EAI Endorsed Transactions
on AI and Robotics

Review Article EAI.EU

Microrobots for the Healthcare System from Design to Application — State of the Art and Challenges

Ata Jahangir Moshayedi[1,*], Amir Sohail Khan[1], Mehdi Davari[2], Tahmineh Mokhtari[3,4] Mehran Emadi Andani[5]

[1]School of Information Engineering, Jiangxi University of Science and Technology, Ganzhou, Jiangxi, 341000, China
[2]Department of Management, Dolatabad Branch, Islamic Azad University, Isfahan, Iran
[3]Department of Pharmacology, Hubei University of Medicine, Shiyan, China
[4]Department of Histology and Embryology, Faculty of Basic Medical Sciences, Hubei University of Medicine, Shiyan, China
[5]Department of Neuro Sciences Bio-medicine and Movement Sciences, University of Verona, Via Casorati, Verona, Italy

Abstract

Micro robots, miniature robotic devices typically ranging from micrometers to a few millimeters in size, hold immense potential in various fields, particularly healthcare. Their diminutive stature enables access to intricate anatomical regions previously unreachable, facilitating targeted drug delivery, localized treatment, and precise monitoring. These robots offer numerous advantages, including enhanced maneuverability, reduced invasiveness, and minimized tissue damage. By navigating through complex biological environments, micro robots can deliver therapies with unprecedented precision, improving treatment efficacy and patient outcomes. Additionally, their small size allows for minimally invasive procedures, reducing recovery times and enhancing patient comfort. Overall, micro robots represent a groundbreaking technological advancement with the potential to revolutionize healthcare delivery and significantly benefit human well-being. Their small size enables access to intricate anatomical regions for targeted drug delivery, localized treatment, and precise monitoring. Despite challenges like size constraints and navigation complexities, innovative solutions and interdisciplinary collaboration are driving their advancement in improving healthcare outcomes.

Received on 01 April 2024; accepted on 12 April 2024; published on 12 April 2024

Keywords: Micro robot, Healthcare, Robotic application, Design

doi:10.4108/airo.5602

1. Introduction

Micro robots represent groundbreaking technology, particularly in healthcare, offering targeted therapies, precise interventions, and the ability to navigate within the body [1]. Among these, microscopic swimming robots, also known as micro swimmers, have demonstrated significant potential in medical treatment. These tiny robotic devices, commonly referred to as micro-robots or miniature robots, are intricately designed to execute various tasks on a small scale. Typically, they possess dimensions on the order of micrometers or millimeters and are crafted using advanced microfabrication techniques [2]. Micro robots deployed for internal navigation within the human body are engineered with specific functionalities and structures tailored for maneuvering through intricate blood vessels [3]. Although the field of micro robots is still in its nascent stages, researchers anticipate numerous potential benefits from their application in human physiology. One compelling application of these micro swimmers is in targeted drug delivery. By affixing drugs to the surface of these micro swimmers, they can be directed precisely to targeted areas within the body where their therapeutic effects are most needed [4].

*Corresponding author. Email: ajm@jxust.edu.cn

Such precision targeting holds the promise of reducing side effects associated with conventional treatments and enhancing overall treatment efficacy.
The aim of this study is to provide a comprehensive review of the current state of art and challenges in the field of microrobots in healthcare. By examining the design, development, and application of microrobots in healthcare settings, we aim to highlight their potential in revolutionizing healthcare practices and improving patient outcomes. To ensure the reliability and accuracy of our findings, we utilized proper scientific search engines and databases to identify relevant studies and select suitable journals for inclusion in this review. By adopting a rigorous approach to the search process, we aim to present a thorough and up-to-date overview of the advancements, limitations, and future prospects of microrobots in healthcare.

2. The Historical Evolution of Microrobots

The evolution of micro robots is a fascinating journey spanning several decades, characterized by notable technological and robotic advancements [5, 6]. This journey can be segmented into seven stages: Early Concepts, Electromechanical Systems, Microelectromechanical Systems (MEMS) and Nanotechnology, Biologically Inspired Designs, Medical and Biological Applications, Advancements in Control and Navigation, and Integration with IoT and Wearable Technologies. Each stage represents a significant milestone in the development of micro robotics, showcasing innovation and progress in various fields as its shown in Figure 1.

As the Figure 1 shown the history of micro robot consist of seven stages as follows.

1. **Early Concepts (1950s-1960s):** The idea of miniaturized robots, capable of performing tasks at a microscopic scale, began to emerge in the 1950s and 1960s. Early discussions and conceptualizations focused on the potential applications of tiny machines for medical procedures and industrial tasks [7].

2. **Electromechanical Systems (1970s-1980s):** During the 1970s and 1980s, researchers and engineers started experimenting with electromechanical systems that could mimic basic movements and functions of larger robots. These systems often relied on simple actuators and sensors, paving the way for more sophisticated designs [8].

3. **MEMS and Nanotechnology (1990s-2000s):** The advent of Microelectromechanical Systems (MEMS) and advancements in nanotechnology in the 1990s and 2000s revolutionized the field of micro robotics. MEMS technology enabled the fabrication of tiny components with precise control over dimensions and functionality. This era saw the development of micro sensors, actuators, and integrated circuits essential for micro robot design [9, 10].

4. **Biologically Inspired Designs (2000s-Present):** In the 2000s and beyond, micro robots began to draw inspiration from biological systems, leading to the emergence of bio-inspired robotics. Researchers explored concepts such as swarm robotics, where multiple tiny robots collaborate to achieve complex tasks resembling behaviors seen in nature, such as collective foraging or pattern formation [11].

5. **Medical and Biological Applications (2000s-Present):** One of the significant areas of application for micro robots is in medicine and biology. Micro robots have been developed for tasks like targeted drug delivery, minimally invasive surgery, and exploratory procedures within the human body. These robots often leverage advanced materials and control mechanisms to navigate intricate environments safely [12].

6. **Advancements in Control and Navigation (2010s-Present):** Recent years have seen remarkable progress in control and navigation systems for micro robots. Advanced algorithms, including artificial intelligence and machine learning, play a crucial role in enabling autonomous and adaptive behavior in these miniature machines. Additionally, improvements in power sources and energy-efficient designs have extended the operational capabilities of micro robots [13].

7. **Integration with IoT and Wearable Technologies (2010s-Present):** The integration of micro robots with the Internet of Things (IoT) and wearable technologies has opened up new possibilities for applications in areas such as environmental monitoring, disaster response, and personalized healthcare. Micro robots can work in concert with larger systems or operate independently as part of distributed networks [14].

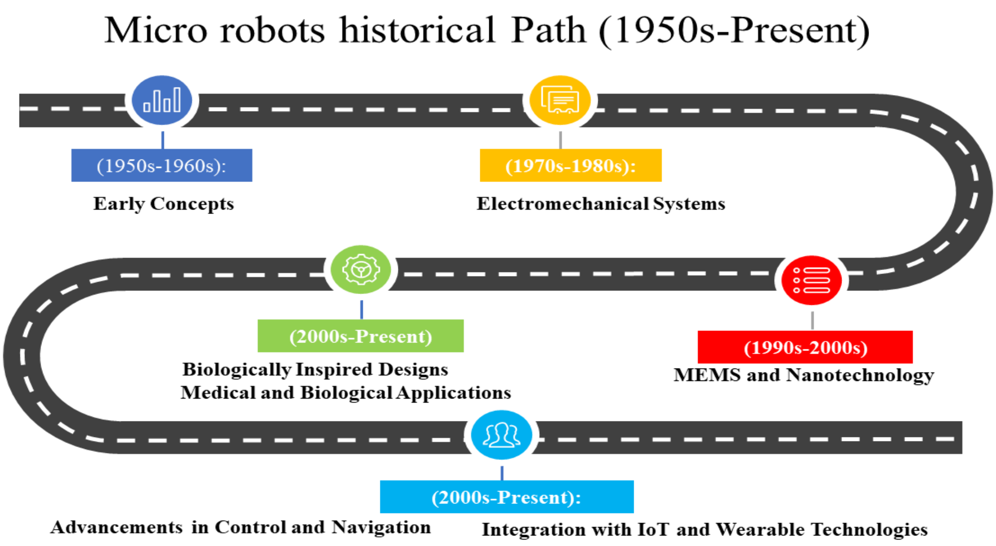

Figure 1. The micro robot history over the years

Table 1. The microrobot application in Human diseases

Disease	Micro Robot Application	Ref
Cancer	Targeted drug delivery to cancerous tumors, enhancing chemotherapy effectiveness.	[19]
Cardio-vascular	Navigation through blood vessels to remove arterial plaque. Delivery of drugs within blood vessels.	[20]
Neurological Disorders	Treatment of brain tumors,aneurysms, and neurovascular diseases through drug delivery in brain regions.	[21]
Gastro-intestinal Disorders	Diagnosis and treatment of gastrointestinal diseases, including locating polyps Delivery of medication within the gastrointestinal tract.	[22]
Respiratory Diseases	Drug delivery to lung tissues in conditions like lung cancer or pulmonary infections. Aid in minimally invasive lung surgeries.	[23]
Infectious Disease	Applications in identifying and eliminating infectious agents within the body, aiding in viral infections.	[24]
Diabetes	Precise delivery of insulin to manage blood sugar levels.	[25]
Autoimmune Disorders	Delivery of immune-modulating medications directly to affected tissues.	[26]
Genetic Disorders	Delivery of gene-editing tools to specific cells or tissues for gene therapy to treat genetic disorders at their source.	[27]
Orthopedic Conditions	Maintenance of orthopedic implants such as artificial joints or bone grafts, improving long-term outcomes of procedures.	[28]
Eye Disorders	Precise delivery of drugs or therapeutic agents to targeted regions within the eye, aiding in the treatment of retinal diseases.	[29]
Urological Disorders	Targeted drug delivery or removal of kidney stones and tumors in urological conditions, reducing the need for invasive procedures.	[30]

The historical evolution of micro robots reflects a trajectory of innovation driven by interdisciplinary collaboration, technological breakthroughs, and a growing understanding of the potential impact of these tiny yet powerful machines in various fields.The Microrobots find applications in targeted drug delivery and minimally invasive surgery in biomedical settings, while also contributing to pollution monitoring and micro-scale manipulation in environmental contexts. Additionally, they play a role in micro assembly and quality control processes within various industrial sectors [15]. With respect to area of use , there are some area and disease that micro robots can be applied. Robotics in medicine encompasses targeted drug delivery [16], surgery assistance [17], and diagnostic support [18] across various fields are shown in Table 1.

3. Advantages and Disadvantages

Micro robots in healthcare excel in targeted drug delivery, minimally invasive surgery, disease diagnosis, and monitoring, targeted imaging and therapy, and microsurgery, offering precise treatments, proactive healthcare, and advancements in tissue engineering. Micro robots offer customized treatment options, ensuring that healthcare interventions are tailored to individual patient needs, leading to improved outcomes and enhanced precision in medical care [31]. The main advantage of these robots can be listed as follows.

1. **Targeted Drug Delivery:** Micro robots can be engineered to transport drugs or therapeutic agents to specific locations within the body with precision. They can navigate through the

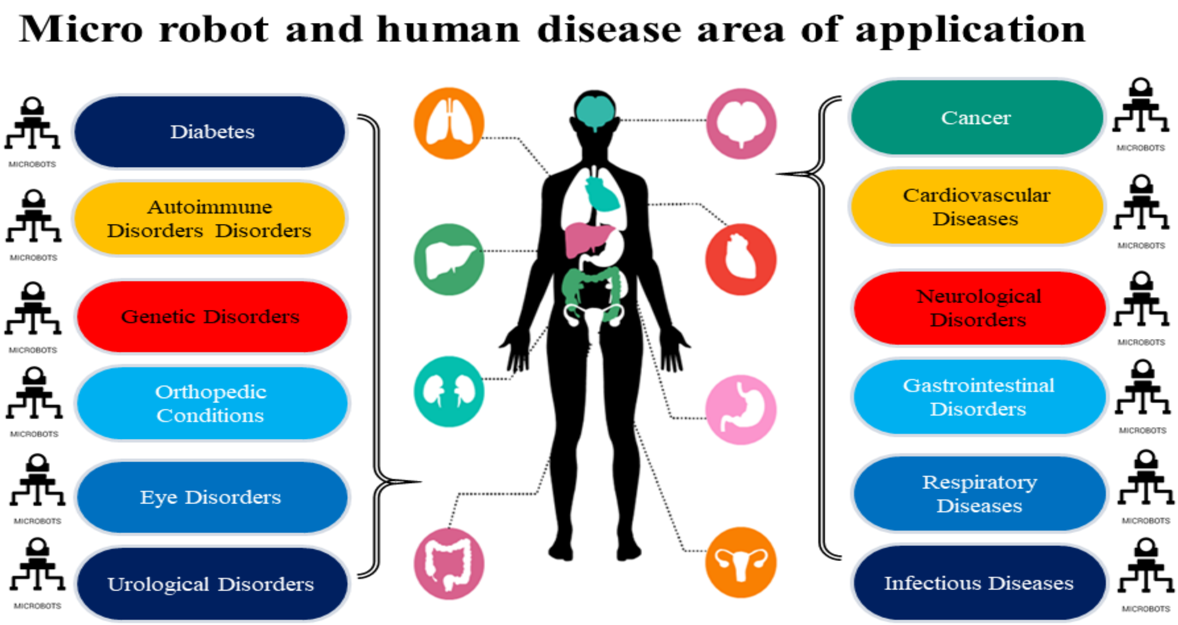

Figure 2. Micro Robot and human disease area of application

bloodstream, cross biological barriers, and deliver medications directly to diseased tissues or organs. This targeted drug delivery can enhance the effectiveness of treatments while minimizing side effects [32].

2. **Minimally Invasive Surgery:** Micro robots have the potential to revolutionize surgical procedures by enabling minimally invasive interventions. These tiny robots can be guided through small incisions or natural orifices, allowing surgeons to access delicate areas of the body that would otherwise require more invasive techniques. They can assist in tasks such as tissue repair, removal of tumors, or precise suturing [33].

3. **Disease Diagnosis and Monitoring:** Micro robots could be used as diagnostic tools, capable of reaching inaccessible areas to gather tissue samples, perform biopsies, or detect early signs of diseases. Additionally, they can continuously monitor various physiological parameters, such as glucose levels or blood pressure, and transmit real-time data to healthcare providers, enabling personalized and proactive healthcare [34].

4. **Targeted Imaging and Therapy:** Micro robots can be equipped with imaging capabilities, such as tiny cameras or sensors, allowing them to capture high-resolution images of specific areas inside the body. These images can provide valuable information for diagnosis or help guide therapeutic interventions. Furthermore, Micro robots can be used to deliver localized therapies, such as heat or light, directly to targeted tissues for more precise and effective treatments [35].

5. **Microsurgery and Tissue Engineering:** Micro robots have the potential to aid in delicate microsurgeries, where their small size and precise control can be advantageous. They can assist in procedures involving delicate blood vessels, nerves, or other tiny anatomical structures. Moreover, Micro robots can be utilized in tissue engineering approaches to assemble and manipulate cells or bio-engineered constructs, enabling the development of complex and functional tissue [36].

It's important to note that while microrobots hold significant promise in these areas, many challenges remain to be addressed, including ensuring their safety, biocompatibility, and effective control mechanisms. Clinical trials and rigorous testing are necessary before widespread adoption of microrobots in the treatment of these diseases and conditions. Additionally, the specific design and capabilities of microrobots may vary depending on the intended medical application [37]. Figure 2 shows the microrobot and human disease area of applications that was mentioned in the table 1. This paper focuses on their benefits, features, design, materials, navigation methods, limitations, and control mechanisms, aiming to understand their potential fully.

4. Type of Microbots

Micro robots come in various types, each designed for specific applications and equipped with unique features [38]. some common types of micro robots based on their design and functionality can be summarized as Biological(biohybrid, cell-based, nanobiobots), Synthetic (MEMS/NEMS, soft, swarm, bio-inspired), and Functional(medical, environmental, industrial), and hybrid (bio-synthetic). Used in medical, environmental, and industrial fields, Offering precise tasks like drug delivery and monitoring which is described as follows:

1. **Biological Microrobots:** These robots encompass three main types: Biohybrid Robots, Cell-Based Robots, and Nanobiobots. **Biohybrid Robots** microrobots combine biological components, such as cells or tissues, with synthetic materials [39]. They can exhibit behaviors similar to living organisms and are often used in biomedical applications, such as targeted drug delivery or tissue engineering. **Cell-Based Robots** are built using living cells, such as bacteria or mammalian cells, integrated into a synthetic structure. They can be programmed to perform tasks like sensing chemicals or moving in response to external stimuli [40]. **Nanobiobots** are Nanoscale robots made from biological materials, such as DNA or proteins, capable of performing nanoscale operations like molecular assembly or manipulation [41].

2. **Synthetic Microrobots:** This group comprises four types of robots: MEMS and Nanoelectromechanical Systems (NEMS) Robots, Soft Robots, Swarm Robots, and Bio-Inspired Robots. **MEMS/NEMS Robots** are fabricated using micro- and nano-scale engineering techniques. They typically feature miniaturized actuators, sensors, and control systems for precise manipulation and sensing tasks [42]. **Soft Robots** are made from flexible or compliant materials, allowing them to deform or change shape for versatile locomotion and manipulation. Soft robots are suitable for applications requiring interactions with delicate environments or biological tissues. Micro robots are designed to work in groups or swarms named Swarm Robots, coordinating their actions to achieve collective goals [43]. **Swarm robotics** principles are inspired by behaviors observed in natural systems, such as ant colonies or bird flocks [44]. **Bio-Inspired Robots** as the group inspired by biological organisms or structures, such as insect-like robots for agile locomotion, fish-inspired robots for underwater exploration, or bird-inspired robots for aerial surveillance [45].

3. **Functional Microrobots:** The third category encompasses Medical Microrobots, Environmental Microrobots, and Industrial Microrobots [46]. **Medical Microrobots** Designed specifically for medical applications, these microrobots can navigate through the body's tissues, deliver drugs to targeted locations, perform minimally invasive surgeries, or assist in diagnostic procedures [47]. **Environmental Microrobots** Used for environmental monitoring and remediation tasks, such as detecting pollutants in water or soil, cleaning up microplastics, or exploring hazardous environments [48] and **Industrial Microrobots** Employed in manufacturing and industrial processes, including micro assembly, quality control inspections, and maintenance tasks in confined spaces [49].

4. **Hybrid Microrobots:** Combining biological and synthetic elements to create hybrid microrobots [50] named as **Bio-Synthetic Hybrids** with enhanced functionalities, such as self-repair mechanisms, adaptive behaviors, or biocompatibility for medical applications [51].

Some of the current types of Micro robots used for navigating inside the human body can be listed as bellow;

1. **Flagellated Micro robots:** These Micro robots mimic the motion of bacterial flagella for propulsion. They have a helical or corkscrew-shaped structure that enables efficient movement through bodily fluids. Flagellated Micro robots offer good maneuverability and can navigate complex environments. However, their fabrication and control can be challenging, and their potential for payload delivery is still being explored [52].

2. **Acoustic Micro Robots:** These Micro robots use acoustic waves to generate propulsion and navigate through fluids. They can be controlled externally using acoustic fields and offer potential for targeted drug delivery and imaging applications. Acoustic Micro robots have the advantage of being non-invasive and can work in various bodily fluids. However, their miniaturization and integration of sensors pose technical challenges [53].

3. **Nano Robots:** Nanorobots are nanoscale robots designed for precise manipulation at the cellular or molecular level. They can perform tasks such as drug delivery, imaging, or sensing. Nanorobots offer high precision and the potential for targeted therapy. However, their development is still in the early stages, and challenges related to manufacturing, control, and biocompatibility need to be addressed [54].

4. **Biohybrid Micro Robots:** These Micro robots combine biological components, such as living

cells or tissues, with synthetic materials to create hybrid systems. They can leverage biological properties, such as self-propulsion or targeting abilities, while benefiting from synthetic control mechanisms. Biohybrid Micro robots offer enhanced biocompatibility and potential for complex tasks. However, their integration of biological components and maintaining long-term functionality pose challenges [55].

5. **Magnetic Micro Robot:** These Micro robots are propelled using external magnetic fields. They are typically made of biocompatible materials and can be guided through blood vessels with precision. They offer good controllability and have the potential for targeted drug delivery. However, their payload carrying capacity is limited due to their small size [56].

When comparing these Micro robots, it's important to consider factors such as propulsion mechanism, controllability, payload capacity, biocompatibility, and specific application requirements. Each type of micro robot has its own strengths and limitations, and ongoing research is focused on addressing these challenges to enhance their capabilities and enable their widespread use in various biomedical applications.

5. Key Features and Functions of Micro robots in design

Micro robots in healthcare possess characteristics such as small size for navigating blood vessels safely, diverse propulsion methods like magnetic fields or biological-inspired mechanisms, built-in sensors for environment detection, precise steering and control mechanisms, capability to carry payloads like drugs or imaging agents for targeted delivery, bio compatibility through the use of safe materials, and various power sources including miniature batteries or energy harvesting from the body's environment [57]. The common design aspect can be listed as bellow:

1. **Size:** Micro robots are typically on the scale of micrometers or nanometers, allowing them to navigate through small blood vessels without causing obstruction or damage [57].

2. **Propulsion:** Micro robots employ various methods of propulsion to move within the bloodstream. Some common propulsion mechanisms include using magnetic fields, acoustic waves, or biological-inspired mechanisms like flagella or cilia [57].

3. **Sensors:** Micro robots often have built-in sensors to detect and respond to their environment. These sensors can include imaging sensors, chemical sensors, or other types of sensors that help the micro robot navigate, detect specific locations, or identify targets [57].

4. **Steering and Control:** Micro robots have mechanisms for steering and control, allowing them to change direction and move precisely within blood vessels. This can be achieved through the use of external magnetic fields, microactuators, or by manipulating the flow of fluids [57].

5. **Payload and Delivery:** Micro robots can carry payloads such as drugs, nanoparticles, or imaging agents. They are designed to deliver these payloads to specific targets within the body, providing targeted therapy or diagnostic capabilities [57].

6. **Biocompatibility:** Micro robots need to be biocompatible to ensure they do not cause harm or elicit an immune response when inside the body. They are often made from biocompatible materials to minimize adverse effects [57].

7. **Power Source:** Micro robots may require a power source for their propulsion and operation. This can be achieved using miniature batteries, wireless energy transfer, or harvesting energy from the surrounding environment, such as utilizing blood flow or temperature gradients [57].

The exact structure and functionality of Micro robots can vary depending on their intended application and the specific engineering approach employed. micro robots offer a paradigm shift in healthcare by combining targeted delivery, precise interventions, and remote capabilities, leading to more effective treatments, improved patient experiences, and advancements in medical research and innovation.

5.1. Design Considerations and steps for Micro robots

Designing micro robots for internal navigation involves addressing unique challenges and considering multiple factors to ensure their efficacy and safety in intricate anatomical environments [58]. This process encompasses four major parts of Shape and Structure, Navigation Sensors, Flexibility and Adaptability and Biocompatible Materials as follows:

- **Shape and Structure:** Micro robots designed for navigating complex anatomical environments must have streamlined shapes and structures to minimize friction and obstruction. Their size and form factor should allow them to maneuver through narrow passages and tight spaces without causing tissue damage [58].

- **Navigation Sensors:** Integration of advanced navigation sensors such as cameras, ultrasound, magnetic sensors, or micro-MEMS gyroscopes enables precise localization and mapping within the body, facilitating accurate navigation through intricate anatomical structures [58].

- **Flexibility and Adaptability:** Micro robots may require flexible or deformable structures to navigate through dynamic anatomical environments where structures can change shape or position. Adaptive mechanisms, such as soft robotics or shape-changing technologies, enhance the robot's ability to navigate diverse anatomical configurations [58].

- **Biocompatible Materials:** Materials used in micro robot construction must be biocompatible to ensure compatibility with biological systems and minimize the risk of immune responses or tissue damage. Biocompatible polymers, metals, and biomaterials are commonly employed in micro robot design [58].

To adhere to the design process, the key design considerations for micro robots in internal navigation are outlined in the following Table 2.

Table 2. Design Steps considerations for Micro Robots in internal Navigation's

Aspect	Description
Design Consideration	Factors include size, shape, materials, power source, locomotion mechanisms, and payload capacity, tailored to the intended application and operating environment.
Miniaturization	Focuses on shrinking components using microelectronics, microactuators, and microsensors to achieve the small scale required for navigating.
Materials Selection	Critical choice of biocompatible, lightweight, durable materials capable of withstanding operating conditions.
Fabrication Methods	Techniques such as MEMS technology, 3D printing, microfluidics, and nanotechnology enable precise manufacturing of microscale components.
Integration of components	Involves combining sensors, actuators, power sources, and control systems into a compact design, requiring careful engineering for seamless operation and compatibility.
Testing and Validation	Rigorous testing for functionality, reliability, durability, and safety, particularly crucial in medical applications.
Scalability	Considerations for mass production scalability to meet demand for widespread deployment in healthcare and other industries.

5.2. Materials Used in Micro Robot Construction

Various materials can be used in the construction of Micro robots for navigating inside the human body. The choice of material depends on factors such as biocompatibility, mechanical properties, functionality, and the specific application of the micro robot. The selection of materials depends on the specific requirements of the micro robot, including its function, compatibility with the human body, and desired physical properties [59]. some commonly used materials can be listed as follows:

1. **Biocompatible Polymers:** Biocompatible polymers, such as polyethylene glycol (PEG), poly(lactic-co-glycolic acid) (PLGA), or polydimethylsiloxane (PDMS), are often used due to their compatibility with biological systems and low toxicity [59].

2. **Magnetic Materials:** Micro robots that are propelled using magnetic fields often incorporate magnetic materials, such as ferromagnetic nanoparticles or magnetic alloys like nickel or cobalt. These materials can respond to external magnetic fields for controlled movement [59].

3. **Biodegradable Materials:** In some cases, Micro robots are designed to degrade or dissolve inside the body after completing their tasks. Biodegradable materials like magnesium alloys, silk-based materials, or hydrogels are employed to ensure the Micro robots do not leave any long-term foreign bodies [59].

4. **Shape Memory Alloys:** Shape memory alloys, such as nitinol (a nickel-titanium alloy), have unique properties that allow them to change shape when exposed to heat or electrical currents. These alloys can be used in Micro robots to achieve reversible changes in shape for navigation or manipulation [59].

5. **Nanoparticles:** Micro robots may incorporate nanoparticles, such as gold nanoparticles or quantum dots, for imaging, drug delivery, or sensing purposes. These nanoparticles can be functionalized with specific ligands or molecules to enhance targeting or therapeutic capabilities [59].

6. **Hybrid Materials:** Micro robots can be constructed using combinations of different materials to leverage their individual properties. For example, a micro robot may have a polymer body with magnetic nanoparticles embedded for propulsion [59].

5.3. Sensing Feedback

Sensing methods are vital for micro robots, enabling precise navigation, interaction with the environment, and detection of biological markers or pollutants. They facilitate tasks such as obstacle avoidance, surface sensing, and environmental monitoring, enhancing the robots' adaptability and effectiveness [60]. Overall, sensing methods play a crucial role in enabling the functionality and autonomy of micro robots across various applications. The sensing method consist of Vision-Based Sensing , Tactile Sensing , Chemical Sensing as follows.

1. **Vision-Based Sensing:** Utilizes cameras or imaging sensors to capture visual information, enabling micro robots to perceive their surroundings and navigate based on visual cues [60].

2. **Tactile Sensing:** Involves sensors that detect touch or pressure, allowing micro robots to interact with objects and surfaces, sense texture, and detect obstacles or changes in the environment [60].

3. **Chemical Sensing:** Incorporates sensors capable of detecting chemical substances or biomarkers, enabling micro robots to perform tasks such as drug delivery, environmental monitoring, or medical diagnostics [60].

By leveraging these sensing modalities, integrating sensors for feedback control(Closed-Loop Control and Sensor Fusion) along with embracing advancements in miniaturized sensing technologies, micro robots can enhance their perception, navigation, manipulation, and interaction capabilities in complex anatomical environments and various application domains.

5.4. Micro Robots Navigation Techniques

These navigation techniques are continuously advancing with innovations in robotics, sensor technology, and medical imaging, contributing to the development of more sophisticated and capable micro robots for biomedical applications [61, 62]. Navigation techniques for micro robots inside the human body include magnetic guidance for precise control, wireless communication for feedback, optical tracking for visualization, and sensor integration for environment awareness. These methods enable accurate navigation, adaptability to dynamic conditions, and enhanced safety during medical procedures. common navigation techniques used for micro robots inside the human body can be listed below.

1. **Magnetic Navigation:** Magnetic navigation utilizes external magnetic fields to guide and control micro robots within the body. These robots are typically equipped with magnetic components that respond to changes in the magnetic field, allowing for precise navigation along desired paths. Magnetic navigation is especially useful in scenarios where direct line-of-sight or physical contact is limited, such as navigating through blood vessels or reaching deep-seated tissues [63].

2. **Wireless Communication and Feedback Control:** Micro robots often rely on wireless communication systems to receive instructions and transmit feedback data. Feedback control mechanisms, such as closed-loop systems, enable real-time adjustments in response to environmental changes or navigational challenges. This ensures accurate navigation and enhances the robot's ability to adapt to dynamic conditions inside the body [64].

3. **Optical Tracking and Imaging:** Optical tracking methods, including cameras or optical sensors, are employed to track the position and movement of micro robots. Imaging techniques such as fluorescence imaging or endoscopic imaging provide real-time visual feedback, allowing operators to monitor the robot's location and trajectory during navigation. Optical tracking is particularly useful for procedures requiring precise localization and visualization, such as tissue targeting or organ exploration [65].

4. **Ultrasound Guidance:** Ultrasound technology is utilized to provide guidance and imaging for micro robots operating inside the body. Ultrasound waves can penetrate tissues, allowing for non-invasive visualization of anatomical structures and the robot's position relative to surrounding tissues. Ultrasound guidance is valuable for navigating through organs or cavities where direct visibility is limited, enhancing the robot's navigational accuracy and safety [65].

5. **Sensor-Based Navigation:** Micro robots often integrate various sensors, such as proximity sensors, pressure sensors, or environmental sensors, to gather information about their surroundings. Sensor data is processed to generate navigation commands, detect obstacles, or adjust the robot's trajectory in real time. Sensor-based navigation enhances the robot's ability to navigate complex and dynamic environments while avoiding collisions or hazards [65].

These navigation techniques are continuously advancing with innovations in robotics, sensor technology, and medical imaging, contributing to the development of more sophisticated and capable micro robots for biomedical applications. These considerations are crucial for developing Micro robots that can navigate through the complex network of blood vessels, deliver payloads, and perform specific tasks with precision.

Table 3. Micro robot Navigation Technique principle along merit and demerit

Technique	Principle	Advantages	Disadvantages
Magnetic Guidance	Controls Movement	Precise Control, Non Invasive	Limited range of movement
Wireless Communication	Wireless signals for control and feedback	Real time adjustments	Limited range
Optical Tracking	Visual tracking and imaging techniques	Real time visualization, precise localization	limited in certain environments
Sensor Integration	Integrates sensors for environmental awareness	Adaptability to dynamic conditions	Data processing complexity

5.5. Micro Robots Control Methods

Micro robots controlling methods inside the human body [66] can be summarized as follows:

1. **Magnetic Control:** Magnetic control using external magnetic fields offers precise control and guidance for Micro robots. It allows for targeted navigation through blood vessels. Magnetic control is particularly beneficial when the micro robot needs to be steered with high accuracy to specific locations. However, it requires the micro robot to be within the range of the external magnetic field source, which may limit its mobility and effective range [66].

2. **On-board Actuation:** This method involves incorporating on-board actuation mechanisms, such as synthetic flagella, within the micro robot itself. On-board actuation provides autonomous propulsion and maneuverability, allowing the micro robot to navigate through bodily fluids. It offers more freedom of movement compared to externally controlled Micro robots. However, the complexity of fabricating and controlling the on-board actuation mechanisms can be a challenge [66].

3. **Acoustic Control:** Acoustic control uses external acoustic fields to manipulate and guide Micro robots. It offers non-invasive control and can work in various bodily fluids. Acoustic control is advantageous when precise control is not required, and a larger area can be influenced by the acoustic field. However, miniaturization and integration of acoustic control systems can be technically challenging [66].

4. **External Control for Nanorobots:** Nanorobots can be externally controlled using various methods such as magnetic fields, ultrasound, or light. External control provides versatility and enables precise manipulation of nanorobots. It allows for flexible control strategies and facilitates targeted delivery and manipulation at the cellular or molecular level. However, the challenge lies in developing reliable and scalable methods for external control at the nanoscale [66].

5. **Biohybrid Control:** Biohybrid Micro robots combine biological and synthetic control mechanisms. This approach leverages the unique properties of biological components for autonomous control while incorporating synthetic control mechanisms for additional functionality. Biohybrid control can offer enhanced adaptability and responsiveness. However, designing and fabricating biohybrid Micro robots are complex processes that require expertise in both biological and synthetic systems [67].

The general comparison of the controlling methods are shown in Table 4.

6. Discussion and Conclusion

The need for micro robots stems from their ability to improve precision, efficiency, safety, and innovation across various industries, making them indispensable tools in modern technological advancements [68]. Micro robots can help in healthcare for surgeries and drug delivery, in manufacturing for precise assembly, and in environmental monitoring for pollution detection. Regarding the used materials in micro robot ,The Table 5 provides a comprehensive overview, including the material types commonly used in micro robot development. it's important to note that the specific materials utilized can vary depending on the micro-bot's design, application, and technological advancements [69, 70]. A The shape and structure considerations listed in the table highlight important aspects of micro robot design for efficient navigation and interaction within the human body.The road map for the micro robots are shown in figure 3. The figure completely describes the whole pattern of micro robots starting from type, applications, design, navigation methods, controlling methods, materials that can be used and finally sensing and feedback.

Table 4. A general comparison of the controlling methods and their suitability for different scenarios

Type	Method	Advantages	Disadvantages
Magnetic	External magnetic fields	Precise Control and guidance	Limited range of control
Flagellated	On-board actuation mechanism	Autonomous propulsion and maneuverability	Complexity in fabrication and control of the flagellated structures.
Acoustic	VExternal acoustic fields	Non-invasive control using external acoustic fields	Challenges in miniaturization and integration of acoustic control system
Nano Robots	External control or Internal biological control	Various external and internal control methods depending on the specific design	Development of reliable and scalable methods for external and internal control.
Biohybrid	Combination biological and Synthetic control mechanism	Integration of biological properties with synthetic control mechanism	Complex design and fabrication processes for integrating biological and synthetic components.

The comparison between the shows Each navigation technique operates based on its specific principle, offering distinct advantages and disadvantages. Magnetic Guidance relies on external magnetic fields for movement control, providing precise control while being non-invasive. Wireless Communication utilizes wireless signals, enabling real-time adjustments and adaptability, yet is susceptible to signal interference and limited in range. Optical Tracking relies on visual techniques for real-time visualization and precise localization but requires line-of-sight and may be restricted in certain environments. Sensor Integration incorporates sensors for environmental awareness, offering adaptability to dynamic conditions but facing challenges such as sensor calibration and data processing complexity. The accuracy of each technique varies based on factors such as environmental conditions and sensor capabilities. Micro robots used to navigate inside the human body face several limitations and difficulties. Some of the key challenges can be listed as follows;

The controlling methods mentioned in the Table 6 highlight the different approaches used to navigate and control Micro robots inside the human body. Each method has its own advantages and challenges, and the choice of controlling method depends on factors such as the specific application, micro robot design, and desired level of control precision. Ongoing research aims to improve the effectiveness and versatility of controlling methods for Micro robots, enabling them to perform complex tasks with greater accuracy and efficiency. Determining the "best" controlling method for Micro robots used for navigating inside the human body depends on various factors, including the specific application, desired level of control, and the micro robot's design constraints. Different controlling methods offer unique advantages and have their own limitations. It's important to note that the choice of controlling method depends on the specific requirements and constraints of the application. Researchers are continuously exploring and developing new controlling methods and techniques to improve the capabilities and control precision of Micro robots for biomedical applications.

- **Size and Scale(challenge:Limited Space and Constrained Movements):** Creating Micro robots small enough to navigate through the intricate network of blood vessels can be challenging. Fabricating and manipulating components at the micro or nanoscale requires advanced manufacturing techniques and precision engineering. The human body's internal spaces impose constraints on micro robot movement, limiting their range of motion and maneuverability. **As the Solution** Designing micro robots with compact yet efficient locomotion mechanisms, such as micro-wheels, micro-treads, or soft actuators, allows for effective movement in confined spaces while maintaining maneuverability.

- **Power and Energy(challenge: Power Supply and Endurance):** Providing power to Micro robots is a significant challenge. Miniaturized power sources with sufficient capacity for sustained operation are limited. Energy-efficient propulsion mechanisms and strategies for energy harvesting from the body's environment are being explored. Micro robots require adequate power sources that can sustain prolonged operation inside the body without compromising performance. **As the Solution** Integrating miniaturized power sources, such as micro-batteries, fuel cells, or wireless power transfer systems, along with energy-efficient design strategies and power management techniques, ensures sustained operation and endurance of micro robots.

- **Biocompatibility (challenge: Biocompatibility and Safety):** Ensuring the biocompatibility of Micro robots is crucial. They must not trigger an immune response or cause harm to surrounding

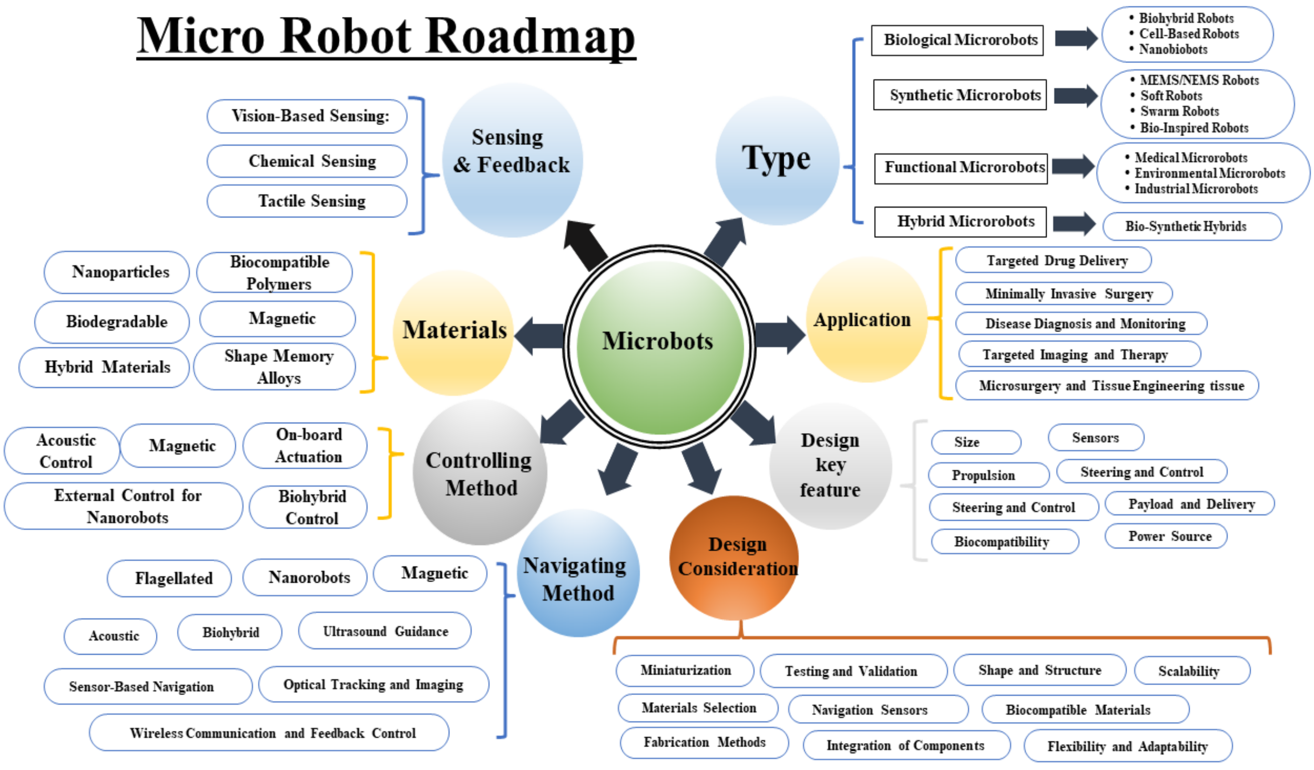

Figure 3. Micro Robot Road-map

tissues. Selecting suitable materials and surface modifications to minimize adverse reactions is a complex task. Ensuring that micro robots are biocompatible and pose minimal risk to biological tissues and organs is critical for their safe deployment in medical applications. **As the Solution** Conducting thorough biocompatibility testing, using non-toxic and bioresorbable materials, and implementing fail-safe mechanisms to prevent unintended interactions with the body's physiological processes mitigate risks and enhance the safety of micro robots.

- **Navigation and Control (challenge:Navigation in Fluidic Environments)** Navigating through the complex and dynamic environment of blood vessels presents significant challenges. Micro robots need precise control and maneuverability to avoid obstacles and reach the desired targets. Developing effective control strategies and autonomous navigation algorithms is a complex task.Fluid-filled anatomical structures pose challenges for micro robots, affecting their stability and control during navigation. **As the Solution** Implementing control algorithms and feedback systems that compensate for fluid dynamics, along with designing specialized coatings or surfaces to minimize drag and enhance stability, improves micro robot performance in fluidic environments.

- **Communication and Localization:** Micro robots often need to transmit data or receive instructions for navigation and operation. Establishing reliable communication within the body is challenging due to signal attenuation and interference. Additionally, localizing the Micro robots within the body with high precision is a difficult task.

- **Payload Delivery and Release:** Releasing payloads, such as drugs or nanoparticles, at specific targets requires precise control and timing. Ensuring controlled release mechanisms that respond to specific triggers or stimuli is a significant challenge.

- **Safety and Ethical Considerations:** Micro robots are still in the early stages of development, and their safety and ethical implications need to be thoroughly studied. Assessing potential risks, ensuring patient safety, and addressing ethical concerns are essential aspects of their deployment.

Table 5. Overall Micro robots design consideration

Aspect	Description	Materials	Advantages	Disadvantages
Size and scale	Micro Robots are designed to be small enough to navigate through blood vessels.	Biocompatible Polymers, Magnetic Materials, Biodegradable Materials, Shape Memory Alloys, Nanoparticles	Ability to access narrow and intricate blood vessels.	Manufacturing challenges at micro or nanoscale.
Power System	Micro Robots required a power source for sustained operations.	Miniature Batteries, Wireless energy transfer, Energy harvesting technologies	Potential for energy harvesting from the body's environment.	Limited capacity of miniaturized power sources
Bio compatibility	Micro Robots must be compatible to avoid harm and immune responses	Biocompatible Polymers, Biodegradable Materials, Surface Modifications	Compatibility with biological systems and reduced toxicity.	Ensuring complete biocompatibility and minimizing adverse reactions.
Navigation Control	Micro Robots needs precise control and maneuverability for navigations	Magnetic materials, Micro-actuators, Shape memory alloys, Control Systems	Compatibility to navigate through complex and dynamic blood vessels environment.	Developing effective control strategies and autonomous navigation algorithm
Communication	Micro Robots may require communication for data transmission and instructions	Wireless communication technologies, Nanoscale Sensors, Signal Implications Systems	Potential for communication within the body for coordination and control	Signal attenuation and interference challenges within the body.
Payload	Micro Robots can carry payloads for targeted therapy images.	Biocompatible polymers, nanoparticles	Targeted delivery of drugs, nanoparticles or imaging agents	Ensuring control and timely release mechanism at specific targets.
Safety Ethics	Consideration regarding the safety and ethical implications of micro-bot technology	-	Through evaluation of potential risks and ethical concerns	Comprehensive assessment and addressing of safety and ethical considerations
Validation Regulations	Rigorous testing, validation, and regulatory	-	Ensuring safety, efficacy, and reliability through rigorous testing	Meeting regulatory requirements can be time consuming and complex

Table 6. Micro robot Type performance and aspect comparison.Precision(Pr), Accuracy(Acc), Moderate(M) ,High(H)

Type	Principle	Part	Advantages	Disadvantages	Pr	Acc
Flagellated	Mimics bacterial flagella	Helical structure	Good maneuverability, complex navigation	Fabrication and control challenges, payload limitations	M	M
Acoustic	Uses acoustic waves	Acoustic components	Non-invasive, potential for targeted drug delivery and imaging	Miniaturization and sensor integration challenges	M	H
Nanorobots	Precise manipulation at cellular/molecular levels	Nanoscale components	High precision, potential for targeted therapy	Early-stage development, manufacturing challenges, biocompatibility concerns	H	H
Biohybrid	Combines biological and synthetic components	Biological and synthetic materials	Enhanced biocompatibility, complex task capabilities	Integration challenges, long-term functionality maintenance	H	M
Magnetic	Propelled by external magnetic fields	Magnetic components	Precise navigation in blood vessels, controllability	Limited payload capacity due to size constraints	H	H

- **Validation and Regulatory Hurdles:** Before Micro robots can be used in clinical applications, rigorous testing, validation, and regulatory approvals are necessary. Meeting the requirements set by regulatory bodies for safety, effi- ... can be a complex and time-

Despite these challenges, ongoing research and advancements in nanotechnology, robotics, and biomedicine continue to push the boundaries of micro robot development. Collaboration among researchers from various fields is crucial in addressing these limitations and overcoming the difficulties associated with micro robot technology.As the ongoing research Several cutting-edge projects worldwide focus on microrobots for targeted drug delivery, minimally invasive surgery, and navigating through the human body. These projects include initiatives like MAGMIR, M$\hat{3}$, STIFF-FLOP, NRL's micro robotics research, MICRO ROBOT, nanorobotics for drug delivery, micro swimmers for biomedical applications, and smart micro/nanorobots for healthcare, showcasing the diverse applications and advancements in this field. These are shown in Table 7.

Several ongoing research projects shown in table 7 are pushing the boundaries of medical robotics, each with distinct focuses and objectives. The MAGMIR project, led by the University of Houston, delves into the realm of magnetic microrobots engineered for targeted drug delivery and minimally invasive surgical procedures. These microrobots are designed to respond to external magnetic fields, offering precise control and maneuverability within the body. Meanwhile, the M$\hat{3}$ initiative at the Wyss Institute for Biologically Inspired Engineering at Harvard University is pioneering the development of micro and mobile medical robots.
These tiny robots are envisioned to navigate through the human body, facilitating procedures such as clearing blocked arteries with unprecedented precision. In Europe, the STIFF-FLOP project, backed by the European Union, focuses on soft and flexible robotics tailored for minimally invasive surgeries. By creating robots capable of traversing confined spaces within the body, STIFF-FLOP aims to revolutionize surgical techniques, potentially minimizing patient trauma and expediting recovery. These projects represent concerted efforts to harness the potential of micro robotics in advancing healthcare delivery and improving patient outcomes.

References

[1] Moshayedi, A. J., Fard, S. S., Liao, L., & Eftekhari, S. A. (2019). Design and development of pipe inspection robot meant for resizable pipe lines. Int. J. Robot. Control, 2(1), 25.

[2] Sun, W., Li, J., Qiu, J., & Sun, Y. (2024). Biomimetic nano/microfabrication techniques in multi-bioinspired superhydrophobic wood: new insight on theory, design and applications. Surfaces and Interfaces, 104217.

[3] Li, P., Wang, Z., Ye, C., Fang, D., Zhang, J., & Liang, C. (2024). Development and verification of a micro magnetically guided helical robot with active locomotion and steering capabilities for guidewires. Sensors and Actuators A: Physical, 115123.

[4] Moshayedi, A. J., & Gharpure, D. C. (2012, May). Development of position monitoring system for studying performance of wind tracking algorithms. In ROBOTIK 2012; 7th German Conference on Robotics (pp. 1-4). VDE.

[5] Chen, Y., Chen, D., Liang, S., Dai, Y., Bai, X., Song, B., ... & Feng, L. (2022). Recent advances in field-controlled micro–nano manipulations and micro–nano robots. Advanced Intelligent Systems, 4(3), 2100116.

[6] Esfahani, O. T., & Moshayedi, A. J. (2014). Accuracy of the Positioning Systems for the Tracking of Alzheimer's Patients-A Review. International Journal of Applied Electronics in Physics & Robotics, 2(2), 10-16.

[7] Kasina, H., Bahubalendruni, M. R., & Botcha, R. (2017). Robots in medicine: past, present and future. International Journal of Manufacturing, Materials, and Mechanical Engineering (IJMMME), 7(4), 44-64.

[8] Zeng, J. (2022, January). The development trend of robots. In 2021 International Conference on Social Development and Media Communication (SDMC 2021) (pp. 1261-1265). Atlantis Press.

[9] Tai, Y. C. (2012). Introduction to MEMS. Microsystems and Nanotechnology, 187-206.

[10] Nikalje, A. P. (2015). Nanotechnology and its applications in medicine. Med chem, 5(2), 081-089.

[11] Moshayedi, A. J., & Gharpure, D. C. (2017, May). Evaluation of bio inspired Mokhtar: Odor localization system. In 2017 18th international carpathian control conference (ICCC) (pp. 527-532). IEEE.

[12] Zhang, D., Gorochowski, T. E., Marucci, L., Lee, H. T., Gil, B., Li, B., ... & Yeatman, E. (2023). Advanced medical micro-robotics for early diagnosis and therapeutic interventions. Frontiers in Robotics and AI, 9, 1086043.

[13] Chen, Y., Chen, D., Liang, S., Dai, Y., Bai, X., Song, B., ... & Feng, L. (2022). Recent advances in field-controlled micro–nano manipulations and micro–nano robots. Advanced Intelligent Systems, 4(3), 2100116.

[14] Maheswari, B. U., Imambi, S. S., Hasan, D., Meenakshi, S., Pratheep, V. G., & Boopathi, S. (2023). Internet of things and machine learning-integrated smart robotics. In Global Perspectives on Robotics and Autonomous Systems: Development and Applications (pp. 240-258). IGI Global.

[15] Mehmood, U., Agyekum, E. B., Kamel, S., Shahinzadeh, H., & Moshayedi, A. J. (2022). Exploring the roles of renewable energy, education spending, and co2 emissions towards health spending in South Asian countries. Sustainability, 14(6), 3549.

[16] Cai, Z., Fu, Q., Zhang, S., Fan, C., Zhang, X., Guo, J., & Guo, S. (2021). Performance evaluation of a magnetically driven microrobot for targeted drug delivery. Micromachines, 12(10), 1210.

[17] van Mulken, T. J., Qiu, S. S., Jonis, Y., Profar, J. J., Blokhuis, T. J., Geurts, J., ... & van der Hulst, R. R. (2023). First-in-Human Integrated Use of a Dedicated Microsurgical Robot with a 4K 3D Exoscope: The Future of Microsurgery. Life, 13(3), 692.

[18] Babeer, A., Oh, M. J., Ren, Z., Liu, Y., Marques, F., Poly, A., ... & Koo, H. (2022). Microrobotics for precision biofilm diagnostics and treatment. Journal of Dental Research, 101(9), 1009-1014.

[19] Ojha, S., Bhusan Singh, R., Shukla, A., Chadha, H., & Mishra, S. (2024). Micro and Nano Robotics-assisted Targeted Drug Delivery, Surgery and Radiotherapy for Cancer Treatment. Current Cancer Therapy Reviews,

Table 7. Micro robots Current project and ongoing research

Project Name	Description
Magnetic Microrobots(MAGMIR)	University of Houston project focusing on magnetic microrobots for targeted drug delivery and minimally invasive surgery, controlled by external magnetic fields.
M$\hat{3}$ (Micro and Mobile Medical Robot)	Wyss Institute for Biologically Inspired Engineering at Harvard University initiative creating tiny robots guided through the human body for medical procedures like clearing blocked arteries.
STIFF-FLOP	European Union-funded project on soft and flexible robotics for minimally invasive surgery, developing robots to navigate through confined spaces within the body.
NRL(NanoRobotics Laboratory)	École Polytechnique Fédérale de Lausanne (EPFL) project on medical microrobotics, including microrobots for targeted drug delivery.
MICRO ROBOT(Microbiorobotics for Single Cell Manipulation)	Institute of Robotics and Intelligent Systems, ETH Zurich project exploring microrobots for manipulating single cells in cell biology research and regenerative medicine.
Nanoengineered Particles for Targeted Drug Delivery	Collaborative project among multiple research institutions focusing on nanorobots for precise drug delivery to cancer cells and other targets.
Microswimmers for Biomedical Applications	Various research teams studying microswimmers (microrobots in fluid environments) for drug delivery and navigating through the circulatory system.
Smart Micro/Nanorobots for Healthcare	A broad category encompassing global projects exploring smart microrobots for healthcare applications such as diagnosis, surgery, and drug delivery.

20(1), 18-25.

[20] Doutel, E., Galindo-Rosales, F. J., & Campo-Deaño, L. (2021). Hemodynamics challenges for the navigation of medical microbots for the treatment of CVDs. Materials, 14(23), 7402.

[21] Tian, M., Ma, Z., & Yang, G. Z. (2024). Micro/nanosystems for controllable drug delivery to the brain. The Innovation, 5(1).

[22] Zhang, Y., Zhang, Y., Han, Y., & Gong, X. (2022). Micro/nanorobots for medical diagnosis and disease treatment. Micromachines, 13(5), 648.

[23] Patole, V., Tupe, A., Tanpure, S., Swami, R., Vitkare, V., & Jadhav, P. (2024). Nanorobotic artificial blood components and its therapeutic applications: A minireview. Irish Journal of Medical Science (1971-), 1-10.

[24] Ozaydin, M. S., Doganturk, L., Ulucan-Karnak, F., Akdogan, O., & Erkoc, P. (2022). Contemporary tools for the cure against pernicious microorganisms: micro-/nanorobots. Prosthesis, 4(3), 424-443.

[25] SHEVKAR, N. (2024). NANOROBOTS: AN EMERGING TOOL IN MEDICAL SCIENCE (Doctoral dissertation, Trinity College).

[26] Xing, G., Yu, X., Zhang, Y., Sheng, S., Jin, L., Zhu, D., ... & Lv, F. (2024). Macrophages-Based Biohybrid Microrobots for Breast Cancer Photothermal Immunotherapy by Inducing Pyroptosis. Small, 20(7), 2305526.

[27] Safdar, M., Ullah, M., Wahab, A., Hamayun, S., Rehman, M. U., Khan, M. A., ... & Naeem, M. (2024). Genomic insights into heart health: Exploring the genetic basis of cardiovascular disease. Current Problems in Cardiology, 49(1), 102182.

[28] Silvera-Tawil, D. (2024). Robotics in Healthcare: A Survey. SN Computer Science, 5(1), 189.

[29] Chen, B., Sun, H., Zhang, J., Xu, J., Song, Z., Zhan, G., ... & Feng, L. (2024). Cell-Based Micro/Nano-Robots for Biomedical Applications: A Review. Small, 20(1), 2304607.

[30] Rassweiler, J. J., Autorino, R., Klein, J., Mottrie, A., Goezen, A. S., Stolzenburg, J. U., ... & Liatsikos, E. (2017). Future of robotic surgery in urology. BJU international, 120(6), 822-841.

[31] Smith, R. (2024). Explosion of Robotics in Healthcare. In The Rise of the Intelligent Health System (pp. 87-111). Productivity Press.

[32] Cai, Z., Fu, Q., Zhang, S., Fan, C., Zhang, X., Guo, J., & Guo, S. (2021). Performance evaluation of a magnetically driven microrobot for targeted drug delivery. Micromachines, 12(10), 1210.

[33] Barua, R. (2024). Innovations in Minimally Invasive Surgery: The Rise of Smart Flexible Surgical Robots. In Emerging Technologies for Health Literacy and Medical Practice (pp. 110-131). IGI Global.

[34] Zhang, D., Gorochowski, T. E., Marucci, L., Lee, H. T., Gil, B., Li, B., ... & Yeatman, E. (2023). Advanced medical micro-robotics for early diagnosis and therapeutic interventions. Frontiers in Robotics and AI, 9, 1086043.

[35] Wang, Y., Shen, J., Handschuh-Wang, S., Qiu, M., Du, S., & Wang, B. (2022). Microrobots for targeted delivery and therapy in digestive system. ACS nano, 17(1), 27-50.

[36] Wang, T., Li, H., Pu, T., & Yang, L. (2023). Microsurgery robots: applications, design, and development. Sensors, 23(20), 8503.

[37] Huang, J., Yu, X., Li, L., Wang, W., Zhang, H., Zhang, Y., ... & Ma, J. (2024). Design of Light-Driven Biocompatible and Biodegradable Microrobots Containing Mg-Based Metallic Glass Nanowires. ACS nano, 18(3), 2006-2016.

[38] Shen, H., Cai, S., Wang, Z., Ge, Z., & Yang, W. (2023). Magnetically driven microrobots: Recent progress and future development. Materials & Design, 227, 111735.

[39] Wang, Z., Klingner, A., Magdanz, V., Misra, S., & Khalil, I. S. (2024). Soft Bio-Microrobots: Toward Biomedical Applications. Advanced Intelligent Systems, 6(2), 2300093.

[40] Chen, B., Sun, H., Zhang, J., Xu, J., Song, Z., Zhan, G., ... & Feng, L. (2024). Cell-Based Micro/Nano-Robots for Biomedical Applications: A Review. Small, 20(1), 2304607.
[41] Madkour, L. H., & Madkour, L. H. (2019). Introduction to nanotechnology (NT) and nanomaterials (NMs). Nanoelectronic materials: fundamentals and applications, 1-47.
[42] Dodampegama, S., Mudugamuwa, A., Konara, M., Perera, N., De Silva, D., Roshan, U., ... & Tamura, H. (2022). A review on the motion of magnetically actuated bio-inspired microrobots. Applied Sciences, 12(22), 11542.
[43] Horibe, K., Walker, K., & Risi, S. (2021). Regenerating soft robots through neural cellular automata. In Genetic Programming: 24th European Conference, EuroGP 2021, Held as Part of EvoStar 2021, Virtual Event, April 7–9, 2021, Proceedings 24 (pp. 36-50). Springer International Publishing.
[44] Cheraghi, A. R., Shahzad, S., & Graffi, K. (2022). Past, present, and future of swarm robotics. In Intelligent Systems and Applications: Proceedings of the 2021 Intelligent Systems Conference (IntelliSys) Volume 3 (pp. 190-233). Springer International Publishing.
[45] Wang, Y., Mei, D., Liu, X., Ji, A., Niu, S., & Li, B. (2023). Bio-Inspired Smart Machines: Structure, Mechanisms and Applications. Machines, 11(3), 405.
[46] Luo, M., Feng, Y., Wang, T., & Guan, J. (2018). Micro-/nanorobots at work in active drug delivery. Advanced Functional Materials, 28(25), 1706100.
[47] Lee, W., Jung, E., Kim, N., Lee, D., Kim, S., Lee, Y., & Jang, G. (2024). Robotically Adjustable Magnetic Navigation System for Medical Magnetic Milli/Microrobots. IEEE/ASME Transactions on Mechatronics.
[48] Peng, X., Urso, M., Kolackova, M., Huska, D., & Pumera, M. (2024). Biohybrid Magnetically Driven Microrobots for Sustainable Removal of Micro/Nanoplastics from the Aquatic Environment. Advanced Functional Materials, 34(3), 2307477.
[49] Wang, Q., Xiang, N., Lang, J., Wang, B., Jin, D., & Zhang, L. (2024). Reconfigurable Liquid-Bodied Miniature Machines: Magnetic Control and Microrobotic Applications. Advanced Intelligent Systems, 6(2), 2300108.
[50] Gao, Y., Guo, Y., Yang, Y., Tang, Y., Wang, B., Yan, Q., ... & Li, D. (2024). Magnetically Manipulated Optoelectronic Hybrid Microrobots for Optically Targeted Non-Genetic Neuromodulation. Advanced Materials, 36(8), 2305632.
[51] Nagappan, S., & Ha, C. S. (2021). Superhydrophobic Polymer/Nanoparticle Hybrids. Materials with Extreme Wetting Properties: Methods and Emerging Industrial Applications, 91-116.
[52] Chikere, N., & Ozkan-Aydin, Y. (2024). Harnessing Flagella Dynamics for Enhanced Robot Locomotion at Low Reynolds Number. IEEE Robotics and Automation Letters.
[53] Xiao, Y., Zhang, J., Fang, B., Zhao, X., & Hao, N. (2022). Acoustics-actuated microrobots. Micromachines, 13(3), 481.
[54] Wang, Q., Yang, S., & Zhang, L. (2024). Untethered micro/nanorobots for remote sensing: Toward intelligent platform. Nano-Micro Letters, 16(1), 40.
[55] Zhang, F., Li, Z., Chen, C., Luan, H., Fang, R. H., Zhang, L., & Wang, J. (2024). Biohybrid Microalgae Robots: Design, Fabrication, Materials, and Applications. Advanced Materials, 36(3), 2303714.
[56] Wang, Q., Xiang, N., Lang, J., Wang, B., Jin, D., & Zhang, L. (2024). Reconfigurable Liquid-Bodied Miniature Machines: Magnetic Control and Microrobotic Applications. Advanced Intelligent Systems, 6(2), 2300108.
[57] Huang, J., Yu, X., Li, L., Wang, W., Zhang, H., Zhang, Y., ... & Ma, J. (2024). Design of Light-Driven Biocompatible and Biodegradable Microrobots Containing Mg-Based Metallic Glass Nanowires. ACS nano, 18(3), 2006-2016.
[58] Yu, S., Liu, C., Sui, M., Wei, H., Cheng, H., Chen, Y., ... & Li, T. (2024). Magnetic-acoustic actuated spinous microrobot for enhanced degradation of organic pollutants. Ultrasonics Sonochemistry, 102, 106714.
[59] Sharma, S., Sudhakara, P., Omran, A. A. B., Singh, J., & Ilyas, R. A. (2021). Recent trends and developments in conducting polymer nanocomposites for multifunctional applications. Polymers, 13(17), 2898.
[60] Adam, G., Boudaoud, M., Reynaud, V., Agnus, J., Cappelleri, D. J., & Clévy, C. (2024). An Overview of Microrobotic Systems for Microforce Sensing. Annual Review of Control, Robotics, and Autonomous Systems, 7.
[61] Lee, W., Jung, E., Kim, N., Lee, D., Kim, S., Lee, Y., & Jang, G. (2024). Robotically Adjustable Magnetic Navigation System for Medical Magnetic Milli/Microrobots. IEEE/ASME Transactions on Mechatronics.
[62] Zarei, M., Moshayedi, A. J., Zhong, Y., Khan, A. S., Kolahdooz, A., & Andani, M. E. (2023, January). Indoor UAV object detection algorithms on three processors: implementation test and comparison. In 2023 3rd International Conference on Consumer Electronics and Computer Engineering (ICCECE) (pp. 812-819). IEEE.
[63] Azimi, M., Kolahdooz, A., & Eftekhari, S. A. (2017). An optimization on the DIN1. 2080 alloy in the electrical discharge machining process using ANN and GA. Journal of Modern Processes in Manufacturing and Production, 6(1), 33-47.
[64] Latifi Rostami, S.A., Ghoddosian, A., Kolahdooz, A. and Zhang, J., 2022. Topology optimization of continuum structures under geometric uncertainty using a new extended finite element method. Engineering Optimization, 54(10), pp.1692-1708.
[65] Chautems, C., Zeydan, B., Charreyron, S., Chatzipirpiridis, G., Pané, S., & Nelson, B. J. (2017). Magnetically powered microrobots: a medical revolution underway?. European Journal of Cardio-Thoracic Surgery, 51(3), 405-407.
[66] Xu, G., Khan, A. S., Moshayedi, A. J., Zhang, X., & Shuxin, Y. (2022). The object detection, perspective and obstacles in robotic: a review. EAI Endorsed Transactions on AI and Robotics, 1(1).
[67] Fu, Q., Zhang, S., Guo, S., & Guo, J. (2018). Performance evaluation of a magnetically actuated capsule microrobotic system for medical applications. Micromachines, 9(12), 641.
[68] Moshayedi, A. J., Sohail Khan, A., Hu, J., Nawaz, A., & Zhu, J. (2023). E-nose-driven advancements in ammonia gas detection: a comprehensive review from traditional

to cutting-edge systems in indoor to outdoor agriculture. Sustainability, 15(15), 11601.

[69] Geng, K., Ata, J. M., Chen, J., Hu, J., & Zhang, H. (2023, March). ENOSE Performance in Transient Time and Steady State Area of Gas Sensor Response for Ammonia Gas: Comparison and Study. In Proceedings of the 2023 2nd Asia Conference on Algorithms, Computing and Machine Learning (pp. 247-252).

[70] Moshayedi, A. J., Khan, A. S., Shuxin, Y., Kuan, G., Jiandong, H., Soleimani, M., & Razi, A. (2023). E-Nose design and structures from statistical analysis to application in robotic: a compressive review. EAI Endorsed Transactions on AI and Robotics, 2.