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Research of Intelligent Control Methods for Industrial Robots in Industrial Automation Casting

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Abstract:

Against the backdrop of the accelerated advancement of Industry 4.0 and intelligent manufacturing, the intelligent upgrade of the foundry industry has become a key path to enhancing core competitiveness. Traditional casting processes, due to issues such as insufficient parameter control accuracy, low levels of equipment intelligence, and frequent manual intervention, are unable to meet the demands of high-quality and high-efficiency production. Industrial robots, with their programmable, high-precision, and automated operation advantages, offer a systematic solution for the intelligent transformation of the entire casting process. This paper reviews the application of intelligent control methods of industrial robots in key industrial processing stages such as batching, melting, temperature measurement, pouring, cleaning, and grinding. The intelligent control technology of industrial robots can significantly enhance the automation level, product quality, stability, and production safety of casting production. However, challenges still exist in aspects such as the compatibility of multi-brand equipment and system integration costs under complex working conditions. In the future, with the deep integration of artificial intelligence, 5G communication and digital twin technology, this technology will evolve towards full-process autonomous decision-making, multi-machine group collaborative operation and energy consumption optimization, promoting the transformation of the casting industry towards a green, intelligent and unmanned production model, and providing technical support for China's leap from a casting power to a casting superpower.

Keywords: Industrial Automation Casting; Industrial Robots; Intelligent Control; Casting Process

1. Introduction

Casting, as a key fundamental process in modern manufacturing, is widely applied in fields such as automobiles and aerospace. With the rapid development of Industry 4.0 and intelligent manufacturing, industrial automated casting has become an inevitable trend in the industry. However, the current casting production process still has problems such as inaccurate parameter control, low intelligence level of equipment, and high reliance on manual labor, which result in low production efficiency, unstable product quality, and difficulty in meeting the market demand for high-quality and personalized castings. Industrial robots, with their high precision, programmability, and automation features, provide an effective solution for the intelligent upgrade of the foundry industry. They can precisely control process parameters, replace manual operations for high-risk tasks, and significantly enhance production efficiency and product quality [1].

In the automotive manufacturing sector, many enterprises have achieved remarkable results by applying intelligent control technologies of industrial robots. For instance, the Hongqi Prosperity Factory of China First Auto Works has achieved a high degree of automation in the production process by integrating robot clusters, implemented precise quality inspection with ultrasonic equipment, and utilized data sensing to map every detail on the production line to a virtual “twin factory”. This not only enhanced production efficiency but also provided strong support for product innovation. After introducing intelligent control technology to its Linhai base, Geely Automobile has continuously optimized the production capacity of its new energy vehicle model, the Starship 7 EM-i. On average, a new vehicle is produced every less than one minute, significantly improving the production efficiency. The Fangrong Factory of First Auto Industry has applied automated control robots to many workshops. For instance, the stamping workshop uses fully automatic cranes to achieve fully automatic transportation tasks; the welding workshop fully applies robot automatic welding and coating technology; the assembly workshop realizes fully automatic assembly of various components through 10 intelligent processes, such as the rear suspension automatic tightening line which is based on autonomous programming for positioning - tightening - monitoring integration; the vehicle’s windshield glass is assembled using robot intelligent assembly. The system has constructed an IT-OT data integration platform, enhancing data collection efficiency through multiple protocol access, optimizing the data processing flow by combining efficient algorithms and point splitting technology, reducing PLC load while achieving horizontal integration of the information system, and achieving IT-OT data fusion and business collaboration. In summary, further systematic review and summary of relevant intelligent control methods are of great significance.

This article will conduct a systematic review of the application of intelligent control methods for industrial robots in all key stages of industrial automated casting. It will deeply analyze the technical principles, advantages, and challenges faced by these methods, and conduct a benefit analysis based on typical cases. At the same time, it will look forward to future development trends, providing a reference for promoting the intelligent development of the casting industry.

2. Intelligent Control of Industrial Robots in the Ingredient Dispensing Process

An overview of the industrial robot automation process is shown in Fig. 1.

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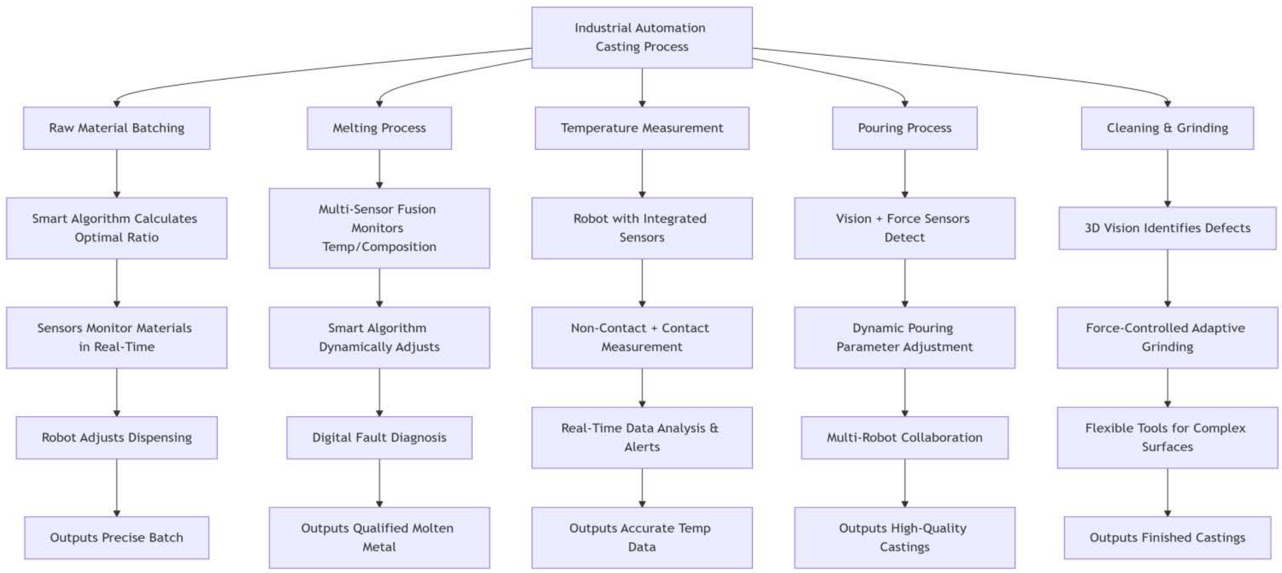

Fig. 1 Industrial Automation Flow Chart (Original)

Traditional casting material preparation relies on manual experience or simple automated equipment, which has problems such as low precision and poor efficiency. Manual operation is prone to being affected by fatigue and differences in experience, resulting in deviation in the ratio; simple automated equipment is difficult to adapt to changes in material properties, causing waste of raw materials. However, the intelligent material preparation system of industrial robots achieves precise control through the combination of intelligent algorithms and sensors. Among them, intelligent algorithms such as genetic algorithms can quickly calculate the optimal ratio plan based on the requirements of the casting and the properties of the materials; weight sensors and component analyzers monitor the material status in real time. When the composition or weight of the raw materials fluctuates, the robot automatically adjusts the dosage.

For instance, the core-making unit of CITIC DAIKAKI adopts the multi-robot collaborative core-making technology. Through high-precision positioning (error < 0.1mm), it completes the processes of core repair, core assembly, and tightening for engine cylinder heads, and realizes the full automation of immersion coating and blowing cleaning, eliminating the problem of uneven coating caused by manual operations [2, 3]. This system has reduced the waste rate of sand cores from 8% to 3%, increased production efficiency by 30%, and supports flexible production of multiple varieties in small batches, significantly improving the accuracy and adaptability of complex casting manufacturing [4]. Industrial robots can enhance efficiency in the industrial batching process, but they have significant limitations. They are sensitive to material characteristics, and factors such as powder agglomeration and changes in liquid viscosity can easily lead to measurement errors. They also require additional protection in harsh environments, which affects their flexibility. When it comes to multi-variety and small-batch production, reprogramming and debugging take a long time during equipment changes, making it difficult to meet flexible requirements. The sensor accuracy is greatly affected by environmental interference, and it lacks direct perception of the physical and chemical properties of the materials. The closed-loop control capability is insufficient. In addition, the initial procurement and operation and maintenance costs are high, the system integration degree is low, and the data is difficult to exchange with the management platform. The collaborative operation of multiple machines is prone to coordination errors due to communication delays, and there is also a risk of collision in human-machine collaboration scenarios. These problems have restricted its application in complex batching scenarios, and it is urgent to improve its adaptability through technological breakthroughs such as intelligent algorithm optimization, sensor fusion, and modular design [5].

3. Intelligent Control of Industrial Robots in the Smelting Process

Melting, as the core process of casting, requires precise control of the temperature, composition, and fluidity of the molten metal. Taking cast iron as an example, the melting temperature should be controlled within 1450-1550℃, with a fluctuation range of ±10℃, and the carbon equivalent fluctuation should be less than 0.05%. However, traditional manual control has many drawbacks: significant energy waste, with energy consumption increasing by 10%-20% compared to the ideal state; unstable component qualification rate, usually ranging from 70% to 85%; severe equipment wear, with electric furnace losses reaching over 30%. The intelligent control system of industrial robots achieves precise control through the integration of multiple sensors and intelligent algorithms. The system integrates thermocouples and infrared thermal imaging technology to construct a three-dimensional temperature field for real-time monitoring of temperature distribution; Combined with a spectrometer, the system can complete the detection of elements such as C, Si, and Mn within 3 seconds. The fuzzy control algorithm dynamically adjusts the heating power, keeping the temperature fluctuation within ±5℃. The neural network model can control the error of adding the tempering agent to within 0.5kg per ton. In addition, the system enhances process management by relying on the digital monitoring and self-diagnosis functions of equipment: edge computing technology can accurately predict the thickness of the furnace lining with an error of ±2mm; acoustic emission technology provides real-time warning of crack risks; the fault self-diagnosis system, based on a 20-category fault library, can achieve a 90% accuracy rate for rapid identification and reduces unplanned downtime by 50%.

For example, the KSM casting group has established a casting automation system, setting a ring-shaped line on the ground, placing two gravity casting machines, and configuring a melting furnace outside the line. The loading and unloading operations are carried out by industrial robots, which also enables communication and digital control of equipment such as the casting machine, drive motor, and industrial robot. The robot not only undertakes the tasks of transporting castings and conducting appearance inspections, but also can transport the castings to the deburring and machining units, effectively reducing the production area, lowering labor intensity, eliminating unsafe factors, improving production efficiency, and reducing production costs [6]. Although industrial robots can undertake high-temperature operations in the industrial smelting process, there are still significant limitations in terms of their technical characteristics and the requirements of the scenarios. Firstly, the hardware reliability in high-temperature environments is insufficient: during the smelting process, the temperature inside the furnace can reach above 1,000 degrees Celsius. Ordinary robot materials are prone to thermal deformation and circuit aging. Even if equipped with high-temperature-resistant coatings or cooling systems, long-term operation will still lead to a decrease in the accuracy of the mechanical arm and even cause sensor failure. Secondly, the adaptability is weak under complex working conditions: during the smelting process, situations such as fluctuations in material composition and adhesion of slag in the furnace occur frequently. The robot relies on preset programs to perform fixed actions, making it difficult to adjust the stirring or slag removal force in real time, which may lead to uneven smelting or equipment stalling. These issues urgently need to be addressed through technological breakthroughs such as innovation in high-temperature-resistant materials, integration of multi-modal perception, and optimization of autonomous decision-making algorithms.

4. Intelligent Control of Industrial Robots in the Temperature Measurement Process

During the casting process, temperature is the key parameter that determines the quality of the castings. It directly affects the fluidity of the molten metal, the solidification speed, and the internal structure, thereby influencing the strength, toughness, and other properties of the castings. Traditional manual thermocouple temperature measurement relies on the experience of operators and has problems such as low efficiency, insufficient coverage of temperature measurement points, and high safety risks in high-temperature environments. Ordinary infrared temperature measurement can achieve non-contact measurement, but is easily interfered with by environmental light and reflection from the metal surface, resulting in insufficient measurement accuracy and being unable to meet the real-time and accuracy requirements of temperature data for precise casting. In addition, manual operation also has defects such as unstandardized data recording and delayed analysis, which cannot provide effective support for process optimization.

The intelligent temperature measurement system integrates non-contact high-precision infrared temperature measurement sensors with contact-type intelligent thermocouples, achieving both rapid response and high-precision measurement. The non-contact sensor is used to quickly obtain the temperature distribution on the surface of the casting, while the contact-type thermocouple penetrates the metal liquid to obtain core temperature data. The two work together to improve measurement accuracy. Industrial robots equipped with sensors perform automated temperature measurement, precisely locating the measurement points through visual positioning technology, and combining motion control algorithms to achieve multi-dimensional and multi-area temperature collection. The collected data is wirelessly transmitted to the central control system. Combined with preset thresholds, it triggers intelligent warnings for abnormal temperatures. At the same time, machine learning algorithms are used to ana-

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lyze historical data, providing a decision-making basis for process optimization. In practical applications, intelligent temperature measurement technology has significantly enhanced the reliability and efficiency of casting production. After introducing an intelligent temperature measurement system into an automotive component casting enterprise, the temperature measurement error of the castings was reduced from ±5℃ to ±1℃. This led to a decrease in defects such as shrinkage cavities and cracks caused by improper temperature control, and the waste rate decreased by 12%. At the same time, the automated operation of robots shortened the single measurement time by 80%, avoiding the risk of workers being exposed to high temperatures. The production safety was significantly improved. Moreover, the temperature data reports automatically generated by the system provided quantitative evidence for optimizing process parameters, helping the enterprise achieve cost reduction, efficiency improvement, and quality enhancement. For example, the robot intelligent temperature measurement and sampling system independently developed by China Metallurgical South (Wuhan) Automation Co., Ltd. was successfully applied in the LF (Ladle Furnace) workshop of Hubei Xinye Steel Co., Ltd. This system is composed of a high-end brand six-axis casting robot and an automatic feeding device. The automatic feeding device can supply two types of materials simultaneously and can also display the operating status and provide fault alarms through a touch screen. The robot, with its intelligent collision prevention function and powerful motion control capability, drives the temperature measurement sampling gun rod and cooperates with the automatic feeding equipment to complete the process. During temperature measurement, the robot‘s gun rod can be lowered to the position for lifting the gun within 24 seconds, and the temperature measurement success rate of molten steel is ≥ 98%, which greatly improves the efficiency and accuracy of temperature measurement and reduces human errors [7].

Although industrial robots can replace human workers in the temperature measurement process and enter high-risk scenarios, there are still significant limitations in their technical characteristics and complex working conditions. Firstly, the environmental adaptability is insufficient: in environments with high temperatures, high humidity, or strong electromagnetic interference, infrared temperature measurement sensors are prone to being affected by dust adhesion and water vapor condensation, resulting in light path obstruction or signal drift. For example, splashes from the steel furnace opening may cover the lens, requiring frequent shutdowns for cleaning. Secondly, the dynamic temperature measurement accuracy is limited: for moving workpieces (such as castings on conveyor belts), the robot needs to simultaneously track the target and complete the temperature measurement. However, the inertia of the mechanical arm may cause sampling delay, especially in high-speed production lines, where the deviation between the temperature measurement position and the actual process point can reach ±5 cm, affecting the real-time control effect. Furthermore, the multi-dimensional temperature measurement capability is weak: Traditional robots can only perform single-point or linear temperature scanning, making it difficult to construct a three-dimensional temperature field. They are insufficient in analyzing the temperature distribution on complex surfaces (such as the blades of an aircraft engine) and require manual supplementary measurements. It is necessary to improve this by breaking through anti-interference sensor design, dynamic path planning algorithms, and edge computing technologies.

5. Intelligent Control of Industrial Robots in the Pouring Process

Pouring, as the final step in the casting process, its speed, temperature, and flow rate directly determine the quality of the castings. If the pouring speed is too fast, it is prone to cause turbulent flow and entrainment of gases, resulting in gas pores. If the temperature is insufficient, it may lead to cold shut defects. If the flow rate is uneven, it may cause shrinkage cavities or dimensional deviations. Traditional manual pouring relies on the operator‘s experience, with large parameter fluctuations (such as temperature deviations of ±30℃), and the scrap rate can reach 8%-12%. Simple mechanical pouring improves efficiency, but lacks dynamic adjustment capabilities and is difficult to adapt to complex mold structures.

Industrial robots have overcome this bottleneck through multimodal perception and intelligent decision-making. Firstly, by using real-time perception and dynamic control, they are equipped with high-frame-rate vision sensors to identify the position of the mold and the shape of the gate, and combine six-dimensional force sensors to capture the reactive force of the metal liquid flow, and then real-time correct the pouring trajectory (with an accuracy of ±1mm) and inclination angle (with an error of <0.5°). For example, the KSM Group uses 3D vision to guide robots for the pouring of engine cylinder blocks, dynamically controlling the pouring speed within the range of 0.5-2.5L/s, reducing porosity defects by 70%. Secondly, data-driven parameter optimization can be adopted. Based on machine learning, it analyzes tens of thousands of historical pouring data (such as temperature curves and flow time series), establishes a casting defect prediction model, and automatically generates the optimal pouring parameters. CITIC Daidakai optimizes the pouring scheme for aluminum alloy wheel hubs using an AI model, reducing the pouring time by 18% and the shrinkage porosity rate from 5% to 0.8%.

Secondly, multi-robot collaborative operations can be adopted. In the production of complex castings such as large wind turbine hubs, two robots adopt a master-slave control strategy. One robot is responsible for pouring, while the other synchronously preheats the mold and monitors the liquid level height. Through 5G communication, a millisecond-level response is achieved, increasing the pouring efficiency by 40%. For example, the intelligent factory of Chang'an Automobile has used an aluminum liquid automatic melting and pouring system. In Changan Automobile's intelligent factory in Chongqing, a 5G + industrial internet-based aluminum liquid automatic melting and pouring system has been introduced, which is used for the production of aluminum alloy structural components for new energy vehicles (such as battery trays, vehicle frames).It employs intelligent melting control, which uses a spectrometer to monitor the composition of the molten aluminum (such as Si and Mg content) in real time. Combined with AI algorithms, it dynamically adjusts the alloy ratio, reducing the element control error from ±0.5% to ±0.1%. At the same time, it also uses precise pouring by robots. The six-axis industrial robot is equipped with high-precision weighing sensors and a visual positioning system. It dynamically adjusts the pouring trajectory according to the shape of the mold, with the pouring speed controlled at 0.8 - 2.2 L/s, and the flow error being less than ±1.5%. Finally, multiple robots collaborate. The melting furnace and the pouring robot are linked through the MES system to achieve unmanned operation throughout the process of aluminum liquid transportation, pouring, and cooling. The single pouring cycle is shortened to within 30 seconds. Here are the actual benefits: the pouring consistency is improved by 60%, the porosity and shrinkage defect rate is reduced from 8% to below 1.5%; the aluminum liquid utilization rate is increased from 85% to 97%, saving over 5 million yuan in raw material costs annually; through dynamic power regulation, the melting energy consumption is reduced by 18%, and the annual carbon dioxide emissions are reduced by approximately 1200 tons.

Although industrial robots are highly efficient in the pouring process, they also have significant drawbacks. Firstly, their flexibility is insufficient. When dealing with complex pouring scenarios (such as irregular molds and multi-curvature surfaces), traditional robots, due to the limitations of preset programs, are unable to adjust the pouring path in real time, which often leads to uneven filling, residual bubbles, and other problems, resulting in fluctuations in the quality rate of castings. Secondly, their environmental adaptability is poor. The high temperatures, metal splashes, and dust generated during the pouring process accelerate the aging of robot sensors and mechanical components, even causing electrical circuit failures. Frequent maintenance and upkeep are required, increasing the downtime costs. Thirdly, the initial investment and operation, and maintenance costs are high. The purchase cost of high-precision industrial robots can reach several hundred thousand yuan, and the accompanying temperature control and dust-proof protection systems further increase the investment. Moreover, professional technicians are needed to debug the programs and replace worn-out components, which is a heavy burden for small and medium-sized enterprises. Fourthly, the safety of human-machine collaboration needs to be improved. In some scenarios, manual assistance is required to adjust the molds. If the dynamic obstacle avoidance algorithm of the robot is not fully optimized, it may cause collision risks due to unexpected situations, presenting certain safety hazards.

6. Intelligent Control of Industrial Robots in the Cleaning and Grinding Process

Cleaning and grinding are the core post-processing steps after casting, directly affecting the quality and performance of the castings. Defects such as burrs, spurs on the surface and sand holes inside the castings, if not dealt with, will affect the appearance, accuracy and mechanical properties. For example, the flatness of the engine cylinder block in automotive engines affects sealing, and the roughness of aviation castings that do not meet the standards will cause stress concentration. In technical applications, visual recognition drives path planning, 3D vision sensors perform scanning and modeling, AI identifies defects, and generates grinding paths. Force control technology dynamically adjusts the grinding force through six-dimensional force sensors. Flexible tools and adaptive algorithms work together to optimize, and elastic grinding discs and other tools fit complex curved surfaces to achieve high-precision control and improve grinding efficiency and quality.

For instance, Dongfeng Automobile uses the LongTai robot's iron casting part cleaning and grinding system in the automated casting process to carry out the cleaning and grinding work of automotive components. The visual recognition technology of this system enables the robot to accurately identify the positions and surface defects of automotive components, with a positioning accuracy of up to 0.1 millimeters. This effectively solves the problem

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that it is difficult for humans to precisely determine the location of complex defects. When grinding the engine cylinder block of an automobile, the robot can quickly plan a targeted grinding path based on the visual recognition results, and efficiently clean the burrs and burrs on the surface of the cylinder block. During the grinding process, force control technology plays a crucial role. For instance, when dealing with unevenly textured automotive wheels, the robot can adjust the grinding force in real time based on the feedback from the force sensor, ensuring uniform grinding quality and preventing over-grinding or insufficient grinding. This results in a surface roughness of Ra0.8 - Ra1.6 μm, meeting the standards for high-precision assembly. At the same time, the system combines flexible grinding tools and intelligent control algorithms to achieve comprehensive and high-precision grinding of complex curved surfaces of automotive components. The grinding efficiency has increased by three times compared to manual operation, and the product's first-time qualification rate has increased from 80% during manual grinding to 95%, significantly improving production efficiency and product quality, and reducing production costs [8].

Although industrial robots have improved efficiency in the cleaning and polishing processes, they still have significant drawbacks. Firstly, their adaptability to complex curved surfaces is insufficient. When dealing with the multi-curvature surfaces of aerospace castings and the irregular structures of car wheels, traditional robots rely on preset trajectories, which makes it difficult for them to precisely fit the undulations of the curved surfaces. This often leads to over-polishing or the presence of residual corners, resulting in uneven surface quality. Moreover, their ability to handle fine defects at the 0.1mm level is limited. Secondly, the reliability of sensors is affected by environmental interference. During the polishing process, metal dust and splashed particles tend to adhere to the surface of the visual sensors or force control sensors, causing deviations in detection data and even leading to incorrect judgments by the robots. For instance, when the 3D vision lens is covered with dust, it may fail to detect the edge burrs of the casting, resulting in secondary rework. Thirdly, the cost of tool wear is high. Consumables such as elastic grinding discs and flexible sand belts need to be replaced frequently. Taking the grinding of aluminum alloy castings as an example, the average lifespan of each sand belt is only 8-12 hours. If continuous operation lasts for 24 hours, the monthly cost of consumables can reach tens of thousands of yuan. Moreover, tool replacement requires downtime, which affects the continuity of the production line.

7. Conclusion

In conclusion, the application of industrial robot intelligent control technology in the industrial automation casting field has demonstrated significant technical advantages and economic benefits throughout the entire process, from material preparation, melting, temperature measurement, pouring to cleaning and polishing. In the material preparation stage, the combination of intelligent algorithms and sensors enables precise proportioning, enhancing production efficiency and the manufacturing accuracy of complex castings; in the melting stage, through the integration of multiple sensors and intelligent algorithms, a closed-loop control system is established, effectively improving the qualification rate of metal liquid components, reducing energy consumption and extending equipment lifespan; in the temperature measurement stage, the automation and intelligence of the process significantly enhance the accuracy and efficiency of temperature measurement, ensuring production safety; in the pouring stage, multi-modal perception, data-driven optimization and multi-robot collaborative operations significantly reduce the defect rate of castings and improve the pouring efficiency; in the cleaning and polishing stage, visual recognition, force control technology and flexible tool applications ensure the surface quality of castings and achieve efficient and precise post-processing.

At present, the application of intelligent control technology for industrial robots in the casting industry faces challenges such as sensor reliability, algorithm adaptability, high integration costs, and equipment compatibility. In the future, with the development of technologies like AI and the Internet of Things, it will move towards precise control, high perception, and real-time intelligent unmanned operation. To accelerate its application and promote the intelligent, efficient, and green development of the casting industry, it is necessary to strengthen cooperation among industry, academia, and research institutions.

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