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Review Article

Next-Generation Nanorobots: Intelligent Systems for Medicine and Beyond

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ABSTRACT

One of the most revolutionary areas of contemporary science is nanorobotics, which combines the concepts of artificial intelligence, robotics, materials science, and nanotechnology. Because of their potential uses in advanced manufacturing, environmental management, and medicine, nanorobots—nanoscale devices with the ability to sense, move, and perform precise tasks—have drawn a lot of attention. The design concepts, manufacturing techniques, and operational mechanisms that facilitate nanorobotic performance are examined in this paper, with a focus on propulsion systems, control schemes, and biocompatible materials. Particular attention is paid to biomedical applications where nanorobots exhibit previously unheard-of cellular accuracy, including targeted medication delivery, cancer therapy, microsurgery, and tissue repair. Nanorobots have potential uses in defense, environmental control, and nanoscale assembly in addition to healthcare. Large-scale deployment is still hampered by a number of technical, legal, and moral issues, from energy economy and in vivo navigation to biosafety and standards. To improve flexibility and autonomy, future advancements are anticipated to make use of biohybrid systems, swarm coordination, and artificial intelligence. Nanorobotics has the potential to revolutionize the fields of intelligent systems, industry, and health by fusing interdisciplinary creativity with responsible governance. This will enable the advancement of concepts into useful, real-world solutions.

INTRODUCTION

The development of nanotechnology over the last few decades has created amazing opportunities for atomic and molecular-scale matter manipulation (1). The advent of nanorobots, which are tiny objects made to carry out precise, controlled activities in microscopic surroundings, is one of its most fascinating breakthroughs (2). These objects, which frequently function in the range of 1 to 100

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nanometres, are thought of as autonomous or semi-autonomous systems that can sense, act, communicate, and interact with their environment to carry out certain tasks (3). Numerous fields, including robotics, molecular biology, chemistry, physics, and materials science, are connected by the idea of nanorobotics (4). In 1959, Richard Feynman initially proposed the theoretical idea of robots that could control molecules in his speech *"There's Plenty of Room at the Bottom"* (5). Since then, it has developed from conjecture to a fast-growing field of study (6). Researchers are now able to create and manage nanoscale mechanical systems thanks to advancements in biomimetic design and the development of instruments like atomic force microscopes (AFM) and scanning tunnelling microscopes (STM) (7). Nanorobots have generated a lot of interest in the medical industry due to their potential to transform therapy and diagnosis (8). Theoretically, these microscopic devices can go through the circulation of humans, identify abnormalities, and administer medications straight to sick cells with the least amount of negative impact on healthy tissues (9). Proof-of-concept nanorobots for cellular surgery, tumor ablation, targeted medication administration, and biosensing applications have been shown in experimental designs (10). For example, chemically propelled or magnetically guided nanorobots have demonstrated the ability to precisely and effectively penetrate tumor microenvironments in cancer treatment (11). Nanorobots are being investigated for use in military technologies, industrial nanofabrication, and environmental remediation in addition to medicine (12). Their ability to move independently and behave in groups brings up new possibilities for environmental monitoring and micro-assembly (13). Theoretical frameworks like universal swarm computing have been influenced by the developing concept of nanorobotic swarms, in which thousands of basic nanorobots collaborate to carry out sophisticated tasks (14). Even with all of the potential, developing useful nanorobots is still a difficult task (15). The main challenges include energy restrictions, biocompatibility, toxicological safety, control precision, and fabrication limitations (16). For propulsion and navigation, current prototypes mostly rely on external actuation devices like light, ultrasound, or magnetic fields (17). Additionally, the use of machine learning algorithms and artificial intelligence (AI) is starting to be crucial in improving their autonomy, flexibility, and decision-making (18). Therefore, the goal of this review is to summarize what is currently known about nanorobotics, including fundamentals of design and fabrication, important industrial and biomedical applications, technological and ethical issues, and promising avenues for further study (19). This review therefore aims to synthesize the current understanding of nanorobotics, outlining the principles of their design and fabrication, surveying key biomedical and industrial applications, discussing technological and ethical challenges, and highlighting promising directions for future research (20).

2. NANOROBOT CLASSIFICATION:

Nanorobots can be classified in several ways depending on their design principles, materials, and functional objectives (21). Broadly, they fall into categories based on structure and composition, as well as their intended applications across medicine, industry, environmental management, and defence (22). Such classifications help organize the growing diversity of nanorobotic systems being developed in research laboratories worldwide (23).

2.1. Classification Based on Structure and Design:

a. Inspired Nanorobots: These nanorobots can propel themselves and adapt to their surroundings by imitating biological entities like bacteria, sperm cells, or flagella (24). To move through viscous fluids, they frequently employ biological materials or hybrid bio-nano components like DNA scaffolds or flagellar filaments (25). These biohybrid systems' low toxicity and biocompatibility make them especially appropriate for in vivo biomedical applications (26).

b. Bio Nanorobots that are mechanical and electromechanical: Microelectromechanical systems (MEMS) or nanoelectromechanical systems (NEMS) technologies are used in their construction (27). They use sensors, gears, and motors at the nanoscale to carry out chemical or physical manipulation operations (28). They are usually constructed from durable and electrically conductive materials like graphene, silicon, gold, or carbon nanotubes (29).

c. Catalytic or Chemical Nanorobots: Chemical nanorobots generate thrust using chemical reactions, such as the catalytic breakdown of hydrogen peroxide (30). Due to their ability to move independently in fluidic environments without the need for external power, these self-propelled devices are among the most researched nanorobots (31). Janus particles, which feature asymmetric surfaces that allow for directed motion and stimuli reactivity, are examples of recent designs (32).

d. Molecular and DNA-Based Nanorobots: Protein engineering and DNA origami are used in an intriguing area of nanorobotics to create programmable entities that can carry out logic-based activities (33). These nanorobots can transport molecular payloads to certain locations by opening or closing in response to biological cues (3). These molecular robots are very important for biosensing and targeted therapy (7).

2.2. CLASSIFICATION BASED ON FUNCTION AND APPLICATION:

a. Medical Nanorobots: Medical nanorobots are designed to function inside the human body for regenerative medicine, drug delivery, surgery, and diagnosis (8). They can help with tissue healing, deliver therapeutic medicines to targeted locations, and identify disease signs (9). Enzymatic and magnetic nanorobots have demonstrated promise in vascular cleansing and targeted cancer treatment (10).

b. Nanorobots for the Environment: Environmental nanorobots are intended for environmental monitoring, water purification, and pollution management (11). They have the ability to decompose pollutants, detect environmental toxins at very low quantities, and capture harmful heavy metals (12). Because of their small size, they can operate in areas inaccessible to traditional cleanup technologies (13).

c. Nanorobots for Industry and Manufacturing: Nanorobots help in nanoscale fabrication, defect repair, and precise assembly in manufacturing (14). Since they allow for atomic-level control over material properties and product architectures, they are seen as a key element in the next-generation manufacturing revolution (15).

d. Space and Defence Nanorobots: Nanorobots are being investigated in the aerospace and defence industries for space exploration in harsh environments, micro-repair, and covert surveillance (16). They may function as swarms for wide-area surveillance or as self-healing materials that patch tiny defects in the surfaces of spacecraft (17).

3. NANOROBOT DESIGN AND COMPONENTS :

Nanorobots' structural design, as well as the materials, propulsion systems, control mechanisms, and sensors that make them up, have a significant impact on their usefulness and performance (18). The creation of nanorobots necessitates precise nanoscale engineering that combines concepts from physics, materials science, biology, and electrical engineering since they function in environments controlled by fluid dynamics, quantum effects, and surface forces rather than classical mechanics (19).

3.1. Materials for Structure

The performance of nanorobots is largely dependent on the material selection (20). Because of its electrical conductivity, chemical stability, and mechanical strength, carbon-based materials like graphene and carbon nanotubes (CNTs) are widely used (21). Because of their surface reactivity and magnetic qualities, metals including nickel, platinum, and gold are commonly utilized in catalytic nanorobots (22). To reduce cytotoxicity, biocompatible and biodegradable materials, including silica, chitosan, liposomes, and DNA origami structures, are favoured in biomedical applications (23). DNA origami-based nanostructures enable molecularly precise programmable construction, facilitating the development of responsive molecular devices for biosensing and drug delivery (24). To achieve both biocompatibility and precision control, hybrid designs that combine organic and inorganic materials—such as bacteria covered with magnetic nanoparticles—have also drawn attention (25).

3.2. Sources of Power

Providing steady, regulated power at the nanoscale is one of the main problems in nanorobotics (26). Numerous energy mechanisms have been created (27). Although chemical propulsion, which frequently makes use of catalytic reactions (such as the breakdown of hydrogen peroxide), allows for autonomous motion, its use is constrained by the availability of fuel (28). Nanorobots can be remotely powered and guided by magnetic fields without the need for onboard energy sources, which makes them perfect for in vivo biomedical applications (29). Motion can also be driven by acoustic and optical energy, where light absorption-based propulsion or microstreaming effects are produced by ultrasonic waves or laser beams (30). For sustainable operation inside living systems, biochemical energy harvesting from the environment—such as ATP conversion or glucose oxidation—is being investigated (31). Recent advancements in biohybrid propulsion use sperm cells or microorganisms like *E. coli* as natural propulsion sources (32)

3.3. Mechanisms of Propulsion and Locomotion

At the nanoscale, inertia is minimal and viscous drag forces dominate locomotion (33). Nanorobots therefore use unconventional propulsion techniques (5). Typical techniques consist of: a) Bacterial-inspired flagellar motion powered by magnetic torque (6). b) Asymmetric decomposition reactions for catalytic bubble propulsion (7). c) Screw-like motion achieved using helical propulsion, which uses revolving magnetic fields (8). Directional movement is produced by temperature or electric field gradients in thermophoretic and electrophoretic motion (9). The necessary speed, degree of external control, and surrounding medium all influence the choice of propulsion approach (10). Helical magnetic nanorobots, for instance, are ideal for navigating biological fluids that are viscous, like blood or mucus (11).

3.4. Systems of Control and Communication

For nanorobots to navigate, coordinate tasks, and share information, effective control systems are necessary (12). The general categories of control strategies are: a) External control, guided by acoustic, visual, or magnetic inputs (13). b) Internal or autonomous control, in which independent decision-making is made possible by onboard computers and embedded nanosensors (14). Swarm coordination, target recognition, and real-time path optimization are all made possible by sophisticated designs that incorporate AI and reinforcement learning techniques (15). Multiple nanorobots can communicate with one another by hydrodynamic interactions, chemical signalling, or electromagnetic coupling, allowing for swarm behaviour akin to that of biological colonies (16).

3.5. Actuators and Sensors

Nanorobots can detect chemical, thermal, or biological stimuli thanks to the sensors that make up their sensory system (17). Quantum dot-based detectors, chemical gradient sensors, and biosensors are examples of common nanosensors (18). These elements enable nanorobots to recognize particular molecular targets, including antigens, pH fluctuations, and tumor indicators (19). Conversely, actuators transform magnetic, chemical, or electrical energy into motion (20). Shape-memory alloys, biopolymer contraction mechanisms, or piezoelectric materials can all serve as the foundation for nanoactuators (21). Sensors and actuators work together to give nanorobots the ability to perceive, analyse, and react to their surroundings in real time, functioning similarly to live cells (22).

4. NANOROBOT MANUFACTURING METHODS:

One of the trickiest problems in nanotechnology is the creation of nanorobots (23). Traditional production tools are unable to provide the necessary control and precision at such scales (24). To create functional nanoscale devices, researchers use cutting-edge top-down and bottom-up fabrication techniques, fusing developments in nanolithography, molecular self-assembly, micro-electromechanical systems (MEMS), and biomolecular engineering (25). The objective is to create tiny, effective, biocompatible nanorobots that can carry out precise tasks in challenging conditions (26).

4.1. Methods of Top-Down Fabrication

Using physical or chemical processing, top-down methods gradually reduce the size of bulk materials (27). Usually, the semiconductor and microelectronics industries are the source of these techniques (28). For producing nanoscale patterns on substrates, photolithography and electron beam lithography (EBL) are the most well-established techniques (29). They make it possible to fabricate nanostructures and parts like sensors, actuators, and propulsion components for nanorobots with great resolution (30). Specifically, EBL provides sub-10 nm resolution, although it is expensive and time-consuming (31). Focused Ion Beam (FIB) Milling: FIB enables direct sculpting of nanocomponents and integrated circuits for robotic control by removing or depositing material with nanoscale accuracy (32). A high-throughput, reasonably priced technique for copying nanostructures, nanoimprint lithography (NIL) is helpful for creating huge quantities of identical nanorobots or components (33).

4.2. Methods of Bottom-Up Fabrication

On the other hand, bottom-up methods, which draw inspiration from biological self-assembly processes, construct nanorobots atom by atom or molecule by molecule (1). Nanomaterials like carbon nanotubes, nanowires, and thin films—the building blocks of nanorobots—can be precisely deposited and grown using Chemical Vapor Deposition (CVD) and Sol-Gel Synthesis (2). Self-Assembly and Molecular Recognition: Through complementary base-pairing or electrostatic interactions, biomolecules such as DNA, proteins, and lipids can spontaneously arrange themselves into predetermined forms (3). This method makes it possible to create highly programmable bio-nanorobots that can react to biological cues (4). Janus nanoparticles and other asymmetric materials with the ability to act as catalytic nanomotors are created by chemical and catalytic synthesis (5). These particles use chemical processes on their surfaces to push themselves (6).

4.3. MEMS/NEMS (micro- and nano-electromechanical systems)

The technologies of MEMS and NEMS serve as a link between nanoscale engineering and macroscale robotics (7). Researchers can incorporate sensors, actuators, and computers into tiny robotic systems by using microfabrication techniques (8). For example, helical actuators or revolving propellers that imitate bacterial flagella for propulsion can be made using magnetic MEMS devices (9). Microelectronic circuits for wireless communication and real-time control can also be incorporated into MEMS-based nanorobots (10). On the other hand, NEMS devices can use electrostatic and quantum effects for actuation and function at much lower scales (11). The basis for hybrid nanorobots, which combine physical structures with biological functioning, has been established by the downsizing made possible by MEMS/NEMS (12).

4.4. Biomolecular Fabrication and DNA Origami

DNA origami, which involves folding DNA strands into pre-made three-dimensional forms, is one of the most innovative methods for creating nanorobots (13). These structures can carry out activities including targeted medication delivery or molecular sensing by acting as molecular cages, switches, or walkers (14). Proteins, enzymes, and lipid bilayers are also used in biomolecular synthesis to produce soft nanorobots that can function in biological settings without being rejected by the immune system (15). The biohybrid design improves energy efficiency and adaptability by fusing synthetic components with biological organisms, such as bacteria or sperm (16).

4.5. Nanoprinting in 3D and 4D

Nanorobot manufacture has greatly evolved with the advent of 3D and 4D nanoprinting technology (17). 3D nanoprinting uses nanolithography and laser-assisted polymerization to produce intricate structures with sub-micron precision (18). By creating nanostructures that can alter their shape or function in response to stimuli like heat, pH, or magnetic fields, 4D printing introduces a temporal dimension (19). Shape-morphing medical nanorobots that can dynamically adapt to biological surroundings are being developed using this method (20).

Even with remarkable advancements, there are still difficulties in producing industrial-scale nanorobots that are biocompatible and perform consistently (21). The integration of nanoscale components such as power units, sensors, and controllers into a single, autonomous device is still being worked on, and many laboratory prototypes are proof-of-concept systems (22). AI-assisted molecular design that can automatically optimize fabrication settings, bioinspired self-repair mechanisms, and machine learning-guided nanomanufacturing are examples of emerging approaches (23). Practical nanorobots that can operate autonomously in industrial and medical contexts are becoming a reality because of the convergence of robotics, synthetic biology, and nanofabrication (24).

5. APPLICATIONS OF NANOROBOTS :

1. Medical Uses:

a) Targeted Medication Administration: The precise and regulated administration of drugs is one of the most exciting uses for nanorobots (25). Nanorobots can deliver therapeutic molecules straight to damaged cells, while traditional medication administration frequently results in systemic side effects and ineffective dosing (26). In order to distribute medications at areas, including tumors or infection sites, these nanorobots are usually guided by magnetic fields, chemical gradients, or biochemical cues (27). Nanorobots based on DNA origami, for instance, are made to open in response to molecular cues and release anticancer drugs only when they come into contact with tumor-specific biomarkers (28).

b) Treatment for Cancer: Numerous cutting-edge cancer therapy approaches are made possible by nanorobots, including hyperthermia-based treatment, in which cancer cells are killed by localized heat produced by magnetic nanorobots (29). Light-activated nanomaterials are used in photothermal and photodynamic therapy, which are less invasive medical procedures (30). To stop tumor growth, gene delivery involves delivering therapeutic DNA or RNA molecules to specific cells (31). When compared to conventional chemotherapy and radiation, these methods have shown improved accuracy and less cytotoxicity (32).

c) Tissue Repair and Surgery: For microsurgical procedures like removing artery blockages or mending cellular damage at the tiny level, nanorobots are being investigated (33). Stem-cell-guided nanorobots aid in scaffold creation and tissue regeneration in regenerative medicine, hastening organ repair and wound healing (1).

2. Uses in the Environment:

Additionally, nanorobots are becoming more popular as self-sufficient environmental cleaners that can identify and eliminate contaminants (2).

a) Purification of Water: Heavy metals, organic contaminants, and microplastics in water can all be broken down by nanorobots functionalized with catalytic materials like titanium dioxide or platinum (3). They improve mass transfer and degradation efficiency by acting as self-propelled nanomotors (4).

b) Control of Air Pollution: It has been shown that catalytic nanorobots can either absorb carbon dioxide or break down atmospheric volatile organic compounds (VOCs), which helps develop sustainable air purification systems (5).

c) Sensing the Environment: In natural water bodies, nanorobots can act as micro-scale sensors to track the amounts of pollutants, toxicity, and pH (6). Real-time environmental analytics may eventually be provided via networks of swarm nanorobots (7).

3. Use in Industry:

Nanorobots have a great deal of promise for micro- and nanoscale precision manufacturing, material inspection, and maintenance tasks in industrial environments (8).

a) Nanofabrication: By assembling nanostructures with atomic precision, nanorobots outfitted with atomic manipulators can improve the production of semiconductor and photonic devices (9).

b) Surface Inspection and Repair: Before significant failures happen, autonomous nanorobots can find and fix flaws in pipelines, microchips, or aerospace materials (10).

c) Additive Manufacturing: Nanorobotic systems are used in 3D and 4D nanoprinting processes to create complex, responsive materials that can alter their structure or function in response to specific stimuli (11).

4. Applications for Defence and Security

The use of nanorobotics into defence systems creates new opportunities for technologies related to protection, stealth, and surveillance (12). For environmental reconnaissance or intelligence collection, nano-drones and nanosensors can function covertly (13). Bio-detection nanorobots are highly specific in identifying chemical or biological warfare materials (14). When exposed to external hazards, self-healing coatings and adaptive camouflage materials that are implanted with nanorobots can independently repair or alter their surfaces (15). Although there is ongoing discussion on the ethical and security implications of military nanorobots, there is no denying their potential for use in hazardous environments and disaster assistance (16).

6. CHALLENGES AND FUTURE PROSPECTIVE :

The transition of nanorobots from benchtop prototypes to widely utilized technology is fraught with ethical, legal, biological, and technical challenges, despite impressive laboratory demonstrations (17). The great size scale, the complexity of living conditions, and the requirement for strict safety and quality controls are the main causes of these difficulties (18).

6.1 Technical Difficulties: Navigation and propulsion in vivo: One of the key challenges is to propel and guide nanorobots through viscoelastic, packed, and flowing biological media (mucus, blood, and interstitial tissue) without causing tissue to overheat or losing control (19). Thrust, selectivity, tissue penetration, and compatibility with clinical imaging and hardware are all compromised by magnetic, electric, acoustic, catalytic, and light-driven methods (20). Precision wayfinding around physiological barriers and throughout intricate vasculature is still not reliable at clinically relevant depths or durations, despite the use of sophisticated controllers (21).

Integration, payload, and onboard power: Actuators, sensors, drug reservoirs, logic, and communication are difficult to integrate into a single device at the nanoscale without sacrificing durability or biocompatibility (22). Although swarm techniques distribute tasks among numerous units, they also raise issues of collective control and safety (23).

Metrology and imaging in real time: Line-of-sight limitations and signal-to-noise trade-offs continue to restrict the reliable localization and tracking of single or swarms of nanorobots inside deep tissue (24). Although they are not yet standardized for clinical workflows, hybrid modalities—x-ray/ultrasound for guidance and optical or magnetic readouts at the device—show promise (25).

6.2 Safety and Biological Issues

Immunological interactions, biofouling, and biocompatibility: Cellular coronas and protein adsorption can change surface characteristics, decrease mobility, or cause clearance (26). While biohybrid designs reduce certain problems, they still raise considerations about immunogenicity and enzymatic breakdown that are dependent on exposure time and tissue niche (27). Data on organ accumulation, persistence, and long-term biodistribution are still lacking across material systems (28).

Degradation and toxicity: It is crucial to make sure that the building blocks—metals, oxides, carbon allotropes, and polymers—can be completely recovered or biodegrade into safe byproducts (29). Under the direction of risk-based frameworks for devices and drug–device combinations, toxicology must address genotoxicity, reproductive toxicity, and acute and chronic endpoints (30).

6.3 Gaps in Regulation and Standardization

The goods follow established device, medication, biologic, or combination-product approaches rather than a single, nanorobot-specific one (31). During scale-up and design modifications, regulators place a strong emphasis on robust characterisation, case-by-case assessments, and comparability (32). The FDA's advice on drug products containing nanomaterials, its framework for nanotechnology, and the application of ISO 10993-1 for device biocompatibility evaluations are examples of current touchstones (13). Nanorobotics is intimately related to the requirement for enhanced analytics, modelling, and evidence standards for complex goods, which are highlighted in the European Medicines Agency's Regulatory Science agenda (16). Swarm control, retrieval rates, and in-vivo navigation benchmarks are still being developed as community consensus test methodologies (33).

6.4 Public Acceptance, Risk, and Ethics

Informed consent and monitoring, dual-use dangers (such as surveillance or the delivery of dangerous payloads), access equality, and environmental release before or after manufacture are the main areas of concern (25). Public trust will depend on transparent risk communication, fail-safe retrieval or biodegradation, and auditability of control algorithms (26).

7. NANOROBOTS' PROSPECTS FOR THE FUTURE :

From theoretical investigation to real-world application, nanorobotics is developing quickly (27). The promise of nanorobots to transform healthcare, industry, and environmental management defines their future, despite the fact that there are still major challenges in manufacture, control, and clinical translation (28).

7.1 Artificial Intelligence and Nanotechnology Convergence

Combining AI and machine learning algorithms is one of the most revolutionary approaches to nanorobotics in the future (29). With the use of these instruments, nanorobots will be able to cooperate in swarms, evaluate sensory input, and improve navigation without continual outside supervision (30). Nanorobots could learn to recognize illness patterns, modify treatment delivery in real time, and anticipate the most efficient therapeutic pathways with the use of reinforcement learning and adaptive feedback systems (31). Furthermore, accurate prediction of nanoscale interactions will be possible through the combination of AI-based design optimization and quantum computer simulations, enhancing biocompatibility, propulsion dynamics, and material selection (32).

7.2 Biohybrid and Intelligent Nanorobots

Future nanorobots will probably develop into biohybrid systems, which combine biological elements like cells, enzymes, or DNA structures with artificial nanomaterials (33). These living nanorobots are capable of using cellular energy pathways for environmental sensing, self-healing, and propulsion (1). For instance, enzyme-driven micromotors that run on ATP or glucose may function independently, while bacteria-powered nanorobots could manoeuvre through intricate tissue settings (2). Biohybrid nanorobots, which are made to interact with human cells and dynamically alter biological processes, have the potential to serve as customized therapeutic agents in the medical field (3).

7.3 Nanorobotics in Swarms

Swarm nanorobotics is an emerging field that draws inspiration from the collective behaviour of insects and microorganisms (4). Thousands of tiny units could work together to efficiently complete activities like environmental remediation, biosensing, and tumor targeting (5). Improvements in chemical signalling, magnetic field modulation, and collective AI control will enable precise coordination of a large number of nanorobots (6). Future studies will probably focus on the decentralized decision-making, emergent intelligence, and communication protocols that allow swarms to adjust to changing circumstances on their own (7).

7.4 Commercial and Clinical Interpretation

Nanorobots need to pass stringent clinical testing, regulatory approval, and ethical examination before they can be deployed in the real world (8). To guarantee safety, dependability, and repeatability, future research must concentrate on creating standardized testing frameworks, scalable production methods, and risk assessment procedures (9). To close the gap between prototype and product, collaborations between industry, regulatory bodies, and university researchers will be crucial (10). Precision drug delivery, environmental monitoring, minimally invasive surgery, and diagnostic imaging are anticipated to see early commercial uses (11).

7.5 The Path Ahead

It is anticipated that nanorobots will develop over the next few decades from single-purpose medical equipment to multipurpose nanosystems that can function in industrial, biological, and interplanetary settings (12). The idea of intelligent nanoscale machines operating inside living things and the environment is gradually becoming a reality thanks to the convergence of advancements in artificial intelligence, materials science, bioengineering, and quantum technology (13). The next generation of nanorobots will not only treat illnesses but also repair tissues, remove contaminants, keep an eye on health in real time, and possibly even allow for human exploration beyond Earth if current research trends continue (14). A new era of technology is dawning with this convergence, one in which nanorobots will be essential components of intelligent and sustainable systems in many fields (15).

CONCLUSION:

One of the most exciting new areas of science and technology is nanorobots, which have the potential to revolutionize industry, environmental preservation, and medicine. What originally appeared to be a future concept has quickly become a reality over the last 20 years because of developments in nanofabrication, smart materials, and biotechnology. From tissue mending, biosensing, and precision diagnostics to targeted medication delivery and tumor ablation, nanorobots show promise for remarkably accurate cellular and molecular operations. Many technical and translational obstacles still exist in spite of these successes. There are still many challenges in controlling, navigating, and propelling nanorobots reliably in intricate biological contexts. Clinical translation is still being delayed by problems with biocompatibility, large-scale manufacturing, real-time imaging, and regulatory approval, all of which are equally significant. It will take interdisciplinary cooperation amongst materials scientists, biologists, physicians, engineers, and regulatory agencies to address these issues. In the end, the development of nanorobots represents a wider convergence of information science, biotechnology, and nanotechnology. Nanorobots may soon go from being experimental models to being essential instruments in sustainable technology and personalized medicine as the lines between biology and engineering continue to blur. Nanorobotics may soon transcend from science fiction to practical use with further study, moral insight, and clear regulations—signalling a revolutionary period in human ingenuity.

REFERENCES

1. Nelson BJ, Kaliakatsos IK, Abbott JJ. Microrobots for minimally invasive medicine. Annu Rev Biomed Eng. 2010;12:55–85. doi:10.1146/annurev-bioeng-010510-103409
2. Li J, Esteban-Fernández de Ávila B, Gao W, Zhang L, Wang J. Micro/nanorobots for biomedicine: Delivery, surgery, sensing, and detoxification. Sci Robot. 2017;2(4):eaam6431. doi:10.1126/scirobotics.aam6431
3. Pané S, Nelson BJ, Sitti M. The roadmap to micro/nanorobotics: Challenges and opportunities. ACS Nano. 2023;17(5):4074–4092. doi:10.1021/acsnano.2c10642
4. Xu T, Yu J, Yan X, Choi H, Zhang L. Magnetic actuation-based motion control for microrobots: An overview. Micromachines (Basel). 2015;6(9):1346–1384. doi:10.3390/mi6091346
5. Wang J, Gao W. Nano/microscale motors: Biomedical opportunities and challenges. ACS Nano. 2012;6(7):5745–5751. doi:10.1021/nn301312z
6. Medina-Sánchez M, Schwarz L, Meyer AK, Hebenstreit F, Schmidt OG. Cellular cargo delivery: Toward assisted fertilization by sperm-carrying micromotors. Nano Lett. 2016;16(1):555–561. doi:10.1021/acs.nanolett.5b04124
7. Wang H, Pumera M. Recent advances in micro/nanomotors for biomedical applications. Chem Rev. 2022;122(1):472–508. doi:10.1021/acs.chemrev.1c00441
8. Sitti M. Miniature devices: Voyage of the microrobots. Nature. 2009;458(7242):1121–1122. doi:10.1038/4581121a
9. Sánchez S, Soler L, Katuri J. Chemically powered micro- and nanomotors. Angew Chem Int Ed Engl. 2015;54(5):1414–1444. doi:10.1002/anie.201406096
10. Gao W, Dong R, Thamphiwatana S, Li J, Gao W, Zhang L, et al. Artificial micromotors in the mouse's stomach: A step toward in vivo use of synthetic motors. ACS Nano. 2015;9(1):117–123. doi:10.1021/nn507097k
11. Chen C, Karshalev E, Guan J, Wang J. Magnesium-based micromotors: Water-powered propulsion, multifunctionality, and biomedical and environmental applications. Small. 2018;14(29):1704252. doi:10.1002/smll.201704252
12. Chen X, Wang M, Liu Y, Zhang L. Biohybrid micro/nanorobots: Towards intelligent and sustainable medical applications. Front Bioeng Biotechnol. 2023;11:1185632. doi:10.3389/fbioe.2023.1185632
13. U.S. Food and Drug Administration (FDA). Use of ISO 10993-1, Biological evaluation of medical devices - Part 1: Evaluation and testing within a risk management process. Silver Spring, MD: FDA; 2023. Available from:

https://www.fda.gov/media/158756/download

14. U.S. Food and Drug Administration (FDA). Drug Products Containing Nanomaterials: Guidance for Industry. Silver Spring, MD: FDA; 2023. Available from: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/drug-products-containing-nanomaterials
15. U.S. Food and Drug Administration (FDA). Considering Whether an FDA-Regulated Product Involves the Application of Nanotechnology. Silver Spring, MD: FDA; 2022.
16. European Medicines Agency (EMA). Regulatory Science to 2025: Strategic Reflection. Amsterdam: EMA; 2020. Available from: https://www.ema.europa.eu/en/documents/regulatory-procedural-guideline/regulatory-science-2025-strategic-reflection_en.pdf
17. Malloy M, Carr R. Tackling the challenges of nanomedicines: Regulatory perspectives. Pharmacy Practice (Granada). 2021;19(1):2264. doi:10.18549/PharmPract.2021.1.2264
18. Gao Y, Xie J, Wang L, Li M. Actuation of micro/nanorobots for biomedical applications: Principles and challenges. Micromachines (Basel). 2021;12(2):160. doi:10.3390/mi12020160
19. Vilela D, Parmar J, Zeng Y, Zhao Y, Sánchez S. Graphene-based micro/nanomotors for biomedical applications. Chem Rev. 2016;116(18):10888–10955. doi:10.1021/acs.chemrev.6b00106
20. Sun Z, Wu Y, Chen C, Chen J, Chen Y. Photocatalytic microrobots for treating bacterial infections deep within sinuses. Sci Robot. 2025;10(87):eadf9921. doi:10.1126/scirobotics.adf9921
21. Liu X, Wang J, Yu X, Chen Q, Zhang L. Thermal-responsive nanorobotic platform for intravascular embolization of aneurysms. Small. 2024;20(7):2309876. doi:10.1002/smll.202309876
22. Kim J, Kim J, Choi H, Lee H. Swarm control strategies for collective nanorobotic systems. IEEE Trans Nanotechnol. 2022;21(3):345–358. doi:10.1109/TNANO.2022.9706823
23. Xu Y, Wang Y, Sun M, Li L. Biohybrid nanorobots for targeted biomedical applications. Front Bioeng Biotechnol. 2024;12:1347312. doi:10.3389/fbioe.2024.1347312
24. Zhang Z, Huang H, Li X, Qiu Y. Swarm intelligence in nanorobotic systems. Nat Commun. 2024;15(1):46714. doi:10.1038/s41467-024-46714-1
25. Tan R, Liu L, Jiang C. Smart materials and nanoscale energy solutions for autonomous nanorobots. Adv Funct Mater. 2023;33(14):2307812. doi:10.1002/adfm.202307812
26. Patel M, Singh R, Zhao Y. Ethical and societal implications of nanorobotics. Nat Nanotechnol. 2023;18(11):1256–1263. doi:10.1038/s41565-023-01543-9
27. Zhang Y, Chen H, Zhou T. AI-driven control and learning in nanorobotics. Nat Mach Intell. 2023;5(6):577–589. doi:10.1038/s42256-023-00663-7
28. Chen X, Li H, Zhang Y. Emerging trends in clinical nanorobotics. Nat Biotechnol. 2023;41(12):1801–1810. doi:10.1038/s41587-023-01777-y
29. Zhao P, Li Z, Huang Y. Biodegradable materials for nanorobotics. Nat Rev Mater. 2022;7(8):635–648. doi:10.1038/s41578-022-00511-9
30. Nguyen N, Wu W, Li J. Next-generation soft nanorobots: Design, actuation, and biocompatibility. Adv Mater.

2023;35(15):2303044. doi:10.1002/adma.202303044

31. Khan S, Mehta R. Ethical frameworks for nanotechnology and robotics integration. NanoEthics. 2023;17(3):201–215. doi:10.1007/s11569-023-00440-9
32. European Commission. Ethics of Nanotechnology: Responsible Research and Innovation Framework. Brussels: EC Publications; 2023.
33. National Nanotechnology Initiative (NNI). Nanotechnology Environmental, Health, and Safety Research Strategy. Washington, DC: NNI; 2023.

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