Shahrekord University

Journal of Microfluidic and Nanofluidic Research

Journal homepage: https://jmnr.sku.ac.ir

Review Article

# Manipulation of Magnetic Microrobots: A Short Review

**Nastaran Faraji***

*Department of Mechanical Engineering, University of Isfahan, Isfahan, Iran*

**ARTICLE INFO**

***Article history:***

Received: 2025-02-20

Revised: 2025-03-10

Accepted: 2025-03-11

***Keywords:***

Microfluidics;

Microrobots;

Magnetic actuation;

Manipulation.

**ABSTRACT**

For accessing and modifying microscale surroundings, magnetic microrobots have shown great promise, especially in healthcare applications. These robots provide accurate navigation and untethered operation by using magnetic fields for propulsion and control. Different propulsion mechanisms, including torque-driven and force-driven systems, as well as creative manufacturing approaches that improve their biocompatibility and performance, are examples of recent developments in magnetic microrobot design. Targeted medication delivery and microsurgery have demonstrated great promise for biohybrid magnetic microrobots, which combine biological entities with magnetic components. This paper analyzes the state of magnetic microrobots, emphasizing their actuation techniques, design approaches, and biomedical applications. Additionally, it presents the challenges and potential paths forward in this area, highlighting how magnetic microrobots might revolutionize microscale manipulation and medical procedures.



## 1. Introduction

A key technology in the creation and functioning of microrobots, especially in the manufacturing and manipulation of these minuscule machines, is microfluidics [1-3]. The precise and dynamic manipulation of fluids at the microscale made possible by developments in microfluidics has made it possible to fabricate complexly formed microparticles that may be employed in small-scale robots with efficiency. With the help of this technology, microrobots with customized morphologies and sophisticated features like improved mobility and precise control may be made [4]. Additionally, microfluidics facilitates the incorporation of diverse materials and payloads into microrobots, enhancing their potential for uses such as environmental sensing and tailored medicine delivery [5-7].

Beyond just manufacturing, microfluidics and microrobots are integrated for control and functionality. Microfluidics is essential to biohybrid robotics because it maintains and scales the architectural complexity of biological tissues, which are utilized to build manipulable devices [8]. This combination makes it possible for biohybrid robots' sensing, processing, and control components to be precisely patterned, improving their capabilities in domains like environmental monitoring and regenerative medicine. Furthermore, developments in microfluidics have demonstrated great promise for biological research, providing enhanced swarm intelligence, motion control, and environment sensing [9]. These developments demonstrate how the field of microrobotics is developing and how microfluidics is a crucial component in enabling sophisticated features and uses [10-12].

Magnetic microrobots are small robotic machines that move, manipulate, and control themselves using magnetic forces. These robots

* **Corresponding author.**
***E-mail address:*** nastaran.faraji55@gmail.com

**Cite this article as:**
Faraji, N., 2025. Manipulation of Magnetic Microrobots: A Review. *Journal of Microfluidic and Nanofluidic Research*, 2(1), pp. 72-77.
https://doi.org/10.22034/jmnr.2025.15170.1010

may be steered by external magnetic fields in a variety of settings, such as fluids, pipes, and tissues because they are usually composed of magnetic materials or have embedded magnetic components [13, 14]. By manipulating magnetic field gradients that apply forces and torques to the microrobots, magnetic actuation allows for fine control over their motion. In the biomedical domains of targeted medication delivery, microsurgery, and microscale sensing, this technology has important uses. External electromagnets or inbuilt magnetic field sources can be used to wirelessly operate magnetic microrobots, providing untethered operation and quick reaction times [15].

The current state of magnetic microrobots is examined in this review paper, with a focus on their biomedical applications, design methodologies, and actuation strategies. It also discusses the difficulties and future directions in this field, emphasizing how magnetic microrobots might transform medical procedures and microscale manipulation.

## 2. Magnetic Actuation

The following is an expression for the force and torque applied on a microrobot [16]:

$$F = V(M \cdot \nabla)B \quad (1)$$

$$T = V(M \times B) \quad (2)$$

where V is the microrobot's volume, B is its magnetic flux, and M is its magnetization.

## 3. Advances in the Field

A novel electromagnetic based actuation (EMA) system for microrobot drilling and three-dimensional (3D) locomotion was presented by Yu et al. [17] (Fig. 1). Three pairs of Helmholtz coils, a pair of Maxwell coils, and a pair of rotating Maxwell coils made up the system's four fixed coil pairs and one rotating coil pair. While the Maxwell coils produced propulsion force, the Helmholtz coil pairs could magnetize and orient the microrobot. Drilling through an obstruction in a vessel was made possible by the system's ability to spin the microrobot around an axis.

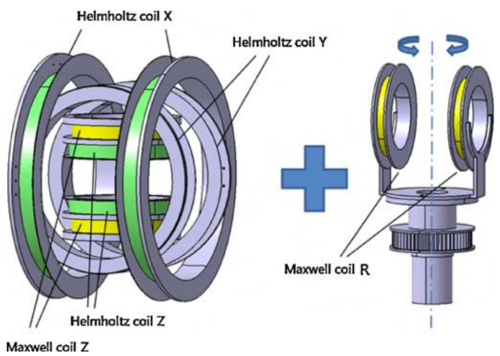

**Fig. 1.** Schematic of an electromagnetic-based actuation (EMA) system [17].

Using permanent magnets and electromagnetic coils, Li et al. [18] effectively achieved synchronized control of the motion position and attitude direction of magnetic microrobots (Fig. 2). A programmable DC power source and a stepper motor made up the drive system, which controls the permanent magnet's attitude and the direction of the magnetic field. NdFeB particles and E-dent400 photosensitive resin were used to create the microrobot, which was then tested on a two- and three-dimensional track that mimicked the veins in the human liver. With an average speed of 1.3 mm/s, the microrobot demonstrated that the drive system could precisely manage its rotational attitude and movement position.

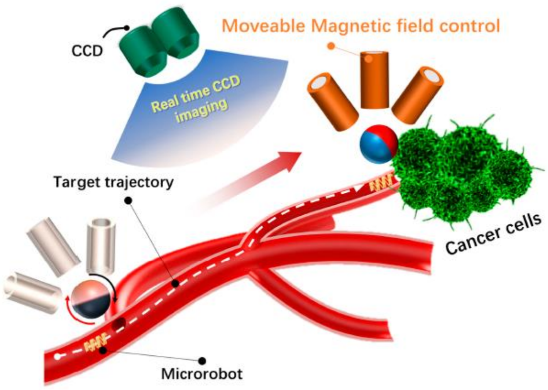

**Fig. 2.** Schematic of an electromagnetic device for a microrobot [18].

Kummer et al. [19] provided wireless magnetic control of a completely untethered microrobot with five degrees of freedom. The microrobot was totally unrestricted in its rotation DOF and could navigate a sizable area. They used an electromagnetic technique they called OctoMag to achieve this degree of wireless control. Its use of complicated nonuniform magnetic fields, which made use of a linear representation of the coupled field contributions of many soft-magnetic-core electromagnets working together, was what gives OctoMag its special capabilities.

By taking into account a non-uniform magnetization profile within the microrobot body, the magnetic actuation approach presented by Diller et al. [20] allowed remote-powered magnetic microrobots to accomplish full six-DOF actuation. This made it possible to use a moment arm to create extra rigid-body torques from magnetic forces. Several discrete-magnetization designs were provided, along with a generic analytical model for continuous and discrete magnetization profiles. To guarantee that a magnetic microrobot design can actuate in six degrees of freedom, design recommendations were presented. To show the correctness of the analytical model in constrained-DOF situations and free motion in a viscous liquid 3-D environment, a basic permanent-magnet prototype was constructed.

Yang et al. [21] described a tiny swimming robot with a flexible link for connection, a nonmagnetic V-shaped head, and an I-shaped tail that was magnetized. By adjusting the input frequencies of an oscillating magnetic field, the robot displayed two vibration modes. While high input frequencies filter high-frequency sounds, the head and tail exhibited comparable vibration amplitudes when input frequencies were below 15 Hz. The forward propelling force was produced by the magnetic tail. To comprehend the whole-body and tail-vibration behaviors of the robot, an analytical model was created. The substrate-water interface was used to characterize the robot's swimming abilities.

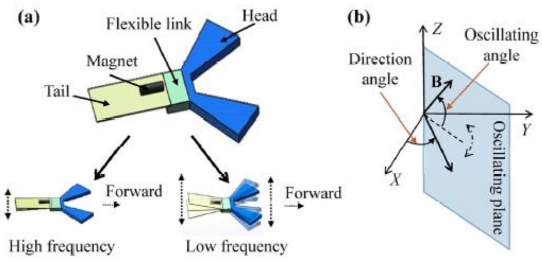


**Fig. 3.** (a) A microrobot designed by Yang et al. [21], and (b) oscillating magnetic field.

Targeting areas inaccessible to catheterization, a unique medical interventional platform based on nanorobotics and nanomedicine was described by Martel et al. [22]. The platform was controlled and navigated in the blood arteries of untethered magnetic carriers, nanorobots, or magnetotactic microorganisms using magnetic resonance imaging. With real-time navigation and trajectory control, the device improved targeting effectiveness and enabled deep-in-the-human body placements. Additional hardware and software components were added to the platform, allowing for operations in challenging areas such as tumoral lesions that were reachable by intricate microvasculature networks.

For targeted medicine administration, real-time X-ray imaging, and microrobot recovery, Nguyen et al. [23] suggested a magnetically guided self-rolled microrobot. The microrobot, which was manufactured using magnetic nanoparticles and focused light, was utilized for X-ray imaging and cancer treatment. Using magnetic field control and computerized targeting, it was accurately deployed to the lesion location. Following delivery, the microrobot was retrieved without any possible toxicity after being photothermally released using near-infrared light. This strategy might overcome the drawbacks of traditional chemotherapy by creating precise localized drug delivery systems.

Although untethered magnetically actuated robots have benefits for biomedical applications, it is still difficult to generate enough force for them to interact with their surroundings. A driving magnet hung between two twisted string actuators made up of the innovative microtransmission system was introduced by Nica et al. [24]. The behavior of the transmission under fixed load and displacement configurations was predicted using an analytical model. Experimental measurements assessed transmission performance over several cycles and confirmed the estimated maximum attainable force. A 3 mm diameter surgical gripper prototype incorporated the transmission, which produced 1.09 N of gripping force with just 20 mT of applied magnetic field. High-strength untethered robots for less invasive surgical applications were made possible by this microtransmission technology.

A technique for producing biocompatible hard magnetic micro/nanomaterials for 3D medical microrobots was presented by Giltinan et al. [25]. The researchers made helical microswimmers from biocompatible trimethylolpropane ethoxylate triacrylate polymer using ferromagnetic and biocompatible iron platinum nanoparticles. At 200 Hz, the helical magnetic microswimmers, which were 30 μm long, could swim more than five body lengths every second. These 3D-printed microrobots were simple to activate, and the produced FePt nanoparticles were experimentally confirmed to be biocompatible in vitro, paving the way for the development of future medical microrobots that were therapeutically feasible.

Dual magnetic/light-responsive self-propelled microrobots that can navigate through a beer sample and pick up yeast cells were presented by Villa et al. [26]. With the help of magnetic nanoparticles, the microrobots operated without fuel and improved their capacity to remove yeast. They eliminated nearly all of the remaining yeasts in an unfiltered beer sample after treatment. Without changing the characteristics of the finished beer, these microrobots may be inserted at the start of fermentation. The food business might take advantage of this creative and affordable approach.

For tumor-targeted imaging and treatment, a photosynthetic biohybrid nanoswimmers system (PBNs) derived from a magnetically manipulated bacterium, Spirulina platensis, was employed by Zhong et al. [27]. Superparamagnetic magnetite was used in the system's fabrication, which enabled magnetic resonance imaging and tumor targeting. By producing oxygen in hypoxic solid tumors through photosynthesis, PBNs increased the efficacy of radiation treatment. Additionally, when exposed to laser radiation, they generated lethal reactive oxygen species, which made photodynamic treatment possible. The PBNs were a potential microrobotic platform for tumor treatment and tumor TME environment monitoring since they also provided photoacoustic imaging and fluorescence-based on chlorophyll.

Indocyanine green nanoparticles and magnetospirillum magneticum were combined by Xing et al. [28] to create an AI microrobot for cancer therapy. Using hypoxia-driven effects and an external magnetic field, the microrobots could swim independently toward the tumor location. Under NIR laser irradiation, photothermal treatment could then eliminate solid tumors. The platform offered a bioinspired approach to focused cargo delivery, remotely controlled propulsion, and effective therapeutic circulation system performance. Real-time motion monitoring, remote-controlled navigation, physiological obstacles, and therapeutic and diagnostic effects made it a viable cancer therapy option.

## 4. Challenges, Research Gaps, and Future Directions

A number of obstacles prevent magnetic microrobots from being widely used in biomedical applications. One of the main problems is the limitations of control systems; electromagnetic methods produce a lot of heat and are limited to defined workspaces, whilst permanent magnet systems frequently have limited degrees of freedom and motion instability. The absence of appropriate imaging techniques with adequate penetration depth makes it difficult to position and monitor microrobots in deep tissues [29].

Scaling accurate manufacturing processes and guaranteeing the long-term safety of the materials utilized are two fabrication and biosafety problems. Addressing magnetic field attenuation in biological tissues and requiring in vivo confirmation further complicates clinical translation. There are research shortages in the areas of creating energy-efficient designs, standardized testing procedures, sophisticated imaging methods, and hybrid control systems. Future objectives include developing machine learning-based control algorithms, enhancing fabrication methods using biodegradable materials, and creating novel system designs, such as mobile electromagnet systems and biohybrid designs.

Clinical validation also requires cooperation with regulatory agencies and extensive in vivo research. Overcoming these obstacles via multidisciplinary research will be essential to transforming magnetic microrobots from lab prototypes to useful clinical instruments.

## 5. Conclusions

Magnetic microrobots have demonstrated considerable potential for accessing and altering microscale environments, particularly in healthcare applications. These robots use magnetic fields for control and propulsion, allowing for precise navigation and untethered operation. Recent advancements in magnetic microrobot design include various propulsion mechanisms, including torque-driven and force-driven systems, as well as innovative manufacturing techniques that enhance their performance and biocompatibility. Biohybrid magnetic microrobots, which mix biological entities with magnetic components, have shown significant potential for targeted drug delivery and microsurgery. The current state of magnetic microrobots is examined in this research, with a focus on their biomedical applications, design methodologies, and actuation strategies. It also discusses the difficulties and future directions in this field, emphasizing how magnetic microrobots might transform medical procedures and microscale manipulation.

Magnetic microrobots face several challenges in biomedical applications, including limitations in control systems, imaging techniques, and ensuring long-term material safety. These issues make it difficult to position and monitor microrobots in deep tissues. Additionally, there are research gaps in energy-efficient designs, standardized testing procedures, sophisticated imaging methods, and hybrid control systems. Future objectives include developing machine learning-based control algorithms, enhancing fabrication methods using biodegradable materials, and creating novel system designs. Clinical validation requires collaboration with regulatory agencies and extensive in vivo research. Overcoming these obstacles through multidisciplinary research is crucial for transforming magnetic microrobots into useful clinical instruments.

## References


[1] Bayareh, M., Nazemi Ashani, M., Usefian, A., 2020. Active and passive micromixers: A comprehensive review, Chem. Eng. Process.: Process Intensif., 147, p. 10777. https://doi.org/10.1016/j.cep.2019.107771

[2] Bayareh, M., 2022. Active cell capturing for organ-on-a-chip systems: a review, Biomedical Engineering, 67, pp. 443-459. 10.1515/bmt-2022-0232.

[3] Ghorbani Kharaji, Z., Bayareh, M., Kalantar, V., 2021. A review on acoustic field-driven micromixers, Int. J. Chem. React. Eng., 19, pp. 553-569. https://doi.org/10.1515/ijcre-2020-0188.

[4] Sourani, S., Bayareh, M., 2025. From theory to application: Exploring the motion dynamics of microrobots, Microchemical Journal, 209, p. 112846. https://doi.org/10.1016/j.microc.2025.112846

[5] S. Palagi, P. Fischer, Bioinspired microrobots, Nature Reviews Materials, 3 (2018) 113-124.

[6] Xu, T., Yu, J., Yan, X., Choi, H., Zhang, L., 2015. Magnetic actuation based motion control for microrobots: An overview, Micromachines, 6, pp. 1346-1364.

[7] Li, j., Pumera, M., 2021. 3D printing of functional microrobots, Chemical Society Reviews, 50, pp. 2794-2838.

[8] Sitti, M., Wiersma, D.S., 2020. Pros and cons: Magnetic versus optical microrobots, Advanced Materials, 32, p. 1906766.

[9] Jiang, J., Yang, Z., Ferreira, A., Zhang, L., 2022. Control and autonomy of microrobots: Recent progress and perspective, Advanced Intelligent Systems, 4, p. 2100279.

[10] Yang, L., Zhang, L., 2021. Motion control in magnetic microrobotics: From individual and multiple robots to swarms, Annual Review of Control, Robotics, and Autonomous Systems, 4, pp. 509-534.

[11] Yu, S., Cai, Y., Wu, Z., He, Q., 2021. Recent progress on motion control of swimming micro/nanorobots, View, 2, p. 2020011.

[12] Chowdhury, S., Jing, W., Cappelleri, D.J., 2015. Controlling multiple microrobots: recent progress and future challenges, Journal of Micro-Bio Robotics, 10, pp. 1-11.

[13] Dodampegama, S., Mudugamuwa, A., Konara, M., Perera, N., De Silva, D., Roshan, D., Amarasinghe, R., Jayaweera, N., Tamura, N., 2022. A review on the motion of magnetically actuated bio-inspired microrobots, Applied Sciences, 12, p. 11542.

[14] Palagi, S., Singh, D.P., Fischer, P., 2019. Light-controlled micromotors and soft microrobots, Advanced Optical Materials, 7, p. 1900370.

[15] Ye, M., Zhou, Y., Zhao, H., Wang, Z., Nelson, B.J., Wang, X., 2023. A review of soft microrobots: Material, fabrication, and actuation, Advanced Intelligent Systems, 5, p. 2300311.

[16] Diller, E., Giltinan, J., Sitti, M., 2013. Independent control of multiple magnetic microrobots in three dimensions, The International Journal of Robotics Research, 32, pp. 614-631.

[17] Yu, C., Kim, J., Choi, H., Choi, J., Jeong, S., Cha, K., Park, J.O., Park, S., 2010. Novel electromagnetic actuation system for three-dimensional locomotion and drilling of intravascular microrobot, Sensors and Actuators A: Physical, 161, pp. 297-304.

[18] Li, H., Zhang, Z., Yi, X., Jin, S., Chen, Y., 2024. Control of self-winding microrobot using an electromagnetic drive system: integration of movable electromagnetic coil and permanent magnet, Micromachines, 15, p. 438.

[19] Kummer, M.P., Abbott, J.J., Kratochvil, B.E., Borer, R., Sengul, A., Nelson, B.J., 2010. OctoMag: An electromagnetic system for 5-DOF wireless micromanipulation, IEEE Transactions on Robotics, 26, pp. 1006-1017.

[20] Diller, E., Giltinan, J., Lum, G.Z., Ye, Z., Sitti, M., 2016. Six-degree-of-freedom magnetic actuation for wireless microrobotics, The International Journal of Robotics Research, 35, pp. 114-128.

[21] Yang, L., Wang, Q., Vong, C.I., Zhang, L., 2017. A miniature flexible-link magnetic swimming robot with two vibration modes: design, modeling and characterization, IEEE Robotics and Automation Letters, 2, pp. 2024-2031.

[22] Martel, S., Felfoul, O., Mathieu, J.B., Chanu, A., Tamaz, S., Mohammadi, M., Mankiewicz, M., Tabatabaei, N., 2009. MRI-based medical nanorobotic platform for the control of magnetic nanoparticles and flagellated bacteria for target interventions in human capillaries, The International Journal of Robotics Research, 28, pp. 1169-1182.

[23] Nguyen, K.T., Go, G., Jin, Z., Darmawan, B.A., Yoo, A., Kim, S., Nan, M., Lee, S.B., Kang, B., Kim, C.S., 2021. A magnetically guided self-rolled microrobot for targeted drug delivery, real-time X-Ray imaging, and microrobot retrieval, Advanced Healthcare Materials, 10, p. 2001681.

[24] Nica, M., Forbrigger, C., Diller, E., 2022. A novel magnetic transmission for powerful miniature surgical robots, IEEE/ASME Transactions on Mechatronics, 27, pp. 5541-5550.

[25] Giltinan, J., Sridhar, V., Bozuyuk, U., Sheehan, D., Sitti, M., 2021. 3D microprinting of iron platinum nanoparticle-based magnetic mobile microrobots, Advanced Intelligent Systems, 3, p. 2000204.

[26] Villa, K., Vyskočil, J., Ying, Y., Zelenka, J., Pumera, M., 2020. Microrobots in brewery: dual magnetic/light-powered hybrid microrobots for preventing microbial contamination in beer, Chemistry–A European Journal, 26, pp. 3039-3043.

[27] Zhong, D., Li, W., Qi, Y., He, J., Zhou, M., 2020. Photosynthetic biohybrid nanoswimmers system to alleviate tumor hypoxia for FL/PA/MR imaging-guided enhanced radio-photodynamic synergetic therapy, Advanced Functional Materials, 30, p. 1910395.

[28] Xing, J., Yin, T., Li, S., Xu, T., Ma, A., Chen, Z., Luo, Y., Lai, Z., Lv, Y., Pan, H., 2021. Sequential magneto-actuated and optics-triggered biomicrorobots for targeted cancer therapy, Advanced Functional Materials, 31, p. 2008262.

[29] Li, Y., Huo, Y., Chu, X., Yang, L., 2024. Automated Magnetic Microrobot Control: From Mathematical Modeling to Machine Learning, Mathematics, 12, p. 2180.