

Bioinspired Elephant Trunk Bristle Sensors for Environmental Mapping

Ganzhou Wu

*Hohai Lille college, Hohai University, Changzhou, China
wuganzhou954@gmail.com*

Abstract: The environmental-exploration robots already have a great capability to adapt to the different harsh environment. Through using some special material, such as low melting point alloy, the environment-exploration robot can regulate the local stiffness. However, the sensing capabilities of the environmental-exploration robots are not perfect enough; the robots can't reflect the environment visually. Herein, inspired by the elephant trunk whisker, a tactile sensor applied to the robots can achieve the robotic visual sensing capability. Inspirations from the elephant trunk's bristles and their associated follicle-sinus complexes (FSC): the sensor uses carbon fiber material to imitate the bristles, which makes the bristle have the stable mechanical support capable of withstanding large forces like the elephant trunk whiskers. To imitate the elephant's FSC, the sensor uses the synergistic microcrack-bristle structure that can allow multiple circuits to connect inside the sensor. This structure ensures efficient transfer of tactile signals and enables rapid responses. The sensor uses the modular design to imitate the high-density distribution of elephant trunk bristles, which enables the sensor to detect subtle tactile stimuli, which is crucial for robots to perform precise manipulation in complex environments.

Keywords: Pressure sensor, Bionics, Finite element analysis method, Elephant trunk bristles

1. Introduction

With the development of AI and robotics, environmental exploration robots have been widely applied across various fields in recent years. Currently, the most common types of environmental exploration robots are quadruped or wheeled robots, which are incapable of exploring complex environments. To achieve variable stiffness regulation, inspired by the local stiffness control of elephant trunks, the stiffness of bioinspired elephant trunk continuum robots can be changed by using an intelligent spring with programmable stiffness (ISPS) [1]. However, there are still deficiencies in the sensing capabilities of robots. To address the issue of environmental exploration robots being unable to map their surroundings and achieve sensitive perception, this article designed a sensor inspired by the structure of elephant trunk bristles. By imitating the bristles and follicle-sinus complexes of elephant trunks, a combination of triboelectric nanogenerators [2] and capacitive sensors [3] will be selected as the sensing elements and installed bioinspired bristles on these sensing elements, enabling the detection of forces in the surrounding environment and mapping of the surroundings. Through modular design, this article densely distributed the sensors at the front end and ventral side of the continuum robot to simulate the distribution of elephant trunk bristles [4], thereby further enhancing the robot's ability to explore the environment. After the design and modeling of the sensor, finite

element analysis was employed to conduct mechanical property testing of the sensor, and tests were also performed to enable the sensor to discriminate between different material surfaces.

2. Result and discussion

2.1. Working principle of elephant trunk bristle

The working principle of elephant trunk whisker sensors is based on the biological structure and functional characteristics of elephant whiskers. Elephant whiskers are robust and non-tapered, providing stable mechanical support to withstand greater forces without deformation when in contact with objects. Whiskers are densely arranged in specific areas of the trunk, such as the tip and ventral side, forming arrays that provide rich tactile information to help elephants accurately perceive the shape, size, and texture of objects.

Elephant whiskers do not actively "whisk" but make contact with objects through the movement of the trunk. When the whiskers touch an object, the resulting mechanical deformation is transmitted to the brain via nerve endings in the follicle-sinus complex (FSC). The FSC contains rich nerve endings, and each whisker's FSC is innervated by multiple nerves with approximately 87 axons, ensuring efficient transmission and processing of tactile signals.

2.2. Design concept and material of the tactile sensor

2.2.1. Design concept and material

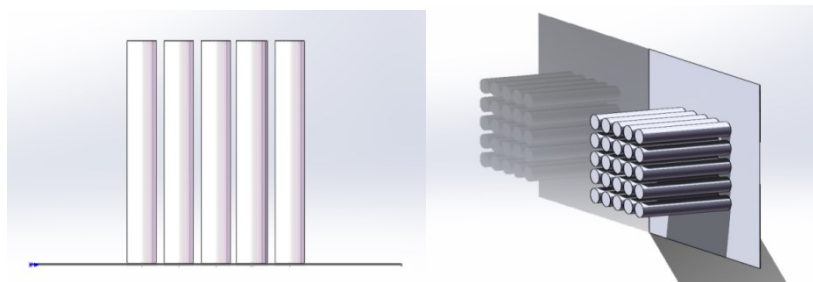


Figure 1: Imitation of elephant trunk bristles

Figure 1 illustrates the shape of the sensor bristle section. The bristles of the elephant trunk are much thicker and longer than those of a rat δ -whisker [4]. Unlike rat whiskers, the tips of elephant bristles do not taper. Moreover, the bristles of African elephants are thicker than those of Asian elephants. This structure endows the trunk bristles with excellent wear resistance. The differences in grasping methods between Asian and African elephants also result in variations in bristle thickness. To achieve the high wear resistance of elephant trunk whiskers and to enable sensing capabilities, the following materials can be considered: carbon fiber composites, conductive materials, and 3D printing materials. Carbon fiber composites are characterized by high strength, high elastic modulus, and wear resistance, making them suitable for applications requiring high rigidity and lightweight. Conductive materials possess conductivity and elasticity, which can be integrated into pressure or strain sensors. When used in tactile sensors, they can detect contact forces, vibrations, or surface textures. 3D printing materials allow for the customization of complex shapes and gradient hardness, enabling rapid prototyping. After comparison, carbon fiber was ultimately selected as the material for fabricating elephant trunk bristles, as it can simultaneously meet the requirements of wear resistance and provide excellent mechanical properties. The synergistic microcrack-bristle structure [5] will be employed in the sensor substrate.

2.2.2. Imitation of the elephant follicle-sinus complex (Fsc)

The follicle-sinus complex (FSC) in elephants is quite large and lacks a circular sinus. Similar to other mammals, a dense network of blood vessels and nervous system components is distributed around the FSC, enabling highly sensitive perception of forces and environmental changes. Moreover, the FSC can amplify the forces it senses internally.

To emulate the sensory mechanism of the elephant follicle-sinus complex (FSC), the sensing elements of the bioinspired sensor are designed by integrating coaxial piezoelectric fiber electronic skin [6] with capacitive sensors [7], and incorporating triboelectric nanogeneration technology [4] within the electronic skin. The combination of the triboelectric nanogenerator (TENG) with the electronic skin fully leverages the self-powering characteristics of TENG and the high-sensitivity sensing capabilities of the electronic skin, thereby realizing a multifunctional, self-powered intelligent electronic skin system.

The specific structure of the bioinspired sensor can consist of a substrate layer, electrode layer, capacitive pressure-sensing layer, TENG layer, and encapsulation layer. Polyimide (PI) or polyurethane (PU) can be selected as the flexible substrate to provide flexibility and protect the internal structure. The electrode layer can be made from breathable conductive fabric or metal films to collect and transmit electrical signals. A bimodulus dielectric layer, such as polydimethylsiloxane (PDMS) and flexible dielectric layers doped with graphene nanoflakes (GNP), can be used as the material for the capacitive pressure-sensing layer. Polymers with different electronegativities, such as polytetrafluoroethylene (PTFE) and PDMS, can be employed as the materials for the TENG layer. Finally, the sensor can be encapsulated using elastic and transparent polyurethane (PU) films or PDMS.

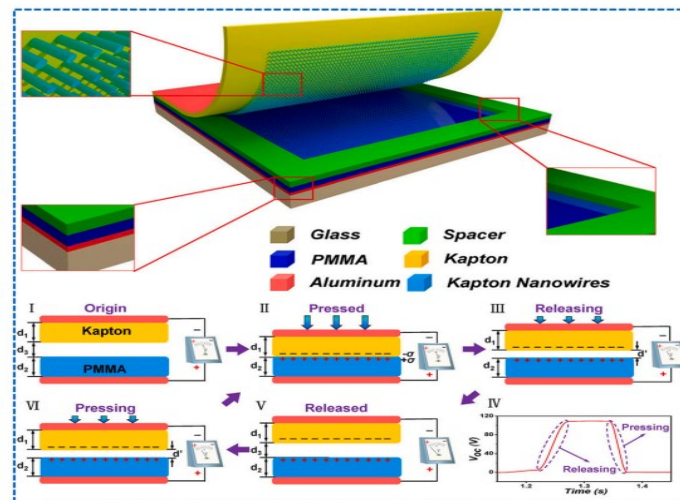


Figure 2: Schematic illustrations of the TENGs structure and materials selection showing the operating principle of the TENGs in contact-separation mode [8]

The fabrication of this sensor can be carried out according to the following steps. **Dielectric Layer Casting:** Mix PDMS with a curing agent in a specific ratio and pour it into a custom mold to prepare both flexible and rigid dielectric layers. Apply a small amount of uncured PDMS on the upper surface of the rigid dielectric layer. Align the flexible dielectric layer with the rigid dielectric layer and gently apply pressure to assemble the two layers, ultimately obtaining a bimodulus dielectric layer. **Electrode Layer Preparation:** Use photolithography and etching processes to fabricate copper electrode layers on a PI substrate. Apply a layer of PI film at the intersections of the electrode layer to protect the electrodes and reduce signal interference. **Capacitive Pressure Sensing Layer Preparation:**

Dope the flexible dielectric layer with GNP. Utilize spin-coating technology to prepare a uniformly distributed GNP layer within the flexible dielectric layer, enhancing the charge storage capacity. Assemble the prepared dielectric layer and electrode layer into a capacitive pressure sensing unit. The structure of TENG Layer is showed in Figure 2. TENG Layer Preparation: Employ PTFE and PDMS as triboelectric materials and fabricate the TENG layer via solution casting or spin-coating methods. Use PTFE and PDMS films as positive and negative triboelectric electrodes, respectively, to achieve electrical output through a contact-separation mode. Sensor Assembly: Apply a small amount of uncured PDMS on the bottom electrode. Sequentially stack the dielectric layer, TENG layer, ultrasonic transducer layer, and top electrode layer. Stack these layers in order and heat them at 80°C for 1 hour to complete the sensor assembly. Finally, encapsulate the entire structure with a PU film or PDMS to ensure waterproofing, dustproofing and breathability.

2.3. Performance test of the tactile sensor

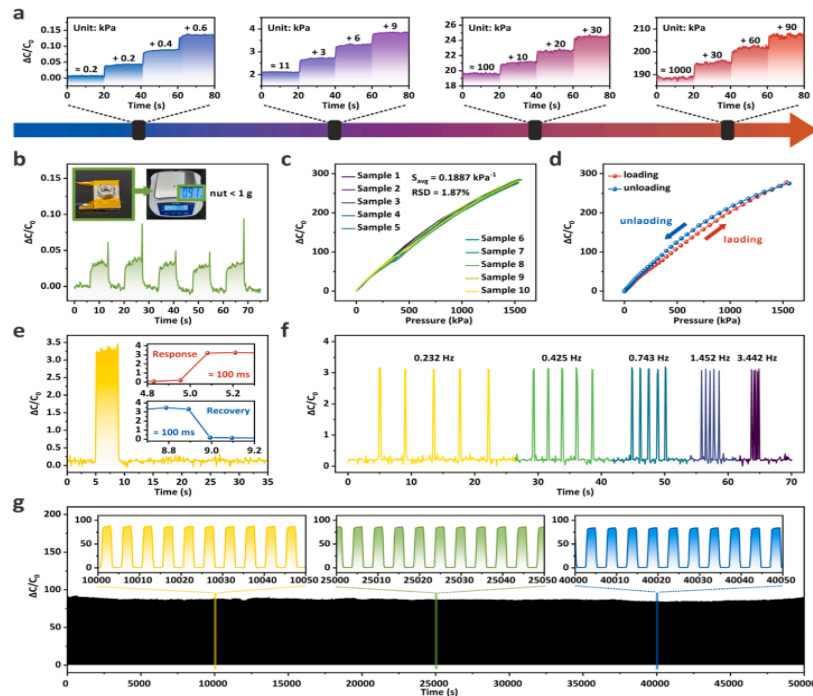


Figure 3: Performance testing of capacitive sensors [9]

As shown in Figure 3, the capacitive sensor based on the triple-gradient effects (permittivity, elastic modulus, and geometry) demonstrates remarkable sensing capabilities. It maintains high resolution across a broad pressure spectrum, as evidenced by its ability to recognize small pressure variations under different preloaded pressures (0.2 kPa, 11 kPa, 100 kPa, and 1000 kPa). When a tiny object (weighing less than 1 g) is repeatedly placed on the sensor, the consistent signal intensity indicates the sensor's capability to distinguish minute pressure changes. The sensor achieves an average sensitivity of 0.1887 kPa⁻¹ with a wide linear range of 0–1500 kPa ($R^2=0.99$) and an exceptionally low relative standard deviation of 1.87%, which underscores its excellent repeatability and reproducibility.

The sensor displays remarkable dynamic response characteristics. During continuous loading/unloading pressure tests, no significant hysteresis is observed, attributing to the excellent elasticity of the dielectric layer. The response and recovery times of the sensor are approximately 100 milliseconds under a pressure of 8 kPa. Moreover, the sensor maintains stable response signals at different frequencies (0.232–3.442 Hz), demonstrating its ability to quickly react to pressure changes at various frequencies.

The long-term stability and durability of the sensor are validated through a fatigue test involving over 10,000 cycles of periodic pressure application (350 kPa). The stable signal waveform without intensity attenuation throughout the entire duration indicates that the sensor possesses excellent durability for long-term use.

The sensor's potential applications across different pressure ranges are demonstrated. In wearable applications, it can monitor physiological signals, such as respiration and pulse, as well as daily actions like mouse clicks and keystrokes. The sensor can also detect finger bending angles, grasping actions, and foot pressure, and dynamically respond to various movements, including standing, walking, jumping, and running. These results highlight the sensor's versatility as a multifunctional monitoring station for health and motion signals.

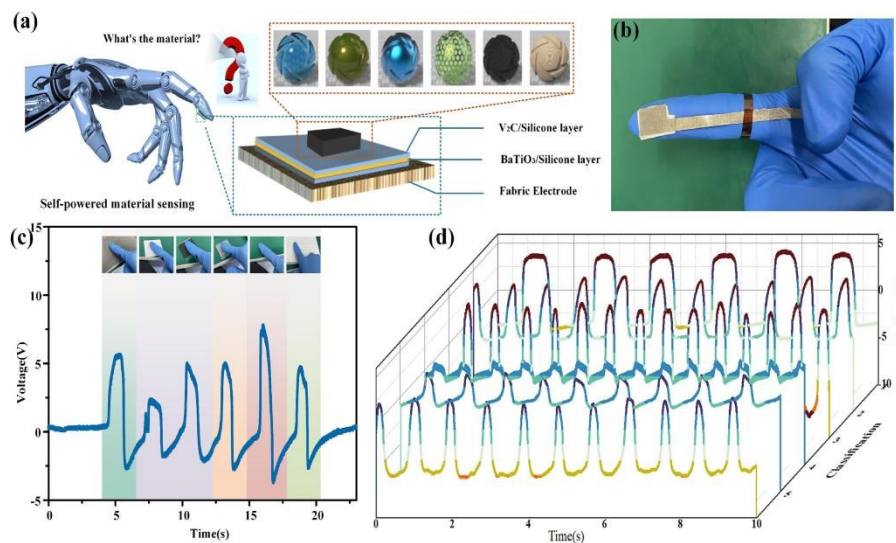


Figure 4: TENG sensors identify different materials [10]

The sensor shows the ability of identify different materials in Figure 4. A single-electrode mode TENG (S-VBV-TENG) was constructed using the VBV composite membrane to explore its functionality for self-powered object material recognition. The S-VBV-TENG consists of a flexible conductive fabric as an electrode and the VBV membrane as a stationary dielectric layer to contact objects of different materials. As different materials possess different electronegativities, contact with the VBV membrane causes the S-VBV-TENG to generate voltage signals of different magnitudes, thus enabling material recognition of the contacted object. This unique property of the VBV composite membrane allows for the development of a versatile and self-powered material recognition sensor.

To further demonstrate its practical application, a flexible material recognition sensor was fabricated by fastening the S-VBV-TENG to a fingertip. When the finger touches objects of different materials, such as kraft paper, resin, sponge, acrylic, desktop, and paper, the S-VBV-TENG generates distinct voltage response signals accordingly. This capability is attributed to the varying electronegativities of the different materials, which result in different magnitudes of voltage signals when they come into contact with the VBV membrane. The distinct voltage signals allow for the effective recognition of different materials, showcasing the potential of the S-VBV-TENG as a material recognition sensor.

Moreover, the response curves when touching different objects multiple times indicate that the flexible material recognition sensor based on S-VBV-TENG exhibits good reproducibility. This reproducibility is crucial for the reliability and accuracy of the sensor in practical applications. The consistent voltage signals generated by the S-VBV-TENG under repeated contact with the same

material demonstrate its potential for stable and accurate material recognition. This feature makes the S-VBV-TENG a promising candidate for various applications, including material identification in industrial settings, quality control processes, and human-computer interaction systems.

3. Conclusion

This study presents a bioinspired tactile sensor inspired by the structural and functional characteristics of elephant trunk bristles and follicle-sinus complexes (FSCs) to enhance robotic environmental perception. The sensor employs carbon fiber bristles for robust mechanical support and a synergistic microcrack-bristle structure to replicate the FSC's signal transduction mechanism. By integrating triboelectric nanogenerators (TENGs) with capacitive sensing layers, the sensor achieves self-powering capabilities, high sensitivity (0.1887 kPa^{-1}), and a broad linear detection range (0–1500 kPa). Its modular design enables dense distribution for precise detection of subtle tactile stimuli, while dynamic response tests confirm rapid reaction times ($\sim 100 \text{ ms}$) and exceptional durability ($>10,000$ cycles). Additionally, the sensor demonstrates material discrimination through voltage signal variations generated by contact with objects of differing electronegativities, highlighting its versatility in complex environments.

The sensor's multifunctional design holds significant potential for advancing robotic systems, particularly in environmental exploration and manipulation. Integration with Spirobs [11]—modular, reconfigurable platforms designed for adaptive locomotion—could enhance their ability to navigate unstructured terrains, perform delicate object handling, and execute real-time environmental mapping. The self-powered nature of TENGs reduces reliance on external power sources, making the sensor ideal for prolonged missions in remote or hazardous settings. Future applications may extend to healthcare (e.g., wearable physiological monitoring), industrial automation (e.g., quality control via material recognition), and human-robot collaboration (e.g., tactile feedback systems). Scalability through 3D printing and advancements in flexible electronics could enable cost-effective mass production and customization for diverse robotic platforms.

Despite its promising features, challenges remain. The fabrication process, involving multilayered materials and precise alignment, is complex and may hinder large-scale manufacturing. While carbon fiber ensures durability, its rigidity could limit adaptability in highly dynamic environments. Performance under extreme conditions, such as high humidity, temperature fluctuations, or chemical exposure—requires further validation. Signal interference between densely packed modules and the long-term stability of TENGs under continuous mechanical stress also warrant investigation. Addressing these limitations through hybrid composites, advanced signal processing algorithms, and optimized manufacturing techniques will be critical for real-world deployment.

In conclusion, this bioinspired sensor represents a significant advancement in tactile sensing technology, with transformative implications for robotics. By bridging biomechanical principles with advanced materials science, it paves the way for next-generation robots like Spirobs to achieve unprecedented environmental interaction and operational autonomy.

References

- [1] Zhang, J., Wang, B., Chen, H., Bai, J., Wu, Z., Liu, J., Peng, H., Wu, J. (2023) *Bioinspired Continuum Robots with Programmable Stiffness by Harnessing Phase Change Materials*. *Adv. Mater. Technol.*, 2201616: 1–9.
- [2] Baburaja A., Kumar S.K.N., Aliyana A.K., Banakara M., Bairagi S., Stylios G. (2023) *Factors affecting the performance of flexible triboelectric nanogenerators (F-TENGs) and their sensing capabilities: A comprehensive review*. *Nano Energy* 118, 108983. Available online 11 October 2023.
- [3] Mitchinson B., Gurney K.N., et al. (2004) *Empirically inspired simulated electro-mechanical model of the rat mystacial follicle-sinus complex*. *Proceedings of the Royal Society Series B: Biological Sciences*, 271, 2509–2516.
- [4] Deiringer, N., Schneeweiß, U., et al. (2023) *The functional anatomy of elephant trunk whiskers*. *Commun. Biol.*, 6: 591.

- [5] Zhang, Y., Liu, Q., Ren, W., Song, Y., Luo, H., Han, Y., He, L., Wu, X., Wang, Z. (2023) *Bioinspired Tactile Sensation Based on Synergistic Microcrack-Bristle Structure Design toward High Mechanical Sensitivity and Direction-Resolving Capability*. *Research*, 6: Article 0172.
- [6] Zhu M., Lou M., Abdalla I., Yu J., Li Z., Ding B. (2020) *Highly shape adaptive fiber based electronic skin for sensitive joint motion monitoring and tactile sensing*. *Nano Energy* 69, 104429.
- [7] Zhang Z., Zhang Z., Mei D., Wang Y., Wang Y. (2025) *Multifunctional flexible sensor with both contact pressure sensing and internal ultrasonic detection for robotic grasping*. *Sensors & Actuators: A. Physical* 383, 116202.
- [8] G. Zhu, et al. (2012) *Triboelectric-generator-driven pulse electrodeposition for micropatterning*, *Nano Lett.* .
- [9] Liu R., Ji B., Lei M., Hu F., Luo J., Zhou B. (2025) *Triple-gradient based dielectric layer for flexible capacitive sensor with broad sensing linearity and high sensitivity*. *Applied Materials Today* 42, 102614.
- [10] Y. Wang, H. Mu, S. He, H. Yao, S. Wang, Y. Yang, G. Zhang, (2025) *An optimized design for dielectric layer charges distribution towards high-performance output of TENG and its multifunctional applications*, *Chemical Engineering Journal*
- [11] Wang Z., Freris N.M., Wei X. (2025) *SpiRobs: Logarithmic spiral-shaped robots for versatile grasping across scales*. *Device* 3, 100646.