

# Progress and Prospects of Micro/Nano-robots in Medical Applications

Mingxuan Li \*

Nexus International School, Singapore, 387293, Singapore

\* Corresponding Author Email: mingxuan.li.26@nexus.edu.sg

**Abstract.** Along with the development of science and technology, micro/nano-robots bring more possibilities to medical surgery. The research and development of micro/nano-robots is vital because precision and the ability to work in a microscale environment can break through the bottleneck of current human medical surgery. However, the traditional type of design and research has some deficiencies, flaws in the design, and some technical issues during the process that obstruct further developments. The review is based on the progress and prospects of micro/nano-robots in medical applications. This review focuses on the principle of nano/micro-robots, the technical routes, the challenges current research teams are facing, and future perspectives. This study summarized the research and experimental reports of relevant professional teams. In summary, the researchers have already developed many kinds of actions and the combination of microorganisms and artificial structures. Currently, many ways of actuation have been invented to suit the robot in different applications, but there are still problems with efficiency, biocompatibility, or positioning and navigation. This research also discusses the challenges and outlook throughout nanorobot research.

**Keywords:** Micro/nano-robots, Medical applications, Actuators.

## 1. Introduction

With the swift development of nanotechnology, micro/nano-robots have become widely used in the medical field, for example in vivo imaging, disease diagnosis and treatment, or targeted drug delivery. These micro nanorobots can work on a microscopic scale in the meantime maintaining high flexibility and precision. The rapid development of micro-nanorobotics technology in the medical field provides innovative solutions for disease diagnosis, treatment, and drug delivery.

The research by Sun and his team demonstrated the wide application of nanorobots in targeted drug delivery, especially precise drug delivery to tumors and inflammatory sites. Micro/nano-robots achieve efficient treatment of lesions by releasing drugs at specific locations and significantly reducing side effects on healthy tissues [1]. In addition, these robots can traverse complex biological barriers and provide more targeted treatment options, laying a technical foundation for precision medicine.

However, micro/nano-robots still face many challenges in medical applications. Preetam and his team pointed out that the stability and control accuracy of nanorobots in complex biological environments are key issues. Due to the dynamic nature of the internal environment, robots are often affected by the flow of body fluids and the immune system, leading to inaccurate navigation or rejection [2]. In response to this problem, researchers have proposed the use of multi-modal actuation and sensing systems, such as combining magnetic and chemical actuation, to improve its navigation accuracy and adaptive capabilities in the living body.

On this basis, the special topic on micro nano robotics published by Springer proposes a solution for smart materials and microstructure design to improve the biocompatibility and immune evasion capabilities of robots [3]. These materials can not only reduce biological rejection reactions, but also monitor and respond to the surrounding environment in real time, increasing the continuous operation time of the robot in the body. This innovative design significantly improves the robot's survival and work efficiency in complex environments and provides important support for the biomedical applications of micro/nano-robots.

Overall, micro/nano-robots show broad application prospects in the medical field. Through innovative strategies such as multi-modal drive and smart material design, researchers are solving the stability and control problems of robots in biological environments, laying a solid foundation for the further development of personalised precision medicine in the future. In this review, research and experiments of micro/nano-robots on medical applications are included, mainly about the sources of drive and revealing issues and challenges that obstruct the development of micro/nano-robots. The innovation of this review is that it provides more ways than traditional studies that suit conditions in medical surgeries.

## 2. Principles of Micro/nano- robots

The main principle of this micro nano robot can be categorised into four types, namely magnetic actuation, biological actuation, acoustic actuation and chemical actuation. As the main source of energy, these actuation methods also have their advantages and disadvantages.

First, magnetic drive, its concept is the technology of using magnetic fields for power transmission. Its basic idea is to convert electrical energy into mechanical energy through electromagnetic action to complete the drive of the robot. This technology mainly relies on the interaction between electric current and magnetic field to achieve power output. The characteristic of this driving method is that there is no need for physical contact during the driving process, and there will be no worn parts. The maintenance requirements of magnetic actuation are extremely low, and it is also highly efficient.

The concept of the drive by biological actuation is based on the perception of microorganisms to the environmental changes and stimulation. These kinds of biohybrid micro robots are often a combination of artificial micro nano structures and living microorganisms. This technology is very advantageous because it can perfectly combine the precision of artificial mechanical structures with the self-propulsion capabilities and good biocompatibility of microorganisms to carry out various medical operations in the complex environment of the human body.

Drive by acoustic actuation can be manipulated by sound waves depending on the Stokes drag force. This kind of force will be generated in a fluid environment that has a high viscosity and high concentration. The sound waves can manipulate the micro nano robot relies on the combination of drag force and acoustic radiation force so that adjusting and controlling the frequency of the sound wave can be used to manipulate the micro/nano-robots.

The principle of chemical actuation is by attaching reactive catalyst materials to the robot. The catalyst reacts with chemicals in the surrounding environment. The reactants usually need to be able to generate enough thrust to drive the micro-nano robot to move, such as hydrogen peroxide, hydrogen, or other controllable decomposition chemicals. There will be bubbles formed during the chemical reaction that create a current enabling the micro nano robot to move. Using peroxide as an example, when the catalyst decomposes hydrogen peroxide, oxygen bubbles are generated, which are discharged from the tail end of the robot, forming a propulsion force.

## 3. Typical Progress and Discussion

The latest research results of magnetically driven micro/nano-robots are now in medicine, especially for tumour treatment, minimally invasive surgery and precision drug delivery. The following are some specific cases, such as the micro/nano-robots driven by external magnetic force used by Chen's team to perform minimally invasive artery cleaning and thrombus removal [4].

The application of magnetically driven micro/nanorobots in targeted drug delivery is its most representative success story. Research shows that these robots can carry anti-cancer drugs, rely on magnetic field navigation to shuttle through blood vessels in the body, accurately reach the tumor site and achieve targeted drug release. Medina-Sánchez and his team further studied the application of this drug delivery system in cancer treatment, stating that this technology can significantly increase the concentration of drugs at the target site and reduce side effects on healthy tissues. This

breakthrough has brought revolutionary progress to targeted therapy, making it possible to carry out efficient drug delivery inside tumors [5].

In addition to targeted drug delivery, magnetically driven nanorobots also show promise in blood vessel cleaning and minimally invasive surgery. For example, Chen and his team used a magnetically driven robot to clear arterial blockages and successfully removed lipid accumulation and thrombus in an experimental model, providing a new solution for minimally invasive cardiovascular surgery. Through magnetic field guidance, nanorobots can safely and efficiently navigate within blood vessels and act on blocked areas, reducing the invasiveness and risks of traditional surgeries [4].

Bio-driven micro/nano-robots are a class of micro-devices that are self-propelled through biological mechanisms and are widely used in the biomedical field. In recent years, with the rapid development of nanotechnology, biomaterials, and robotics, researchers have made significant progress in the design, manufacturing, and application of biologically driven micro/nano-robots. Koleoso and his team pointed out that these robots can use the materials and environment in the organism to navigate, and effectively perform tasks such as targeted drug delivery and treatment of diseased tissues [6]. Through continuous optimization of micro nano robotics technology, researchers have achieved higher control accuracy and flexibility, providing new possibilities for biomedical innovation.

The design process of bio-driven micro nanorobots involves multi-faceted materials development and system integration. Wang and his team emphasised that researchers are exploring new biocompatible materials to improve the performance and stability of robots. In addition, advances in driving and positioning technology have significantly contributed to the development of this field. Researchers use various means such as magnetic fields, light stimulation, and chemical reactions to achieve precise control of robots to ensure their effective navigation in complex biological environments [7]. These advances have enabled biologically driven micro/nano-robots to show great potential applications in cancer treatment, targeted drug release, and disease monitoring.

Sound-driven micro/nano-robots are an emerging class of micro-devices that are precisely manipulated by sound waves. This technology uses acoustic principles to drive and manipulate the movement of tiny robots through the generated sound field, and has the advantages of high efficiency, non-contact, and easy control [8]. In recent years, with the advancement of acoustic technology, researchers have achieved remarkable results in the design and application of sound-driven micro/nano-robots.

Xiao and his team pointed out that sound-driven microrobots have shown broad application potential in fields such as medicine, environmental monitoring, and material processing. These robots can achieve autonomous navigation in complex fluid environments and accurately locate and manipulate them through sound waves. For example, researchers have developed an acoustically driven microrobot that can move quickly in liquids and capture targets, providing a new solution for drug delivery and biological sample processing [9]. This new type of robot uses the pressure changes of sound waves to control the direction and speed of movement, demonstrating the flexibility of sound-driven technology.

In addition, Lu and his team proposed a human-machine interface based on acoustic manipulation and demonstrated the practical application of sound-driven microrobots. The research team used the microfluidic effect generated by sound waves to achieve efficient control of the robot's movement, enabling it to perform complex tasks in the body environment [10]. This interface not only improves the robot's control accuracy but also makes it possible for precise operations in the medical field, such as targeted drug delivery in the body and minimally invasive surgery.

In summary, the research on sound-driven micro/nano-robots is constantly developing. Although it faces many challenges, its potential application prospects are exciting. Through continuous technological innovation and multidisciplinary collaboration, this field is expected to bring revolutionary changes to future micro-robotics technology.

Chemically driven micro/nano-robots are microdevices that use the energy generated by chemical reactions to drive themselves. This technology has shown a wide range of application potential in

fields such as biomedicine, environmental monitoring, and materials science. In recent years, with the rapid development of nanotechnology, researchers have made significant progress in the design, manufacturing and application of chemically driven micro/nano-robots.

Feng and his team explored recent advances in chemically driven micro nano robotics in detail in their review, emphasising their diversity and effectiveness in biological applications. These robots can generate power in the *in vivo* environment through specific chemical reactions, enabling functions such as targeted drug delivery, detection of intracellular components, and removal of pollutants. For example, some researchers have developed metal nanoparticles that can produce gas through chemical reactions such as decomposing hydrogen peroxide, thereby propelling micro/nano-robots to move. This driving method not only achieves efficient movement but also allows the robot to navigate adaptively in complex biological environments [11].

Furthermore, the study by Gui and his team reviewed the widespread use of chemically driven micro/nano-motors in chemical science applications, pointing out the important roles of these micromotors in catalysis, sensing, and drug delivery. These motors achieve power conversion through different chemical mechanisms, such as catalytic reactions and electrochemical reactions, demonstrating extreme flexibility and adaptability. Researchers have also explored optimising the performance of micromotors by changing reaction conditions or material composition, thereby improving their effectiveness in practical applications [12].

The future research vision is to develop more intelligent and autonomous chemically driven micro/nano-robots that can operate efficiently under a variety of biological and environmental conditions. By combining artificial intelligence and machine learning technologies, these robots will be able to sense and respond to environmental changes in real-time, improving their efficiency in performing complex tasks. For example, using smart materials and adaptive control strategies, future chemically driven robots may be able to self-repair and optimise, thereby playing a greater role in fields such as medical care, environmental protection, and smart material development.

In conclusion, despite many challenges, its potential application prospects are exciting. Through continuous technological innovation and interdisciplinary cooperation, this field is expected to bring revolutionary changes to future micro-robotics technology.

#### **4. Challenges and Opportunities of Micro/nano- Robot Design**

Although magnetically driven micro/nano-robots have achieved remarkable results in the laboratory, they still face multiple challenges in clinical application. First, external magnetic fields are easily disturbed in complex biological environments, which may lead to reduced robot control accuracy. Different tissues and fluid flow in the human body affect the propagation of the magnetic field and the movement of the robot, resulting in reduced stability of the robot in specific parts. Chen and his team pointed out that to overcome this problem, future research needs to develop more accurate magnetic field generation equipment to improve the control ability and adapt it to the dynamic biological environment.

The biocompatibility and degradability of materials are also important areas of research. In order to ensure that nanorobots do not cause immune responses in the human body, the research team has developed a series of biocompatible materials that can automatically degrade after completing the task, reducing the risk of long-term stay in the body. However, how to further optimise the strength and degradation rate of the material to meet the needs of different tasks is still an urgent problem to be solved.

In summary, magnetically driven micro/nano-robots provide new treatment methods for modern medicine, especially in drug delivery and minimally invasive treatment. It shows great application potential. However, to achieve its large-scale clinical application, key technical issues such as control accuracy, biocompatibility and material safety still need to be solved [4].

However, despite a series of research results, bio-driven micro/nano-robots still face many challenges. First, the complexity of the biological environment places higher demands on the

navigation and control of robots, especially in dynamic body fluid and cell environments. How to maintain stable control and accurate targeted release remains a technical challenge. In addition, the interaction between robots and organisms may lead to toxic reactions and immune responses, which requires researchers to innovate in materials and design to ensure biosafety [8]. Finally, the problems of biocompatibility, manipulation accuracy and repeatability in practical applications also need to be solved urgently to achieve clinical transformation.

The vision for the future is to develop more intelligent and autonomous bio-driven micro/nano-robots that can autonomously adapt and perform multiple functions in complex biological environments. For example, using smart materials and artificial intelligence algorithms, future nanorobots will be able to sense environmental changes in organisms in real time and adjust their behaviour accordingly. With the advancement of these technologies, bio-driven micro/nano-robots are expected to play a more important role in precision medicine, personalised treatment, and disease prevention.

In short, the research on bio-driven micro/nano-robots has made significant progress, and the challenges faced also point out the direction for future research. Through continuous technological innovation and interdisciplinary collaboration, this field is expected to bring revolutionary changes to medicine and biotechnology.

Although sound-driven micro/nano-robots have shown great potential in many aspects, they still face some challenges. First, the propagation and attenuation characteristics of sound waves in different media may affect the robot's navigation ability and control accuracy. In addition, in biological environments, noise and interference may also affect the performance of sound-driven systems. This requires researchers to continuously optimise acoustic design to improve the robustness and adaptability of the system [13]. Second, current sound-driven technology still needs to solve problems such as material selection and manufacturing process to ensure the long-term stability and biocompatibility of robots in complex environments.

The future research vision is to develop more intelligent and autonomous sound-driven micro/nano-robots that can achieve self-regulation and efficient execution in complex organisms and environments. With the advancement of artificial intelligence and machine learning technologies, sound-driven robots will be able to better understand environmental information and make intelligent decisions based on real-time feedback. This will greatly promote the practical application of sound-driven micro/nano-robots and enable them to play a greater role in precision medicine, environmental protection, and biological monitoring.

Even though chemically driven micro nano robotics have shown great potential in many aspects, they still face many challenges. First, the stability and reliability of robots in complex biological environments still need to be addressed. The complexity and unpredictability of chemical reactions may lead to uncertainty in robot movement, which requires researchers to continuously optimise the design and material selection to improve the controllability of their operation. In addition, the biocompatibility and safety of chemically driven systems are also key issues, especially in applications such as drug delivery and cell therapy, where robots must ensure that they do not cause harm to organisms [11, 12].

## 5. Conclusion

As a conclusion, this review collects and summarises the research progress, technical route, results, and challenges of micro/nano-robots in medical applications from many professional teams. In one word, the actuation methods are the main development and research direction. For example, magnetic driven micro robots are more suitable in tumor treatments and blood vessel cleaning; biological-driven robots are suitable in targeted drug delivery and treatment of disease issues; acoustic-driven robots are suitable in drug delivery and minimally invasive surgery; chemical-driven robots are suitable for detection of intracellular components and removal of pollutants. Further developments are held back by challenges, for example biocompatibility inside the human body of micro/nano-

robots or the inefficiency of power. Micro/nano-robots have great development prospects in the future. Through the continuous updating of science and technology, these existing challenges and problems will be solved one by one.

## References

- [1] Sun T, Chen J, Zhang J, et al. Application of micro/nanorobot in medicine. *Frontiers in Bioengineering and Biotechnology*, 2024, 12: 1347312.
- [2] Preetam S, Pritam P, Mishra R, et al. Empowering tomorrow's medicine: energy-driven micro/nano-robots redefining biomedical applications. *Molecular Systems Design & Engineering*, 2024.
- [3] Selected topics in micro/nano-robotics for biomedical applications. Springer, 2013.
- [4] Hu N, Ding L, Liu Y, et al. Development of 3D-Printed Magnetic Micro-Nanorobots for Targeted Therapeutics: the State of Art. *Advanced NanoBiomed Research*, 2023, 3 (10): 2300018.
- [5] Dufil Y, Dietrich M, Zigah D, et al. Local degradation of PEDOT: PSS on silicon nanostructures using scanning electrochemical microscopy. *Small*, 2023, 19 (10): 2206789.
- [6] Koleoso M, Feng X, Xue Y, et al. Micro/nanoscale magnetic robots for biomedical applications. *Materials Today Bio*, 2020, 8: 100085.
- [7] Wang B, Kostarelos K, Nelson B J, et al. Trends in micro-/nanorobotics: materials development, actuation, localization, and system integration for biomedical applications. *Advanced Materials*, 2021, 33 (4): 2002047.
- [8] Chen B, Sun H, Zhang J, et al. Cell-Based Micro/Nano-Robots for Biomedical Applications: A Review. *Small*, 2024, 20 (1): 2304607.
- [9] Xiao Y, Zhang J, Fang B, et al. Acoustics-actuated microrobots. *Micromachines*, 2022, 13 (3): 481.
- [10] Lu X, Zhao K, Liu W, et al. A human microrobot interface based on acoustic manipulation. *ACS Nano*, 2019, 13 (10): 11443-11452.
- [11] Feng Y, An M, Liu Y, et al. Advances in chemically powered micro/nanorobots for biological applications: a review. *Advanced Functional Materials*, 2023, 33 (1): 2209883.
- [12] Guix M, Mayorga-Martinez C C, Merkoçi A. Nano/micromotors in (bio)chemical science applications. *Chemical Reviews*, 2014, 114 (12): 6285-6322.
- [13] Zhang J, et al. Acoustic Manipulation of Microrobots: A Review. *Micromachines*, 2022, 13 (4): 618.