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Navigating Challenges in Micro- and Nano-Robotics for Medical Advances: An Explanatory Review

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Abstract: Micro- and nano-robotics involve creating and controlling robots at microscopic and nanoscopic scales, applicable in fields like medicine, electronics, and environmental monitoring. These robots, less than a millimeter in size, promise advances in targeted drug delivery, minimally invasive surgeries, and precise medical interventions. In electronics, they improve manufacturing and assembly precision. Environmental uses include pollutant detection and data collection in hazardous areas. Fabrication techniques for these robots include micro-electromechanical systems (MEMS), 3D printing, nanolithography, self-assembly, and DNA origami. Actuation methods utilizing magnetic fields, acoustic waves, and light are necessary for their operation. Challenges such as power supply, control and navigation, sensor integration, and biocompatibility must be addressed. Overcoming these requires interdisciplinary collaboration across engineering, physics, chemistry, and biology. Despite these challenges, advancements continue, promising significant benefits across various industries. The potential applications of micro- and nano-robots in enhancing medical treatments, improving manufacturing processes, and advancing environmental monitoring are vast and continually expanding.

Keywords: Micro-robots, Nano-robots, Targeted drug delivery, MEMS, 3D printing, Nanolithography, Biocompatibility, Environmental monitoring

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Introduction

Micro- and nano-robotics represent inter-disciplinary areas that revolve around creating, producing, and governing miniature robots at incredibly small scales. These diminutive machines, known as micro-bots and nanobots, are usually less than a millimeter in size and find applications across numerous domains, such as medicine, electronics, manufacturing, and environmental monitoring (Ying *et al.*, 2019).

The field of micro- and nano-robotics involves a collaborative effort between multiple disciplines, including engineering, physics, chemistry, and biology. Researchers and scientists collaborate to design and fabricate these minuscule robots using cutting-edge technologies and techniques. The ultimate goal is to manipulate and control these micro-bots and nanobots in complex environments with high precision and accuracy (Dong *et al.*, 2020).

In the medical field, micro-bots and nanobots hold immense promise for applications in targeted drug delivery, minimally invasive surgeries, and precise medical interventions. By constructing these tiny robots, researchers aim to navigate through the human body to deliver drugs to specific locations or perform delicate procedures without invasive surgeries (Zeeshan *et al.*, 2013). In electronics, micro- and nano-robotics have the potential to revolutionize the manufacturing and assembly processes of electronic components. These robots can be employed to manipulate and position tiny electronic components with unparalleled precision, enhancing the performance and reliability of electronic devices. Additionally, micro-bots and nanobots are crucial for environmental monitoring tasks. They can be deployed in hard-to-reach or hazardous environments to gather data, detect pollutants, or even aid in disaster management.To construct these miniature robots, advanced fabrication techniques are employed, including micro-electromechanical systems (MEMS) and nanofabrication processes. MEMS technology enables the production of microscale devices with moving parts, while nanofabrication techniques allow the creation of nanoscale structures with intricate functionalities. The control and operation of micro-bots and nanobots present significant challenges due to their small size and the constraints of working at such scales. Researchers use various control strategies, such as magnetic fields, acoustic waves, or light manipulation, to guide and navigate these tiny robots. As research and development in the field of micro- and nano-robotics continue to progress, the potential applications are expected to grow exponentially, further benefiting diverse industries and pushing the boundaries of what is achievable at the micro and nanoscale (Pourrahimi *et al.*, 2013).

Key aspects of micro- and nano-robotics

Actuation:

The actuation of these tiny robots involves different mechanisms, as conventional methods used in larger robots may not be suitable due to their size. Three common actuation methods for micro- and nano-robots are:

Magnetic Fields: Many micro and nano-robots are equipped with magnetic materials or particles, allowing them to be actuated through external magnetic fields. By applying varying magnetic fields, these robots can be directed and controlled with precision (Breger *et al.*, 2015).

Acoustic Waves: Some micro and nano-robots are designed to respond to acoustic waves. By manipulating sound waves in the environment, these robots can be guided and moved to specific locations for various tasks (Sridhar *et al.*, 2020).

Light: Light actuation is another technique used for micro and nano-robots. By employing light-sensitive materials or photonic forces, these robots can be propelled and maneuverer with the help of lasers or other light sources. The development of these innovative actuation methods has opened up new possibilities for applications in fields such as medicine, environmental monitoring, and manufacturing, where the small size and precise control of micro and nano-robots offer unique advantages (Nocentini *et al.*, 2018).

Size and Shape: Micro-robots are in the micrometre to millimetre size range, while nano-robots are even smaller, operating at the nanometre scale. Their different size categories give them distinct advantages and capabilities for various applications in fields such as medicine, manufacturing, and scientific research (Aghakhan *et al.*, 2020).

Fabrication Techniques

This is for micro- and nano-robots involving advanced processes that enable precise manufacturing at extremely small scales. Some of the key specialized techniques used in this field include:

Micro-electro-mechanical systems (*MEMS*): MEMS technology involves the integration of miniaturized mechanical and electrical components on a semiconductor chip.

3D Printing/Additive Manufacturing: Additive manufacturing techniques have evolved to work at micro- and nanoscales, allowing the creation of complex geometries with high precision. Techniques like two-photon lithography and nano-3D printing enable the fabrication of intricate structures with resolutions down to the nanometre level (Villa and Pumera, 2019).

Nanolithography: Nanolithography refers to a group of techniques used to pattern nanoscale structures on various substrates. These techniques include electron-beam lithography (e-beam lithography), focused ion beam (FIB) lithography, and nanoimprint lithography, among others. They allow researchers to create patterns and structures at the nanoscale with high accuracy and control (Erin *et al.*, 2020).

Self-assembly: Self-assembly is a technique where materials are designed to spontaneously arrange themselves into desired structures. It relies on the intrinsic properties of the materials to form complex patterns without external guidance, making it a promising approach for the fabrication of nano-robots with minimal human intervention (Wang and Pumera, 2020).

DNA Origami: DNA origami is a technique that uses DNA molecules as programmable "scaffolds" to self-assemble into specific shapes at the nanoscale. By manipulating the DNA sequence, researchers can create nanoscale structures with great precision, offering potential applications in the construction of nanorobots (Huang *et al.*, 2020).

Applications of nano-robots in medical field (Fig. 1)

Biosensor: In conventional medical examinations, human tissues are analyzed using a variety of physical and chemical techniques in disciplines such as immunology, microbiology, biochemistry, hematology, and cytology. The development of precision medicine has led to increasing need for greater precision and precision in these tests. But conventional medical examination techniques possess limits. As an inspection technique, biosensors can identify biological data in samples. Conventional biosensors frequently call for rigorous sample conditions. Power supply, control and navigation, sensor integration, and biocompatibility for medical applications are some of the difficulties that micro- and nano-robots must overcome during development (Wang *et al.*, 2019). In order to address the power requirements of these devices, researchers are looking into energy harvesting methods and smaller batteries. Their effective deployment depends on control and navigation, and sophisticated control algorithms and strategies are being created through the use of machine learning and artificial intelligence approaches. Real-time feedback and environmental awareness depend on sensor integration, and nanoscale MEMS (Micro-Electro-Mechanical Systems) are being investigated for this purpose. Materials must be non-toxic and biocompatible in order to be used in medical applications. To overcome these obstacles, interdisciplinary cooperation amongst specialists in robotics, materials science, engineering, biology, and medicine is required (Patiño *et al.*, 2018).

Diagnosis: As demonstrated by procedures like endoscopy or biopsy, it is difficult to access deep tissues without causing discomfort or stress to patients because traditional medical examinations generally function at a macro level. Furthermore, metal interference or patient movement may affect some imaging tests, such as

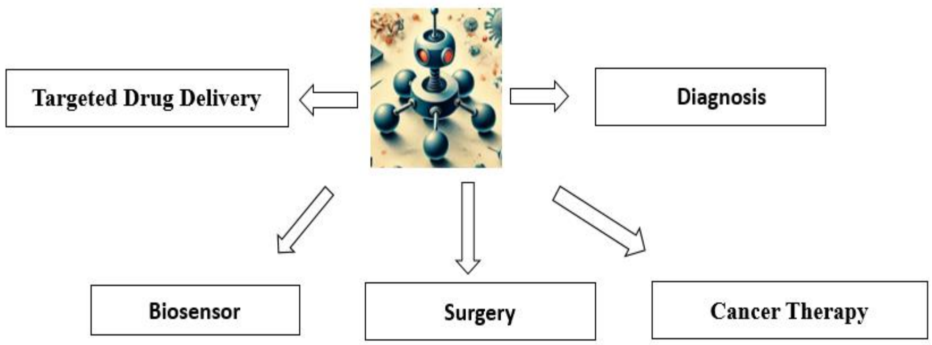

Fig. 1: Applications of Micro- and Nano-Robotics.

those utilizing radiation or magnetic resonance imaging. When diagnosing intestinal disorders, micro/nanorobots may eventually take the role of traditional endoscopes. There are certain disadvantages to the well-established clinical procedure of traditional colonoscopy, which involves direct intestinal inspection and biopsy (Table 1). Its increased size in comparison to microscopic items may make patients uncomfortable or injure them during the process. Additionally, there are intrinsic restrictions to operating and observing in specific intestinal blind spots during inspections (Kong *et al.*, 2018).

Targeting drug delivery: Systemic circulation is the main component of the conventional drug delivery pathway; nevertheless, it has drawbacks such low tissue permeability and local drug delivery capacity, which lead to ineffective drug administration. These difficulties can be adder-ssed, though, as microrobot technology advances. Targeting deep tissues for accurate drug delivery through the use of microrobots for drug trans-porttation increases delivery efficiency and lowers doses including optical, magnetic and even pH-based methods. Avoiding the consequences of chemical propulsion that can potentially damage human circulatory and tissue systems, magnetic propulsion in particular stands out as a safer option.

Numerous magnetic drive-powered micro- and nanorobotic systems have been developed, demonstrating improved *in vitro* and *in vivo* drug delivery efficiency (Erkoc *et al.*, 2019).

Surgery: There is a growing need for less trauma and more accuracy in achieving surgical goals as surgical techniques advance, especially with the introduction of less invasive procedures. Conventional methods, whether open or minimally invasive, face difficulties in accessing deep tissue and in performing operations in extremely small spaces. These difficulties should be lessened with the advent of micro/ nanorobotics in surgical settings. Under the guidance of external stimuli, these tiny robots are made to accurately navigate and gather at predetermined locations. Their small size makes it possible to pass through capillary networks to areas that would be impossible to reach with traditional surgical techniques, allowing for cellular-scale interventions. This skill signals great opportunities for therapeutic treatments by reducing the size of surgical incisions and shortening the recovery period (Jia *et al.*, 2018).

Cancer Therapy: Chemotherapy and radiation therapy for cancer frequently harm both cancerous and healthy cells. Micro/nanorobots can be designed to specifically target and eliminate cancer cells without harming healthy tissues. It is possible to program these robots to identify particular cancer cell markers. As an illustration, DNA nanobots have been created to locate and attach to cancer cells, releasing

Table 1: List of recent advancements of Nano Robots in the Medical Field (2020-2025)

Advancement	**Description**	**References**
Precision Surgery	Nano robots capable of performing microsurgeries with high precision.	Soto *et al*. (2020)
Immunotherapy Enhancement	Nano robots boosting the effectiveness of immunotherapy treatments.	Kong *et al.* (2023)
Stem Cell Delivery	Nano robots facilitating the delivery and integration of stem cells into tissues.	Chen *et al.* (2022a)
Biodegradable Nano Robots	Development of biodegradable nano robots that safely dissolve after use.	Rahimi *et al.* (2023)
Targeted Radiation Therapy	Nano robots delivering radioactive particles to tumor sites, enhancing therapy precision.	Wang *et al.* (2022)
Non-invasive Blood Sugar Monitoring	Nano robots providing continuous and non-invasive blood glucose monitoring.	Di Fillipo *et al.* (2023)
Personalized Medicine	Nano robots enabling personalized treatment plans based on individual genetic profiles.	Mahmood *et al.* (2024)
Intracellular Imaging	Nano robots that provide high-resolution images of cellular structures.	Chen *et al.* (2022b)
Bio-integrated Nano Robots	Development of bio-integrated nano robots for seamless integration with human tissues.	Ban *et al*. (2025)
Cancer Treatment	Nano robots used for the targeted destruction of cancer cells through thermal ablation.	Zhang *et al.* (2025)
Biohybrid Nano Robots	Combining biological cells with synthetic materials for advanced functionalities.	Maleki *et al.* (2022)
Biofilm Disruption	Nano robots breaking down biofilms to enhance the effectiveness of treatments.	Martinez *et al.* (2024)
Epigenetic Therapy	Nano robots delivering agents for epigenetic modifications to treat diseases.	Al-Joufi *et al.* (2022)
Metastasis Prevention	Nano robots targeting and preventing the spread of metastatic cancer cells.	Zhou *et al.* (2024)
Nano Robots in Orthopedics	Use of nano robots in orthopedic surgery for improved outcomes.	Abaszadeh *et al.* (2023)
Nano Robots in Pulmonology	Use of nano robots in the treatment of lung diseases and conditions.	Pradeep *et al.* (2023)

medication only upon identifying the malignant indicators (Table 1) (Xu *et al.*, 2018).

Challenges

Power supply, control and navigation, sensor integration, and biocompatibility for medical applications are some of the difficulties that micro- and nano-robots must overcome during development. In order to address the power requirements of these devices, researchers are looking into energy harvesting methods and smaller batteries. Their effective deployment depends on control and navigation, and sophisticated control algorithms and strategies are being created through the use of machine learning and artificial intelligence approaches. Real-time feedback and environmental awareness depend on sensor integration, and nanoscale MEMS (Micro-Electro-Mechanical Systems) are being investigated for this purpose. Materials must be non-toxic and biocompatible in order to be used in medical applications. To overcome these obstacles, interdisciplinary cooperation amongst specialists in robotics, materials science, engineering, biology, and medicine is required (Palagi *et al.*, 2019).

Robots are also being used in long-term care settings, such as daily tasks, medication dispensing, remote monitoring, rehabilitation assistance, data collection and analysis, and telemedicine support. However, challenges remain, such as ensuring patient safety, addressing ethical concerns, maintaining a human touch in care giving, and adapting technology to diverse patient needs and preferences (Singh *et al.*, 2019).

Conclusion

The field of micro- and nano-robotics, despite its inherent challenges, holds immense potential to revolutionize various sectors, particularly medicine and environmental monitoring. As advancements in fabrication techniques such as micro-electromechanical systems (MEMS), 3D printing, nanolithography, self-assembly, and DNA origami continue to evolve, the precision and functionality of these tiny robots will enhance significantly. The ability to operate at microscopic and nanoscopic scales allows for groundbreaking applications, including targeted drug delivery, minimally invasive surgeries, and precise pollutant detection. However, realizing the full potential of micro- and nano-robots requires addressing several key challenges. Power supply, control and navigation, sensor integration, and biocompatibility remain significant hurdles. Innovative solutions, such as using magnetic fields, acoustic waves, and light for actuation, are being explored to overcome these obstacles. Additionally, interdisciplinary collaboration among engineers, physicists, chemists, and biologists is crucial for developing robust and efficient micro- and nano-robotic systems. The future of micro- and nano-robotics is promising, with ongoing research and development paving the way for extensive applications. In medicine, these robots can transform how diseases are treated, offering highly targeted therapies and reducing the need for invasive procedures. In environmental monitoring, they can provide precise and efficient methods for detecting and mitigating pollutants, contributing to a healthier planet. As technological advancements continue, micro- and nano-robots are poised to become integral tools in various industries. Their potential to improve healthcare outcomes and enhance environmental protection underscores the importance of continued investment and research in this dynamic field. With persistence and innovation, the challenges facing micro- and nano-robotics can be surmounted, leading to significant scientific and practical breakthroughs.

Conflict of Interest

The authors declare no conflicts of interest.

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