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Research Progress and Prospect of Piezoelectric-Driven Microrobots

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Abstract. Piezoelectric-driven microrobots have become a frontier direction in micro-electromechanical systems (MEMS) and intelligent robotics due to their high precision, fast response, compact structure, low power consumption, and immunity to electromagnetic interference. Based on a series of robotic researches including bionic robots, soft piezoelectric robots, pipeline robots, climbing robots, tactile sensing robots, energy harvesting materials, biomedical robots, and path planning algorithms, this paper systematically summarizes the actuation principle, material systems, structural design, motion modes, and typical applications of piezoelectric microrobots. The development status of soft high-speed robots, pipeline crawling robots, climbing robots, quadruped robots, dual-mode robots, tactile imaging robots, and biomedical robots is reviewed in detail. The key bottlenecks of endurance, load capacity, motion stability, and integration are analyzed. Finally, the development trends including full-flexible integration, multi-modal motion, self-powered energy harvesting, tactile perception, and biomedical applications are prospected. This review aims to provide a rigorous and comprehensive reference for the design and optimization of piezoelectric microrobots.

Keywords: Piezoelectric drive, Microrobot, Soft robot, Bionic structure, Pipeline robot, Tactile sensing

1. Introduction

With the development of micro-electro-mechanical system (MEMS) technology, microrobots generate broad application demands, such as micro-nano operation, narrow space detection, pipeline inspection and biomedical treatment. Traditional electromagnetic drive meets the problems of large volume and low torque density in centimeter-scale and millimeter-scale robots. Piezoelectric drive can directly convert electrical energy into mechanical deformation, and has advantages of high-power density, sub-micron positioning accuracy and fast response, which is an ideal driving scheme for microrobots [1].

In recent years, with the breakthrough of new piezoelectric materials such as perovskite ceramics, halide perovskites, flexible PVDF-based polymers, and natural biomaterials, as well as the innovation of bionic design, micro-nano manufacturing, sensing integration, and energy harvesting technologies, piezoelectric microrobots have developed rapidly from single rigid drive to flexible bionic, multi-modal motion, and perception-drive integration. A variety of piezoelectric microrobots

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with different motion modes have been developed, but there are still challenges in wireless energy supply, complex environment adaptability, system integration, and large-scale preparation. Based on the latest research progress at home and abroad, this paper systematically reviews the research progress of piezoelectric-driven microrobots from the aspects of driving principle, material system, robot design, sensing and energy harvesting applications, technical bottlenecks, and development trends, so as to provide reference for the design optimization and engineering application of high-performance piezoelectric microrobots [1].

2. Piezoelectric drive principle and typical materials

2.1. Working principle

Piezoelectric actuation relies on the converse piezoelectric effect: an applied electric field causes lattice deformation inside the material, and micro-deformation is transformed into macroscopic motion through structural amplification, friction coupling, or resonance enhancement [2]. Common motion mechanisms include stick-slip actuation, inertial actuation, resonant actuation, and bionic cooperative actuation [3]. Stick-slip actuation uses the difference between static and dynamic friction to realize high-precision stepping motion, which is widely used in pipeline robots and positioning platforms. Resonant actuation amplifies amplitude at resonance frequency for high-speed movement and flapping-wing flight [4].

2.2. Typical piezoelectric material

Piezoelectric materials can be divided into three categories [5]:

1.Inorganic piezoelectric materials: PZT, BTO, and polycrystalline diamond films, with high piezoelectric coefficient, high output force, and high-temperature stability [6].

2.Flexible piezoelectric polymers: PVDF, P(VDF TrFE), and MFC films, with light weight, flexibility, and good biocompatibility, widely used in soft robots and pipeline robots [2].

3.Natural biomaterials: amino acids, collagen, chitin, with good biocompatibility and degradability, suitable for biomedical robots [7].

3. Typical piezoelectric-driven microrobots

Piezoelectric actuation has been widely used in microrobot systems because of its fast response, high precision, simple structure, and easy miniaturization. Combined with the latest research, typical piezoelectric microrobots are classified into soft biomimetic high-speed robots, micro in-pipe robots, rod-climbing robots, multi-legged robots, crawling-jumping dual-mode robots, piezoelectric tactile imaging robots, piezoelectric medical microrobots, and autonomous resonant microrobots. Their structures, principles, and performances are summarized below.

3.1. Soft bionic fast-moving piezoelectric robots

Soft piezoelectric robot features lightweight, flexibility, and impact resistance, ideal for unstructured environments. Chen et al. proposed a cheetah-inspired soft piezoelectric robot capable of high-speed movement and self-recovery after overturning [2]. Using a PVDF piezoelectric actuator and a symmetric double-helix structure, the robot is only 10 mm long and weighs 0.058 g. At resonant frequency, it achieves a speed of 42.8 body lengths per second, with a maximum turning speed of 482°/s. Benefiting from the centrosymmetric structure, it can still move at 16 body lengths per

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second after overturning, greatly improving terrain adaptability [2]. It can climb slopes, carry 8 times its own weight, and perform temperature sensing, representing the development trend of high speed and high adaptability.

3.2. Micro in-pipe piezoelectric robots

Pipeline inspection is one of the most important applications. Jiang designed an MFC-based piezoelectric in-pipe robot for 15–20 mm narrow pipes [3]. With a composite structure of supporting and driving feet, the robot weighs 3.89 g and is 50 mm long. It moves stably in horizontal, vertical, and curved pipes at a maximum speed of 13.54 mm/s and can carry 9 times its weight. It is suitable for nuclear, medical, and industrial pipeline inspection [3]. Ning established a dynamic model of stick-slip actuation and analyzed the effects of voltage, frequency, and friction, providing a theoretical basis for high-precision motion [8].

3.3. Flexible piezoelectric rod-climbing robots

Hao developed a flexible piezoelectric rod-climbing robot with a weight of only 82 mg [9]. Using piezoelectric actuators and bionic footpads, it climbs stably on slender rods at a maximum speed of 120 mm/s. Based on asymmetric friction and impact motion, it adapts to different rod diameters. It is small, quiet, and electromagnetic-interference-free, suitable for inspection of towers, pipes, and cables [9].

3.4. Multi-legged and modular piezoelectric crawling robots

Crawling is the most mature motion mode of piezoelectric microrobots. Luo et al. pointed out in the review of micro-bionic robots that piezoelectric drive is a core solution for centimeter-scale insect-like robots, represented by Harvard HAMR series hexapod crawling robots, which have high speed, strong obstacle-surmounting ability, and can walk on water [1]. Li designed a quadruped piezoelectric mobile robot based on inertial actuation, using a double piezoelectric wafer driving structure to achieve stable movement with small step and high precision, which is suitable for precision operation and micro-assembly scenarios [10]. Jia proposed a modular piezoelectric-driven multi-legged micro-crawling robot, which improves the adaptability and stability of the robot on different grounds through replaceable foot modules and parallel driving structure, realizing flexible straight and steering movement [11].

3.5. Crawling-jumping dual-mode piezoelectric robots

To improve obstacle-surmounting ability, researchers combined crawling and jumping to form dual-mode robots. Cao developed a centimeter-scale crawling-jumping dual-mode robot driven by piezoelectric actuators [12]. The robot uses piezoelectric vibration to realize high-speed crawling and stores elastic energy through the structure to complete explosive jumping. It combines the flexibility of crawling and the high obstacle-surmounting ability of jumping, and can perform detection tasks in complex environments such as ruins and rugged terrain, expanding the operating range of microrobots [12].

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3.6. Piezoelectric tactile imaging robots

Piezoelectric materials have both driving and sensing functions to realize perception-actuation integration. Kolesar et al. realized object imaging through a piezoelectric polymer tactile sensor array [13]. The robot obtains surface morphology, hardness, and texture information through contact, and completes tactile imaging without visual signals, which improves the intelligence of micro-operation. This technology can be combined with piezoelectric mobile robots to realize fully autonomous operation of "moving, touching, and recognizing" [13].

3.7. Piezoelectric biomedical targeted microrobots

Piezoelectric effect shows unique value in biomedical microrobots. Ji et al. developed an oral bionic piezoelectric nanorobot for targeted therapy of colorectal cancer [7]. Under ultrasound excitation, the piezoelectric material generates catalytic reactions to kill tumor cells and activate the immune system. The robot uses biological targeting to enrich in the tumor area, with high treatment efficiency, good biocompatibility, and low side effects. This research represents an important leap of piezoelectric robots from motion execution to diagnosis-treatment integration [7].

3.8.Autonomous resonant piezoelectric microrobots

Miniaturization and integration are important trends to realize cable-free autonomous movement. Robles-Cuenca et al. developed a miniature autonomous robot based on in-plane piezoelectric resonators [4]. The robot integrates piezoelectric drive, on-board power supply, and control circuit, and realizes high-efficiency movement through resonant drive. It can move autonomously and stably without external cables, providing a feasible solution for environmental detection and closed-space operations [4].

4. Technical problems and future trends

Although piezoelectric-driven microrobots have achieved rapid development, they still face problems such as short endurance, insufficient load capacity, poor motion stability in complex environments, and low system integration. In the future piezoelectric microrobots will develop toward full-flexible structure, multi-modal cross-medium motion, wireless autonomous control, self-powered energy harvesting, high-performance new piezoelectric materials, and biomedical diagnosis and treatment integration.

5. Conclusion

Piezoelectric drive provides an effective scheme for the miniaturization, high precision and flexibility of microrobots. With the innovation of materials, structures and integration technologies, piezoelectric microrobots have been widely studied in crawling, pipeline, flying, medical and other fields. Breaking through energy, load and stability bottlenecks and developing intelligent and integrated systems will further promote the engineering application of piezoelectric-driven microrobots.

References

[1] Z. Luo, Y. Hong, T. Jiang, Z. Lin, Y. Yang, Q. Zhu, Review of micro-bionic robots. J. Mech. Eng. 61, 178 (2025).

DOI: 10.54254/2755-2721/2026.33738

[2] E. Chen, Y. Yang, M. Li, B. Li, G. Liu, W. Mu, R. Yin, Bio-mimic, fast-moving, and flippable soft piezoelectric robots. Adv. Sci. 10, 2300673 (2023).
[3] Y. Jiang, C. Li, Design and experimental research of piezoelectric-driven micro pipeline crawling robot. Jiangsu Univ. Sci. Technol. (2024).
[4] D. Robles-Cuenca, M. R. Ramírez-Palma, V. Ruiz-Díez, J. Hernando-García, J. L. Sánchez-Rojas, Miniature autonomous robot based on legged in-plane piezoelectric resonators. Micromachines 13, 1815 (2022).
[5] Y. Luo, B. Wang, J. Jing, Piezoelectric effect in polycrystalline diamond membranes. Sci. Adv. 12, eaea8318 (2026).
[6] L. Persano, A. Camposeo, F. Matino, Advanced materials for energy harvesting and soft robotics. Adv. Mater. 36, 2405363 (2024).
[7] X. Ji, Y. Fan, J. Ye, Y. Kang, X. Chen, X. Zhang, X. Wang, Biomimetic piezoelectric nanomaterial-modified oral microrobots for targeted catalytic and immunotherapy of colorectal cancer. Sci. Adv. 10, eadm9561 (2024).
[8] C. Ning, Y. Jiang, C. Li, Driving mechanism and dynamic characteristics of piezoelectric inertial robot for micro-pipeline operation. J. Micromech. Microeng. 33, 085001 (2023).
[9] P. Hao, Design and manufacturing of a flexible micro climbing robot based on piezoelectric drive. J. Mech. Eng. 58, 1 (2023).
[10] Y. Li, X. Liu, Y. Zhang, A quadruped piezoelectric mobile robot based on inertial actuation. Micromachines 11, 321 (2020).
[11] H. Jia, Z. Wang, Y. Li, Modular piezoelectric-driven multi-legged micro-crawling robot. IEEE Access 8, 156789 (2020).
[12] L. Cao, J. Qin, J. Liu, Centimeter-scale microrobot with crawling and jumping dual-mode motion. Extrem. Mech. Lett. 21, 9 (2018).
[13] E. S. Kolesar, T. J. Reston, S. L. Ford, J. R. Fitch, Object imaging with a multiplexed piezoelectric polymer tactile sensor. IEEE Trans. Robot. Autom. 8, 490 (1992).