



A Comprehensive Study on Driving Strategies, Control Systems, and Interaction Methods of Intelligent Robotics: Exemplified by Industrial Robotic Arms

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Abstract. This study comprehensively examines the technological evolution of industrial robotic arms from the 1980s to 2025, analyzing key advancements in drive mechanisms, control systems, and human-robot interaction paradigms. Drive systems have progressed from bulky hydraulic actuators to high-efficiency servo motors and further to lightweight modular bionic drives, significantly improving energy efficiency and motion precision. Control architectures evolved from rigid pre-programmed sequences to adaptive AI-driven systems incorporating machine learning and real-time optimization. Human-robot interaction modes transitioned from offline programming to sophisticated multimodal interfaces integrating force feedback, computer vision, and emerging brain-computer interaction technologies, enabling seamless collaboration. Future development trends point toward composite drive systems, autonomous decision-making capabilities, and intuitive natural interfaces, supported by enabling technologies like digital twins and swarm intelligence. As fundamental enablers of smart manufacturing, robotic arms both reflect and drive industrial automation progress, with continued innovation promising to expand their applications across industries while fostering more efficient, flexible, and intelligent production ecosystems. The integration of these advancements is reshaping manufacturing paradigms and creating new possibilities for human-machine cooperation.

Keywords: First Keyword, Second Keyword, Third Keyword.

1 Introduction

As the core equipment of intelligent manufacturing, the technological progress of industrial robotic arms directly reflects the development level of industrial automation. Since the advent of Unimate in 1959, robotic arm technology has undergone a leapfrog development from simple repetitive operations to intelligent autonomous decision-making. Especially since the 1980s, with breakthroughs in drive technology, control algorithms and human-machine interaction methods, industrial robotic arms have achieved significant improvements in terms of precision, efficiency and adaptability,

and have been widely applied in fields such as automotive manufacturing, electronic assembly and medical surgery. However, most of the existing research focuses on a single technical field (such as drive or control), lacking a systematic analysis of the overall technological evolution path of industrial robotic arms. In particular, the discussion on how multi-technology collaborative innovation can promote the intelligent development of robotic arms is still insufficient.

This article systematically reviews the technological development process of industrial robotic arms from 1980 to 2025, focusing on the three core technologies of drive mode, control system and interaction mode, and analyzes their iterative patterns and breakthrough progress. The research reveals the transformation trajectory of robotic arms from rigid architecture to flexible intelligence by comparing the technical parameters of typical products in different periods (such as the energy efficiency difference between Unimate's hydraulic drive and modern servo drive). At the same time, by integrating the cutting-edge technological trends such as digital twins and brain-computer interfaces, the potential development directions of future robotic arms in terms of compound drive, autonomous decision-making, and natural interaction are explored.

2 Technical characteristics of Early Industrial Robotic arms (1980s-2000s)

2.1 Early drive mode

Early industrial robotic arms mainly used hydraulic drive systems or high-power DC motors as power sources. This type of drive system has obvious technical limitations: the mechanical structure design is relatively bulky and occupies a large space; High energy consumption and persistently high operating costs; The system maintenance is complex and requires frequent inspections and repairs by professional technicians.

The first generation of industrial robotic arms generally adopted hydraulic drive or high-power DC motor systems. Although these drive methods had strong load capacity, they also had obvious technical limitations. Take the world's first industrial robot, Unimate, as an example, as shown in Figure 1. The hydraulic drive system it adopted could provide an output torque of up to 200kgf, which was sufficient to meet the application requirements of heavy industries such as automotive manufacturing at that time. However, this driving mode has exposed many problems in practical applications: Firstly, the system's energy efficiency is extremely low, with an energy conversion efficiency of less than 40%, and it requires continuous maintenance of oil pressure, resulting in a large amount of energy waste; Secondly, the maintenance work is arduous. On average, the seals need to be replaced every month. Frequent oil leakage not only increases the maintenance cost but also leads to severe oil contamination in the working environment. Finally, it performs poorly in terms of accuracy, with a repeat positioning accuracy of only $\pm 1.5\text{mm}$. This accuracy level is difficult to meet the increasingly demanding requirements of precision assembly processes. These deficiencies severely restricted the application expansion of early industrial robotic

arms in the field of precision manufacturing and also became an important driving force for subsequent technological innovation [1, 2].



Fig.1. Unimate image.

2.2 Constraints of rigid control systems

The control systems of early industrial robotic arms adopted rigid hardware architectures, which posed significant technical constraints in terms of functional realization. In terms of programming methods, operators must manually record position data at each point through the teaching device. A typical welding path programming often takes 4 to 6 hours of cumbersome operation, which greatly affects production efficiency. In terms of motion control capabilities, the system can only support basic point-to-point (PTP) motion and limited continuous path (CP) control, lacking complex trajectory planning functions and making it difficult to meet the demands of refined industrial processing. What is more serious is that the system has almost no fault-tolerant processing capability. According to the industry statistics of 1995, mechanical collision accidents caused by program errors accounted for 32% of the total faults. This not only leads to equipment damage but also brings safety hazards. The limitations of these control systems severely restricted the application scope and performance of early industrial robotic arms, prompting subsequent control technologies to develop in a more intelligent direction [3].

2.3 One-way interaction mode

Early industrial robotic arms exhibited obvious unidirectional characteristics in human-computer interaction and had many operational limitations. Firstly, the interactive

system is highly dependent on the online teaching mode. Any modification of the operation path requires the operator to be present at the production site in person and re-record the movement trajectory and action instructions of the robotic arm point by point through a handheld teaching device [2]. This not only seriously affects the continuity and efficiency of production but also poses a risk of collision and injury to the operator [4].

Secondly, due to technical limitations, early robotic arms had significant deficiencies in terms of environmental adaptability and interaction capabilities. They lack real-time environmental perception capabilities and can only rely on preset programs to perform fixed-trajectory operations, unable to independently adjust their actions according to changes in the working scene. Secondly, the sensing system is simple and crude, only equipped with basic position encoders or switch quantity sensors, making it difficult to accurately perceive multi-dimensional information such as contact force and spatial position. This leads to poor operational flexibility and makes it highly prone to failure in unstructured environments. The execution efficiency is low and requires frequent manual intervention and adjustment [5]. This backward state of human-computer interaction has also become an important driving force for the development of subsequent interaction technologies

3 Breakthroughs in Modern Industrial Robotic Arm Technology (2010s-2020s)

3.1 High energy efficiency drives reform

Modern industrial robotic arms are undergoing a high-efficiency revolution in drive systems. Innovative products represented by ABB's 7th generation IRB 6700 series are redefining the energy efficiency standards for industrial drives. The ABB IRB 6700 is shown in Figure 2.

This series has achieved a leap in the energy efficiency of the drive system through three core technological innovations. Firstly, a major breakthrough has been achieved in energy conversion efficiency. It adopts a new generation of permanent magnet synchronous motors in combination with silicon carbide (SiC) power devices, which has increased the overall energy efficiency of the system to over 92% and reduced energy consumption by 15% compared to the previous generation [6]. Its innovative compact gearbox design keeps mechanical transmission loss within 5%, significantly enhancing energy utilization efficiency. Secondly, in terms of energy management, dynamic load regulation is achieved through intelligent power distribution algorithms, and it can automatically switch to energy-saving mode during non-peak loads. In combination with the Lean ID cable solution, not only is the trouble-free operation time extended to 400,000 hours [7], but also the standby power consumption is reduced by 30%. Most importantly, this drive system achieves a perfect balance between energy efficiency and performance: while maintaining a load capacity of 150-300kg, the repeat positioning accuracy reaches $\pm 0.05\text{mm}$, and the acceleration response is improved by 40%. Its "plug and play" modular design enables energy consumption to precisely

match the requirements of different processes such as stamping and welding, making it suitable for high-intensity applications in automotive manufacturing and other fields. These innovations mark that the drive system of industrial robotic arms has evolved from a simple power output to a new generation of energy control platform integrating high efficiency, intelligence and energy conservation, providing key technical support for the green transformation of the manufacturing industry.



Fig.2. Global launch ceremony of ABB IRB6700 series robots.

3.2 Evolution of Intelligent Control Systems

The modern robotic arm control system has developed into a highly integrated multi-modal intelligent collaborative system. By deeply integrating the three core technical modules of perception, decision-making and execution, an intelligent control architecture with autonomous learning and self-adaptation capabilities has been constructed. This system adopts a modular design concept, organically integrating core functions such as visual perception, force feedback, and motion planning, and achieving seamless collaboration among various subsystems through an advanced algorithm architecture. At the perception level, the system integrates multi-modal sensing devices such as high-precision vision sensors, six-dimensional force sensors, and inertial measurement units [8,9]; At the decision-making level, AI algorithms such as deep learning and reinforcement learning are employed to achieve real-time path planning and dynamic adjustment [10,11]; At the execution level, precise motion is ensured through high-performance servo drives and intelligent control algorithms [12]. This highly integrated control system not only significantly enhances the operational accuracy and response speed of the robotic arm, but also endows it with autonomous adaptability in complex dynamic environments, enabling it to handle various high-difficulty tasks ranging from precision assembly to medical surgeries. It demonstrates a level of flexibility and intelligence that traditional robotic arm systems lack. Its core features are mainly reflected in the following aspects.

Intelligent Hybrid Control. The intelligent hybrid control technology of modern robotic arms enhances the environmental perception capability of robotic arms by integrating multi-source data such as vision, force perception, touch, and inertial measurement units, and integrating multi-modal perception. For instance, the visual servo system, in collaboration with a six-dimensional force sensor, achieves high-precision positioning ($\pm 0.02\text{mm}$) and smooth operation, making it suitable for precision assembly and medical surgeries. Depth cameras and lidars have further expanded the 3D reconstruction and obstacle avoidance capabilities of robotic arms in complex scenarios.

Ai-enhanced decision-making. AI technology, especially reinforcement learning, is completely transforming the decision-making and control methods of modern robotic arms. Through the reinforcement learning framework, the robotic arm can independently learn the optimal operation strategy (such as grasping, assembling or obstacle avoidance) in interaction with the environment without relying on precise pre-programming. For instance, motion planning methods based on deep reinforcement learning can generate efficient trajectories through trial-and-error learning, significantly enhancing the adaptability to complex tasks [10]. Moreover, AI endows the robotic arm with real-time adjustment capabilities to cope with uncertainties and environmental changes. This feature enables it to maintain high-precision recognition even in complex scenarios such as stacking and soil covering. By integrating visual, tactile and force perception data, AI algorithms can achieve more precise environmental understanding and operation planning [11].

Flexibility and variable stiffness control. The flexibility and variable stiffness control technology of modern robotic arms refers to the combination of force sensor feedback and impedance/admittance control algorithms, which can adjust the stiffness and damping parameters in real time according to different operational requirements [12]. For instance, in precision assembly operations, the system can automatically switch to a high-stiffness mode to ensure positioning accuracy, and when grasping fragile items, it can quickly adjust to a low-stiffness mode to guarantee operational safety. This technology is mainly achieved through three methods: Firstly, bionic structures such as tandem elastic actuators (SEA) and pneumatic muscles are adopted to endow the robotic arm with the flexibility characteristics similar to biological muscles, significantly reducing the impact force during collisions [13,14]. Secondly, the control system based on surface electromyographic signals (sEMG) analyzes the muscle activity state of the operator through algorithms such as PSO-GRNN to achieve dynamic adjustment of the stiffness of the robotic arm [12]. With the development of artificial intelligence technology, reinforcement learning algorithms have been used to optimize stiffness parameters [15], further enhancing the response speed and control accuracy of the system.

3.3 Modern Human-Computer Interaction System

The interaction system of modern industrial robotic arms has developed into a highly intelligent multimodal system, establishing an all-round perception network.

Physical contact interaction. Physical contact interaction in the field of industrial robots mainly includes two methods: force control teaching and teaching device control. The two methods complement each other. Force control teaching emphasizes the intuitiveness of human-machine collaboration, while teaching device operation provides standardized and reusable programmed control, jointly enhancing the ease of use and adaptability of industrial robots. The force control teaching adopts a highly sensitive torque sensor. The operator can directly apply physical force to the end effector of the robotic arm for dragging. The system records the movement trajectory in real time and automatically generates a control program. This method is equipped with collision detection and safety protection mechanisms, and is particularly suitable for scenarios that require high-precision compliance control, such as precision assembly and flexible workpiece operation. The control of the teaching device is achieved through a dedicated industrial-grade handheld terminal. The device integrates an emergency stop button, an enable switch and a 6D joystick to ensure operational safety and flexibility. It supports three programming modes: The first is point-to-point teaching, which uses point-by-point recording of the joint angles of the robotic arm and is suitable for discrete action programming; Then comes trajectory reproduction, which achieves precise reproduction of complex trajectories by continuously recording the movement path. The last one is parametric programming, which customizes logical flows through scripts to meet the flexible requirements of automation tasks.

Visual Perception Interaction. Visual perception interaction in the field of industrial automation mainly includes two advanced methods: machine vision guidance and AR visual interaction. They respectively enhance interaction efficiency from two dimensions: "machines perceiving the environment" and "humans understanding machines". Visual guidance ensures operational accuracy [16], while AR interaction optimizes the intuitiveness of human-machine collaboration [17], jointly promoting the visualization and intelligence process of intelligent manufacturing. The machine vision guidance system is composed of industrial cameras, high-precision optical lenses and image processing algorithms to form a closed-loop control. Its typical workflow is: image acquisition → feature extraction [18] → coordinate transformation → motion control. The improved ROA-SURF algorithm (feature matching accuracy >95%) is adopted to achieve sub-millimeter positioning accuracy, which is suitable for scenarios such as precision sorting and high-precision assembly. AR visualization interaction is based on HoloLens 2. Through SLAM spatial positioning, waveguide optical display and depth-sensing gesture recognition, virtual instructions are superimposed in real time onto the real scene, and then mixed with reality devices to achieve natural interactive AR visualization operations. Three innovative core functions have been realized. Firstly, the three-dimensional holographic instruction superposition function

can precisely project digital operation guidance onto the real working scene, achieving seamless integration of virtual information and the physical environment. Secondly, the real-time motion trajectory preview function visually rehearses the movement path of the robotic arm, enabling the operator to intuitively predict and verify the equipment's operating trajectory. Thirdly, the remote expert annotation sharing function enables experts from different locations to conduct real-time annotation and guidance through the AR interface, effectively breaking through geographical limitations. This system adopts a human-computer interaction method that combines natural gesture recognition with voice commands [17], significantly enhancing operational convenience. It is particularly suitable for industrial application scenarios such as complex assembly operations involving multiple people and maintenance of precision equipment [16,18], notably improving work efficiency and operational safety.

Natural Behavior Interaction. Natural behavior interaction in the field of robot control mainly includes two innovative methods: gesture control systems and motion imitation control. The gesture control system is implemented based on the Leap Motion sensor (200Hz high sampling rate). By capturing the data of 28 key points of the hand, it adopts a five-layer processing architecture: raw data acquisition, noise filtering, feature extraction, pattern matching and instruction output to complete instruction recognition. This system supports the recognition of 8 static gestures (such as clenching fists and stretching) and 6 dynamic gestures, with an average response delay controlled within 50ms, meeting the real-time control requirements [19]. The motion imitation control builds the human-robotic arm motion mapping system through the inertial measurement unit (IMU). Firstly, the mathematical model of the human joint chain and the D-H parameters of the robotic arm is established. Then, the quaternion interpolation algorithm is adopted to achieve the smooth conversion of the motion trajectory. Finally, the adaptive filtering technology is integrated to eliminate the random jitter within $\pm 3^\circ$ range. Complete the conversion from human body movements to mechanical arm movements. This technology is particularly suitable for teaching scenarios that require the reproduction of human movement, such as rehabilitation training, programming of dance robots, and other applications [20].

Neural Signal interaction. The neural signal interaction system has achieved a revolutionary human-computer interaction method through brain-computer interface control. Its core technical path includes three progressive stages of development: In the consciousness input stage, the system adopts electroencephalogram (EEG) signal classification technology based on the steady-state visual evoked potential (SSVEP) paradigm, which can accurately identify user intentions within 800 milliseconds. After entering the physical fusion stage, the response time is significantly reduced to 200 milliseconds by decoding the neural signals of the motor cortex. The final stage of human-machine symbiosis achieves ultra-low latency interaction of less than 50 milliseconds through a bidirectional neural feedback mechanism, achieving near-real-time control effects [17]. Meanwhile, the system innovatively established a biofeedback regulation mechanism, precisely analyzing the dynamic mapping relationship between

characteristic brain waves such as α , β , and θ and the operating status of the robotic arm: The operator's attention level is transformed into the adjustment signal of the mechanical arm's movement speed, the relaxation degree is correspondingly adjusted to the operation force of the end actuator, and the emotional state is quantified as the control parameter of obstacle avoidance sensitivity. Thus, a complete "perception - decision-making - execution" closed-loop intelligent regulation system is constructed. This cutting-edge interaction mode not only breaks through the physical limitations of traditional human-computer interaction, but also pioneers a new paradigm of intelligent control based on neurophysiological signals [21].

Summary. In industrial application scenarios, various interaction methods exhibit distinct differences in technical characteristics. Force control teaching, with its $\pm 0.1\text{mm}$ accuracy and immediate response capability, has become the preferred choice for precision assembly. The visual guidance system is competent for dynamic sorting tasks with an ultra-high precision of $\pm 0.02\text{mm}$ and a delay of 30ms. Gesture control demonstrates advantages in the field of education and training with an accuracy of $\pm 5\text{mm}$ and a delay of 50ms. Although brain-computer interfaces have a delay of 200 to 800ms and a relatively high learning cost, they have irreplaceable value in the field of disability assistance. Modern industrial systems achieve flexible combinations of various interaction methods through modular design. For instance, the combination of "AR visualization + force control teaching" is suitable for precision assembly operations of spacecraft, and the solution of "visual guidance + brain-computer interface" is applied to effectively meet the demands of hazardous environment operations. These intelligent interaction solutions are driving human-machine collaboration to continuously evolve towards greater efficiency, security and intelligence.

4 Future Technological Development Trends (2025+)

4.1 Composite Drive Architecture

The drive strategy of future robotic arms will rapidly develop in the direction of high efficiency, lightweight and bionic integration. The core lies in breaking through the limitations of traditional rigid drives to achieve more flexible and energy-efficient motion control. In terms of new drive technologies, bionic muscle drive will become an important trend. By adopting flexible drives such as shape memory alloy (SMA), pneumatic artificial muscle (PAM), or dielectric elastomer (DEA), robotic arms can simulate the smooth movement characteristics of biological muscles, thereby better adapting to complex environments. For example, to achieve precise and safe operations in scenarios such as medical surgeries or disaster rescue. Meanwhile, modular drive technology will also be widely applied. By means of reconfigurable drive units (such as modular motors or hydraulic systems), the configuration of the robotic arm can be quickly adjusted to meet the requirements of different tasks, while significantly reducing maintenance and upgrade costs. In addition, advancements in energy recovery

technologies, such as regenerative braking and environmental vibration energy harvesting, will further enhance the energy efficiency of robotic arms, especially for mobile robotic arm applications that require long endurance, such as field exploration or logistics handling robots. To strike a balance between motion accuracy and environmental adaptability, future drive systems will increasingly adopt hybrid drive modes, that is, combining the high-precision control advantages of traditional motors with the flexible response characteristics of new smart materials (such as magnetorheological fluids and electroactive polymers). For instance, in the field of surgical robots, high-precision servo motors can ensure the stability of operation, while flexible drivers can buffer accidental impacts and prevent damage to fragile human tissues. This collaborative control strategy not only enhances the performance of the robotic arm but also expands its application potential in high-end fields such as precision manufacturing and rehabilitation medicine. Overall, innovations in driving technology will make robotic arms more efficient, lightweight and close to the naturalness of biological movement, laying a solid foundation for the next generation of robotic systems.

4.2 Autonomous Decision-making System

The control system of future robotic arms will deeply integrate artificial intelligence and distributed computing technologies, and develop in a more intelligent and reliable direction. In terms of AI-driven autonomous decision-making, reinforcement learning (RL) and adaptive control technologies will enable robotic arms to have the ability to optimize their movement trajectories in real time, and be able to autonomously adjust their action strategies based on environmental feedback, such as accurately grasping randomly placed objects in logistics sorting scenarios. Meanwhile, the application of digital twin technology will enable precise simulation of the operating status of robotic arms, predict potential faults through virtual models, and dynamically adjust control parameters, significantly enhancing the reliability and service life of the equipment. At the computing architecture level, the popularization of edge intelligence will change the traditional model that relies on cloud processing. By deploying lightweight AI models on local devices such as embedded Gpus or FPGAs, communication latency can be significantly reduced, meeting high-response requirements such as real-time obstacle avoidance in industrial scenarios. In addition, the introduction of blockchain technology will provide a secure and efficient task allocation mechanism for the collaborative operation of multiple robotic arms, ensuring the trusted sharing of data and transparency of processes in scenarios such as distributed warehousing and logistics. Particularly worth noting is the breakthrough in brain-like control architecture. By drawing on the sparse computing characteristics of spiky neural networks (SNN), future control systems will achieve low power consumption and high fault tolerance performance comparable to biological neural networks. This bionic control mode is especially suitable for long-term autonomous operations in extreme environments such as space and deep sea. These technological advancements will jointly drive the rapid development of robotic arm control systems towards autonomy, distribution, and bio-heuristic directions.

4.3 Natural Interaction Interface

The interaction methods of future robotic arms will rapidly develop in the direction of naturalization and multi-modal integration, making human-machine collaboration more intuitive and efficient. In terms of intuitive human-computer interaction, brain-computer interface (BCI) technology will achieve a revolutionary breakthrough. Through non-invasive electroencephalogram (EEG) or implantable electrode arrays, users can directly control robotic arms with their minds, which will provide a brand-new means of life assistance for paralyzed patients. Meanwhile, the gesture and eye-tracking system integrated with AR/VR technology will create an immersive operating environment, enabling industrial maintenance personnel to remotely guide robotic arms to perform precise operations through natural movements.

At the level of perception and feedback, multimodal fusion technology will significantly enhance the sense of reality in interaction. By integrating electronic skin and advanced force sensors, the robotic arm can precisely sense the hardness characteristics of the objects in contact, enabling surgeons to obtain real tissue tactile feedback during minimally invasive surgeries. The audio-visual coordination system further enriches the interaction dimensions. With the help of intelligent voice interaction and 3D holographic projection technology, service robots can understand and respond to user needs in a more natural way. For complex working scenarios, group collaborative interaction will demonstrate powerful advantages. Based on swarm intelligence algorithms, multiple robotic arms can autonomously coordinate tasks through local communication technologies such as ZigBee and UWB, achieving efficient division of labor in scenarios like collaborative material handling at construction sites. This decentralized collaboration model not only enhances work efficiency but also strengthens the system's robustness in the face of unexpected situations. The integrated application of these innovative interaction technologies will drive robotic arms to evolve from mere execution tools into truly intelligent collaborative partners.

5 Conclusion

This article systematically reviews the technological development process of industrial robotic arms from the 1980s to the present, with a focus on analyzing the evolution paths of the three core technologies: drive mode, control system, and interaction mode. Research shows that industrial robotic arm technology has undergone a qualitative leap from being bulky and inefficient to being precise and efficient: the drive system has evolved from hydraulic drive to high-efficiency servo motors and bionic drive; The control system has been upgraded from a rigid hardware architecture to an intelligent platform with AI decision-making capabilities. The interaction mode has shifted from one-way offline programming to multi-modal natural interaction, achieving the intelligence and intuitiveness of human-machine collaboration.

In the future, industrial robotic arms will continue to develop in the direction of high integration, intelligence and naturalization. The innovative integration of composite drive architecture, autonomous decision-making system and natural interaction

interface will further expand the application scenarios of robotic arms and enhance their adaptability and collaboration capabilities in complex environments. The introduction of cutting-edge technologies such as digital twins, swarm intelligence and quantum computing will bring revolutionary changes to industrial automation. Meanwhile, breakthroughs in technologies such as brain-computer interfaces and affective computing will drive human-computer interaction into a new stage of "emotional collaboration".

As the core equipment of intelligent manufacturing, the technological progress of industrial robotic arms not only reflects the development level of industrial automation, but also provides key support for the transformation and upgrading of the future manufacturing industry. With the continuous innovation of technology, industrial robotic arms are bound to play a significant role in a wider range of fields, promoting industrial production to move towards greater efficiency, flexibility and intelligence.

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