepancies of the sensing elements when combining unidimensional sensing units for orthogonal 2D force measurement.Consequently, the sensor must undergo calibration prior to use to ensure measurement accuracy.However, in practical applications, the calibration process may introduce errors.On one hand, the precision of the calibration equipment may be limited, preventing the provision of accurate reference force values. On the other hand, discrepancies between the calibration environment and the actual operating conditions may prevent the simulation of real-world force scenarios.This results in inaccurate calibration outcomes in practical applications, thereby complicating the enhancement of measurement accuracy.Furthermore, the complex force field environment in practical applications imposes stringent requirements on the sensor's decoupling algorithm. However, existing decoupling algorithms exhibit numerous limitations.The primary issue lies in the extreme sensitivity to environmental disturbances, making it difficult to effectively distinguish between output signals induced by electromagnetic, temperature, or mechanical vibrations and the actual force signals.As a result, erroneous decoupling outcomes lead to a significant reduction in measurement accuracy.

6 Conclusion

This paper explores the differences in size, material, and measurement range across various types of sensors from the perspective of sensing mechanisms.Additionally, it summarizes the configuration design and application cases of 2D force sensors, incorporating both domestic and international research trends.The paper analyzes the key technological issues hindering the industrialization of orthogonal 2D force sensors.Provides insights into the latest advances and practical applications of 2D force sensors.

In the future, the application and innovation of novel design methods for flexible mechanisms, including equivalent rigid body replacement, the degree-of-freedom and constraint space topology synthesis (FACT) method, and graph theory, will drive further advancements in elastomer configuration design.The development of serial and parallel structure theories, including stiffness matrices and forward/inverse kinematics analysis, will provide powerful tools for constructing theoretical models to guide sensor design, performance evaluation, and calibration compensation.The development of multi-dimensional calibration equipment, the introduction of joint calibration techniques, and the advancement of intelligent decoupling algorithms are expected to significantly improve the accuracy of sensor calibration results, optimize the sensor's ability to resist external interference, and enable real-time adaptation to force field variations in complex application scenarios.

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