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Chapter 5

Advanced topics in robotics

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Abstract: Robotics is a futuristic multidisciplinary area to make machines think and work to accomplish specific tasks. It brings innovations from various engineering disciplines, such as computer science and artificial intelligence. The increasing number of research publications over the years shows that the topic interests' researchers. This chapter explores six cutting-edge and emerging topics in robotics. A literature review and content analysis helped identify six advanced topics on robotics, which this chapter discussed. The topics included are Soft Robotics, Swarm Robotics, Human-Robot Interaction/Collaboration (HRI/HRC), integration of robotics with artificial intelligence, Micro and Nanorobotics, and quantum robotics. A list of 10 more advanced emerging areas of robotics is listed. This chapter identifies future research directions and provides a roadmap for academicians and practitioners to leverage these advancements for societal and industrial impact. This chapter helps academicians and professionals across various industries, especially in computer science, engineering, and electronic engineering, as well as practitioners from various industries focusing on technology applications such as healthcare, manufacturing, and exploration.

Keywords: microrobots, nanorobots, quantum robots, human-robot interaction, robotic arm, swarm robots

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Introduction

Robotics is a multidisciplinary field that combines engineering, computer science, and artificial intelligence. It involves robot design, construction, operation, and use. A robot is a programmable machine capable of carrying out complex actions automatically. A typical robot typically has the following key aspects:

1. Physical systems - from large industrial robots to microscopic nanorobots
2. Control systems - including AI and quantum computing integration
3. Human interaction capabilities - through interfaces and collaborative systems
4. Adaptable designs - like soft robotics that can change shape and function
5. Collective behaviors - as seen in swarm robotics
6. Intelligence - through AI integration enabling learning and autonomous decision-making

Over the years of development, Robotics has evolved from simple automated machines to sophisticated systems. Robots can now interact with their environment, make decisions, and work alongside humans in various fields. Robots have applications in healthcare, manufacturing, exploration, and research. Studying robots is essential because it drives technological innovation, enhances automation, and improves our ability to solve complex problems across various industries, ultimately leading to a more advanced and efficient society.

This chapter focuses on six significant trends in robotics. It presents cutting-edge innovations that are reshaping industries and research spheres. Soft robotics utilizes flexible materials for applications in healthcare and beyond. Biological collectives inspire swarm robotics. Advancements in the field showcase the interdisciplinary nature of the field. Emerging topics such as human-robot collaboration (HRC), artificial intelligence integration, and quantum robotics highlight the transformative potential of technology in creating systems that are adaptive, intelligent, and capable of operating in dynamic environments. This chapter also highlights the application of robotics in critical areas like medical interventions, construction, and autonomous systems. With these topics, the chapter provides insights into the future directions of robotics. It highlights the innovation, collaboration, and the growing impact of technology on society.

Literature Review

Since robotics is still a developing and emerging topic, only published literature from 2020 onwards is considered for this study. As Fig 15.1 shows, there is an increasing trend in the number of publications on Robotics

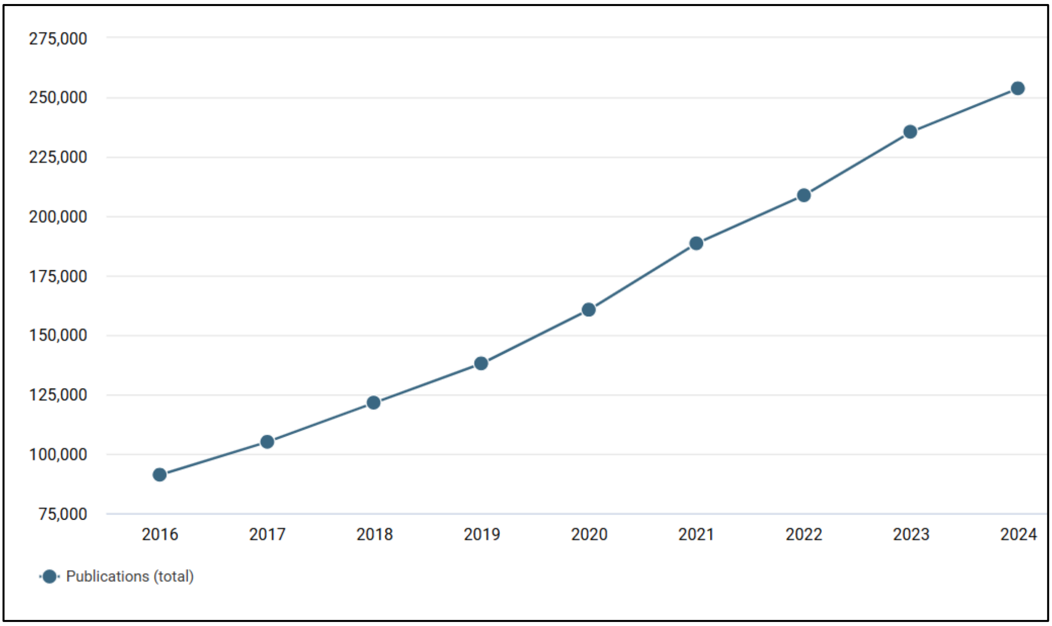

Fig. 15.1 Increasing publications on "robotics" as per dimensions.ai

Methods and Materials

Content Analysis is done on the shortlisted publications, and six topics are identified. A narrative review is done to summarize the content. The six topics identified are:

1. Soft Robotics
2. Swarm Robotics
3. Human-Robot Interaction/Collaboration
4. Artificial Intelligence Integration
5. Nanorobotics
6. Quantum Robotics

Results and Discussions

Soft Robotics

Soft Robotics aims to design and control robots that use soft, flexible, and adaptable materials (such as flexible actuators) to interact with the environment (such as tissues in the human body). These robots mimic biological systems. The inspiration for this area came because of the availability of new materials and fabrication methods. Figure 15.2 shows a soft robotic glove.

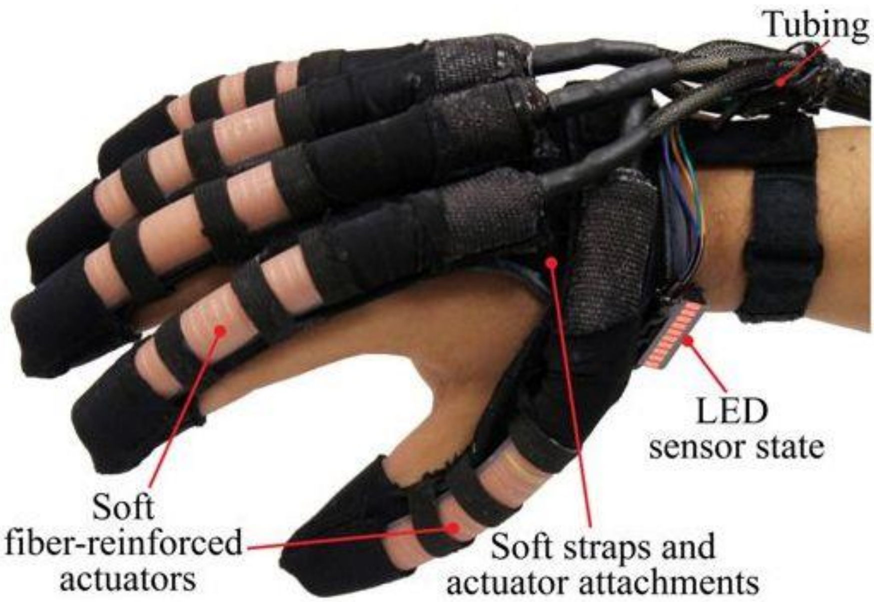

Fig. 15.2 A Soft Robotic Glove designed for at-home Neuromuscular Rehabilitation
Source: https://www.wevolver.com/specs/soft.robotic.glove

This discipline has applications where traditional rigid robots are not well-suited. Some such areas include healthcare, agriculture, food processing, manufacturing, and search and rescue operations. Healthcare systems alone have many soft robotic applications, such as surgery, rehabilitation, prosthetics, and assistive devices (Gaskins et al., 2025). Some soft robotics applications are assistive prostheses, soft orthotic devices, soft robotic gloves, soft robotic arms, soft exoskeletons, and soft robotic 3rd arms (SR3As) (Anil Chandra et al., 2024).

Minature Soft Robots are small and have active mobility and intrinsic softness, enabling access to deep regions inside living bodies. They offer compelling agility, adaptability, and safety for biomedical applications. Ferromagnetic soft materials are used in their design, fabrication, and applications (Chen et al., 2025). A pneumatic actuation system is a simple and accessible actuation method in soft robotics. Such systems use soft pneumatic actuators (SPAs) for varying active volumes in pneumatic systems with adjustable flow rates (S. Liu et al., 2025). They can be found in wearable soft robots, medical devices, bio-inspired robots, and soft grippers.

Researchers so far have limited exploration of the concept of wood as a natural polymer with shape memory capabilities. However, smart-shaped memory materials are gaining attention due to their applications in flexible electronics. From a soft robot perspective, Shape Memory Wood Actuators (SMWA) can provide efficient rigidity/flexibility modulation and heat-activated control (Jin et al., 2025).

Soft robotics can draw inspiration from biology. For example, modular design can bring the biological concept to Voxel-based Soft Robots (VSRs). Specifically, inspiration can come from the cellular totipotency perspective. Cellular totipotency is the ability of a single zygote to develop into specialized cells. It provides modular adaptability and scalability (Ferigo et al., 2025). Soft robots are modeled on human arms' physiological structure and movement and help build pipeline robots in small, low-bending-radius environments. Such robots bring in concepts from LCE-MXene-Spring (LMS) artificial muscles for enhanced flexibility and strength (Li et al., 2025).

Magnetically-actuated soft robots are robots fabricated from ferromagnetic soft materials. They can be precisely controlled to navigate through complex biological environments. Their unique flexibility and magnetic responsiveness combination enables targeted drug delivery to specific anatomical locations. They allow minimally invasive surgical procedures and controlled tissue manipulation in rehabilitation therapy. Such soft robots can also be empowered with decision-making capabilities (Tian et al., 2025). Magnetically Actuated Origami Soft Robots (MAOSRs) is another Potential Application area. It can be used for precision tasks (such as pick-and-place operations) and navigation and obstacle avoidance (in confined or complex environments). These automated design advances improve efficiency and reduce reliance on expertise (Cui et al., 2025).

Swarm Robotics

Also called Robot swarms, this robotics area involves large numbers of robots working together for complex tasks (or common goals) such as coordination, communication, distributed intelligence, and decision-making strategies. They involve specialized collective behavior algorithms and have decentralized control. They are often bio-inspired by social insects.

Swarm behavior or swarming can be seen in animals (migration), birds (flocking), insects such as ants and bees (herding), fishes (shoaling), and phytoplankton (blooms). Practical applications include search and rescue, exploration, manufacturing, or surveillance. Swarm robots are demonstrated in the movie *Big Hero 6* by the protagonist, Hiro Hamada, who, as a part of his project, demonstrates how barrels of tiny black microbots work together to accomplish tasks. While swarm robots have been researched for a while, applications of mass and commercial scale have yet to emerge. Practical applications of swarm robotics include designing User-Centric Autonomous Architectural Layouts (Yousefi, 2024) and precision agriculture (Hamid et al., 2025). Fig 15.3 shows a group of swarm robots.

Fig. 15.3 Low-cost autonomous robots that mimic honeybee swarming behavior
Source: University of Lincoln via https://newatlas.com/colias-swarm-robot/33897/

Swarm algorithms are computational techniques inspired by the collective behavior of natural systems. These can be Centralized algorithms or Decentralized algorithms. Centralized Swarm Algorithms rely on a single controlling unit and can be heuristic, probabilistic, or deterministic. Decentralized Swarm Algorithms distribute control among agents and can function in undistributed or distributed manners. Distributed systems within decentralized algorithms can also exhibit deterministic behavior, where decisions are entirely rule-based. This hierarchy reflects how the control and decision-making structure affect the design and implementation of swarm algorithms in problem-solving scenarios like optimization, robotics, and collective decision-making (Yousefi, 2024). Heterogeneous swarm navigation involves robots (or agents) with different sensors or locomotion to communicate or interact with others in the vicinity (Mohaddesi et al., 2025).

Human-Robot Interaction (HRI) / Collaboration (HRC)

Human-Robot Interaction/Collaboration (HRI/HRC) involves building seamless teamwork between humans and robots in shared environments. The topic involves

Human-centered design and implementation of robots that can interact with humans naturally and intuitively. These include gesture recognition, speech recognition, facial expressions, emotional intelligence, and other haptic interfaces. It is expected to be emotionally aware and socially intelligent robots (or social robots). It also involves social learning and skill transfer between humans and robots. Various technologies, such as Advanced natural language processing (NLP) for communication and natural interaction interfaces. Augmented reality (AR) interfaces are used for robot interaction. The theme also focuses on the safety and trust protocols for collaborative environments. Fig 15.4 speaks of the upcoming humanoid robotics - a field where people could encounter real-life robots.

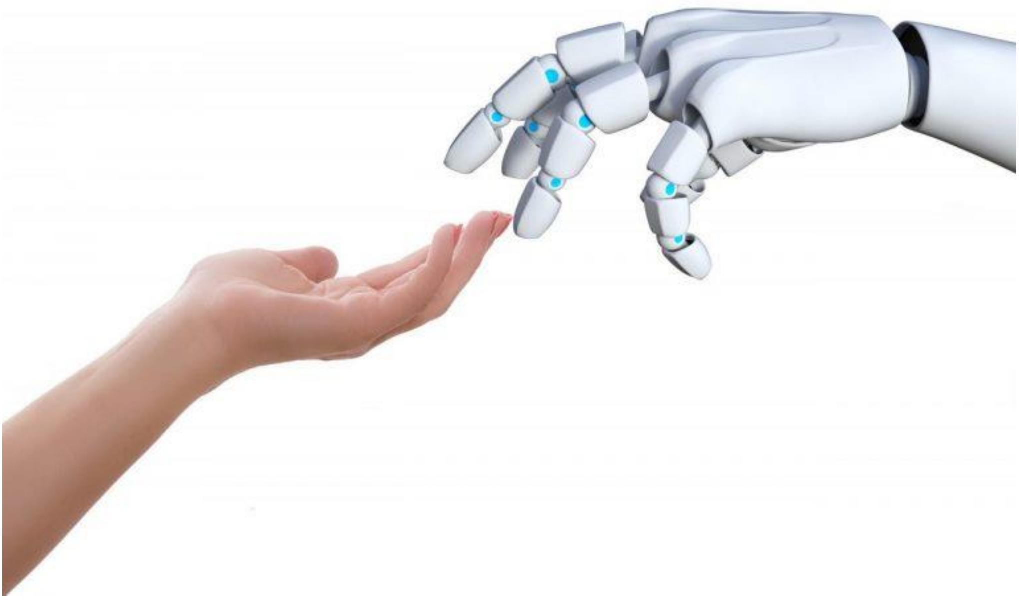

Fig. 15.4 Humanoid Robotics & Human-Robot Interaction
Source: https://www.czechstartups.org/en/novinky/humanoid-robotics-human-robot-interaction

Socially engaging robotic platforms can monitor posture and enhance therapy with personalized cues when dealing with Parkinson’s Disease (PD). Research that combined dance therapy with robotic exergaming shows promise for enhancing motor abilities, balance, and quality of life in PD patients (Bevilacqua et al., 2025).

HRC usage in the construction industry aims to enhance safety and productivity. Some advances in collaborative robot design include exoskeleton robots for construction trades and non-exoskeleton robots with rigid-flexible-soft configurations (J. Liu et al., 2025).

Artificial Intelligence Integration

Artificial Intelligence and Machine Learning (AI&ML) have revolutionized modern robotics. This is possible because machines are made to learn from experiences. They are made to adapt to new situations and make autonomous decisions. Embodied AI brings AI with physical robotics. It creates systems that sense and respond to environments directly. They are used in "agents" such as robots and drones (Kourav et al., 2024) and have applications in autonomous driving and robotic caregiving (Khan & Ishrat, 2024). Similarly, Computational Intelligence Techniques such as fuzzy logic (Tian et al., 2025), genetic algorithms, and neural networks are used in robotics. The techniques handle uncertainty, optimize robot performance, and enable learning from experience (Kandati & Sirasanambeti, 2025). Fig 15.5 shows various subfields of AI&ML with significant applications in robotics.

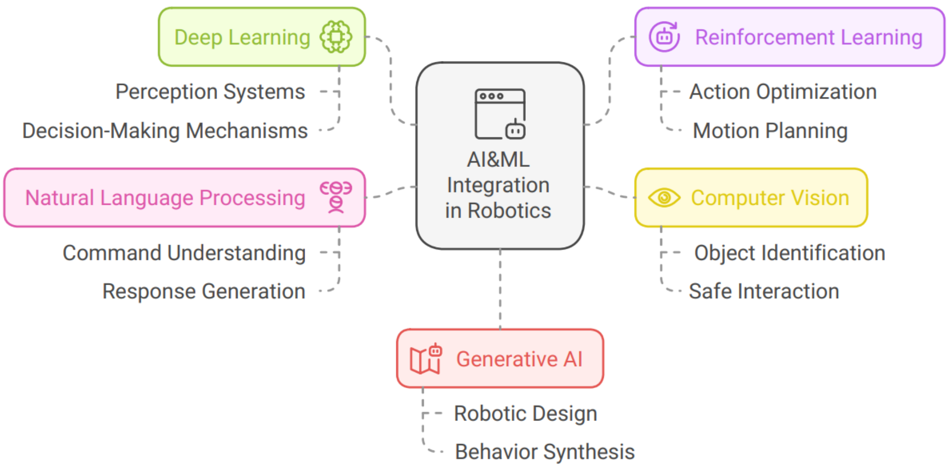

Fig. 15.5 Select AI&ML sub-systems used in Robotics

Deep Learning (DL) is a key technology in robotic systems. It includes perception systems that help robots understand their environment. They have Decision-making mechanisms for autonomous operation. They can help execute complex tasks through learned behaviors. One notable application is precision agriculture, in which DL algorithms help robots detect weeds and identify plant diseases, improving farming efficiency (Hamid et al., 2025). Reinforcement Learning (RL) plays a crucial role in robot control. Teaching robots can use RL to optimize their actions through trial and error. RL enables adaptation to dynamic environments. RL can help in developing sophisticated motion planning strategies. DL and RL can both be used to enhance robots' decision-making and problem-solving abilities in complex scenarios. RL algorithms and the particle filter (PF) method are used in geosteering robots for look-ahead decision-making (Muhammad et al., 2025).

Computer vision systems enhance robots' ability to interpret visual information from their environment. It also helps robots move and navigate spaces effectively. It helps in identifying and manipulating objects. It can interact safely with humans and other robots.

Natural Language Processing (NLP) capabilities allow robots to understand and respond to human commands. They help generate natural language responses. They facilitate human-robot collaboration. NLP allows robots to process and act on textual information. There is an increasing use of Generative AI in robotics. Recent advances in generative AI have opened new possibilities. Some applications include robotic design optimization, behavior synthesis, motion pattern generation, and novel solution discovery for complex tasks.

AI brings precision, safety, and innovation, allowing for complex surgeries and reducing human errors. So, patients recover faster and have improved outcomes (Maguluri, 2024). AI-driven robotics change employment trends and social well-being. However, there are concerns around ethical concerns, legal issues, regulations, societal implications, and job market impacts, including workforce adaptation and skill development (Sutikno, 2024). Robotics and AI can automate science laboratories, allowing scientists to accelerate science discovery and enabling fundamental breakthroughs (Cooper et al., 2025).

AI Integration can happen for soft robots that are biologically inspired mechanisms. Such integration in advanced modular robotics can be an evolutionary process and benefit adaptive learning (Ferigo et al., 2025).

Micro and Nanorobotics

Both micro-robots and nanorobots are advanced miniature machines. They are designed for precise tasks in confined or complex environments. They use cutting-edge materials and technologies to achieve high adaptability and functionality. Fig 15.6 gives a glimpse of microrobots. Despite the commonalities, a few differences between the two are shown in Table 15.1.

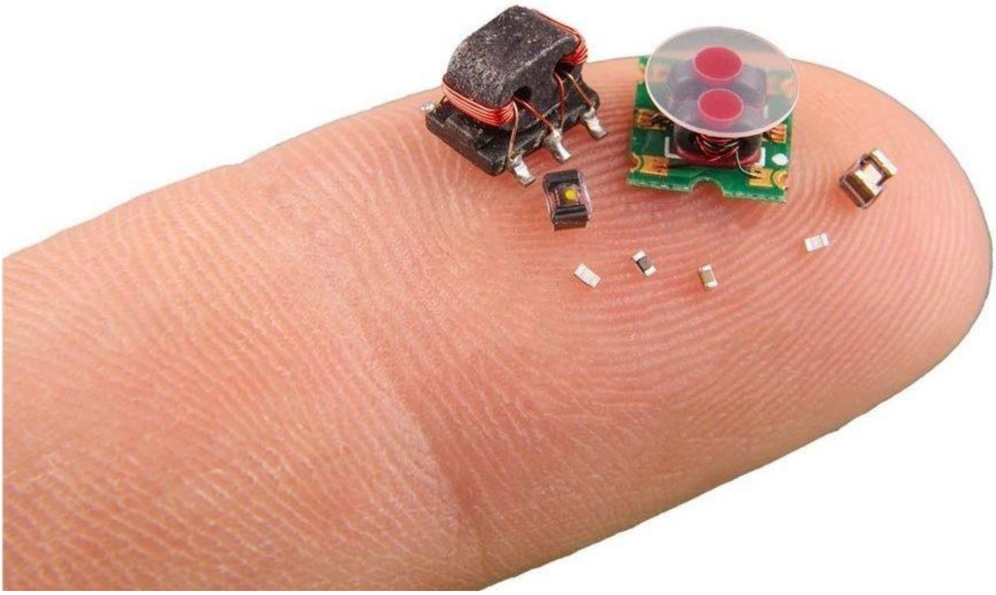

Fig. 15.6 Microrobots of DARPA SHRIMP program
Source: https://www.therobotreport.com/darpa-shrimp-microbots-disaster/

Table 15.1 Differences between Micro and Nano Robots

Feature	Micro-Robot	Nanorobot
Scale	Micrometer to millimeter	Nanometer (molecular scale)
Materials	MEMS-compatible materials	Nanomaterials (e.g., nanotubes)
Power	External energy sources	Chemical/biological processes
Applications	Inspection, surgery	Cellular-level drug delivery
Precision	Micro-scale precision	Molecular precision

These are tiny robots designed for medical applications like targeted drug delivery and surgery. These robots use miniaturization and fabrication techniques. Such robots have biomedical (medical interventions) and industrial (for inspection, rescue operations, and repair) applications. Microscale swimming robots are designed for biomedical applications (inspired by sperm motility, such as for drug delivery or diagnostics) and industrial applications (Asghar et al., 2025).

For example, Piezoelectric Micro-Robots mimic butterfly motion for efficient movement in complex and confined spaces. Such robots can be used in exploration, mapping, and sampling (Shi et al., 2025).

Quantum Robotics

Quantum Robotics (QR) is an emerging interdisciplinary field. It brings the best quantum computing principles and robotic technologies (Yan et al., 2024). It revolutionizes computational capabilities and decision-making processes in robotic systems. The field will probably be building advanced robots controlled by quantum resources (Yan et al., 2024). At the core of this domain is the usage of quantum algorithms. Grover's search algorithm and Shor's factoring algorithm are seminal quantum algorithms. These algorithms have significantly influenced the field of quantum computing. Grover's algorithm provides a quadratic speedup for unstructured search problems (Grover, 1996). Shor's algorithm offers an exponential speedup for integer factorization. It solves the polynomial time problem on a quantum computer (Shor, 1997). These algorithms address computational bottlenecks in classical robotic systems and allow for the rapid processing of vast datasets. This is critical for environmental mapping, real-time path optimization, and sensor fusion in complex, dynamic environments.

Integrating quantum mechanics principles helps in advancements in quantum sensing and metrology. They offer high precision in measurements and navigational accuracy for autonomous systems. Quantum sensors use superposition and entanglement. It improves accuracy in spatial mapping and object detection. These sensors use quantum coherence to detect minute variations in electromagnetic fields. Robots equipped with this can navigate with sub-millimeter precision in challenging environments. Quantum-enhanced imaging is used in areas like quantum entanglement. It can improve the ability of robots to detect objects in low-visibility conditions. Applications for this exist in deep-sea exploration and disaster response scenarios. Quantum neural networks enhance machine learning frameworks exponentially. They are used in adaptive control and decision-making. Robots can now use efficient strategies for tackling highly non-linear and multi-dimensional problems. Advanced human-robot collaboration and swarm robotics are applications for this. Quantum error correction protocols improve the reliability of quantum-controlled robotic systems. It addresses previous limitations in quantum state preservation. Quantum-inspired reinforcement learning algorithms have shown a 40% improvement in adaptive behavior compared to classical methods. The integration of topological quantum computing has enhanced robotic system resilience against environmental decoherence. This is a significant advancement in operational stability. These systems have demonstrated particular promise in extreme environments where classical sensors fail, such as in high-radiation zones or under intense electromagnetic interference. A separate branch called quantum control systems is now evolving, too.

Qubot-One is considered the first Quantum Robot (KOSASIH, 2025). It is an initiative merging quantum computing and AI to develop hyper-intelligent, quantum-powered robots (Qubots). These robots feature advanced quantum processors for real-time analysis. They have self-optimizing AI for adaptability and multi-modal sensory systems for precise interaction with environments. Key capabilities include quantum-enhanced navigation, swarm intelligence, and instantaneous quantum communication. They are designed for seamless human-robot collaboration. Qubots also integrates ethical frameworks to prioritize safety and societal norms. Qubots' applications will be in manufacturing, healthcare, disaster response, research, and space exploration. Once operational, these Qubots will revolutionize industries by providing unparalleled efficiency, adaptability, and cognitive decision-making, setting new standards for intelligent robotics and human productivity.

Researchers began proposing using quantum computing principles to simulate local swarm-robot interactions. The Ant Foraging model is inspired by the back-and-forth ant movement between the nest and a food source and is used to build a swarm. The study so far allows running toy swarm simulations (3 and 10 robots) to show how entanglement can influence collective decisions (Mannone et al., 2023).

Despite the many promising results available, QR has a few challenges. QR requires quantum hardware scalability, error correction, and integration with existing robotic platforms. It requires an interdisciplinary research effort.

Other emerging areas in Robotics

Robotics is continuing to emerge. Apart from the six themes discussed above, Table 15.2 lists ten more emerging topics in robotics, along with a brief description explaining the scope of each robotic area.

Table 15.2 Other advanced and emerging areas of Robotics are:

Sr. No.	Robotics Area	Description
1	Cognitive Robotics	The development of robots with advanced cognitive abilities, such as perception, attention, and reasoning, will enable more human-like behavior and decision-making.
2	Haptic Robotics	Design of robots that can interact with humans through touch, providing a sense of presence and immersion in virtual

		environments and enabling more natural human-robot interaction.
3	Morphological Computing Robotics	Robots use their physical structure and materials to perform computations, reducing the need for central processing and enabling more efficient, nature-inspired control systems.
4	Neuromorphic Robotics	Development of robots that mimic the structure and function of the human brain, with applications in real-time processing, learning, and adaptation.
5	Self-Healing Robotics	Systems incorporating materials and mechanisms that can detect damage and autonomously repair themselves significantly improve robotic longevity and reliability.
6	Bio-Hybrid Robotics	Integrating living biological tissue with mechanical systems creates robots with enhanced sensing, actuation, and adaptation capabilities.
7	Biologically Inspired Robotics	Design robots based on biological principles like movement, sensing, and adaptation.
8	Evolutionary Robotics	Systems that can modify their physical structure and behavior over time through algorithmic evolution, adapting to new environments and tasks without explicit programming.
9	Autonomous Underwater Robotics	Development of robots that can operate underwater, with applications in ocean exploration, marine conservation, and underwater construction.
10	Moral and Ethical Robotics	Exploring the development of ethical decision-making capabilities in robots.

Future Research Considerations

Considering the six futuristic themes identified, future researchers can consider the following aspects for future research:

1. Soft Robotics researchers can consider addressing material, fabrication, and control complexities. There is a need for improving reliability, scalability, and integration with current biomedical technologies. Insights are needed for developing adaptive next-generation miniature robots (Chen et al., 2025).
2. Future research priorities in HRC include creating advanced exoskeleton and hybrid robots for specialized construction tasks. This involves developing innovative multi-modal interactive methods for improved collaboration. There is a need to expand the use of digital twins for safer and more efficient task execution (J. Liu et al., 2025).
3. The current success of quantum robots is encouraging. However, there is a potential for quantum computing to be integrated to enhance swarm decision-

making systems. Further research can focus on more enormous swarms and refined quantum interaction rules (Mannone et al., 2023).

4. Current simulations on swarms are on 3 to 10 swarms. It is yet to be seen how more swarms work and behave. Tests involving hundreds or thousands of swarms are yet to be evaluated and researched.
5. Integration-related issues can arise when robotics are used in critical industrial and health applications. The challenges include managing computational complexity, ensuring safety, and addressing ethical concerns in AI-driven robotics (Kandati & Sirasanambeti, 2025).
6. Robot manufacturing needs to be scalable. Efficient and cost-effective fabrication techniques are needed to produce these robots sufficiently for practical medical and industrial applications.
7. Robots' design, development, usage, and marketing involve several regulatory hurdles. Safety Standards and Certification, Medical Device Approval, Privacy and Data Protection, Liability and Responsibility, Questions about ownership of data collected by autonomous robots, Unclear boundaries for autonomous robot decision-making, and Need for guidelines on robot rights and responsibilities are a few things that need to be considered.

Conclusion

This chapter comprehensively analyzes six transformative areas in robotics: soft robotics, swarm robotics, human-robot interaction/collaboration, AI integration, micro/nanorobotics, and quantum robotics. These emerging fields represent the cutting edge of robotics research. Robotics as a field of research study promises significant implications for healthcare, manufacturing, exploration, and scientific discovery. Integrating advanced materials, artificial intelligence, quantum computing principles, and collaborative capabilities can change the robots' interaction with humans and their environment. Particularly noteworthy are the developments in soft robotics for medical applications, swarm intelligence for complex problem-solving, and quantum robotics for enhanced computational capabilities. While challenges remain in areas such as material engineering, quantum hardware scalability, and ethical considerations, the growth path of these technologies appears promising. This synthesis of current developments and future directions is a valuable resource for researchers, practitioners, and industry leaders working to advance robotic technologies and their applications across diverse sectors.

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