Actuation Technologies for Bio-inspired Microrobots

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Abstract. Bio-inspired microrobots have a bright future for application in many fields, such as biomedical, industrial, and environmental fields. Actuators are critical components that define the performance of robots. This paper systematically reviews the driving mechanisms for bio-inspired microrobots, including electromagnetic, piezoelectric, optical, thermal, chemical, and biological actuation. Fundamentals of actuation technology for bio-inspired microrobots, research status of actuation technology for bio-inspired microrobots, and challenges and future prospects are summarized in the main body of this paper. However, the driving technology of microrobots still has many difficulties. Various actuation technologies have their own advantages and limitations. There are several future directions for this topic, including low-power drive circuit, multi-field hybrid actuation, and autonomy. This study provides a foundational framework of actuation technologies for bio-inspired microrobots and aims to give a practical guidance for future researches.

Keywords: Bio-Inspired Microrobots, Actuation Technology, Actuation Mechanisms.

1 Introduction

The research on micro-bio-inspired robots can be traced back to Richard Feynman's famous speech “There's Plenty of Room at the Bottom” in 1959. Nowadays, this science-fiction vision is gradually becoming a reality, as bio-inspired microrobots are widely applied and showing its bright application future in fields such as biomedicine and environmental monitoring.

The application of micro bio-inspired robots is inseparable from the development of their various components, and actuation technology is a crucial aspect among them. Over the past two decades, significant progress has been made in the research on actuation technologies for bio-inspired microrobots. Depending on the driving method, researchers have primarily explored some technical routes. One is based on chemical reactions. Another is based on external physical fields such as electric, magnetic, and optical fields. The other is smart materials actuation, such as shape memory alloy actuation [1].

In the field of electromagnetic actuation, compared to other actuation methods, magnetic fields exhibit excellent biocompatibility, tissue penetration capability, and strong adaptability to complex environments. They enable remote and precise manipulation of microrobots without the need for onboard power sources [2].

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In the field of optical actuation, light, as a rich, powerful, and multifunctional energy source, provides a high spatiotemporal resolution control method. In scenarios requiring extremely high spatial precision, such as in vitro diagnostics and single-cell analysis, optical actuation is an ideal choice [3].

In the field of thermal actuation, shape memory alloy (SMA) actuators have advantages such as simple structure, noiseless operation, high power density, and good biocompatibility, making them particularly suitable for micro-robot systems that demand compactness and flexibility in movement. It shows broad application prospects in cutting-edge fields like minimally invasive surgery, targeted drug delivery, and narrow space exploration [4].

However, the actuation technology of microrobots still faces many challenges. Various actuation technologies have their own advantages and limitations.

Electromagnetic actuation is easy to achieve fast movement, but its structure is complex and susceptible to electromagnetic interference. Piezoelectric actuation has high precision and fast response, but faces the contradiction between balancing load capacity and flexible motion. Shape memory alloy actuation in thermal actuation has simple structure, with high energy density, but it has weaknesses such as low response speed and inherent nonlinear hysteresis [1]. In addition, low energy conversion efficiency limits the development of actuation technology. Traditional batteries are difficult to integrate when robots become smaller, which will lead to bad energy storage [5].

Based on the rapid development and challenges of bio-inspired microrobots, this study will systematically discuss the actuation technology for bio-inspired microrobots and aims to provide ideas for future researches in this field. The arrangement of this paper is as follows. The second section describes the working mechanisms and characteristics of six actuation technologies for bio-inspired microrobots. The third section summarizes the current research status of six actuation technologies. The fourth section summarizes the challenges and future prospects for the actuation technology for bio-inspired microrobots.

2 Fundamentals of actuation technologies for bio-inspired microrobots

Actuation system is a core component of bio-inspired microrobots. It functions as the muscular system of robots, converting various forms of energy into mechanical motion. However, when robots are miniaturized to the millimeter or even micrometer scale, they operate in a fundamentally distinct physical environment, where surface forces dominate over volume forces. Furthermore, in fluidic environments, viscous effects prevail over the inertial effects. In this environment, objects encounter high drag, and their motion patterns are altered accordingly. Consequently, traditional actuation methods often reduce efficiency or even become infeasible.

Leveraging advances across multiple subjects, researchers have developed a variety of actuation technologies suitable for bio-inspired microrobots in recent decades. Based on energy sources and conversion mechanisms, these actuation technologies are categorized into six types in this study, including electromagnetic actuation, piezoelectric actuation, optical actuation, thermal actuation, chemical actuation, and biological actuation.

2.1 Electromagnetic actuation

Electromagnetic actuation is a method of producing force by the interaction of magnetic fields and magnetic materials. According to electromagnetic theory, a coil of current will generate a magnetic field with a force and a torque acting on a magnetic object to propel the object.

There are three major types of magnetic control systems of microrobots. Stationary electromagnet systems feature fixed coils with programmable currents. It is very precise and responsive but also suffers drawbacks like coil heating and workspaces. Permanent magnet systems utilize permanent magnets. It can generate strong fields without power supply, but it lacks flexibility. The third one is the mobile electromagnet system. The coil of the mobile electromagnet system is mounted on a mobile platform. This system integrates the ease of control of the electromagnet with the big working space of the permanent magnet, although it is very complex and expensive [2].

Common configurations of coils include Helmholtz coils to create uniform fields and Maxwell coils to create uniform gradient fields. These types of coils can be incorporated into electromagnetic systems to allow the movement of microrobots in three dimensions with precise control.

There are a few important benefits for electromagnetic actuation in low-frequency magnetic fields. They do not cause harm to any biological tissues, can enter deep into biological tissues, and are controlled wirelessly by modulating input current. But this actuation approach is frequently complex in structure and is vulnerable to electromagnetic noise.

2.2 Piezoelectric actuation

Piezoelectric actuation uses the principle of the inverse piezoelectric effect, where some materials deform when they are exposed to an electric field. It finds application in micro-robotics to convert electrical energy into very small mechanical strains, and then to convert them into macroscopic motion by special structures, including flexible hinges or ultrasonic resonators.This approach has high precision, fast response, high energy density, and is immune to electromagnetic interference. Therefore, it is appropriate in operations where space is limited or complex [6].

A core challenge in this discipline is doing away with a tethered power supply. This would allow robots to achieve unrestricted operation, though it involves the creation of a miniaturized boost converter to bridge the gap between the low voltage of typical batteries and the high voltage needed by piezoelectric components.

2.3 Optical actuation

The capability of optical-actuated microrobots to work out complex tasks at the micro-level has recently made the topic of optical-actuated microrobots a hot spot in research. They show good prospects in biomedicine and the environment. Light, as a renewable energy, is beneficial because it has the advantage of being highly resolved, being simple and noncontact. However, its conversion efficiency is generally low and the conventional optical actuation mechanisms usually find it difficult to penetrate biological tissues [3].

Mechanical energy is produced from optical energy via optical actuation in three primary ways. Optical radiation pressure uses photon momentum to physically propel micro-objects through forces of gradient and scattering. Photothermal mechanism is based on the absorption of light by matter to produce local heat, which can propel objects by processes such as thermal swimming or the formation of bubbles. Such a variety of strategies enables the exact control of microrobots in different settings [3].

2.4 Thermal actuation

Thermal actuation relies on temperature changes to cause changes in volume or phase state of a material, therefore generating driving forces. There are many ways that can generate heat, including on-board chemical fuel, resistive heating, and photothermal conversion.

Popular thermal actuation methods are the thermal expansion effect and the shape memory effect. In the case of the thermal expansion effect, the two materials used in a bilayer structure do not expand or contract at the same rate in response to changes in temperature because their thermal expansion coefficients do not match. The resulting internal stresses due to this differential deformation will cause the structure to bend and provide mechanical motion. In the case of shape memory, shape memory alloys or polymers retrieve their original shape after heating above the phase transition temperature, producing recovery force and displacement [4].

The features of thermal actuation are that it has a simple construction and high driving force. However, its responsiveness is slow, and thermal management is a primary challenge in designs of miniature dimensions.

2.5 Chemical actuation

Chemical actuation takes advantage of products formed as a result of chemical reaction to drive the motion of microrobots. It is mainly applicable to microscale liquid environments.

Depending on the kind of reaction products, there are four categories of chemical actuation. Bubble propulsion is founded on catalytic reactions that generate bubbles at the back of the microrobot, and the resulting recoil force moves the robot forward. Concentration gradient propulsion is based on the principle of producing neutral solutes that generate a concentration gradient around the surface of microrobots, causing movement by the effect of diffusiophoresis. Unilateral charge separation is achieved by reactions on one side only. The diffusion of charged products froms an electric field that exerts electrostatic force on the side. Bilateral charge separation, by contrast, involves reactions on both sides, with high-concentration ions diffusing toward the opposite side and creating a bilateral electric field, which drives the microrobot [7]. Basically, the core concept of the chemical actuation process is to cause asymmetric catalytic physicochemical reactions on the microrobot to produce imbalanced forces and cause motion.

The main benefit of chemical actuation is that it is autonomous and tunable. It does not require any external energy or complex structures, and it can move spontaneously and freely at the microscale and nanoscale through surface catalytic reactions. In addition, it is possible to precisely control the speed, direction and functionality of the microrobot through the choice of catalysts and reactants, which makes the implementation of the robots in biomedical applications, where access to external power is challenging, especially feasible [7]. However, chemical-actuated microrobots have a limited operational lifespan. Microrobots cannot carry large amounts of fuel. When the fuel is exhausted, propulsion stops. Meanwhile, continuous exposure to reactive chemicals can corrode robots and some types of fuel are toxic to living organisms.

2.6 Biological actuation

In the case of biological actuation, the motion of biological objects is used to propel robots. Common techniques utilize the directional movement of bacteria, the phototactic response of algae, and the contractile force of myocardial cells. By integrating living cells into the structure of the robot, the reaction of microorganisms to external stimuli can be exploited to generate controllable robotic movement [8].

At smaller scales, such as micro- or millimeter scale, traditional actuators face challenges including increased manufacturing difficulty, decreased power density, and low energy efficiency. On the contrary, biological-actuated robots have the properties of biological tissue. Biological actuation has the benefits of flexability, the ability to heal itself, and multi-degree-of-freedom movement. However, control precision and stability are the main issues with this approach [8].

3 Research status of actuation technologies for bio-inspired microrobots

In recent years, significant progress has been made in the research of actuation technology for bio-inspired microrobots. This section summarizes the recent research results of these six actuation methods. Representative devices for each method are presented in Fig. 1 [9-14].

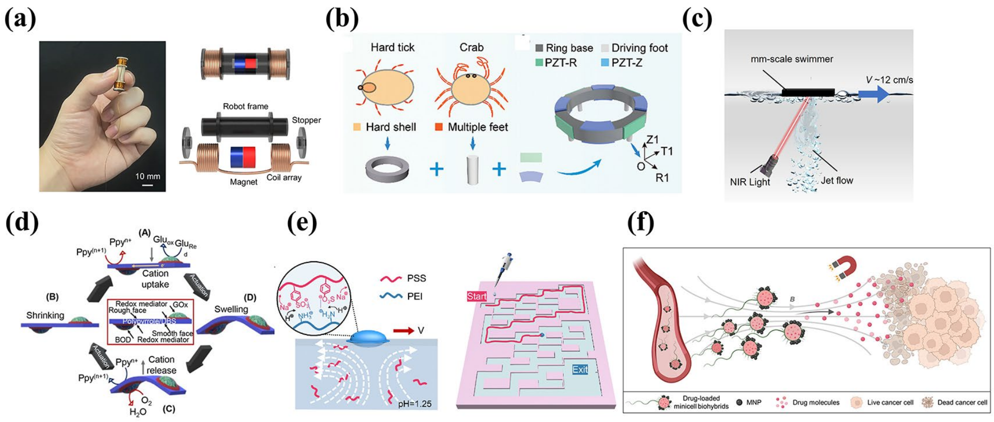

Fig. 1. (a) Overview and mechanism of magnetic-actuated robot [9]; (b) Structure and expected applications of piezoelectric-actuated robot [10]; (c) Swimmers driven by photothermal cavitation [11]; (d) NiTi wire-based actuator driven by fuel-induced heating [12]; (e) Chemical echolocation: robustness to maze geometry and parameter variation [13]; (f). Conceptual illustration of sub-micron scale minicell biohybrids for targeted therapy applications [14].

3.1 Current status of electromagnetic actuation research

Electromagnetic drive is one of the most widely studied driving methods in the field of microrobots. Recent research has made significant breakthroughs in improving output power and adaptability to complex environments.

A study proposed a momentum driven millimeter robot (MiaBot) based on internal magnetic field drive. It innovatively combines the internal drive of permanent magnet electromagnetic coil with kinetic energy conversion impact drive. Based on this core technology, although the robot weighs only 5.82 grams, it can still provide a high output of 16.67 N. Meanwhile, this robot achieved stable operation in environments with high flow resistance, such as viscous liquids, granular media, and pressurized pipeline systems. In these environments, it still had the ability to transport heavy loads that exceeded its own weight by 300 times. This study provided a new paradigm for the application of microrobots in scenarios with strict output requirements, such as underground resource exploration, industrial pipeline inspection, and search and rescue [9].

Another research has been inspired by the peristalsis of rotifers. The robot adopted a flexible elastic body and two finger-like structures with embedded soft magnets. It was driven by a vertical oscillating magnetic field to achieve continuous wave motion, simulating the gait of a vortex worm. The experimental results showed that the system could achieve a bidirectional motion speed of 4 to 7 millimeters per second on a flat surface and could overcome bending obstacles up to 16 times its own body thickness. Pressure testing showed that the robot could transport a weight of 6 grams without affecting its movement speed. Therefore, it had potential applications in fields such as biomedical capsule endoscopy and industrial pipeline inspection [15].

In addition, FilMBot was a thin film based electromagnetic driven soft parallel robotic arm. The robot could achieve a speed of about 1.50 meters per second and an accuracy of about 6.3 micrometers in path tracking tasks, demonstrating the potential of electromagnetic drive in high-speed and high-precision operations in microscale [16].

3.2 Current status of piezoelectric actuation research

Recent research for piezoelectric actuation has made significant progress in material properties and device integration.

Professor Ren Xiaobing's team has developed a super piezoelectric ceramic. The team has increased the piezoelectric coefficient of polycrystalline ceramics to about 6850 pC/N, which was 10-30 times higher than commercial lead zirconate titanate ceramics and 2-4 times better than expensive relax or ferroelectric single crystals. Moreover, the performance of this super piezoelectric ceramic could remain stable over a wide temperature range. Stronger performance allowed robots for the same driving effect to be achieved in smaller sizes. This provided a material foundation for manufacturing smaller robot. In the future, it is expected to become the core component of precision equipment [17].

In terms of piezoelectric robot, Professor Liu Yingxiang's team was inspired by hard shell animals and proposed a quadruped piezoelectric robot based on a rigid circular ring structure. The robot has a volume of only $30 \times 30 \times 14.3$ mm^3, weighs 6.9 grams, and has a maximum linear motion speed of 255 mm/s. It can maintain a motion speed of 92 mm/s under a load of

200 grams, which is about 30 times of its own weight. This study provides a solution for bio-inspired microrobots to achieve fast movement with high load capacity [10].

3.3 Current status of optical actuation research

Recent research of optical actuation has made significant progress in near-infrared light driving and photothermal driving.

Near infrared light actuation is a new method of optical actuation. It has the advantages of tissue penetration and small light damage, enabling microrobots to achieve remote driving inside organization. Photocatalytic micro/nanomotors is another method. It relies on local surface redox reactions to generate photochemical gradients for autonomous propulsion. This redox photoactivation mechanism can be promoted under low-intensity light conditions and naturally occurring chemical environments.

The Wang Dan team applied the principle of cavitation to the field of biomimetic actuators for the first time. Under the irradiation of 808 nm near-infrared laser, the fastest movement speed of millimeter scale polymer composite materials can reach 12 m/s, with an acceleration of up to 7.14×10^4 m/s^2 and a jumping height of 1.5 meters. Based on this mechanism, the research team has developed various demonstration devices such as swimming robots, grippers, and jet systems [11].

3.4 Current status of thermal actuation research

In terms of fuel driven thermal actuators, research has utilized the thermal energy generated by fuel reactions to drive materials such as shape memory alloys, eliminating reliance on external batteries. As is noted in the review by Zhou, a 7 mg catalytic engine using a NiTi–Pt wire can lift objects that weighs 650 times its own weight [12]. This strategy utilizes the high output power of shape memory alloys, which not only frees robots from the constraints of power lines, but also ensures strong driving force, making it an important breakthrough in promoting truly autonomous operation of microrobots.

A miniature coiled artificial muscle was developed by embedding a soft, heat-responsive polymer matrix with magnetic nanoparticles [18]. This design has driving performance far beyond traditional magnetic soft actuators, such as its fast response. The Radio Frequency thermal mechanism enables precise remote control of robots without the need for onboard power sources This promotes the integration of multifunctional wireless tools such as suture needles, scissors, and drills, which can be applied to minimally invasive surgery and wireless medical robots.

3.5 Current status of chemical actuation research

In the last few years, chemical actuation has gained tremendous progress and studies are being conducted now on intelligence and autonomy.

The chemically echolocation mechanism has been demonstrated. The complexation of polyethyleneimine and sodium polystyrene sulfonate created millimeter-sized droplets which the team used. Polyelectrolytes were given off by these droplets during the self-solidification process, which contributed to their propulsion. These droplets interacted with the environment and were able to navigate complex mazes when left to do so independently in the experiment.

The mechanism is all dependent on self-generated chemical signals. The authors noted that this mechanism would be applied in small environments, including microfluidic channel navigation and exploring closed spaces [13].

A different study investigated a single-chamber, fuel- powered artificial muscle. Hydrogen peroxide was used as fuel. It was dissolved in aqueous electrolyte containing NaCl and HNO3, and decomposed through a dismutation reaction, without the need for additional oxidants. This design reached stabilized conditions of actuation and maintained safety as the reaction conditions were mild leading to a reduced risk of explosion [12].

3.6 Current status of biological actuation research

In case of biological actuation, recent research has achieved breakthroughs in the autonomous decision-making ability.

A study indicated a biohybrid design of targeted cargo transportation by the use of bacterial minicell-based sub-micron swimmers. In this experiment, the authors employed bacterial microcells produced by Escherichia coli as autonomous microswimmers and employed their natural motility to facilitate precise transportation of their cargo. These microswimmers are capable of effectively transporting drugs and navigate complex biological environments. This design integrates the drug-loading ability of synthetic micro-materials with the active propulsion and sensing ability of bacterial systems. In brief, this study would provide a promising approach towards addressing the major limitations of the current drug delivery systems by establishing targeted delivery at the microscale. The finding opens up the possibility of integrating active biological components with synthetic design for next-generation biomedical applications [14].

4 Challenges and future prospects

4.1 Low energy conversion efficiency and power management

One of the fundamental issues that run across actuation technologies used in bio-inspired microrobots is energy conversion efficiency. In piezoelectric actuation, defects in materials will limit conversion efficiency. In electromagnetic actuation, it means that miniaturization enlarges resistance and energy losses, which makes it more difficult to achieve high levels of energy conversion. Chemical actuation relies on external fuel supply, and its efficiency is limited by the chemical reaction. In addition, when optical actuation is used, absorption losses in biological tissues tend to reduce its efficiency of converting light to heat, and makes its medical application more challenging.

Low-power driver circuits and intelligent power management are some of the solutions that researchers are investigating in order to solve these problems. The process of creating effective direct current-direct current (DC-DC) converters, dynamic voltage control, and ultra-low-power standby models of bio-inspired microrobots can be considered in future researches.

4.2 Hybrid actuation

Since different actuation technologies possess individual benefits and drawbacks, single actuation method is hard to balance all the performance metrics. In contrast, collaborative actuation of several actuation approaches could have the strengths of several driving approaches and avoid the limitations. Future studies could further explore how actuation can be used together. For instance, microrobots combining the high precision of light fields with the high penetrability of magnetic fields will be a promising direction in complex medical applications [3].

4.3 Intelligence and autonomy

Bio-inspired microrobots are expected to work in intelligence and autonomy directions. Swarm intelligence has been born in this direction as a promising approach. Swarm intelligence can be defined as groups of robots that work together by means of communicating to achieve complicated tasks. The algorithms that have been developed to train robot swarms on how to navigate in a maze have been referred to as the deep reinforcement learning, and are set to form the basis of future research studies.

The other trend that may occur is the combination of the actuation technologies with the robotic perception and decision-making functionalities. An example is that through optical actuation and visual feedback, the robots are able to have completely autonomous control. Such integration increases the adaptability of microrobots and paves the way for higher level of autonomy.

5 Conclusion

In conclusion, this paper has summarized the basic principles, advantages, and challenges of six actuation technologies for bio-inspired microrobots. These findings provide a reference for researchers in selecting proper actuation strategies. Moreover, this paper summarizes the recent research status of these six actuation methods, and identify the core bottlenecks and potential solutions for actuation technologies, which may help future researchers deal with technical challenges. Each actuation technology offers distinct trade-offs between advantages and limitations. As the field advances, bio-inspired microrobots would transcend the limitations of single actuation mode and evolves toward hybrid, autonomous, and intelligent actuation. This evolution will ultimately drive a shift from constrained actuators toward environment-adaptive actuators.

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