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Industrial Robots: Why They can both Replace and Augment Human Labor

Zhang Suiyi

Shanghai Qibao Dwight High School, Shanghai, China
CocoZhang1236@163.com

Abstract. Since their emergence, industrial robots have advanced from mechanical-replication devices toward human-robot collaborative intelligent systems, driven by iterative progress in sensing and artificial-intelligence technologies. This paper classifies their evolution into three phases: teaching-reproduction, perception-driven operation, and intelligent collaboration. It examines core technologies including robot sensing, machine vision, and force control, and clarifies how AI and human-robot collaboration underpin flexible manufacturing. Based on industrial realities, three development trends are outlined: deep large-model integration for autonomous decision-making, expanded application scenarios enabled by flexible bionic mechanisms, and full-production-line collaboration via the Industrial Internet. Key industry challenges involve deficient core-component technologies, high deployment costs for SMEs, interdisciplinary talent shortages, incomplete industrial standards, and ethical issues stemming from labor transformation. This study argues that smart-manufacturing transformation emphasizes human-machine complementary coordination rather than simple machine substitution of labor. These findings offer theoretical references for industrial-robot R&D and standardized industry promotion.

Keywords: industrial robots, human-robot collaboration, flexible manufacturing, intelligent manufacturing

1. Introduction

Since the 1960s, when the United States developed the first teaching-type industrial robot, industrial robots have evolved from the early teaching-type models to today's intelligent collaborative robots, driven by continuous advances in technology, research and development, and practical applications. With the increasing economic growth and demand, continuous technological innovation, and the increasing application and development of artificial intelligence, industrial robots have also played a very important role in the manufacturing industry.

In the modern industrial sector, as robotic technologies continue to advance, industrial robots have become increasingly widespread, with both the scale and scope of their applications reaching unprecedented levels. Industrial robots are also playing an important role in replacing humans while assisting them. With the introduction of a large number of advanced industrial robots into various production fields, production efficiency can be significantly improved within a limited scope. At the

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same time, with the intelligent development and technological improvement of robots, they have played an important collaborative and auxiliary roles in the precise and complex fields. Therefore, it is of great significance to understand the development process and current core technologies of industrial robots. This paper will summarize the development of industrial robots, summarize the current core technologies and operating mechanisms of industrial robots, and put forward discussions on the future development direction in combination with the current situation and difficulties faced.

2. Development history of industrial robots

The development of industrial robots can be roughly divided into three stages, showing an evolutionary path from mechanical execution to intelligent collaboration.

2.1. The first generation: teaching-reproducing robots (1950s - 1980s)

In 1954, George Devol applied for a patent related to programmable robots, establishing the feasible path for programmable robotic arms to achieve automated operations at the technical principle level [1]. In 1959, the Unimate industrial robot was officially launched, marking the official start of the commercial application era of industrial robots [2]. Robots of this generation were generally not equipped with external sensing devices and lacked the ability to perceive their environment or make autonomous decisions. Their working logic was that the operator taught the complete movement trajectory in advance, and the device could only repeatedly reproduce the preset actions [3]. Their advantage was high reliability of repeated positioning, but the operation flexibility was extremely poor. They were primarily suitable for standardized workstations with fixed processes and stable operating conditions, such as material handling and spot welding. Once the workpiece placement position or process requirements were slightly adjusted, they could not operate normally.

2.2. The second generation: perceptive robots (1980s - early 21st century)

Advances in sensor hardware and computing technology enabled robots to perceive their external environment and marked the transition of industrial robots into an era of perceptual control [4]. Vision, force, and position sensors were successively integrated and installed. Robots could independently identify the shape of workpieces, detect deviations in the operation trajectory, and correct the motion parameters in real-time, getting rid of the shackles of pure mechanical repetitive operations.

The application scenarios were expanded from simple point - to - point operations to more complex processes such as assembly, quality inspection, and automatic spraying. The operation accuracy and adaptability to working conditions were greatly improved, and they gradually became the main equipment in the production lines of automobile manufacturing and consumer electronics assembly.

2.3. The third generation: intelligent collaborative robots (2010s to present)

Artificial intelligence algorithms, edge computing, multisensor fusion, and lightweight, flexible actuators have rapidly advanced and matured. The new-generation robots have multiple capabilities such as autonomous learning, adaptation to dynamic environments, and safe human-machine interaction [5]. The typical feature is that collaborative robots can share the same working space with operators and work synchronously without installing traditional safety isolation guards.

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Relying on artificial intelligence technology, they can adapt to unstructured production scenarios, realize rapid re - configuration and debugging of production lines, and flexible manufacturing of multi - variety products in mixed lines. Industrial robots have entered a new stage of human–machine collaborative intelligent manufacturing [5].

3. Three key technologies and operating mechanisms of industrial robots

3.1. Analysis of the three key technologies

An industrial robot consists of three major parts and six subsystems. The three major parts are the mechanical, sensing, and control parts. The six subsystems can be divided into the mechanical structure system, the drive system, the perception system, the robot - environment interaction system, the human - robot interaction system, and the control system [6]. The core capabilities of industrial robots are supported by three major perception and control technologies, forming a complete closed - loop of "seeing, touching, and controlling".

3.1.1. Robot sensing technology

Sensing technology serves as the "nervous system" of robots and is divided into internal sensing and external sensing [7]. Internal sensors (encoders, gyroscopes) provide real - time feedback on joint position, speed, and attitude to ensure precise movement. External sensors (vision, force, tactile, and distance sensors) acquire environmental information for obstacle avoidance, positioning, and interaction. Multisensor fusion algorithms integrate heterogeneous data to improve robustness, enabling robots to operate reliably under challenging conditions such as changing lighting, workpiece deviations, and dust interference [8]. Sensing technology determines whether a robot can perceive the environment and adapt to changes, and it is the foundation for the transition from mechanical execution to intelligent operation and the integration with AI.

3.1.2. Machine vision: enabling robots to "see" part positions and inspect quality

Machine vision is one of the core perception systems of a robot, functioning as its "eyes" [9]. Through hardware such as 2D/3D cameras, structured light, and time-of-flight (ToF) sensors, combined with image processing and deep - learning algorithms, robots can perform workpiece recognition, pose positioning, dimension measurement, and defect detection. In the production of 3C (computer, communication, and consumer) electronics and automotive parts, the vision system can achieve micron - level positioning to guide grasping and assembly. In quality inspection, it can automatically identify scratches, deformations, assembly misalignments, and other defects, with a much lower missed - detection rate than manual inspection. Machine vision overcomes the fatigue and subjective errors of human eyes, enabling high - speed, high - precision, and all-weather visual inspection and guidance, and it is a key support for flexible manufacturing [9].

3.1.3. Force - control sensing: endowing robots with "tactile sense" for precision assembly and grinding

Force - control sensing endows robots with "tactile sense" and compliant control capabilities [10]. Torque sensors detect contact forces and torques at the robot's end effector in real time, and the control system adjusts the robot's posture and applied force based on this feedback to prevent rigid collisions and damage to workpieces. In precision processes such as mobile phone screen assembly,

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bearing press - fitting, mold grinding, and deburring, force-control technology enables robots to operate with a constant force, ensuring consistency and quality.

In human-robot collaboration, force - control technology enables collision detection and safe stopping to ensure the safety of operators. Force - control technology fills the gap of robots' "seeing without feeling", enabling them to perform complex operations with high precision and high safety.

3.2. Integration of artificial intelligence and robots

AI injects a "brain" into industrial robots, enabling an upgrade from "program-based execution" to "autonomous decision-making" [11]. Deep learning improves the accuracy of visual recognition and anomaly detection, reinforcement learning allows robots to optimize their motion trajectories through trial - and - error, transfer learning enables rapid adaptation across different scenarios, digital twin and predictive maintenance reduce the risk of downtime [12]. The integration of AI and robots brings three major values: first, enhanced flexibility to quickly change production lines for multi - variety and small - batch production, second, intelligent upgrade to autonomously handle deviations, faults, and anomalies more quickly and efficiently, third, efficiency optimization with full - process data - driven optimal production capacity and energy consumption [13].

3.3. Human - robot collaboration

Human - robot collaboration (HRC) breaks the physical isolation of traditional robots, forming a new model of division of labor, collaboration, and complementary advantages [14]. Humans are responsible for decision-making, creativity, complex debugging, and anomaly handling, while robots undertake repetitive, high - intensity, high - precision, and high - risk tasks. Collaborative robots are characterized by lightweight designs, force-control safety features, and ease of programming, which lower the barrier to deployment. Through dual safety mechanisms of vision and force - control, they enable human-robot collaboration in the same space without guardrails [15]. In scenarios such as automobile final assembly, aerospace assembly, and precision machining, human - robot collaboration retains the decision - making advantages of humans and leverages the precision and endurance of machines, solving the "last 15% automation problem" and promoting the transition from rigid automation to flexible intelligent manufacturing [14].

4. Future trends and real challenges

4.1. Future development trends of industrial robots

Intelligence, high flexibility, and full-domain collaboration are the three core development directions of the industrial robot industry. In terms of intelligent upgrading, large language models and edge computing are becoming increasingly integrated with robot control systems. The equipment can complete multi - modal information understanding, autonomous planning of motion paths, and continuous iterative optimization of processes. Through natural-language interaction, these systems can lower the barrier to programming and debugging [16] and quickly adapt to new production tasks.

In the aspect of flexible upgrading, soft robots based on bionic structures can adapt to special - shaped and fragile processing objects with the help of soft materials, and are widely used in the assembly scenarios of food and medical consumables [17]. The modular body architecture supports the rapid reconfiguration of equipment to meet the customized production needs of multiple product

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categories. In terms of collaborative upgrading, the scope of human–robot collaboration continues to expand, extending from collaboration at individual workstations to entire production lines and even factory-wide operations [18]. Relying on 5G communication, digital twin, and the industrial Internet platform, it connects the data links of all dimensions including personnel, equipment, materials, processes, and the environment, creating a transparent and self - adaptive intelligent unmanned factory system.

4.2. Existing real challenges in the industry

Currently, the large - scale popularization of industrial robots still faces multiple real constraints. At the technical level, robots still lack sufficient operational stability in unstructured and dynamic environments. There are technical shortcomings in core components such as high - end sensors, servos, and controllers. At the same time, the limited interpretability of black-box AI models makes it difficult to meet the safety and regulatory requirements of industrial applications [19]. At the industrial implementation level, the investment cost of complete sets of intelligent robot integration solutions is relatively high, which significantly increases the burden of digital transformation for small and medium - sized enterprises. There is an obvious shortage of compound talents with comprehensive capabilities in machinery, electrical control, artificial intelligence, and production processes, which limits the large - scale implementation and application of technologies [20]. From the perspective of social ethics, the automation replacement of traditional repetitive positions brings short - term labor transformation pressure. Relevant laws and regulations governing the allocation of rights and responsibilities in human–robot operations, industrial data privacy, and cybersecurity still require further development [21]. At the industry ecosystem level, the communication protocols of equipment from different manufacturers are incompatible with each other, resulting in high equipment integration costs. A unified standard for safety detection, performance evaluation, and data interaction has not been fully established, which hinders the standardized and orderly development of the industry [22].

5. Conclusion

Industrial robots replace humans in repetitive and high - risk operations with efficiency, precision, and stability, and become a reliable assistant in human production with sensing, vision, force control, and AI technologies. Humans and robots share the common goals of improving quality and efficiency, ensuring safety, and optimizing intelligent manufacturing processes. The development of industrial robots has followed an evolutionary path from mechanical execution to perceptual intelligence and, ultimately, collaborative intelligence. Core technologies support robots to "see clearly, operate accurately, and learn effectively". Human - robot collaboration realizes complementary advantages rather than simple replacement.

In the future, industrial robots will develop towards greater intelligence, flexibility, and collaboration, while facing multiple challenges such as technology, cost, talent, ethics, and standards. The essence of the transformation of the manufacturing industry is not the replacement of humans by machines, but the integration and collaborative evolution of humans and machines. Through technological breakthroughs, talent cultivation, standard improvement, and policy guidance, industrial robots will continue to empower the upgrading of the manufacturing industry, promote the production mode to move towards high - efficiency, safety, greenness, and intelligence, and provide solid support for high - quality economic development.

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