Structure and Mechanisms of Micro-Nano Scale Microrobots

Xinyang Xie*

Starlight Education, Beijing, China

*Corresponding author: xinyangxie081122@gmail.com

Abstract. Micro-robots refer to mechanical devices designed to operate at the micro-scale, with dimensions smaller than one millimetre. Traditional MEMS-based designs encounter bottlenecks when scaled down to the micro- and nanoscale, experiencing power reduction alongside diminished reliability and lifespan. Advances in bioengineering and nanotechnology have overcome this impasse, giving rise to three core propulsion methods: chemically driven, externally physically field-driven, and bio-hybrid driven. These approaches lay the foundation for further micro-robot development, enabling micro and nanoscale devices to transition from conceptualisation to practical application.This paper focuses on the structure and mechanisms of micro-nano robots. By analysing structural types and outlining core design principles, it details the motion and control methods for various classes of microrobots through case studies. It explores practical applications to highlight potential and structural constraints, emphasising challenges such as biocompatibility, precise navigation control, and scalable production. This review aims to provide practitioners with a broad perspective and increase awareness within the field.

Keywords: Microrobots; chemical; propulsion; field-driven; bio-hybrid actuation.

1. Introduction

Microrobots denote mechanical devices smaller than one millimetre, primarily designed to operate at the micro-scale. In his 1959 lecture *There's Plenty of Room at the Bottom*, Richard Feynman concluded by proposing the concept of constructing a miniature electric motor. Traditional microrobots are quintessential microelectromechanical systems (MEMS), encompassing disciplines such as microelectronics, materials science, and mechanics. With advances in MEMS technology over recent decades, microrobotics has progressed from concept to reality. Millimetre-scale microrobots can now access confined spaces for exploration or perform minimally invasive surgery. However, when drive sizes must be reduced to the micrometre or nanometre scale, the core physical characteristic governing micro- and nanorobot motion in microfluidic environments is their extremely low Reynolds number ($Re << 1$). This implies viscous drag from the fluid far outweighs inertial effects. Such conditions drastically increase the difficulty of manufacturing conventional drives, causing their power density to decrease exponentially while reliability and lifespan diminish. Micro-robots reliant on micro-electro-mechanical systems (MEMS) manufacturing are encountering setbacks [1].

Advances in bioengineering and nanotechnology have introduced novel methods for fabricating components via DNA origami or chemical synthesis, yielding three propulsion approaches: external physical field actuation (magnetic/optical/acoustic fields), chemical propulsion (active release of propellants), and bio-hybrid actuation (integration with biological structures). The convergence of multiple technologies has accelerated the development of micro-nano-scale microrobots, broadening their application scope and enabling higher-precision operations at smaller scales.

Micro-nano medical microrobots hold significant promise in biomedical engineering and have demonstrated feasibility in laboratory settings. As a frontier of medical technology, micro-nano robots leverage the unique advantages of structures optimised for the micro-nano scale. They have demonstrated immense potential in biomedical applications such as targeted drug delivery, precision surgical manipulation, disease diagnosis, and health monitoring. However, their clinical translation remains hindered by critical challenges including biocompatibility, precise in-vivo navigation and control, and large-scale production, necessitating further technological breakthroughs.

This paper focuses on the structure and mechanisms of micro-nano-scale microrobots, introducing three distinct types based on their operational principles. Firstly, it analyses core design principles according to structural typology, detailing movement and manipulation methods alongside their respective advantages and limitations. Design and experimental case studies are cited for illustrative purposes. Finally, practical applications are examined to highlight potential prospects and structural constraints, concluding with a summary and outlook for microrobotic development.esponding authors grant us the copyright to use the paper for the book or journal in question.

2. Chemically Driven Microrobots

Chemical propulsion constitutes an autonomous drive system, offering advantages such as high flexibility and the ability to utilise diverse gradients for propulsion. Chemically driven micro-nano robots convert chemical energy into mechanical energy for propulsion by placing chemical materials that react with substances in the environment, as shown in figure 1. Active metals (Pt, Ag, Mg, Zn, etc.), enzymes, and metal oxides serve as catalysts for fuel conversion, as illustrated in Figure 1. In biomedical applications, micro-robots must prioritise biocompatibility to minimise contamination or tissue damage. However, current experimental chemically driven micro-nano motors often utilise H_2O_2 as a propellant fuel, yet H_2O_2 generally lacks biocompatibility in biomedical contexts. Consequently, developing micro-nano motors tailored for the human body remains a critical research focus. Most chemically driven microrobots employing Janus surfaces or similar methods cannot steer directionally, moving only along gradients. Consequently, practical applications may require complementary field-driven mechanisms such as magnetic field actuation [1].

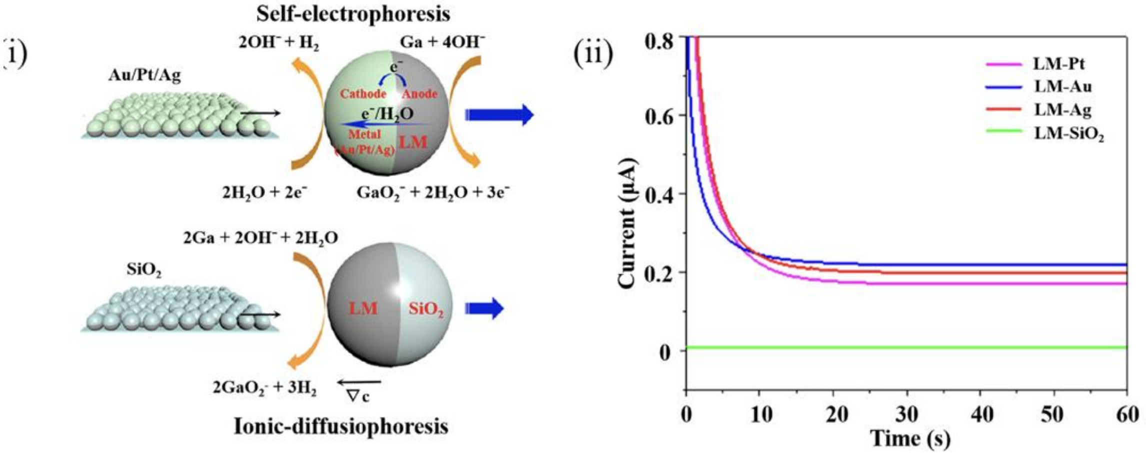

Fig. 1 Electrochemical measurement for distinguishing the driving mechanism of GaInSn liquid metal Janus micromotor (LMJM): i) Schematic diagram of the driving mechanism of GaInSn LMJMs, and ii) Electrochemical measurement diagram of the LMJMs materials in the sodium hydroxide solution [1].

2.1. Bubble Propulsion

Bubble propulsion achieves unidirectional thrust by incorporating nanomotors within the robot structure. Reactive substances react with the surrounding medium to generate gas, expelling bubbles from one end of the robot. Xu Zheng et al. documented the motion characteristics of oxygen microbubbles generated by H_2O_2 decomposition, where cavitation-induced jet streams propel the microbubbles rapidly [2].A common core feature of chemically driven micro-nano robots is asymmetric design, most frequently realised through Janus structures. This configuration typically involves placing catalytic materials on one side while maintaining inertia on the other. Such structures enable continuous unidirectional thrust generation at one end of the machine. The catalytic material reacts with a fuel present in the liquid medium. To meet biocompatibility requirements, the catalytic material must be compatible with fuels found in human bodily fluids, such as glucose, water, or gastric acid, to generate hydrogen or oxygen [1].

2.2. Autodiffusive Swimming Propulsion

Autodiffusive swimming propulsion shares similarities with bubble-driven propulsion, both requiring asymmetric designs to ensure directional movement, typically employing Janus structures. By placing catalytic material at one end of the robot, it reacts with compatible fuel to continuously produce molecular products. This creates a molecular concentration gradient at the catalytic end, generating a permeation flow. This permeation flow propels the robot's movement. Xing Ma et al. deposited Pt onto Mg microspheres; Pt catalysed the decomposition of H_2O_2, generating thrust through self-diffusive swimming driven by the chemical gradient [1, 3].

3. Field-Driven Microrobots

At the microscopic scale, fluids typically exhibit low Reynolds number flow characteristics. Consequently, microrobots cease motion rapidly once propulsion ceases, unlike macroscopic objects which coast for a distance. Advancements in self-propelled micromotors enable efficient movement within fluids. However, practical applications face challenges of uncontrollable direction and limited lifespan. Externally field-driven microrobots utilise magnetic, optical, or acoustic fields for sustained, precise actuation. In biomedical applications, driven microrobots typically exhibit good biocompatibility, though non-degradability remains a persistent issue [4, 1].

3.1. Magnetic Field Actuation

Magnetic fields exert magnetic forces and torques on various metallic materials. By incorporating metallic alloys within the microbot, it can perform actions such as rotation, movement towards magnetic gradients, shape transformation, and directional changes through controlled magnetic fields. Magnetic fields used to drive microbots primarily include gradient, oscillating, rotating, and hybrid magnetic fields [4].Gradient magnetic fields vary in intensity with spatial position, enabling microrobots to move towards regions of higher magnetic strength. Oscillating magnetic fields exhibit periodic changes in both intensity and direction, facilitating directional motion. Tianlong Li et al. employed magnetically coated Janus microsphere dimers, using magnetic fields to induce alternating rotation. The periodic reversal of direction in rotating magnetic fields renders them suitable for driving micromotors [5].Xu Wang et al. deposited Fe_2O_4 nanoparticles onto a biological template of spirulina, enabling highly efficient locomotion with a maximum speed of 526.2μm/s [6].Composite magnetic fields allow microrobots to execute complex steering manoeuvres during motion. Simultaneously, flexible control of microrobot swarms is achievable; some studies propose applying different magnetic field types to manipulate swarms while rapidly performing intricate operations [7].Magnetically driven microrobots are currently evolving into diverse configurations, with ongoing research into biocompatibility. Magnetically controlled robots integrated with biological cells/tissues have garnered significant attention. These robots may find extensive applications in the medical field in the future [1, 4].

3.2. Optical Control

Optical tweezers enable precise manipulation of objects at the micro- and nanoscale. Optical tweezers operate by generating light pressure via lasers, trapping micro- and nano-scale objects within optical traps. This enables the capture, manipulation, and measurement of mechanical properties in minute particles. Applications include manipulating and assembling nanoparticles, studying biomacromolecules, and moving or dissecting individual cells and microorganisms. However, optical tweezers may present significant challenges for driving microrobots. Firstly, objects manipulable by optical tweezers are typically smaller than 30 micrometres [8], and the number of particles they can manipulate is limited. Secondly, the lasers required for optical tweezers may be harmful to human tissue in medical applications or unable to penetrate sufficiently into the body [4].

3.3. Acoustic Actuation

Acoustic actuation converts sound wave vibrations into propulsion for microrobots, typically utilising ultrasonic waves for micronano-scale manipulation. Micronano-robots with Janus structures harness their structural asymmetry for directional acoustic control. Surface flagella and cilia oscillate in response to sound vibrations; when cilia encounter sound waves near their resonance frequency, they maintain regular oscillations and propel fluids [9].Xiaolong Lu et al. employed ultrasound to power micromotors, incorporating hydrophobic layers to trap bubbles. Ultrasonic excitation of these bubbles generated enhanced local flow, enabling rapid movement at 1100 body lengths per second [4, 10].

4. Bio-inspired Micro-Robots

Numerous organisms in nature exhibit remarkable locomotive efficiency and flexibility, as shown in figure 2. Under optical microscopy, microorganisms or certain biological tissues demonstrate rapid movement and directional changes. Biological locomotion has garnered extensive attention, and with advancements in bioengineering,bionics,and nanotechnology, bio-inspired nanorobotics has progressed rapidly. In 2005, Jianzhong Xi et al. pioneered a microdevice integrating muscle bundles with micro-mechanical systems. This innovation charted a new trajectory for bio-hybrid micro-robots. As autonomously propelled micro-machines, these devices offer significant advantages in locomotive efficiency and velocity, alongside potential for structural self-assembly. Bio-integrated microrobots demonstrate vast potential in medical applications, with surface modifications enabling reduced immune system restrictions. Current primary challenges lie in post-integration compatibility issues and the intrinsic lifespan limitations of the microrobots themselves [1, 11].

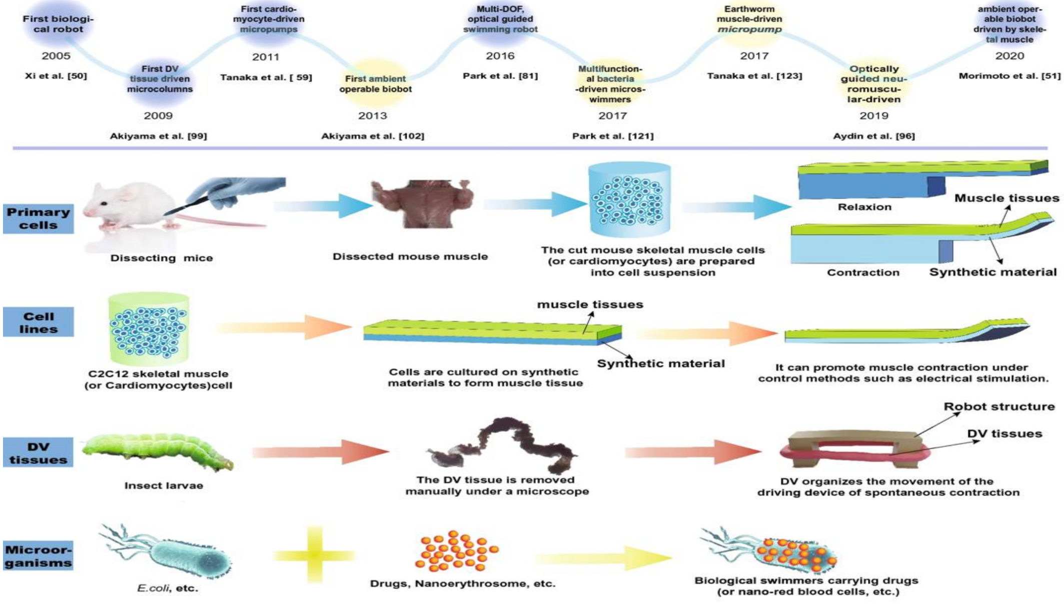

Fig. 2 The top of the figure shows some major milestones in biomaterial-driven bio-robot research from 2005 to 2020. The overall design process of a biological robot made up of primary cells, cell lines, dorsal vascular (DV) tissue, and microorganisms is demonstrated at the bottom [11].

4.1. Microrobots Integrated with Muscle Cells

Currently employed muscle cells primarily include cardiomyocytes and skeletal muscle cells. Cardiomyocytes exhibit spontaneous contraction, requiring only glucose to sustain rhythmic contractions without electrical stimulation. However, practical applications often necessitate electrical stimulation to synchronise dispersed cardiomyocytes. Existing approaches involve placing cardiomyocytes on conductive scaffolds that mimic their native environment. Currently, cardiomyocytes are primarily sourced from neonatal rats, while research into differentiating cardiomyocytes from artificial stem cells continues. Cardiac myocytes possess inherent biocompatibility and excellent locomotive efficiency. However, their spontaneous contractions present drawbacks in precise control, coupled with a relatively short lifespan [11].In contrast, skeletal muscle cells do not undergo spontaneous contractions. They can achieve precise, directional movement through electrical stimulation and possess regenerative capacity, with lifespans extending to several decades. Both cardiac and skeletal muscle contraction require conductive matrix materials for control. Insect tissues/cells are also employed in biohybrid microrobotics, characterised by high tolerance to environmental conditions such as pH and temperature [11].

4.2. Micro-robots fused with microorganisms

Most self-propelled microorganisms possess built-in molecular motors, such as flagella. E. coli flagella comprise over 20 proteins and can rotate at speeds exceeding 20,000 revolutions per minute. Metin Sitti and colleagues designed biohybrid microswimmers combining E. coli with nanoscale erythrocytes, achieving high fabrication efficiencies and efficient locomotion [12].Sperm cells, equipped with flagella, also serve as targets for micro-robot integration. They are suitable carriers for hydrophilic drugs and exhibit high motility efficiency in viscous media. Microalgae demonstrate superior biocompatibility compared to microorganisms like E. coli. The unicellular green alga Chlamydomonas reinhardtii (CR), possessing flagella and exhibiting phototaxis, holds potential for targeted delivery [11, 12].

5. Conclusion

Micro- and nanorobots achieve micro-scale locomotion through chemical propulsion, external field actuation, and bio-integration mechanisms, demonstrating significant potential in targeted delivery and human imaging. Current laboratory-stage development challenges include insufficient biocompatibility and degradability, achieving precise control in complex environments, and scaling micro-robot production. Future advancement must prioritise overcoming the challenge of mass-producing micronano-scale robots, achieving efficient autonomous or externally controlled operation, and resolving issues of biotoxicity and immunological constraints. Micronano-scale robots hold vast promise in biomedicine, potentially breaking through current limitations in medical diagnostics to enable precise, efficient treatments and advance medical research.These micronano-scale devices also hold future potential as crucial tools for environmental remediation, finding applications in pollution control and microenvironmental modification.

References

[1] Huang, L., Pan, Y., Wang, M., et al. Driving modes and characteristics of biomedical micro-robots. Engineered Regeneration, 2023, 4(4): 411-426.

[2] Zhang, J., Zheng, X., Cui, J., et al. The Self-Propulsion of the Spherical Pt–SiO2 Janus Micro-Motor. Micromachines, 2017, 8(4): 123.

[3] Ma, X., Hahn, K., Sanchez, S., et al. Catalytic mesoporous Janus nanomotors for active cargo delivery. Journal of the American Chemical Society, 2015, 137(15): 4976–4979.

[4] Chen, Y., Chen, D., Liang, S., et al. Recent advances in field-controlled micro-nano manipulations and micro-nano robots. Advanced Intelligent Systems, 2022, 4(3): 2100116.

[5] Li, T., Zhang, A., Shao, G., et al. Janus microspheres: janus microdimer surface walkers propelled by oscillating magnetic fields. Advanced Functional Materials, 2018 ,28(25): Inside Back Cover

[6] Wang, X., Cai, J., Sun, L., et al. Facile fabrication of magnetic microrobots based on spirulina templates for targeted delivery and synergistic chemo-photothermal therapy. ACS Applied Materials & Interfaces, 2019, 11(5): 4745–4756.

[7] Bunea, A.-I., Martella, D., Nocentini, S., et al. Light-powered microrobots: challenges and opportunities for hard and soft responsive microswimmers. Advanced Intelligent Systems, 2021, 3(4): 2000256.

[8] Ahmed, D., Baasch, T., Jang, B., et al. Artificial swimmers propelled by acoustically activated flagella. Nano Letters, 2016, 16(8): 4968–4974.

[9] Lu, X., Ou, H., et al. Superfast fuel-free tubular hydrophobic micromotors powered by ultrasound. Sensors and Actuators B: Chemical, 2022, 372: 132667.

[10] Chen, Z., Fu, F., Yu, Y., et al. Cardiomyocytes-actuated morpho butterfly wings. Advanced Materials, 2018, 31(8): 1805431.

[11] Lin, Z., Jiang, T., & Shang, J. The emerging technology of biohybrid micro-robots: a review. Bio-Design and Manufacturing, 2021, 5: 107–132.

[12] Buss, N., Yasa, O., Alapan, Y., et al. Nanoerythrosome-functionalized biohybrid microswimmers. APL Bioengineering, 2020, 4: 026103.