

Bionic tactile sensor based on starfish tube foot structure

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Received: December 27, 2025

Revised: January 31, 2026

Accepted: March 1, 2026

Abstract: Artificial tactile perception sensors have great application value in robotics, medical health, intelligent prosthetics, and human-computer interaction. However, existing sensors encounter difficulties in achieving high sensitivity, good linear response, and high spatial resolution, which has become a key problem restricting their practical application. Here, inspired by the tube foot system in starfish, we report the design, fabrication, and performance of a multi-level dome structure tactile sensor (MLDSTS) that provides simultaneous high sensitivity, excellent linearity, stability, and high resolution. Through a series of experiments, a comprehensive and systematic characterization and analysis of its sensing performance were conducted. The experimental results showed that the constructed multi-level dome array structure could effectively expand the linear detection range of the sensor while stably maintaining high spatial resolution. Its linear range was increased by about 2 times compared with the single-level dome structure, and realized segmented sensitive response. The sensor could detect weak external forces as low as 0.1 N, with a sensitivity of 1.309 V/N in the range of 0.1–3 N and 0.447 V/N in the range of 4–10 N, possessing both high precision and large-range detection capabilities. Through tests in various practical application scenarios such as respiration monitoring, water droplet detection, fabric texture recognition, and knuckle movement monitoring, it was confirmed that the sensor exhibited excellent stability and detection accuracy in different pressure scenarios, and its performance was significantly superior to that of single-dome structure sensors. The research results indicated that the multi-level dome structure provided an effective strategy to solve the industry problem that it was difficult to balance the sensitivity, linearity, and resolution of tactile sensors. With its comprehensively excellent performance, the MLDSTS sensor has broad application prospects in the fields of flexible electronics, intelligent health monitoring, human-computer interaction, and intelligent robots.

Key words: tactile sensor; piezoelectric response; dome structure; PVDF; flexible electronics; human-computer interaction

0 Introduction

Embodied perception serves as a cornerstone of embodied artificial intelligence, empowering humanoid robots to interpret their surrounding environment and human intentions, thereby facilitating the execution of complex, high-level tasks. In addition to visual perception, the integration of tactile sensing is critical for addressing the limitations of vision—especially in scenarios where visual information is inadequate, ambiguous, or completely absent, such as unstructured settings, dark environments, or occluded spaces. Higher spatial resolution can be more readily accomplished for tactile sensors for capturing finer haptic details and enabling precise manipulation with generally array-based. Thus, as a key element in achieving natural and intuitive human-computer interaction, tactile perception technology—has become increasingly prominent

in importance. Benefiting from significant breakthroughs in the field of bionics, flexible electronic materials have greatly promoted the development of tactile sensors. The sensor inspired by human skin retains high-precision pressure sensing capabilities even when seamlessly conforming to irregular surfaces. Nowadays, endowed with distinctive advantages, tactile sensors have achieved significant advancements across diverse frontier domains, including robotic tactile perception^[1-5], medical healthcare^[6-8], and human-computer interaction^[9-11], thereby emerging as a prominent research focus. However, existing tactile sensors are constrained by the difficulty of balancing sensitivity, linear response, and spatial resolution, which severely restricts their in-depth application in wearable devices and robotics.

Flexible tactile sensors operational mechanisms include capacitive^[12-13], piezoelectric^[14-16], piezoresistive^[17-18], and

triboelectric^[11,19-20] types. Among them, tactile sensors based on the piezoelectric mechanism have garnered extensive attention owing to having advantages of high sensitivity, wide measurement range, self-powering capability, and low energy consumption^[21]. When subjected to mechanical stress, tactile sensors based on the piezoelectric mechanism will convert mechanical energy into electric charge due to their internal crystal structure without a symmetric center undergoing polarization. This property makes them excellent in dynamic pressure measurement. Among numerous piezoelectric materials, lead zirconate titanate ($\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$, PZT)^[22-23] and polyvinylidene fluoride (PVDF)^[24-25] are the most representative. While inorganic piezoelectric materials such as PZT, aluminum nitride (AlN)^[26-27], and zinc oxide (ZnO) possess high piezoelectric coefficients, their inherent rigidity has greatly limited their applicability in wearable electronics and electronic skin. PZT requires high-temperature sintering and high polarization voltage, AlN relies on sputtering equipment, and ZnO requires precise control of crystal orientation. The process is complex and has high power consumption, which does not meet the requirements of sensor miniaturization and low power consumption. At the same time, PZT also contains toxic lead, and ZnO^[28-29] is easily affected by humidity, making it difficult to meet the core application requirements of tactile sensors as a whole. In contrast, PVDF is widely acknowledged as one of the most promising candidate materials for flexible piezoelectric tactile sensors, owing to its advantageous properties, including low dielectric constant, excellent flexibility, high mechanical strength, good acoustic impedance matching, wide frequency response range, outstanding chemical corrosion resistance, and ease of preparation into large-area films with complex shapes^[30-31].

Researchers have explored tactile sensors from the synthesis of piezoelectric materials to the structural design for enhancing sensitivity. Liu et al.^[32] proposed a layered PVDF-TrFE/ZnO NRs-based flexible tactile sensor with a sensitivity of 935 mV/N, representing a notable enhancement in piezoelectric response compared to pristine PVDF-TrFE films. Despite this advantage, the device is limited by a narrow linear measurement range of merely 4 N, restricting its applicability in wide-range pressure sensing scenarios. Huang et al.^[24] proposed a piezoelectric tactile sensor array composed of truncated pyramid-shaped rigid-flexible structures, with a sensitivity of 35.6 mV/N. While this value represents a ~ 1.7 -fold enhancement relative to sensors without rigid column regulation, it remains relatively low compared with other PVDF-based

sensors; additionally, its linear force detection range is confined to 1–11 N, failing to meet the demands of broad-range pressure sensing. Ye et al.^[33] reported a capacitive tactile sensor with an elastic dome-shaped electrode, which has a sensitivity of 0.115 kPa^{-1} lower than similar capacitive tactile sensors, and its linear range can only reach 120 kPa. Acer et al.^[34] designed a PZT sensor array embedded in silicon material, which exhibits linear characteristics under a pulsed force of 0–1 N with a sensitivity of $0.578 - 0.821 \text{ V/N}$. Zhang et al.^[35] combined PVDF-TrFE/AgNWs films with an-IGZO flexible TFTs. The pressure sensor can be arranged into a 4×4 array using an active matrix design, with a high sensitivity of 1.1 V/N . Chen et al.^[36] drew inspiration from the structural features of starfish and incorporated high and low spine structures to design a piezoresistive pressure sensor. However, its sensitivity is low in the low-pressure range, and the manufacturing process is complex. Although there are many studies now, the issues of multi-level sensitivity and the mutual constraint between sensitivity and range have not been resolved.

To address the compromise between sensitivity and measurement range in flexible piezoelectric tactile sensors, we propose a multi-level dome strategy to develop a flexible piezoelectric tactile sensor. In addition, gradient optimization design on the structure was performed, effectively improving the smoothness of the sensor's response curve. The experimental results demonstrated that the sensor exhibited superior resolution and excellent robustness, and the sensitivity of MLDSTS could reach 1.309 V/N . Moreover, the linear range remained favorable even at a pressure of 20 N. Finally, the developed sensor was used to perform tactile perception of different pressures. To verify the feasibility of this sensor in large-scale detection, its performance in detecting finger joint movements was demonstrated. This proved that the developed sensor had excellent sensitivity and a wide detection range, thereby confirming that MLDSTS had a promising application prospect in the fields of tactile perception and healthcare. At the same time, in terms of weak pressure tactile perception, applications such as breathing monitoring, water droplet gravity testing, and fabric material identification were carried out, verifying that the sensor had sufficient sensitivity in terms of weak pressure.

1 Experiment

1.1 Design concept and working principle

Starfishes possess a unique tube foot system, which

not only serves as a key for their movement but also exhibits acute tactile perception and adsorption capabilities, enabling them to precisely detect changes in the surrounding environment. The ends of starfish tube feet are distributed with suckers of various morphologies (see Fig. 1(a)). When a starfish's tube feet make contact with an object, the variously shaped suckers adjust flexibly to achieve efficient tactile feedback. Inspired by starfish's tube feet, we present a tactile sensor based on a multi-level dome structure.

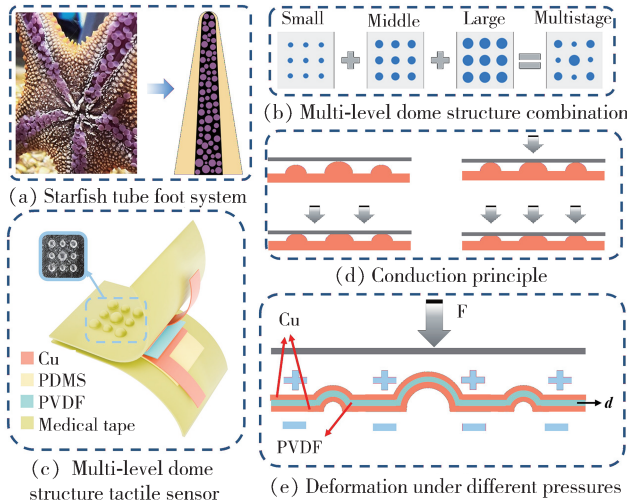


Fig. 1 Sensing mechanism

Although a single-level dome structure can effectively enhance sensor sensitivity during the stress process, the stress distribution tends to concentrate at the top or edge of the structure, which easily causes local overload. This not only reduces structural stability but may also trigger non-linear responses, affecting measurement accuracy. In contrast, the multi-level gradient design can make stress distribution more uniform, avoid local stress concentration, and thus improve the structural fatigue resistance and service life. On the other hand, through reasonable regulation of gradient parameters, the dynamic response characteristics of the sensor can be optimized, enabling the sensor to maintain good linearity within different pressure ranges and avoiding signal saturation or distortion caused by excessive pressure in traditional structures. Dome structures with different radii have different sensitivities and linear ranges. Combining multi-level dome structures with different radii can broaden the linear range while maintaining high sensitivity (Fig. 1(b)). Based on this principle, this paper designs a tactile sensor based on a multi-level dome structure (Fig. 1(c)).

The conduction principle of the multi-level dome structure is shown in Fig. 1(d) and 1(e). Initially, the large-diameter dome undergoes slight deformation. As the

pressure increases, the large-diameter dome undergoes more significant deformation. Meanwhile, the medium-diameter domes start to deform. When the pressure becomes even greater, the small-diameter domes also begin to deform. Therefore, the multi-level dome structure can maintain high sensitivity under small pressures and ensure continuous growth of the deformation area under large pressures, thereby achieving a wide sensitivity range.

This level-based deformation characteristic is further converted into detectable electrical signals through the piezoelectric effect of the PVDF film coated on the surface of the dome. When an external force acts in a specific direction to cause deformation of the piezoelectric film, polarization occurs inside it, and equal amounts of opposite charges are induced on the two surfaces of the film. When the external force is removed, the film returns to an uncharged state. Since the amount of induced charge is positively correlated with the magnitude of the external force, this implies that there is also a positive correlation between the output voltage of the piezoelectric material and the external load. Based on this basic mechanism of piezoelectric response, the output voltage V of the piezoelectric tactile sensor can be initially calculated by

$$V = \frac{g_{3n} F_n t}{A}, \quad (1)$$

where F_n represents the applied force in the relevant direction, g_{3n} denotes the voltage output coefficient corresponding to the force application axis, t and A are respectively the thickness and surface area of the piezoelectric film.

$$g_{3n} = \frac{d_{3n}}{\epsilon_r \epsilon_0}, \quad (2)$$

where d_{3n} is the piezoelectric strain constant, ϵ_r represents the relative dielectric constant of the piezoelectric film, while ϵ_0 is the vacuum dielectric constant.

In this context, the equivalent load F_n acting on the PVDF film is directly derived from the deflection deformation of the dome structure. To establish a correlation between the geometric parameters of the dome and the voltage output, this study constructed a dome deflection model based on the Kirchhoff-Love thin-shell theory. By solving the equilibrium equations, geometric relations, and constitutive equations in the cylindrical coordinate system, the expression for the deflection (vertical displacement) of the dome at the radial position r is obtained as

$$w(r) = \frac{q_0 R^4}{Et^3} \cdot f\left(\frac{r}{R}\right), \quad (3)$$

where q_0 is the uniformly distributed load on the dome surface, R is the base radius of the dome, E is the elastic modulus of the dome structure, t is the shell thickness, and $f(r/R)$ is the dimensionless deflection function related to the geometric shape. This formula indicates that the dome deflection is proportional to R^4 and inversely proportional to t^3 , which theoretically explains why large-diameter domes can generate significant deformation even under low pressure.

Further, the dome deflection $w(r)$ induces bending strain $\epsilon \propto dw/dr$ in the PVDF film, which is then converted into internal stress $\sigma = E\epsilon$ of the film. By integrating the stress over the effective sensing area, the equivalent load F_n can be obtained, thereby establishing a direct mapping relationship between dome deflection and film stress. By combining the dome deflection formula with the modified voltage model, the correlation between the applied pressure q_0 and the output voltage V can be derived as

$$V \propto \frac{d_{3n} q_0 R^3}{\epsilon_r \epsilon_0 t^2}. \quad (4)$$

The sensitivity S of the sensor, defined as the ratio of the output voltage to the total applied force, is

$$S \propto \frac{d_{3n} R}{\epsilon_r \epsilon_0 t^2}. \quad (5)$$

Eq.(5) reveals that the sensitivity scales with the dome radius R and inversely with the square of the structural thickness t . The upper-limit force $F_{\max}$ of the linear response range is applied over the entire substrate area, leading to

$$F_{\max} = K_F \cdot t^2, \quad (6)$$

where K_F is a constant determined by the material and fixed boundary conditions.

By combining Eqs.(5) and (6), eliminating the geometric parameter t , a trade-off equation directly relating the sensitivity S to $F_{\max}$ can be derived as

$$S \cdot F_{\max} \propto \frac{d_{3n} K_F}{\epsilon_r \epsilon_0} \cdot R. \quad (7)$$

Eq. (7) indicates that the size of the dome radius R is a key parameter for adjusting sensitivity and linear range. It also demonstrates that a single-dome structure cannot achieve both high sensitivity and a wide linear range simultaneously. Accordingly, a multi-level dome structure is adopted in this work to implement the optimization strategy. Large-radius domes are utilized to achieve high sensitivity under low-pressure conditions, while small-radius domes extend the linear response range in the high-pressure regime. The selection of R

must also account for the overall device dimensions required for bioinspired wearable applications and the fabrication resolution of the laboratory molding process. In this work, tactile sensors with different dome radii were fabricated, and their key performance metrics, including sensitivity, linearity, and stability, were characterized over a wide pressure range.

1.2 Preparation process of sensors

The fabrication of the sensor primarily involves five key steps: mold preparation, substrate fabrication, sensitive material layer preparation, electrode configuration, and encapsulation (Fig.2).

Mold preparation: A 16 mm×16 mm mold was produced via 3D printing for the fabrication of the sensor's dome-structured substrate.

Substrate fabrication: The mold with dome structures was first ultrasonically cleaned in ethanol and deionized water for 15 min each and then dried to remove surface impurities, thereby ensuring the quality of dome structure transfer and the precision of substrate fabrication. PDMS (DC184, Dow coming corporation) base and curing agent were mixed at a mass ratio of 10 : 1. After thorough stirring, the mixture was poured into the mold and spin-coated at 500 r/min for 1 min on a spin coater to ensure uniform coverage of the mold surface. Subsequently, the mold was placed in a vacuum desiccator for 30 min to eliminate bubbles in the mixture, followed by curing on a 45 °C hot plate for 24 h. After completing curing, the PDMS was peeled off to obtain a substrate with micro-dome structures.

Sensitive material layer preparation: A copper-plated PVDF piezoelectric film was selected. To ensure the functional material remain flat during fabrication, the film was laid flat on the mold, and a certain pressure was applied to make it closely adhere to the micro-dome structures of the mold. After 24 h of imprinting, the film was removed, which has replicated the identical dome structures of the mold. The side with convex domes serves as the upper surface, used to contact external forces, while the other side acts as the lower surface, providing conditions for subsequent electrode configuration.

Electrode configuration: Copper foil was served as the electrode material for signal extraction. Pieces were cut to match the size of the PVDF film and attached to its upper and lower surfaces using polyimide (PI) tape, forming the top and bottom electrodes. Signal wires were then soldered to copper foil to establish connections for testing.

Encapsulation: For the encapsulation process, the

sensitive material layer with soldered electrodes was first aligned and firmly attached to the PDMS substrate (with pre-fabricated micro-dome structures). Biocompatible medical tape was then used to cover and protect both the

bottom surface of the PDMS substrate and the top electrode. This encapsulation design prevents the intrusion of impurities such as water vapor and dust, thereby enhancing the long-term operational stability of the sensor.

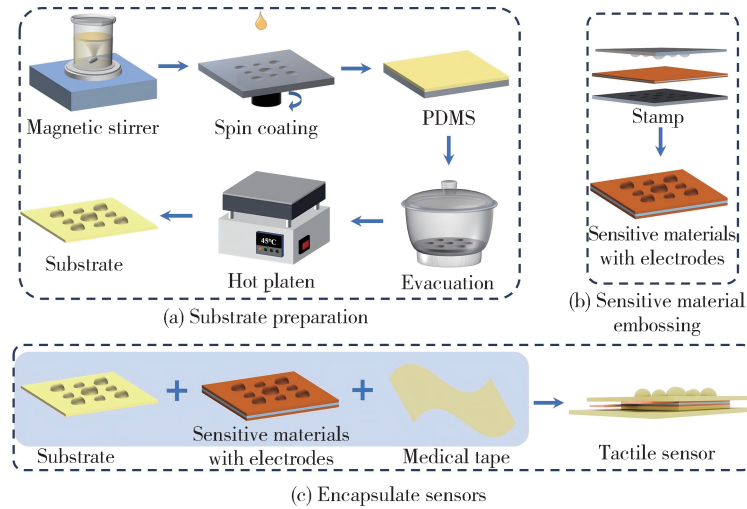


Fig. 2 Preparation process of sensor

1.3 Sensing characteristics of tactile sensors

To investigate the piezoelectric response characteristics of the tactile sensor, a precision piezoelectric testing system comprising a charge amplifier (VK103-C, Gain=2), DC power supply, oscilloscope, pressure gauge, and computer is

constructed (Fig.3(a)).

During the testing process, an external force was applied to the sensor by the presser through a dynamic cyclic loading-unloading method, with pressure being applied and then immediately unloaded in each cycle at a loading frequency of approximately one cycle per second.

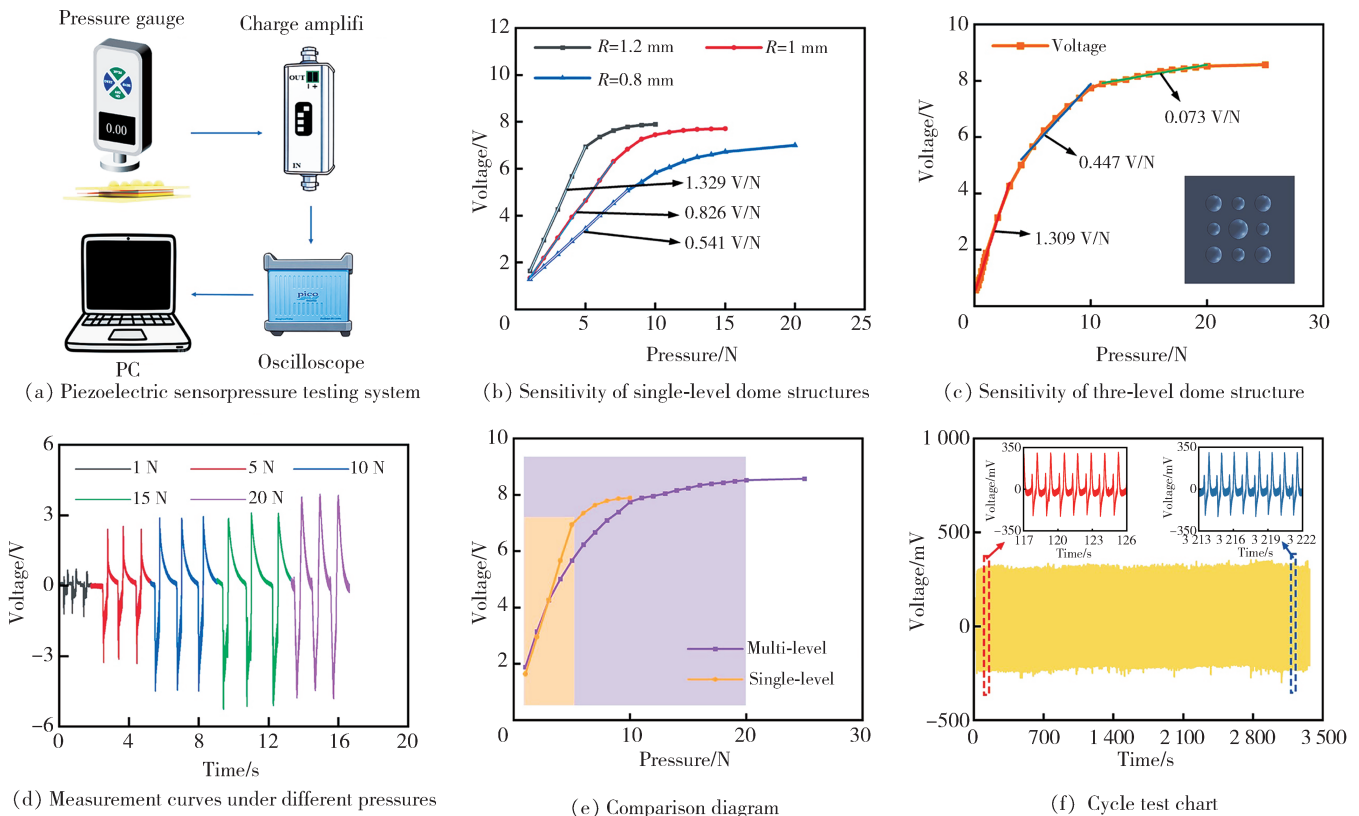


Fig. 3 Sensing characteristics of sensors

The pressure detection module simultaneously displayed the applied force value. The dynamic charge generated by the sensor was converted into a voltage signal via a charge amplifier, which was then transmitted to a computer via an oscilloscope. Signal acquisition software collected and recorded the voltage waveforms in real-time, providing reliable data for analyzing the piezoelectric performance of the sensor.

In the low-pressure range, the multi-level dome structure requires minimal pressure to undergo deformation, and its deformation increases rapidly with rising pressure, resulting in extremely high sensitivity of the sensor in this stage. As the pressure continues to increase, the growth rate of the dome structure's deformation gradually slows down, and the sensor's sensitivity decreases accordingly. Owing to this stage-dependent deformation response characteristic, the sensor exhibits distinct sensitivity levels across different pressure ranges (Fig.3(c)). The sensor features high reliability and performance in both design and fabrication, enabling its application in high-precision pressure measurement and control. Forces of 1 N, 5 N, 10 N, 15 N, and 20 N were sequentially applied to the tactile sensor with a three-level dome structure. The output voltage of the sensing unit increases with the applied pressure (Fig.3(d)), indicating that the sensing unit is highly sensitive to pressure variations. In addition, the response of the sensing unit remains stable throughout each pressure loading cycle, demonstrating its excellent pressure response characteristics and repeatability. A cyclic loading-unloading test with 2 600 repetitions is conducted on the sensor under 0.5 N (Fig.3(f)). After prolonged cyclic testing, no significant deviation in sensing performance is observed; the initial response voltage is 560 mV, and the late-stage response voltage is 555 mV.

The sensitivity and linear range of the sensor can be tailored to meet the requirements of different application scenarios by adjusting the dimensions of the multi-level dome structure. Three types of single-level dome structures with different radii are fabricated (Fig.3(b)).

Finite element analysis (FEA) is conducted on different dome structures, which reveals that an increase in dome radius improves the sensor's sensitivity but compromises its pressure limit. Under the same pressure variation, the large-dome structure undergoes a larger deformation than the small-dome counterpart. Accordingly, the sensor's sensitivity increases with the rise in dome radius, while its linear range decreases as the dome radius increases. To achieve higher sensitivity, more large dome units can be incorporated into the

structure, which serves to enhance the pressure concentration effect and boost the electrical signal conversion efficiency of the sensor. To expand the linear measurement range of the sensor, the number of small dome units can be increased and a gradient design can be applied to the multilayer structure. The dimensional gradient characteristic enables uniform stress distribution and a smooth transition of the sensing response. Fig.3(e) presents a comparison between the single-level and three-level dome structures. The pressure sensor with a single-level dome structure exhibits high linearity in the range of 1 – 5 N, with a correlation coefficient (R^2) of 0.99. The three-level dome structure achieves high linearity in three intervals: 0.1 – 3 N ($R^2=0.99$), 4 – 10 N ($R^2=0.977$), and 11 – 20 N ($R^2=0.968$). The tactile sensor with the three-level dome structure can realize linear output over a pressure range of 0.1 – 20 N. Therefore, compared with the single-level dome structure, the three-level dome structure extends the linear working range of the sensor by nearly 4 times, achieving dual optimization of measurement range and sensitivity.

The characteristic frequencies of major human physiological movements (such as joint flexion and respiration) are typically below 5 Hz^[32,37]. The MLDSTS achieves an operational frequency of up to 10 Hz, it well exceeds the requirements for applications in human motion monitoring and related dynamic tactile sensing scenarios, confirming its reliability and suitability.

2 Results and discussion

As presented in Table 1, compared with the reported PVDF-based tactile sensors with composite structures, the proposed MLDSTS exhibits significant advantages in both sensitivity and linear range. This demonstrates its promising application potential in both weak pressure perception and large-range detection scenarios.

Table 1 Comparison of reported piezoelectric tactile sensors

Sensor type	Sensitivity/ (V·N ⁻¹)	Linear range/N	Main structure
MLDSTS (This work)	1.309 0 0.447 0 0.073 0	[0.1, 3] [4, 10] [10, 20]	Multi-level dome
Huang et al. ^[24]	0.035 6	[1, 11]	Truncated pyramid structure
Liu et al. ^[32]	0.935 0	[0, 4]	Hierarchically structured
Zhang et al. ^[35]	1.100 0	[0.5, 2.5]	Vertical stacking structure

Through in-depth analysis, the performance errors of the sensors fabricated in this study are mainly attributed to inherent process limitations during actual manufacturing. Constrained by the existing laboratory

preparation conditions and technical capabilities, such errors are difficult to completely eliminate. Multiple sets of repeated tests have verified that the aforementioned errors exert negligible impacts on the tactile signal detection accuracy under the current application scenarios.

2.1 Large-scale detection

All studies involving human subjects, including self-experiments, were conducted with the subject's written informed consent, in full compliance with the principles of the declaration of Helsinki.

In order to verify the sensor's ability to detect large-scale pressure and perceive dynamic deformation of human joints, the proximal interphalangeal joint of an adult index finger was selected as the test target. The sensor was fixed on the dorsal side of the joint using polyimide tape, ensuring that it deforms synchronously with the joint during bending without slipping. An angle-adjustable fixture was employed to control the bending angles of the finger (30° , 60° , 90°). Different bending angles result in varying degrees of deformation at the joint, which in turn exerts pressure on the sensor surface. This causes the dome structures inside the sensor to be squeezed and deformed, thereby outputting electrical signals, as shown in Fig.4(a). When measuring the piezoelectric response output of the sensor with the finger bent at different angles, the output voltage increases from 0.514 V to 1.4 V as the bending angle increases from 30° to 90° .

2.2 Weak pressure tactile perception

To comprehensively verify the performance reliability and adaptability of the sensor in micro pressure measurement scenarios, we designed a multidimensional verification experiment. Firstly, in the respiratory detection scenario, the sensor was attached to a mask to capture the micro pressure during breathing and verify its sensitivity to slowly-changing micro pressures. Continue with water droplet testing, utilizing micro droplet impact sensors to detect the response capability of instantaneous micro impact pressure. Finally, fabric recognition was performed by allowing sensors to lightly touch fabrics with different textures, verifying their resolution through the small pressure differences generated by fabric contact, and covering different application scenarios with small pressures in all directions.

2.2.1 Breath detection

Respiratory rate is a crucial physiological indicator, with significant variations among different populations

(44 breaths per minute for newborns and 12–20 breaths per minute for adults). It maintains a 1 : 4 ratio with the pulse rate, and abnormal changes indicate pathological conditions (e. g., tachypnea associated with fever or heart failure, and bradypnea caused by drug overdose). Accurate monitoring of respiratory rate and intensity is vital for health assessment, especially for patients and the elderly, and a comfortable-wearing respiratory sensor can enable abnormal warning.

In this experiment, a tactile sensor with a three-level dome structure is integrated into the surface of a mask (Fig.4(b)) to test its sensing performance under three states: deep breathing, normal breathing, and rapid breathing. At room temperature, the sensor outputs stable and repeatable voltage signals for different breathing patterns. Taking normal breathing as an example (Fig.4(c)), the period of the output waveform is approximately 0.324 Hz (corresponding to 3.09 s), which converts to a respiratory rate of about 19 breaths per minute, falling within the normal range for adults.

In addition, as shown in Fig.4(d), during rapid breathing, the intensity of the electrical signal increases significantly with the rise in respiratory rate. This is because the amplitude of the coupled vibration between the mask and the sensor increases when breathing accelerates, leading to greater deformation of the sensor and thus enhanced electrical signals. During deep breathing, the human body actively increases the breathing amplitude and reduces the respiratory rate, which also results in increased deformation of the sensor and enhanced electrical signals.

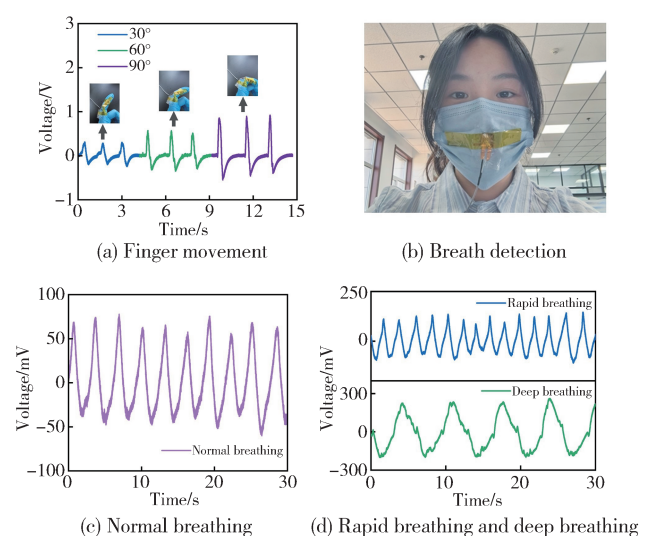


Fig. 4 Finger movement test and breath detection

The experiment demonstrates that this tactile sensor shows great application potential in wearable health monitoring devices. It is not only expected to provide an

efficient solution for real-time physiological parameter monitoring but also of great significance for advancing the development of the medical field.

2.2.1 Water droplet test

The tactile sensor with a multi-level dome structure can convert mechanical energy into electrical energy. Based on this, a simple rain intensity testing device was built. To ensure uniform distribution of the droplet impact force within the sensing area, the central region of the sensor is marked, and all water droplets are released vertically onto this designated zone (Fig.5(a)). The sensor was fixed on a glass rod, and a transparent acrylic water-receiving tray was placed below to avoid environmental interference. The test simulated complex rain conditions through three variable controls: ① changing the distance between the syringe and the sensor to simulate differences in the falling height of raindrops; ② replacing the syringe specifications to control the volume of water droplets; ③ adjusting the frequency of water droplet generation to simulate the intensity of rain.

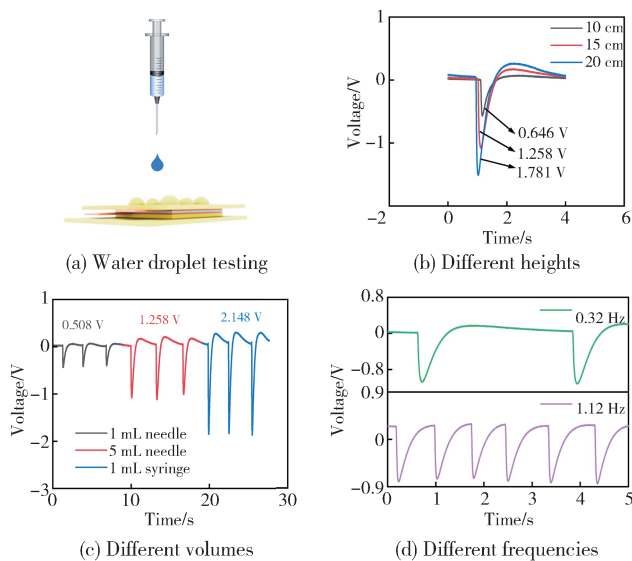


Fig. 5 Water droplet test

When water droplets of the same volume fall vertically onto the effective sensing area of the sensor from heights of 10 cm, 15 cm, and 20 cm, the collected data displayed on the PC terminal indicate that the peak output voltages are 0.646 V, 1.258 V, and 1.781 V, respectively (Fig.5(b)). According to Newton's second law and the law of conservation of energy, the force exerted by the water droplets on the sensor is proportional to the square root of the falling height. The greater the height, the greater the kinetic energy of the water droplets and the stronger the force, leading to a higher output voltage of the sensor.

When water droplets of different volumes (from 1 mL needle, 5 mL needle, and 1 mL syringe) fall freely from a

height of 15 cm, the peak output voltages of the sensor are 0.508 V, 1.258 V, and 2.148 V, respectively, as shown in Fig. 5(c). This indicates that the sensor can infer the volume of water droplets through voltage signals, providing a quantitative basis for rain intensity classification (such as light rain, moderate rain, and heavy rain).

When water droplets fall at a fixed height of 15 cm, with the same volume (from a 5 mL needle) but different frequencies, the faster the frequency, the smaller the output voltage of the sensor, as shown in Fig.5(d). The reason is that at high frequencies, the previous water droplets do not completely dissipate, forming a buffer layer, which weakens the impact force of subsequent water droplets, resulting in reduced pressure on the sensor and thus a smaller output voltage.

2.2.3 Fabric identification

Differences in physical properties such as texture and hardness of fabrics can be distinguished via contact force signals. To verify the sensor's material recognition capability, five typical fabrics were selected, namely polyester, wool cloth, denim, leather, and gauze. These five materials are cut into identical dimensions and fixed onto the surface of the test bench (Fig.6(a)).

During the experiment, the sensor was fixed to the ventral side of the index finger. Through prior calibration and practice using a miniature spring dynamometer, the operator was able to apply and maintain a constant normal force of approximately 1.0 N. The sliding speed was controlled and maintained at approximately 2 cm/s by following the constant rhythm of a metronome during training, ensuring a uniform, unidirectional sliding motion over the fabric surface. The output signals of the sensor are collected in real time and processed, and Fig.6(c) shows the output signals of the five different fabrics.

The experiment employs a random forest classifier as the algorithm (Fig.6(b)). As a classic ensemble learning algorithm, it constructs multiple decision tree models and integrates their prediction results, effectively improving the model's prediction accuracy and generalization performance. This algorithm has several significant advantages. It not only achieves high-precision prediction but also adapts to complex data relationships and resists noise interference. It supports parallel computing, greatly improving training efficiency. It also has a feature importance evaluation function and has lenient requirements for parameter settings, eliminating the need for cumbersome data preprocessing procedures. Therefore, this method was used for fabric recognition. In this study, the raw voltage signal sequences were first imported, and 13-

dimensional feature vectors were extracted from each sample. A stratified sampling method was employed to randomly divide the dataset into training and test sets with a 1 : 1 ratio, ensuring a consistent distribution across all classes. The features were standardized using a standard scaler. The standardized feature vectors along

with their corresponding labels were then used as input for training and testing the random forest classifier. If the predicted category of the sample matches the actual category, then the sample is regarded as being correctly identified; otherwise, it is considered as being wrongly identified.

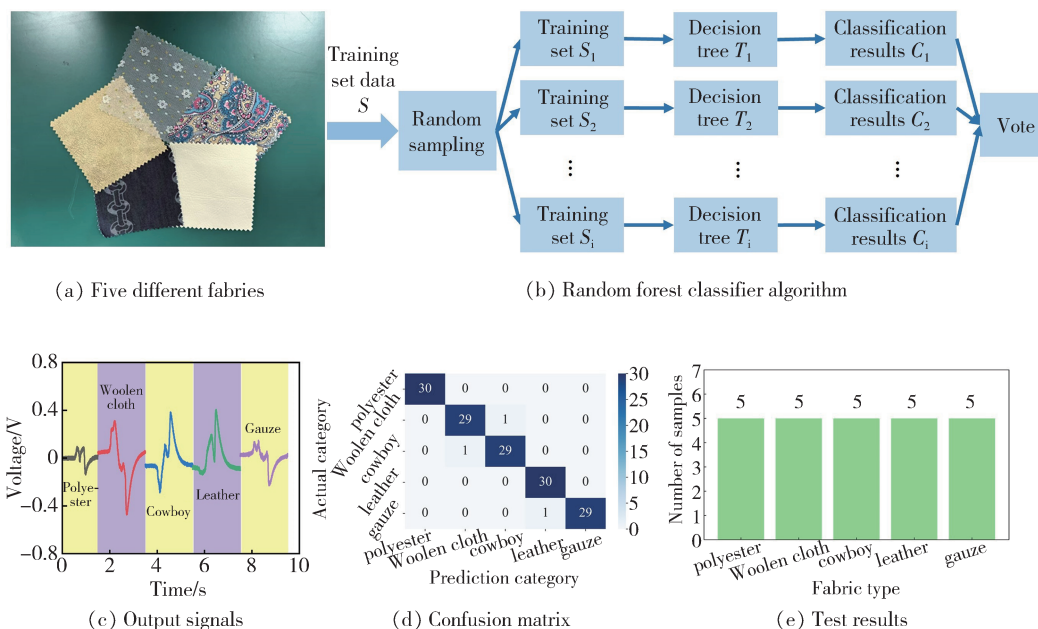


Fig. 6 Fabric recognition

3 Conclusions

This paper proposes a piezoelectric tactile sensor based on a multi-level dome structure, which combines theoretical modeling, finite element simulation, and experimental verification to achieve high-precision tactile perception function. The study found that the sensitivity of single-stage dome sensors was significantly positively correlated with the dome radius, which was consistent with the prediction of thin shell structure theory. On this basis, the innovative multi-level gradient dome array design can achieve uniform stress distribution and smooth response transition, increasing the sensor sensitivity to 1.309 V/N and expanding the linear working range to 0.1 – 20 N, effectively solving the technical problem of balancing high sensitivity and large measurement range of traditional sensors. The sensor has excellent stability, with a voltage decay rate of less than 0.5% after 2 600 cycles of loading. Practical scenario verification has shown that it can accurately capture finger joint movements, monitor respiratory status, perceive changes in water droplet pressure, and recognize fabric textures. It has broad application prospects in fields such as medical health and human-computer interaction, providing a new technological

solution for the development of high-performance intelligent sensors.

Acknowledgement

This work was supported by Shanxi Province Basic Research Program Project (No. 202403021212163).

Declaration of conflicting interests

The authors have no conflict of interests related to this publication.

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基于海星管足结构的仿生触觉传感器

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摘要: 人工触觉感知传感器在机器人、医疗卫生、智能假肢及人机交互等领域具有重要应用价值。然而, 现有传感器难以兼顾高灵敏度、优良线性响应与高空间分辨率, 这已成为制约其实际应用的瓶颈。受海星管足系统的结构启发, 本文设计并制备了一种多级圆顶结构触觉传感器, 实现了高灵敏度、优异线性度、稳定性与高分辨率的同步提升。通过一系列实验, 对该传感器的感知性能进行了全面、系统的表征与分析。实验结果表明, 所构建的多级圆顶阵列结构在稳定保持高空间分辨率的同时, 可有效拓展传感器的线性检测范围; 其线性范围较单级圆顶结构提升约2倍, 且实现了分段式灵敏响应。该传感器能够检测低至0.1 N的微弱外力, 在0.1—3 N区间内灵敏度达1.309 V/N, 在4—10 N区间内灵敏度为0.447 V/N, 兼具高精度与大范围检测能力。通过呼吸监测、水滴检测、织物纹理识别及关节运动监测等多种实际应用场景测试, 验证了该传感器在不同压力工况下均表现出优异的稳定性与检测精度, 性能显著优于单圆顶结构传感器。研究表明, 多级圆顶结构为解决触觉传感器灵敏度、线性度与分辨率难以兼顾的行业难题提供了有效策略。凭借综合优异的性能, 该传感器在柔性电子、智能健康监测、人机交互及智能机器人等领域具有广阔应用前景。

关键词: 触觉传感器; 压电响应; 圆顶结构; 聚偏氟乙烯(PVDF); 柔性电子; 人机交互

引用格式: WANG Jiaqi, YANG Xiaopeng, WANG Yuxi, et al. Bionic tactile sensor based on starfish tube foot structure. *Journal of Measurement Science and Instrumentation*, 2026, 17(2): 344-354. DOI: 10.62756/jmsi.1674-8042.2026029