Flexible Robots in the Smart Manufacturing Industry: Review

Yiqin Wang[1*]

[1]North China Institute of Aerospace Engineering, Langfang, Hebei Province, 065000, China

*marshallwyq@stumail.nciae.edu.cn

Abstract. Flexible robot, as a emerging technology in smart manufacturing industry, has been arousing great interest widely. This essay begins with the characteristics and classification of soft robots, exploring their advantages, current applications, industrial prospects, as well as the challenges and opportunities they face in the field of smart manufacturing. Firstly, s the advantages of flexible robots in smart manufacturing - high adaptability, superior dexterity and safer human-robot collaboration - are discussed through the classification of flexible robots and their respective characteristics. Then the current application status of flexible robots in smart manufacturing are introduced, illustrating their practical implementations in the industry through specific case analyses. The industrial development status of flexible robots in smart manufacturing and the encountered technical and market challenges are also analyzed, while proposing potential opportunities and development trends. Finally, the findings and provides prospects for the development direction of flexible robots in intelligent manufacturing are summarized. This paper aims to provide valuable insights for researchers and enterprises engaged in flexible robot applications within the smart manufacturing domain.

Keywords: Flexible Robots, Flexibility, Smart Manufacturing

1 Introduction

The traditional manufacturing industry, making a great contribution worldwide, has been undergoing a thorough revolution over the past few decades. At present, major advanced manufacturing countries worldwide have also successively put forward ambitious plans for the development of smart manufacturing. Among them, the most representative ones are the "Industrial Internet Initiative" in the United States, the "Industry 4.0 Initiative" in Germany, the "Future Manufacturing Initiative" in France, and the "Made in China 2025 Initiative" proposed by the Chinese government, etc. [1]. In the manufacturing domain, smart manufacturing technology has become the driving force, promoting industrial upgrading and innovation. Flexible robot, as an emerging technology in smart manufacturing industry, has been arousing great interest widely. It has presented great potential in increasing production efficiency, product quality and the competitiveness of enterprises.

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The rapid evolution of smart manufacturing has raised the bar for production equipment and technology. As a result, the manufacturing industry is changing from mass production of a single variety to flexible production of multiple varieties [2]. Traditional rigid robots often have limitations in adapting to complex, dynamic production environments and diversified demands. However flexible robots can offer innovative solutions to all these challenges.

With unique properties, flexible robots can better meet the requirements and demands of smart manufacturing industry. Flexible robots like the AMM not only enable rapid switching between different production tasks through modular hardware and containerized software, but also integrate with Deep Reinforcement Learning (Deep RL) technology to progressively optimize performance, achieving peak operational efficiency [3]. This approach enables better integration between robots and humans, allowing for the full utilization of human intelligence alongside the precision and efficiency of robots, thereby enhancing the overall productivity and quality of manufacturing processes.

Based on the latest technological trends and market developments, the application of soft robots in smart manufacturing is expected to have vast growth potential. In the coming years, research and development in soft robotics will expand into more fields and scenarios, driving comprehensive advancements in smart manufacturing. However, the development of soft robots is not without challenges—technical hurdles, cost control, and market expansion remain key obstacles. Yet, these challenges also present critical opportunities for enterprises and research institutions to seek breakthroughs in the industry.

The advancement of soft robots holds significant importance and broad prospects for smart manufacturing. In-depth research and exploration in this field will further propel the progress of smart manufacturing, contributing substantially to economic and societal development.

2 Characteristics, Classifications, and Advantages of Flexible Robots

Flexible robots can inject new vitality into various sectors of intelligent manufacturing with their high efficiency and wide-ranging applications. In automobile manufacturing, when different vehicle models are required, flexible robots can swiftly switch production types, performing tasks like welding and assembly for various cars with speed. In electronics manufacturing, where production processes iterate rapidly and chip packaging demands high precision, flexible robots can respond and act quickly based on system instructions to achieve precise operations. Additionally, flexible robots can plan efficient transportation routes based on factors such as destination and time. The use of flexible robots can significantly enhance production and efficiency, reduce labor costs, and drive industries toward increasingly flexible and intelligent development. With advancements in technology and expanding market demand, their future applications will become even more widespread.

2.1 Characteristics and Classifications

Flexible robot is a kind of robot made of soft(flexible) materials, or composed of highly flexible structures. This leads to various classifications of FMRs according to different methods.

Via different manifestations of flexibility, flexible robots can be categorized as.
(1) Flexible Joint Manipulators (FJM):Joints simulate elastic deformation through elastic components (e.g., linear springs or dampers), making them suitable for precision assembly and surgical operations [4].
(2) Flexible Link Manipulators (FLM): Utilize distributed parameter models (e.g., partial differential equations) or finite-dimensional models (e.g., assumed mode method) to describe the continuous deformation of links, widely applied in long-arm operations in aerospace fields [4].
(3) Joint-Link Coupled Manipulators:Require simultaneous modeling of the dynamic coupling effects between joint elasticity and link flexibility. Typical applications include space station robotic arms and high-load industrial scenarios [4].

Via different actuation methods, flexible robots can be categorized as. Pneumatic Actuation: This mechanism operates by using compressed air to drive flexible structures (e.g., pneumatic artificial muscles, soft actuators) for robot motion. For example, Harvard University's bio-inspired "Octobot" employs microfluidic logic control, utilizing hydrogen peroxide monopropellant decomposition to generate gas that inflates pneumatic networks, enabling untethered operation [5].

Hydraulic Actuation: This method uses fluid pressure to actuate flexible structures (e.g., hydraulic artificial muscles, soft actuators) for robotic movement. An example is MIT's "Hydraulic-driven Bionic Elephant Trunk Robot," which mimics the multi-degree-of-freedom motion of an elephant trunk via hydraulic soft actuators, achieving tasks like coiling, grasping, and precise manipulation [6].

Material-based Actuation: By altering one or several physical parameters of the external environment to achieve material shape change and thus enable mechanism motion, this actuation method offers fast response but low efficiency. For example, the inchworm-inspired bipedal crawling soft robot employs flexible magnetic films as its actuation source. By adjusting the magnetic field's intensity and direction, it modifies its movement posture. With a simple structure, compact size, and agile mobility in pipelines and rough surfaces, it provides a possible solution for narrow-space exploration [7].

Classifying flexible robots by materials can also be an approach. Soft Flexible Robots: Harvard University's bionic octopus robot "Octobot" can be one of the examples. These robots are primarily composed of continuously deformable soft materials (e.g., silicone, hydrogel) and lack traditional rigid components, relying instead on the material’s inherent elasticity or fluid-based actuation (e.g., pneumatic or hydraulic systems).

Rigid Flexible Robots: An example is a novel bionic finger design using 3D-printed ABS material for phalanges [8]. These robots are constructed from conventional rigid materials (e.g., metals, hard plastics) but achieve overall flexibility through compliant actuation mechanisms or joint designs (e.g., springs, hinges, pneumatic artificial muscles), enabling soft-motion capabilities.

Hybrid Rigid-Soft Flexible Robots: Examples include a biomechanics-inspired belt-type soft exoskeleton for hip assistance [9]. Their flexibility stems from a combination of rigid structures, flexible layers (e.g., textiles, silicone), and compliant joints (e.g., hinges). Additionally, they maintain a balance between dexterity and structural rigidity.

Broadly defined flexible robots. Robots that are task-adaptive, environmentally interactive (capable of continuously perceiving in real-time through sensors and dynamically adjusting their behaviors—such as obstacle avoidance, force control, etc.—based on perception results), and flexibly reconfigurable also belong to a category of flexible robots [10].be accepted for publication unless all formatting requirements are met.

2.2 Advantages

Flexible Robots possess inherent flexibility and a wide range of applications, demonstrating significant potential in intelligent manufacturing. Compared to traditional rigid robots, their advantages include the following aspects:

Lightweight Structural Design with Low Power Consumption and Fast Response. Guided by lightweight design principles, flexible robots weigh only 30%-50% of traditional rigid robots while reducing power consumption by over 40% and achieving approximately 25% higher operational speeds [4]. This design makes flexible robots particularly suitable for confined workspaces or energy-constrained scenarios. Their applications in aerospace are especially notable—compared to rigid manipulators, flexible robots are lighter, faster to respond, and more efficient for transportation and in-orbit operations.

Superior Flexibility. With specialized joint and link structures, flexible robots can achieve multi-degree-of-freedom deformations, including bending with a curvature radius ≤5 cm, ±180° torsion, and axial compression up to 20% of their original length. This exceptional deformability enables them to adapt to unstructured environments and perform tasks challenging for rigid robots. For instance, in minimally invasive surgery, a 3mm-diameter flexible robot can navigate complex anatomical structures to reach areas inaccessible to conventional instruments [11]. Such precise and flexible operations could revolutionize smart manufacturing, particularly in complex component production or precision machining.

Enhanced Safety. Experimental data show that, due to their lower inertia and energy-absorbing elastic materials, flexible robots reduce peak collision forces by 60%-80% compared to rigid robots of similar size [4]. This feature makes them ideal for human-robot collaboration. For example, on industrial assembly lines, workers can directly interact with flexible robots, significantly lowering the risk of severe injuries from accidental contact.

Environmental Adaptability. Flexible robots can handle dynamic and unstructured task requirements, such as facility maintenance, with greater ease and efficiency [11].

3 Current Application Status

3.1 Analysis of Specific Application Scenarios

Flexible robots have a wide range of applications and are particularly well-suited for the intelligent manufacturing industry, bringing new vitality to its development.

Automotive Manufacturing. In automobile production, flexible robots enable adaptable manufacturing based on different vehicle models. They can perform complex processes such as body welding and component assembly. Their high adaptability and versatility allow production lines to quickly adjust to market demands for various vehicle types. For example, in assembling automotive parts like front and rear axles, flexible robots can accurately install components of different specifications and shapes, improving precision, productivity, and product quality.

Electronics Manufacturing. Flexible robots are ideal for electronics manufacturing, including circuit board assembly and chip packaging. Given the rapid evolution of electronic products, production methods must keep pace. Flexible robots can adapt to different manufacturing processes, allowing for quick deployment and shutdown as needed. They ensure precise placement of micro-components on circuit boards, reducing errors caused by manual assembly.

Food Processing Industry. In food processing, flexible robots meet strict hygiene standards and accommodate diverse product requirements. They are widely used in packaging, sorting, and other applications. Since they do not introduce contaminants or cause secondary pollution, they offer a convenient and sometimes even superior alternative to human labor. For instance, in food packaging, flexible robots can quickly adjust to different product sizes and packaging specifications, enhancing both efficiency and packaging quality.

Warehousing and Logistics. In logistics and warehousing, flexible robots perform tasks such as material handling, sorting, and storage. They optimize path planning based on warehouse layouts and cargo types, improving space utilization and operational efficiency.

The adoption of flexible robots significantly enhances manufacturing efficiency, reduces costs, and improves product quality, contributing to overall enterprise performance. As technology advances, their applications will continue to expand and deepen across industries.

3.2 Demonstration of Practical Application cases of Flexible Robots

Introduction to AMR (Autonomous Mobile Robots). An autonomous robot is defined as one that requires little to no human intervention and is capable of independently determining actions to perform tasks, utilizing perception systems to assist in navigation [12]. AMRs are a prime example of autonomous robotic systems with flexible applications in smart manufacturing.

AMRs employ AI/ML methods and sensory data to recognize their environment, then use SLAM (Simultaneous Localization and Mapping) navigation and dynamic path planning to operate without fixed routes, enabling high environmental adaptability [13]. Since the first AGV (Automated Guided Vehicle) was introduced in 1955 (Muller, 1983), the guidance *systems* at the core of AGV material handling have evolved through mechanical, optical, inductive, inertial, and laser-based guidance, eventually leading to today's vision-based systems (Fig.1) [14]. Additionally, modular design(e.g., adding robotic arms or shelves) allows AMRs to adapt to different tasks, making them highly versatile in dynamic work environments.

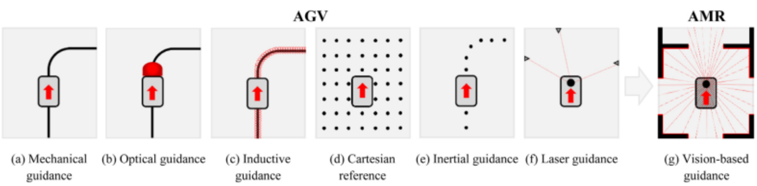

Fig. 1. Guiding systems for AGVs and AMRs (top view of the system) [14]

Although AMRs are still an emerging technology, their applications in smart manufacturing are vast. Equipped with advanced sensors and virtual spatial mapping, AMRs achieve precise positioning, making them suitable for storage, transportation, and production environments [15].

Practical Applications of AMR (Autonomous Mobile Robots). (1) BMW Group's Flexible Logistics AMR System

At its Dingolfing plant in Germany, BMW Group deployed a fleet of 200 AMRs supplied by Mobile Industrial Robots for dynamic transportation of automotive components. These AMRs utilize multi-sensor fusion-based laser SLAM technology (combined with UWB positioning compensation) and a deep reinforcement learning-based real-time path planning algorithm to navigate autonomously in a complex workshop environment with 15 assembly zones [16]. Experimental results show that compared to traditional AGV fixed-path transportation, the improved system enables flexible scheduling, increasing logistics efficiency by 30%—from 80 deliveries per hour to 104 deliveries per hour. Additionally, due to reduced path reconfiguration costs during production line adjustments, the reconfiguration cost decreased significantly from €50,000 per instance to €8,000 per instance [17].

When AMRs share workspace with human workers, a three-tier safety protection system is implemented:

Force Feedback Collision Avoidance: Joint torque sensors detect contact forces below 5N.

3D Visual Warning: Intel RealSense D435i cameras track dynamic obstacles within a 2m range.

Audible and Visual Alarms: Emergency stop devices compliant with ISO 13849-1 PLd safety requirements (i.e., the safety circuit's emergency stop function) [18].

The system fully complies with the ISO/TS 15066 collaborative robot safety standard and received the Industrial 4.0 Safety Certificationfrom TÜV Rheinland in 2021 [19,20].

(2) Foxconn's AMR-Robotic Arm Collaborative System for Electronics Manufacturing

At its Shenzhen factory, Foxconn has implemented an intelligent logistics system for flexible smartphone motherboard production lines using Geek+ P-series AMRs integrated with UR10e collaborative robots. This flexible unit is responsible for full-process material transfer and partial precision assembly operations. The key technologies of the system are as follows:

1. Dynamic Priority Scheduling

The system employs RFID to identify multiple PCB models (supporting up to 50 SKUs) and utilizes a genetic algorithm-based task allocation model, reducing transportation response time to 8 seconds [21].

2. High-Precision Docking

The AMRs adopt the DockPro™ positioning system with ±0.5mm repeatability, combining visual servo control with robotic arm closed-loop control.

After delivering motherboards to the vision inspection station, robotic arms with ±0.02mm repeatability place 0201-sized components (0.2mm×0.1mm) in just 1 second per operation. This implementation has reduced production line changeover time from 4 hours to under 30 minutes while decreasing failure rates from 0.8% to 0.05% [22].

The key innovations include modular design where AMRs feature interchangeable vacuum grippers/electromagnetic fixtures with tool changeover completed in under 3 minutes; digital twin verification through a virtual production line built using Siemens software that enables online simulation of production output variations, and energy optimization where the implementation of smart charging for AMRs has reduced overall energy consumption by 22% compared to AGV systems [23,24].

4 Industry Prospects, Challenges, and Opportunities

4.1 Technical and Market Challenges

The development of flexible robots has brought boundless possibilities to the smart manufacturing industry, yet significant technological and market challenges remain to be overcome [25].

From a technical perspective, the research and application of flexible robots face multiple unresolved issues. First, the development and fabrication of their complex mechanical structures and control systems are highly challenging and demanding. For instance, flexible joints require materials with exceptional elasticity to adapt to specific operational environments while ensuring reliability and durability, imposing stringent requirements on materials science and engineering. Second, the high-precision sensors used in flexible robots are relatively complex, with notable shortcomings in stability and reliability under extreme conditions, necessitating substantial efforts for further improvement. Third, energy supply remains a major bottleneck for flexible robots. The ability of power systems to deliver efficient, sustained energy and enable prolonged operation directly impacts the product's practical value [26].

Market adoption of flexible robots also faces hurdles: First, their current high costs place them beyond the financial reach of small and medium-sized enterprises (SMEs) [27]. Second, as flexible robots are still in the developmental stage, their technologies lack maturity and stability. During initial deployment, various operational issues may arise, making SMEs hesitant to adopt them for R&D, production, or maintenance purely from a cost perspective. Additionally, public skepticism toward emerging technologies—doubts about whether performance and quality meet expectations—may lead businesses to adopt a wait-and-see approach. Moreover, the competitive landscape is intense, with numerous robotics companies vying for market share. For flexible robots to gain traction, they must demonstrate clear advantages in performance, cost-effectiveness, and after-sales service [28].

Despite these challenges, the inherent strengths of flexible robots cannot be overlooked. With continuous technological innovation and market cultivation, their technical barriers will gradually be overcome, overall costs will decline, and market acceptance will grow. In the future, flexible robots are poised to play a pivotal role in smart manufacturing. Governments and enterprises must ramp up R&D investments, promote industry-academia-research integration, and strengthen collaborative efforts in technology development and university-industry partnerships to jointly overcome technical and market obstacles. This will enable the smart manufacturing sector to complete its transformation and advance toward a brighter future.

4.2 Potential Development Opportunities and Trends

Flexible robots are poised to drive the flourishing development of the smart manufacturing industry, with numerous possible directions and emerging trends.

Driven by technological advancements and the transformation of the manufacturing sector, demands for production efficiency and product quality are increasing. Flexible robots align perfectly with this trend, offering vast growth potential. On the other hand, as smart manufacturing increasingly emphasizes product customization, flexible robots—with their inherent flexibility and adaptability—can swiftly adjust production processes, providing robust support for diversified, small-batch manufacturing. For instance, they can be applied in high-precision disassembly and assembly processes in electronics manufacturing [29].

The integration of artificial intelligence (AI) and big data technologies can further enhance the intelligence of flexible robots. By analyzing and learning from vast production datasets, they can optimize their movements and decision-making, thereby improving efficiency and product consistency. Additionally, the adoption of 5G communication technology enables near-zero latency and high-bandwidth remote control and collaborative operations, overcoming geographical limitations and facilitating high-speed production. From a design perspective, flexible robots are trending toward miniaturization, lightweight construction, and higher integration, allowing easier deployment into existing production lines at relatively low retrofitting costs. Advances in materials science will also endow flexible robots with superior elasticity and durability, expanding their applicability across more scenarios [30].

The rise of green manufacturing principles has further propelled the emergence of flexible robots. Their energy-efficient operation, resource-saving design, and recyclability help enterprises achieve sustainable development goals, positioning them as a cornerstone of future manufacturing.

Looking ahead, flexible robots will play a pivotal role in smart manufacturing, with their development characterized by diversification and innovation. As their adoption grows, they will significantly contribute to industrial upgrading and economic growth [31].

5 Conclusion

As an emerging technology in smart manufacturing, flexible robots are reshaping modern production paradigms with their high adaptability, flexibility, and safety. This study analyzes the technical characteristics, application scenarios, and representative cases of flexible robots, demonstrating their significant efficacy in automotive manufacturing, electronics assembly, and logistics warehousing. Practical implementations by BMW Group and Foxconn reveal that flexible robots not only enhance production efficiency and product quality but also reduce operational costs through modular design and intelligent scheduling, establishing a safe and reliable pathway for human-robot collaboration. However, current technological bottlenecks—such as complex environmental perception, unstable energy supply, and the development of high-precision sensors—remain critical barriers to widespread adoption. Additionally, high initial investments and insufficient technological maturity limit acceptance among small and medium-sized enterprises (SMEs). Nevertheless, these challenges present opportunities for innovation and industrial collaboration. Through deeper industry-academia-research integration and policy support, flexible robots are poised to overcome existing limitations and emerge as a core driver of smart manufacturing transformation.

The future development of flexible robots will focus on technological iteration and market demands. The integration of artificial intelligence (AI) and 5G technology will enhance autonomous decision-making and remote collaboration capabilities. For instance, deep learning-based dynamic path planning and zero-latency communication control could further optimize production processes. Advances in materials science will facilitate the development of lightweight, high-durability flexible materials, expanding applications in extreme environments (e.g., minimally invasive surgery, deep-sea exploration). As green manufacturing principles gain traction, the low-energy consumption and high resource efficiency of flexible robots will support corporate sustainability goals.

From a market perspective, growing demand for personalized customization will accelerate the adoption of flexible robots in small-batch, multi-variant production scenarios. Large-scale deployment and industrial chain integration are expected to significantly reduce costs. Policy-wise, national smart manufacturing initiatives—such as "Made in China 2025" and "Industry 4.0"—will provide frameworks for standardizing technologies and fostering cross-sector collaboration.

Flexible robots are anticipated to evolve from single-function devices into interconnected nodes within smart manufacturing ecosystems, driving the industry toward greater efficiency, intelligence, and sustainability.

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