



# Advances in Intelligent Control and Collaborative Technologies for Industrial Robots

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**Abstract.** This article provides a systematic review of the current research status and development trends of intelligent control and collaboration technologies for industrial robots. As the demand for flexibility and personalization in manufacturing continues to rise, artificial intelligence is deeply integrating with mechatronics. With the increasing demand for flexibility and personalization in manufacturing, the deep integration of artificial intelligence and mechatronics has presented challenges for traditional robot systems in terms of dynamic adaptability, collaborative capabilities, and intelligence level. This article focuses on the progress of industrial robots in the two core areas of intelligent control and collaboration. In the field of intelligent control, the evolution path of the embodied intelligent system from the execution of preset programs to a "multimodal perception - autonomous decision-making - dynamic execution" closed loop was analyzed. This part covers key technologies such as perception decision fusion, high-precision motion control, and low-code teaching. In terms of collaborative technology, the human-machine collaborative safety framework, multi-robot collaborative control algorithms, and system integration solutions were discussed. The development trend indicates that industrial robots are moving towards higher autonomy, stronger collaboration capabilities, and cross-scenario adaptability. The conclusion of this article states that in the future, efforts should be focused on breaking through key bottlenecks such as dynamic scene adaptability, real-time collaborative control, and the domestic production of core components. By establishing a collaborative innovation ecosystem covering the "perception - decision-making - execution" full technical chain.

**Keywords:** Industrial robots, Intelligent control, Cooperative technology

## 1 Introduction

In recent years, the intelligent industry has developed rapidly. The application of traditional robots has been unable to fully meet the requirements of the mechanical field. The latest technologies in the field of robotics have made significant progress, particularly highlighting breakthroughs in domestic production, multi-machine collaboration, and human-machine interaction, among other cutting-edge directions. The development and application of intelligent robots are centered around intelligent industrial robots, including typical categories such as collaborative robotic arms,

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heavy-duty robots, and humanoid robots. The in-depth advancement of various technologies has made the control and collaboration of robots more refined. Planning trajectories and forcing control accuracy on intelligent control technology. In terms of collaborative technology, develop a human-machine collaborative security framework and a multirobot task allocation system. The integration of intelligent control and collaboration technologies is indispensable for promoting the practical application of industrial robots. The AI-driven perception-decision-execution loop can not exist without the combination of the two. At the same time, there are also some issues that need to be addressed and improved. Lacking the adaptability for complex dynamic scenarios. The control accuracy fails to meet the required standards. In heavy - load scenarios, it is arduous to effectively suppress vibrations. The task allocation for multi-machine collaboration is highly complex, which can affect operational efficiency. In human-machine coexistence scenarios, the real-time obstacle avoidance mechanism and sudden shutdown protection measures are often insufficient. The domestic production rate of precision reducers and high-dynamic servo motors remains low.

This article conducts a technical integration, reviews the development of intelligent control and collaboration technologies, reveals the evolutionary path from individual intelligence to group intelligence, summarizing the numerous localization progress, providing technical reference for alternative solutions in high-risk scenarios. These offers ideas for the improvement of future multi-scenario applications and real-time collaborative work of robots.

## **2 Development of Intelligent Control Technology**

The development of intelligent control for industrial robots is the result of the inherent demand for manufacturing industry transformation and upgrading, combined with the external empowerment from disruptive technologies such as artificial intelligence, sensing, computing, and communication. Facing with the increasing demands for efficiency and accuracy as well as the rising cost pressures, industrial automation has become an inevitable trend. For assembly lines in industries such as automobiles and electronics, highly coordinated and stable execution units are required. Industrial robots thus became the ideal choice.

The significant progress made in intelligent control of industrial robots would not have been possible without mature supporting technologies and reduced costs. 5G, industrial Ethernet and other technologies offer high speed, low latency and highly reliable data transmission, supporting cloud robots, multirobot collaboration and remote control. Cloud computing provides robots with nearly unlimited computing resources and storage capabilities and supports large scale data training, algorithm optimization, and remote monitoring/diagnosis. Big data analysis is used for predictive maintenance and process optimization. The high-fidelity physical simulation environment enables robot algorithms to be trained and verified efficiently and safely in a virtual world, significantly reducing the risks and costs associated with actual deployment.

### 2.1 Perception and Decision-making Layer: Integration of Environmental Cognition and Intelligent Decision-making

Multimodal perception collaboration constitutes the physical foundation for environmental modeling. Embodied intelligent decision-making relies on large models to achieve the ability of task generalization. During the development of the perception and decision-making layers, distinct technical systems have been formed. The visual-force integration system combines high-precision vision with force feedback, aiming at highly precise processing and assembly scenarios that require extremely high accuracy. The radar haptic cooperative system is particularly adept at dealing with dynamic environments. The multisource fusion perception system builds a spatial geometric model by integrating a high precision 3D vision module (with a resolution of 0.05mm/pixel). Millimeter-wave radar (with a detection range of 0.1 - 15 meters) detects the distance of moving obstacles. The quantum dot flexible tactile sensor array (with a sensitivity of  $\pm 0.1N$ ) captures micro-force feedback. Finally form a triple perception loop of "visual - kinesthetic - spatial", and construct a three-dimensional perception network of spatial geometry - dynamic obstacles - micro-force feedback. By leveraging the long-range detection capability of radar and the close range fine perception ability of touch, the safety of the mobile robot's operations has been effectively guaranteed. Real time environmental perception and dynamic path adjustment not only improve the efficiency of robots but also reduce human errors and operational risks. [1] The VLA multimodal model represents a cutting edge exploration. It achieves this by establishing a mapping framework of visual, language and action, aiming to break through the limitations of traditional teaching methods and realize more natural human-machine interaction and complex instruction understanding. These technical systems collectively form a diverse range of solutions for environmental perception and intelligent decision making, significantly enhancing the adaptability of industrial robots. The specific performance indicators and application features are shown in Table 1.

**Table 1.** Performance Comparison of Multimodal Sensing Technologies (Representative Achievements from 2023 to 2025) [2-4]

Technical System	Core Sensor	Application Scenario	Key Property index
Visual-kinesthetic fusion technology	Structured light camera + six dimensional force sensor	Robot weld seam information detection and grinding	Grade Sa2.5
Millimeter wave radar - Quantum tactile synergy	Millimeter-wave radar + Quantum dot tactile array	UBTECH Walker S1 factory inspection Task	Response delay: $98 \pm 12$ meters
VLA Multimodal Model Technology	RGB-D Camera + Voice Interaction Module	Robot Directional Voice Interaction	Success Rate Over 90%

## 2.2 Motion Control Layer: Coordinated Optimization of High Precision and Energy Efficiency

High precision control of motion is achieved through a dual-loop architecture, that is, the position loop and the force control loop work together. It enhances the precision of the robot in practical applications such as welding by using the jitter suppression algorithm. Bionic trajectory modulation energy consumption optimization, braking energy feedback, and reduction of harmonic pollution control breakthroughs all rely on the collaborative innovation of algorithms and hardware.

The jitter suppression algorithm is a type of technology used to reduce unstable fluctuations in signals or systems, widely applied in fields such as network communication, mechanical vibration control, and electronic signal processing. There are mainly five types: linear de-jitter filtering method, software filtering algorithm, amplitude limiting de-jitter filtering method, motion compensation algorithms, and digital signal processing algorithms. The Evft ARC12-2000 arc welding robot adopts an adaptive cascaded PID architecture (Adaptive Cascaded PID). Its friction compensation feedforward module significantly suppresses the joint nonlinear disturbances. Under high-load conditions, the amplitude of the end vibration significantly decreases, the welding repeatability positioning accuracy is stable, and it has improved the anti-interference performance compared to the traditional PID control. Omid Asvadi Kermani and his colleagues proposed an adaptive sliding mode model predictive control (ASMPC) strategy based on model predictive control (MPC). Abandoning the traditional force regulation method, by embedding the sliding mode term in the MPC framework and enforcing clear stability criteria, the closed-loop robustness is optimized. The experiment shows that the application of this model has achieved a faster stabilization time, smaller voltage ripple, and an energy efficiency improvement of approximately 3% to 6% in all scenarios [5].

## 2.3 Teaching Technology Innovation: Low-code Implementation and Cross-modal Interaction

The multimodal training mechanism lowers the operational threshold. Teaching technology innovation is driving a fundamental transformation in the interaction mode of industrial robots. The traditional teaching method that relies on professional programming is gradually being replaced by multimodal natural interaction. Zero-code teaching enables industrial robots to transform from expert systems to frontline production tools, making human-machine interaction and collaboration more convenient. The VDI (Virtual Demonstration Interface) tool integrates three teaching modes: virtual reality, physical guidance, and action demonstration. The operator can mark the point cloud of the welding path through the VR helmet. The robot learns the action mapping based on the Deep Deterministic Policy Gradient (DDPG) algorithm, and the training cycle is shortened. Zero-code programming platform accelerates application deployment. By integrating various training mechanisms such as virtual demonstration, physical guidance and action imitation, the operational threshold has been significantly lowered. The new generation of zero-code programming platform

enables users to complete the trajectory teaching system by simply dragging the robotic arm and other methods, and automatically generate optimized code. These advancements have significantly enhanced the efficiency of robot deployment, while reducing the reliance on professional engineers. The intelligent development of the teaching process has enabled industrial robots to transform from expert systems to frontline production tools, and expands its application scope significantly.

### 3 Key Breakthrough in Collaborative Technology

#### 3.1 Background of Human-Machine Collaboration Development

**Table 2** Performance comparison of some industrial robots [6-8]

Type of robot	Technical feature	Typical application scenarios
Collaborative robotic arm	Flexible, Maneuvering stability	Manufacture in different environments
Patrol robot	Perfect evadible system and inductor multidimensionally	Inspect the environment and product quality
Humanoid robot	Advanced perception system, Stable motion control	Manufacturing, Logistics, Chemical industry

The development of industrial robot collaboration technology is the result of the combined effect of multiple factors such as the demand for manufacturing transformation, technological breakthroughs, and policy promotion. The rise of human-robot collaboration (HRC) reflects both the maturation of safety standards and technological progress, enabling robots and humans to work together safely and efficiently within shared spaces by combining human flexibility with robotic strength and precision. Evolving manufacturing needs have driven the shift from rigid automation to flexible collaboration in robotics. The trend toward personalized consumption has prompted manufacturing to transition from mass production of single variants to small batch, multivariety production models. Traditional programmed robots, constrained by fixed environments and routines, struggle to adapt to frequently changing production requirements. Meanwhile, early industrial robots required isolated operation to prevent accidents, limiting human-robot interaction scenarios. In contrast, collaborative robots achieve safe coexistence through technologies such as force control and collision detection, allowing shared-space operation that enhances flexibility while reducing isolation costs.

In the field of collaborative robotics, different types of robotic platforms exhibit distinct technical strengths. Collaborative robotic arms integrate joint torque sensing and collision detection algorithms to achieve intrinsic safety in close proximity human-robot collaboration. Mobile inspection robots leverage multisensor fusion navigation and remote communication capabilities to autonomously perform monitoring and

inspection tasks in complex, dynamic environments. Humanoid robots, with their biomimetic structures and multi-degree of freedom coordinated control, demonstrate significant potential in adapting to human workspaces and performing complex dexterous operations. As detailed in Table 2, the specific performance metrics and collaborative capabilities of these robotic systems highlight the trend toward diversification and specialization in industrial robotics technology.

### **3.2 The algorithm operates multi-robot collaborative control.**

Research on Unmanned Aerial Vehicle (UAV) path planning in complex environments not only presents technical challenges but also holds substantial value across various domains [9]. The MADER algorithm, a multi-agent trajectory planning system initially proposed by a research team at the Massachusetts Institute of Technology in 2020, was designed to address collision avoidance in cooperative drone operations. To tackle communication delays in practical applications, the team introduced an enhanced version, Robust MADER, significantly improving system reliability and safety. Multi-Agent Trajectory Planner (MADER) is an asynchronous, decentralized trajectory planner specifically designed for collaborative missions of drone swarms. Its core concept involves real-time optimization and shared trajectory information to ensure each UAV generates collision-free paths in dynamic environments. Each drone independently computes its own trajectory without relying on a central controller, making it suitable for large-scale clusters and long-range operations. UAVs do not require synchronous consensus; they merely broadcast their trajectories and receive information from other agents, iteratively optimizing and adjusting paths. During hardware testing, researchers identified collision risks in the original MADER due to communication delays and implemented optimizations to ensure each drone maintains two trajectories: a known safe path confirmed through collision checks and a newly optimized path that undergoes repeated safety validation during a deferred check period. If a potential conflict is detected, the path is re-optimized. In UAV path planning within complex environments, path feasibility is closely tied to flight constraints such as flight duration, distance, altitude, turning rate, climb angle variation, and safety factors [10]. Before committing to a new trajectory, each UAV waits for a fixed period while continuously monitoring updates from other agents, with the delay duration dynamically adjusted based on environmental factors such as distance and interference intensity.

## **4 Analysis of Typical Application Scenarios**

### **4.1 High-End Manufacturing**

The intelligent upgrading of industrial robots is expanding from structured production lines to complex dynamic scenarios, with high end manufacturing applications placing paramount emphasis on heavy duty precision operations. The core challenge lies in achieving compatibility between high payload capacity and ultra high precision. The

critical requirements for industrial robots in this sector are manifested in precise control under heavy load conditions and rapid response capabilities for mixed model production lines. Technologically, this is characterized by a multi-contact cooperative control architecture that unifies substantial payload handling with micron-level accuracy. By employing distributed force control algorithms to compute the generalized inverse of the Jacobian matrix in real time, the system dynamically allocates joint torques to counteract end effector drift caused by load deformation. Simultaneously, the integration of harmonic voltage compensation technology in smart joint modules reduces torque ripple, maintaining submillimeter positioning accuracy even under hundred kilogram loads. In flexible production, a dynamic adaptive control framework significantly reduces line changeover time through tripartite coordination: self-adjusting process parameters, optimized acceleration profiles, and energy-aware scheduling. This approach breaks the traditional trade off between precision and efficiency, meeting the stringent requirements of precision tasks such as aerospace component manufacturing while adapting to rapid model changes in automotive mixed-line production. Furthermore, energy feedback technology reduces energy consumption per unit output, creating a triple value added effect encompassing precision, efficiency, and sustainability.

#### **4.2 High-Risk Special Operations**

Specialized operations in high risk environments represent adaptive innovations under extreme conditions, with aerospace fuel tank welding and nuclear waste handling being among the most challenging applications. The core paradigm shift in hazardous scenarios involves transitioning from predefined obstacle avoidance to online risk modeling. The bottleneck in aerospace fuel tank welding lies in thermal deformation control, which is addressed through a dual-robot mirroring system utilizing hybrid admittance-impedance control. The primary robot tracks the weld seam trajectory via admittance control, while the secondary robot applies counter forging forces through impedance control. The system incorporates infrared thermal imagers to monitor the weld temperature field and employs finite element simulation to predict deformation, dynamically adjusting the welding path accordingly. Nuclear waste handling necessitates overcoming perceptual degradation in radioactive environments. A seven degree of freedom redundant robotic arm architecture ensures continued task execution—such as sealed container grasping—even with single-joint failure, maintaining millimeter level accuracy. The system utilizes germanium crystal radiation resistant cameras combined with quantum dot tactile sensors to preserve tactile sensitivity in high radiation conditions, enabling vision force controlled collision avoidance.

### **5 Challenges**

In practical application, the intelligent control mode has relatively high technical requirements for industrial robot technology. If its technology fails to meet the actual

requirements, it will have an impact on production efficiency. Despite significant technological advancements, industrial robots still face dual bottlenecks of fundamental theory and engineering in their march towards ubiquitous intelligence. There are many difficulties in implementing theory into practice. Including but not limited to insufficient dynamic adaptability, real time performance bottlenecks, and shortcomings in domestic production. The essence of insufficient dynamic adaptability lies in the absence of physical world modeling, which makes it impossible to effectively express the characteristics of fluid dynamics. Real time performance bottlenecks, such as communication latency sensitivity and decision -execution decoupling delays, constrain the scalability of cluster systems. Domestication shortfalls are primarily concentrated in core components and data ecosystems. The economic viability and universal applicability of technology implementation are jointly impeded. These challenges fundamentally reveal underlying issues in current technologies, including insufficient depth in physical modeling, lack of hardware-software co-optimization, and limited ecosystem openness. Future technological breakthroughs will require interdisciplinary integration and architectural innovation. On one hand, major embodied AI enterprises will achieve breakthroughs in core technologies. Integrating physical simulators with world models enhances sim-to-real transfer capabilities, enabling collaborative robot optimization in simulation environments and accelerating technological iteration. On the other hand, fostering an open-source ecosystem necessitates breaking down "protocol silos" and promoting interdisciplinary integration across information science, life sciences, and robotics technology. Concurrently, a security framework is established to ensure the technological safety and feasibility through interpretable decision analysis and behavioral norm verification, thereby constructing an intelligent safety assessment system and an integrated governance mechanism. Only through the synergistic advancement of theoretical innovation, engineering optimization, and standardization can the industrial robotics sector achieve a transformative leap forward

## 6 Conclusion

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