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Revolutionizing Robotics: Empowering Self-Sustainability with Triboelectric Nanogenerators

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Abstract

Triboelectric nanogenerators (TENGs) represent an innovative technology poised to revolutionize the field of self-powered robotic systems. These devices can efficiently convert mechanical energy into electrical energy, eliminating the need for external power sources and offering exceptional actuation, grasping, and sensing capabilities. This comprehensive review explores the extensive potential of TENG mechanisms and modes in various robotic applications. Initially, we investigate the enhanced efficiency and reliability of TENG-based actuation systems, highlighting their inherent self-powering capabilities. Subsequently, we focus on TENG-driven grippers, equipped with precise gripping capabilities and the unique ability to self-calibrate, enabling agile and accurate object manipulation.

1. Introduction

Sensing and actuation are pivotal aspects of robotic systems, enabling them to function effectively in various contexts [1]. These components work in harmony to gather data about the robot's surroundings and respond to physical movements [2]. As technology progresses, we anticipate the emergence of robots with more advanced sensing and control capabilities, empowering them to handle complex tasks in a broader range of circumstances [3]. Unlike their early counterparts confined to structured industrial environments and pre-programmed tasks, smart robots now operate in unstructured settings and interact safely with humans.

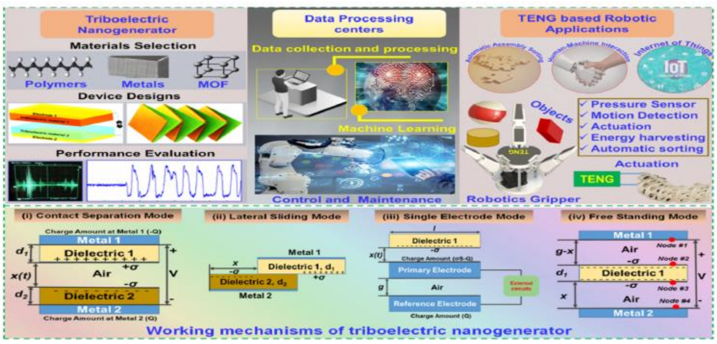

Fig. 1. : Illustration of Triboelectric nanogenerator-based robotics applications and working mechanism of triboelectric nanogenerators.

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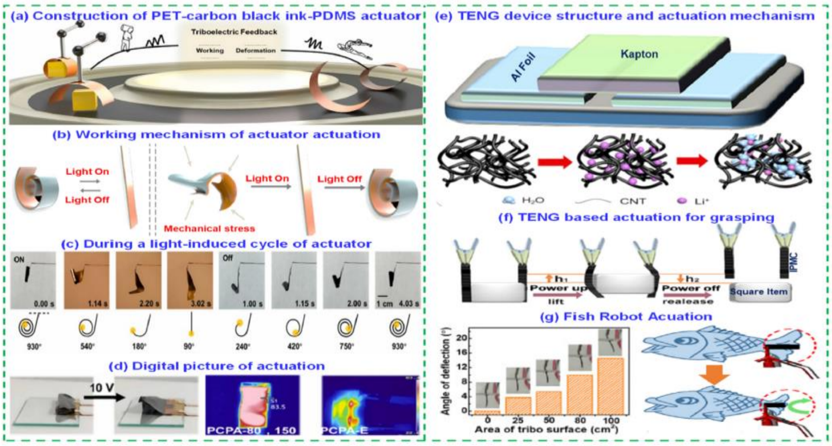

Fig. 2. : (a) Schematic of the contact feedback of the PET-carbon black ink-PDMS (PCPA) actuator; (b) Schematic illustration of the actuation of the PCPA actuator induced by the light, as well as the shape memory of the PCPA actuator; (c) Photographs of the PCPA-150 in different states during a light-induced cycle; (d) Digital image of actuation of PCPA. Reprinted from. (e) Device design and on-intercalation induced actuation mechanism of Ionic polymer-metal composites (IPMC); (f) Schematic of operation diagram of TENG drive IPMC to clamp the object and (g) actuation and angle of detection measured by TENG driving IPMC at fishtail (a) [86] with permission from Elsevier, Copyright © 2022, Elsevier; (b) Reprinted from [89] with permission from Elsevier, Copyright © 2019, Elsevier.

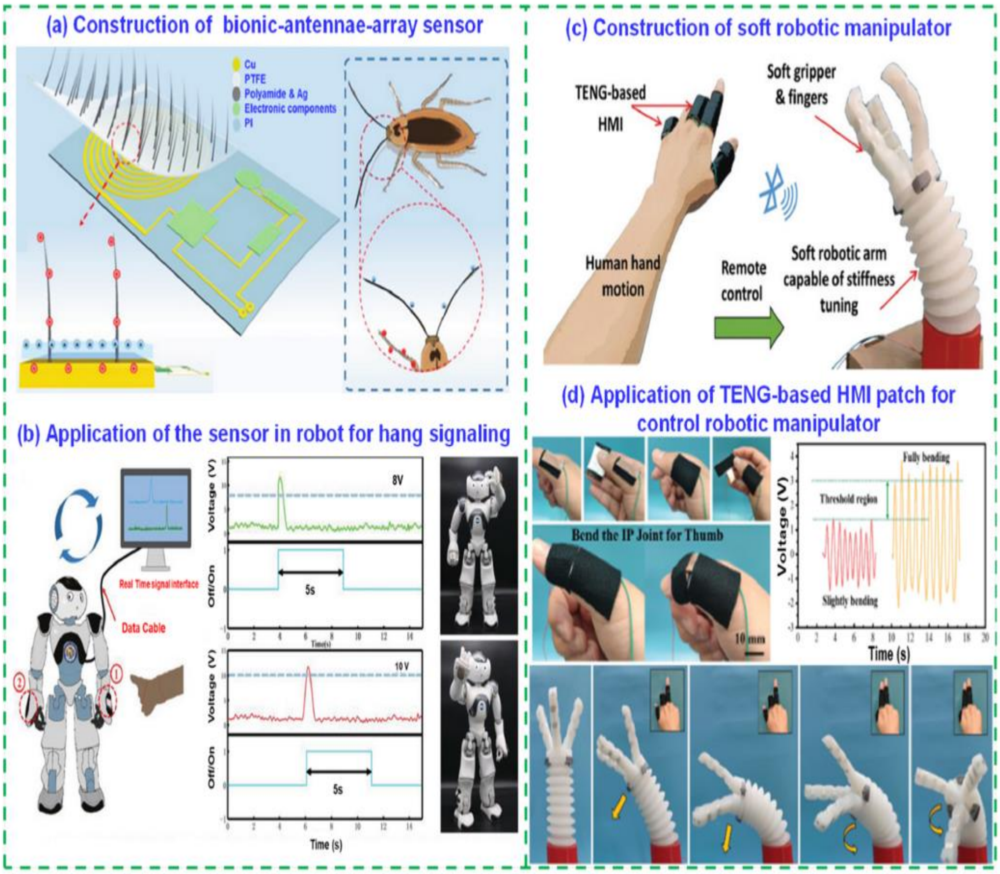

Fig. 3. : (a) Basic structure scheme of the bionic-antennae-array (BAA) sensor, Charge distribution on the BAA sensor, Schematic diagram of a cockroach, and charge distribution; (b) Application of the BAA sensor in robot for avoiding human hand. The output voltage and corresponding digital signals of 1# arm and 2# arm and their action images. (c) Schematic illustration of the soft robotic manipulator system under the remote control of human–machine interface (HMI) and (d) design and characterization of the self-powered HMI for remote operations

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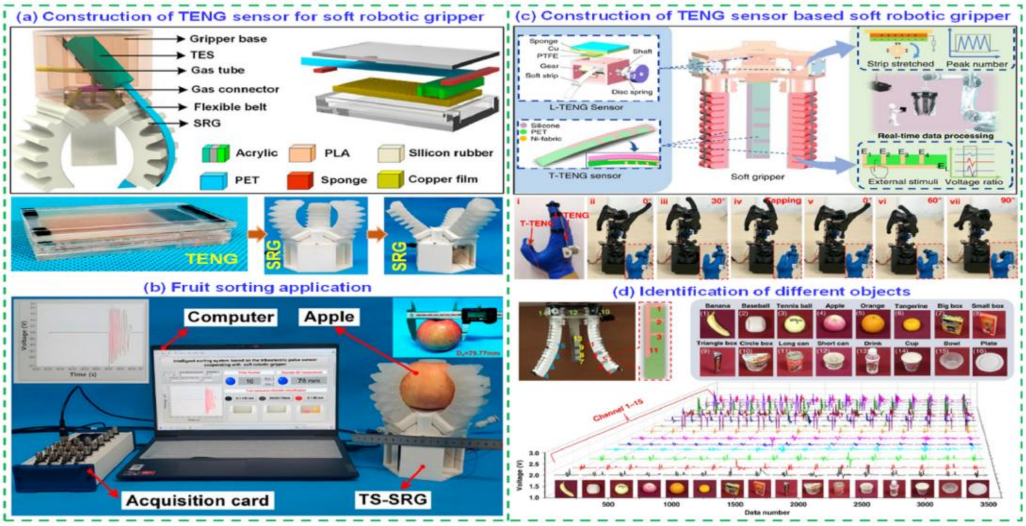

Fig. 4. : Fig. 4: (a) Structural design and fabrication of the Triboelectric sensor-based soft robotic gripper (TS-SRG): schematic structure of the TS-SRG, schematic structure of the TES, photographs of the TS-SRG prototype, and photographs of the TES prototype; (b) Digital image of the non-destructive system. (c) The as-fabricated TENG sensors and their basic structures: The length TENG (L-TENG) sensor and the tactile TENG (T-TENG) sensor, The soft gripper integrated with the TENG sensors, The intelligent sensory data processing strategies. E1 to E4 and EL represent the electrodes in the T-TENG sensor, and (d) The channel arrangement of integrated sensors for collecting data, 16 objects to be gripped and recognized, and 3D plots of the robotic sensor outputs corresponding to different objects. Reprinted from [104], Copyright © 2022 American Chemical Society. Reprinted from [110] 4.0 International (CC BY 4.0).

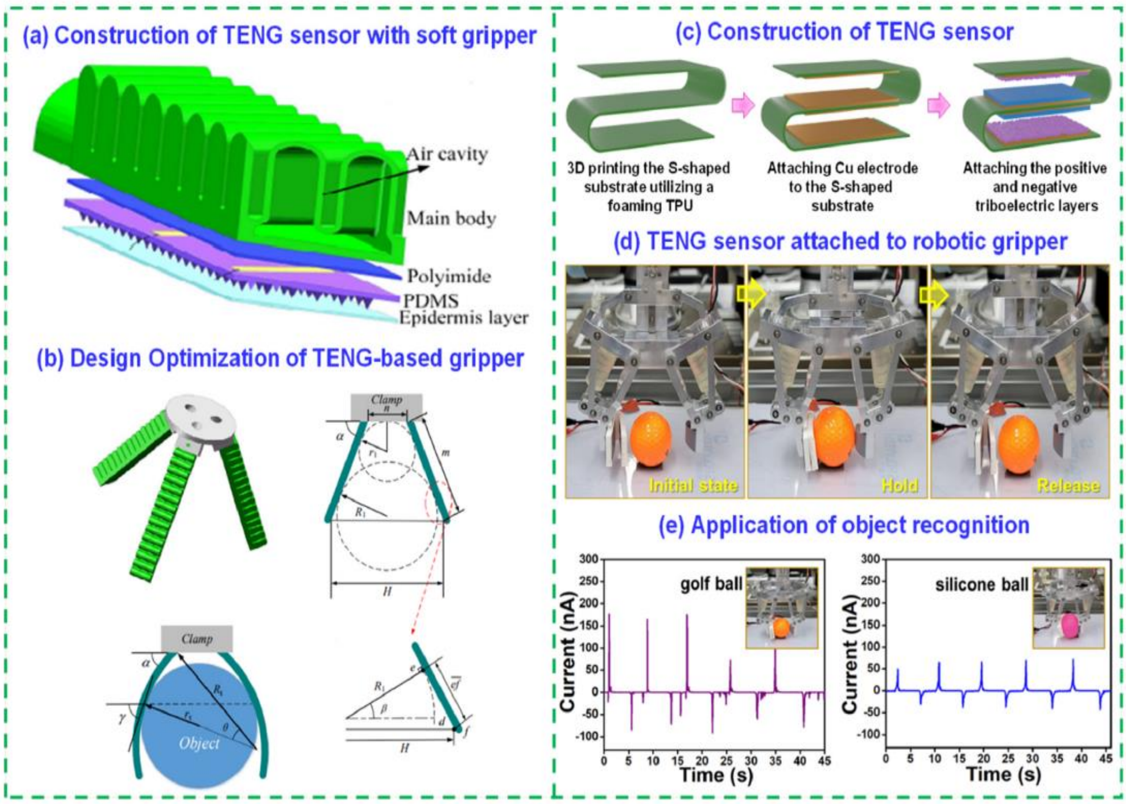

Fig. 5. : (a) The structure of the soft gripper integrated with a TENG-based tactile sensor; (b) the size analysis of the object by soft fingers grasping device; (c) Construction of the TENG sensor step-by-step; (d) digital image of the TENG based robotic gripper and (e) voltage output of the TENG while grabbing and release of ball of different shapes.

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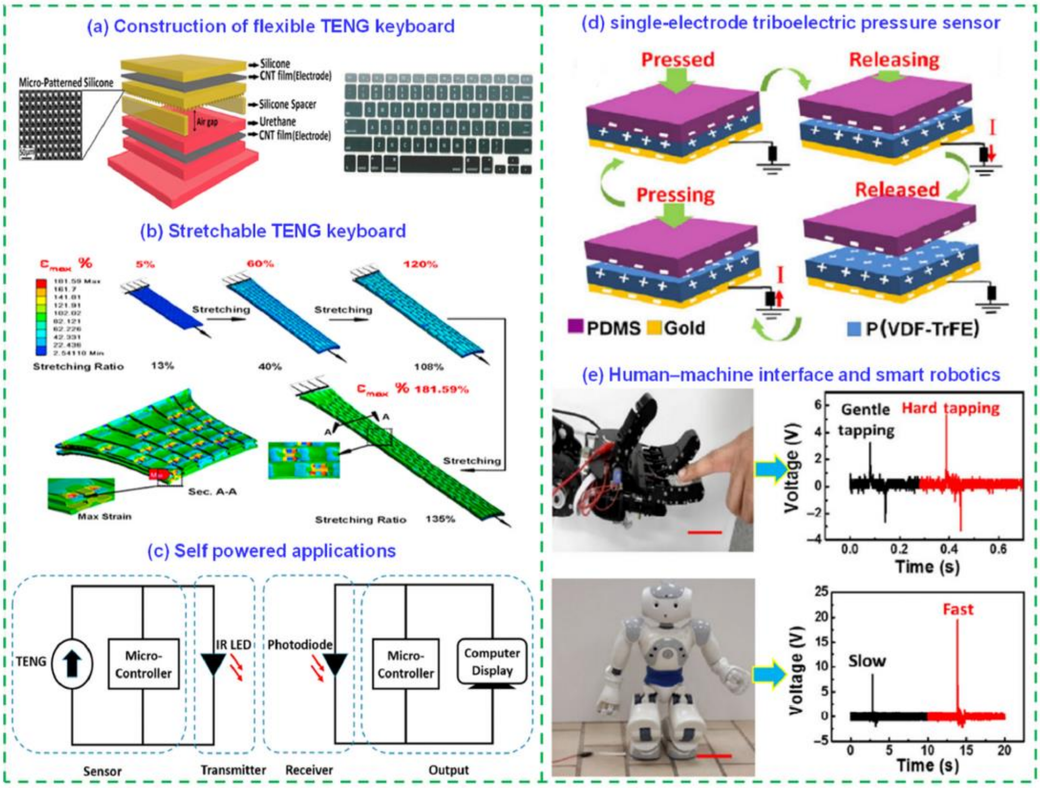

Fig. 6. : (a) Structural design of the flexible TENG keyboard, SEM image of the micro-patterned silicone, and as-fabricated keyboard; (b) Maximum principal strain distribution computed by FEM simulation for the Keyboard mesh after applying the displacement; (c) A schematic circuit diagram of the self-powered wireless sensing system enabled by the keyboard typing;
(d) Working mechanism single-electrode based pressure sensor and (e) applications towards HMI and smart robotics.

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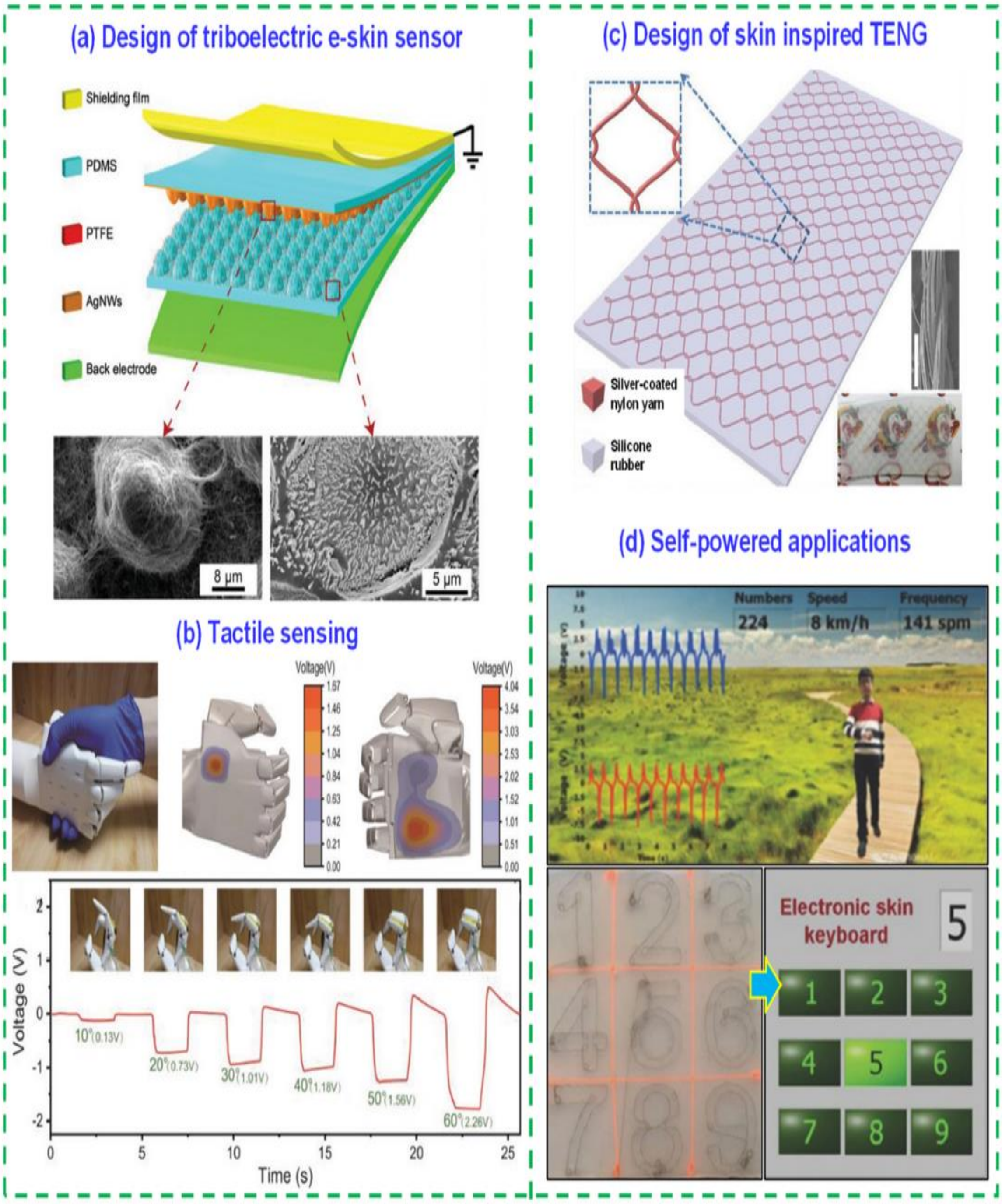

Fig. 7. a) Schematic diagram of the TENG e-skin sensor structure, micromorphology of silver nanowires sprayed on PDMS pillar, SEM image of the PTFE tiny burrs on PDMS surface; (b) Tactile sensing of the triboelectric sensor through integration on a bionic hand, photographs of human–robot handshaking, the voltage contour profiles on the back and palm of the bionic hand during handshaking, real-time voltage signals in response to index finger gestures with different bending angles (c) Schematic illustration of the SI-TENG with "chain-link" fence-shaped structure and rhombic unit design, a basic repeated rhombic unit of the conductive yarn network is enlarged in its top left, an SEM image of the surface morphology of the three-ply-twisted silver-coated nylon yarn is presented on the right; (d) Applications of the SI-TENG-based pressure sensor in a self-powered pedometer/speedometer, and a flexible digital keyboard, software output interface of the self-powered pedometer and speedometer, photograph of a flexible digital keyboard with nine key buttons, digital display interface for the self-powered digital keyboard.

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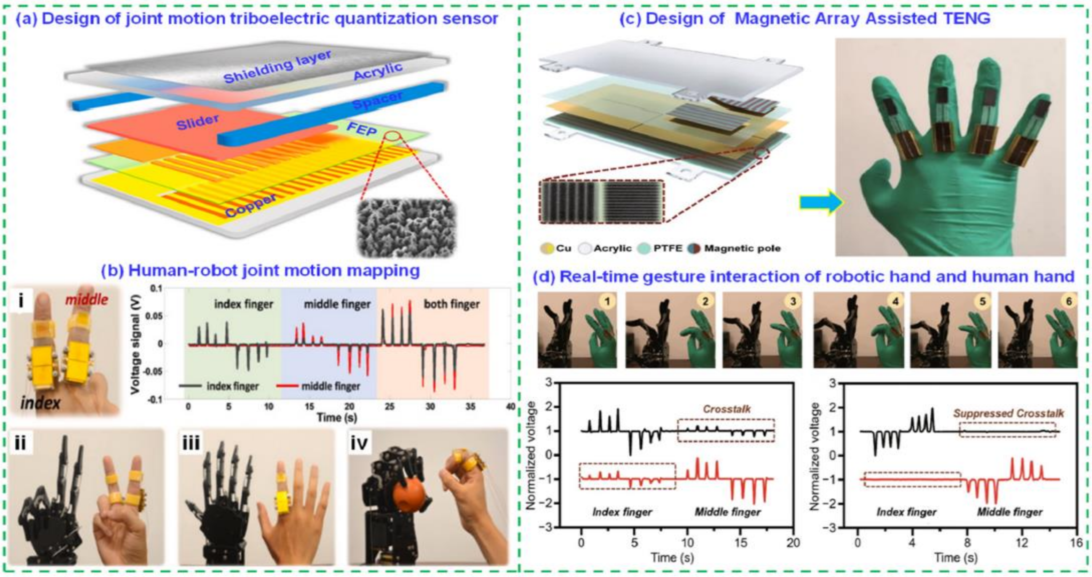

Fig. 8. **:** (a) Multilayer structure of the jmTQS; an SEM image of FEP nanowires. (b) Human-robot joint motion mapping via jmTQS and its application; the control signals from jmTQSs worn on the index finger and the middle finger; counting the pulse number in unit time and signing the positive/negative peak can accurately detect the flexion-extension degree/speed of each finger; (ii) an example of performing the victory v-sign with two fingers. (iii) and (iv) demonstrate grasping one object via a single-finger control signal with certain programming.
(c) Schematic diagram and multilayer structure of the Ma-s-TS; the Ma-s-TS worn on the fingers; (d) Real-time gesture interaction of robotic hand and human hand based on the signal, comparison with jmTQS on cross-talk between channels (d jmTQS, e Ma-s-TS).
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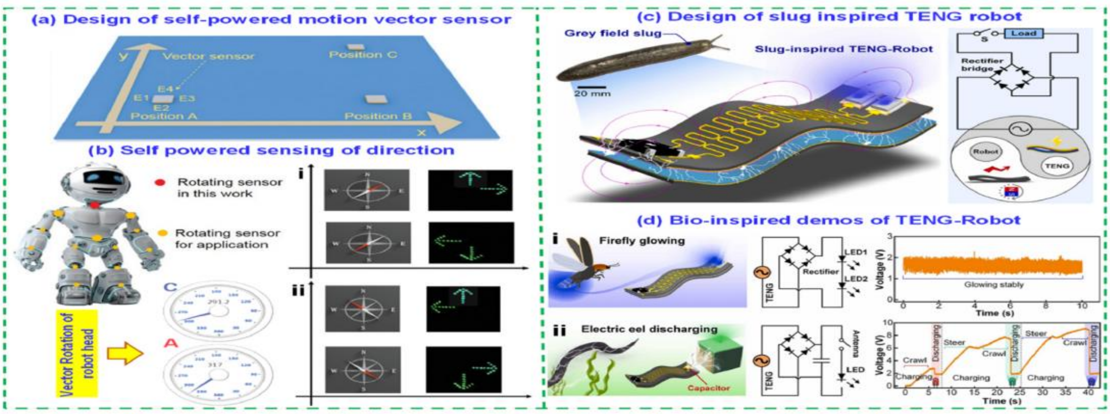

Fig. 9. **:** (a) Schematic to describe the displacement of the self-powered motion vector sensor in a plane; (b) proposed concept of rotary TVS as a rotary joint for monitoring the rotary motion of the robot, as a rotary joint for monitoring the rotary motion of the robot. (i) image of T-TVS moving in NE and WS direction, (ii) image of T-TVS moving in WN and SE direction. c) Schematic illustration of the Slug-inspired TENG-Robot. (d-i) Bio-inspired demos of TENG-Robot inspired by firefly, a self-glowing TENG-Robot was designed to light its eyes; circuit diagram of self-glowing TENG-Robot; the triboelectric voltage waveform of TENG-Robot after bridge rectifier during the crawling and self-glowing. (d-ii) Inspired by an electric eel, a self-powered TENG-Robot was designed to charge external electric devices; circuit diagram of self-powered TENG-Robot for charging the external loads; the triboelectric voltage waveform of TENG-Robot after bridge rectifier during the locomotion for charging and discharging.
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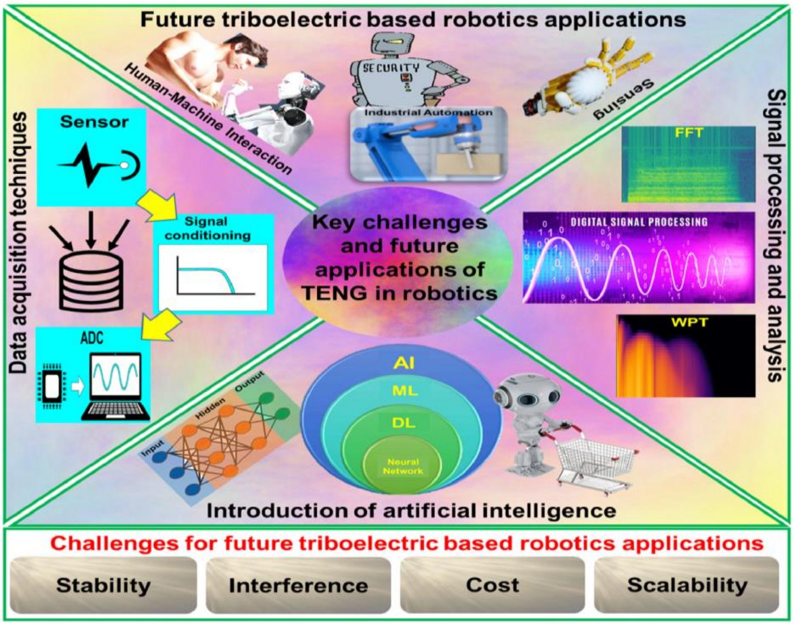

Fig. 10. : Challenges and future solutions for applications of triboelectric nanogenerators in robotics.

6. Conclusions

Triboelectric nanogenerators (TENGs) are an exciting area of research with the potential to revolutionize robotics by significantly enhancing their actuation, gripping, and sensing capabilities. TENGs offer a plethora of advantages, such as their lightweight nature, flexibility, and seamless integrability into various materials. These characteristics make them an exceptionally promising choice for integration into robotic systems and components, opening up new horizons for advanced robotic applications.

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