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Application of Workstation Robots in Welding Processes of Automotive OEMs

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Abstract: Workstation robots play an important role in the welding process of automotive OEMs. Its multi axis degrees of freedom, high-precision motion control, and modular design enable it to demonstrate efficient performance in body welding, component optimization, and process support. By integrating intelligent technology with traditional processes, workstation robots have improved welding efficiency and quality, reducing the risk of manual intervention. Despite facing challenges such as complex weld seam recognition and multi machine collaboration, with technological optimization and innovation, its application prospects are broad, which will promote the development of automotive manufacturing towards intelligence and green direction.

Keywords: Workstation robot; Automotive welding; Intelligent manufacturing

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1. Introduction

The global automotive industry is accelerating its transformation towards intelligence and greenness, and the precision and efficiency of welding processes are of great significance to the safety and production efficiency of the entire vehicle. In recent years, workstation robots have gradually replaced manual welding with advantages such as multi axis degrees of freedom, becoming a key carrier for upgrading automotive manufacturing automation. The 2025 government work report proposes to develop intelligent connected new energy vehicles, promote the "Artificial Intelligence+" action, and provide policy support for innovation in robot welding technology. In 2024, China's industrial robot production will be 556400 sets, with a significant proportion of welding robots, which have high reliability and consistency in welding processes such as battery trays for new energy vehicles. The demand for green manufacturing drives the popularization of low-energy welding processes, reducing energy consumption by 15–20%. However, technological bottlenecks such as complex weld seam identification need to be overcome, and cross disciplinary collaborative innovation and improvement of the standard system are required. The intelligent upgrade and large-scale application of workstation robots are the core path to enhance the competitiveness of automobile manufacturing and promote high-quality development of the industry.

2. Overview of workstation robots and their positioning in automotive manufacturing

2.1. Definition and core functions of workstation robots

Workstation robots are automated equipment integrated into fixed workstations to perform specific process tasks, with core functions including multi axis degrees of freedom, high-precision motion control, and modular design [1]. Multi axis degrees of freedom enable robots to have flexible spatial motion capabilities. Typical industrial robots have 4 to 7 rotational or linear axes, which can meet complex welding trajectory requirements, such as 3D curve welding of vehicle body side panels. High precision motion control achieves repetitive positioning accuracy within ± 0.05mm through the collaborative action of servo motors and other components, meeting the stringent requirements for weld consistency and weld quality in automotive welding. Modular design is reflected in the replaceability of the robot body and end effector, supporting rapid adaptation to the welding needs of different vehicle models, and achieving multi vehicle hybrid production by replacing fixture modules.

2.2. Application status of workstation robots in automotive manufacturing

In the field of automobile manufacturing, workstation robots are widely used in key process links such as welding, assembly, and spraying. In the welding scene, robots use multi-sensor fusion technology to complete body spot welding and arc welding tasks. For example, after using a vision system to locate the weld seam, they can complete the welding of the white body at a speed of 5–10 weld points per second, improving efficiency and reducing the risk of virtual welding and leakage. In the assembly process, robots use high-precision force control technology to locate and tighten precision components such as engines and transmissions. For example, six axis collaborative robots can complete millimeter level tolerance assembly of door hinges. In the spraying scenario, robots use path planning algorithms to achieve uniform coating coverage on the inner and outer surfaces of the vehicle body, avoiding the problem of uneven thickness caused by manual spraying and reducing paint waste and environmental pollution.

3. Technical requirements for automotive welding processes and advantages of robot applications

3.1. Basic principles and quality requirements of automotive welding process

Automotive welding processes mainly include spot welding, arc welding, and laser welding, and their principles and quality requirements are determined by materials and structures. Spot welding uses electrode pressure to generate resistance heat fusion of metal plates, suitable for connecting car body coverings. The welding point diameter is required to be ≥ 4mm and the shear strength is required to be ≥ 6kN to avoid virtual welding or overburning. Arc welding uses arc heat to melt the base metal and welding wire, commonly used in frame and chassis structural components. The standard includes a weld penetration depth of ≥ 2mm, no pores or cracks on the surface, and inert gas protection to prevent oxidation. Laser welding utilizes high-energy beams to achieve rapid melting connections with micrometer level accuracy, which is commonly used for high-strength steel and aluminum alloy vehicle bodies. It requires a weld depth to width ratio of ≥ 3:1 and a heat affected zone width of ≤ 0.5mm, and strict control of beam focusing parameters to ensure airtightness. All three types of technologies must meet industry standards such as ISO 3834 and AWS D1.1 to ensure the safety and durability of the entire vehicle [3].

3.2. Limitations of traditional manual welding and the inevitability of robot substitution

Traditional manual welding has significant issues in terms of efficiency, quality, and safety. In terms of efficiency, manual operations are limited by physiological fatigue and skill differences, and the number of welding points in a single shift is usually less than 2000, making it difficult to adapt to the increasingly shortened production pace of car companies (such as 60 seconds per car). In terms of quality, problems such as uneven distribution of solder joints, insufficient penetration depth, or defects in weld morphology occur frequently, and the manual welding repair rate is as high as 3–5%, significantly increasing manufacturing costs. In terms of safety, labor safety risks such as high temperature splashes, harmful smoke and dust, and strong light radiation are high. Long term exposure can easily lead to occupational lung disease and eye injury. Even with protective equipment, the accident rate still reaches 0.8 cases per thousand working hours [4]. In contrast, robot welding can improve the efficiency of welding points to over 5000 per hour through programmed control and sensor feedback, with a repeat positioning accuracy of better than ± 0.1mm, and completely avoid the risks of manual work environment.

4. Specific application scenarios of workstation robots in welding processes

4.1. Typical applications of body welding

4.1.1. Side panel welding

The welding of automotive side panels needs to address the technical challenges of multi curved structures and high-density weld distribution. A joint venture car company adopts a six axis welding robot cluster, which achieves precise docking between the side outer panel and the inner lining through offline programming and visual positioning system. The number of welding points on one side reaches 120–150, and the welding cycle is compressed to 45 seconds per piece [5]. Research examples have shown that robots equipped with 3D laser scanning sensors can dynamically compensate for assembly tolerances of sheet metal parts (± 1.5 mm), and control welding point position deviations within ± 0.3 mm. Taking the side panel welding of a certain vehicle model as an example, the robot system optimizes the welding gun posture through path planning algorithm, which increases the welding qualification rate of complex curved surface areas from 92% in manual operation to 98.6%, while reducing the frequency of downtime caused by electrode wear and reducing annual maintenance costs by 18%.

4.1.2. Chassis welding

Chassis welding requires extremely high connection quality between high-strength steel (HSS) and hot formed steel (PHS), and traditional manual welding is prone to strength fluctuations due to uneven heat input [6]. A certain brand of pure electric vehicle chassis production line has introduced laser welding robots, which work together with high dynamic linear motors through fiber laser (power 6kW) to achieve stable weld penetration depth of 2.2–2.5 mm, heat affected zone width ≤ 0.4mm, and tensile strength of over 1500 MPa. Case data shows that after fatigue testing, the crack initiation life of the chassis assembly welded by robots is extended by 37% compared to the manual welding group. In addition, the robot uses force position hybrid control technology to adaptively adjust the welding pressure within the range of 800–1200 N, ensuring that the overlap gap of different thickness plates (1.2–2.0 mm) is ≤ 0.1 mm. The yield rate has increased from 94.1% to 99.3%, and the defect repair cost has decreased by 65%.

4.2. Welding optimization of key components

4.2.1. Welding of car doors

The welding of car doors places extremely high demands on the rapid changeover capability of flexible production lines to meet the production needs of multi vehicle hybrid lines. A certain German car company adopts a welding system that combines modular fixtures with a four station rotating turntable. Through standardized gas and circuit interfaces, the fixture replacement time is reduced to 2–3 minutes [7]. The research example shows that the system is capable of welding the inner and outer panels of car doors using robots equipped with multiple types of welding tongs (such as C-type and X-type), and can simultaneously support welding tasks for 5 vehicle models. The program call time for changing models is less than 30 seconds, and the overall production efficiency is improved by 23%. Taking a new energy vehicle door production line as an example, robots automatically recognize vehicle characteristics through a visual positioning system, dynamically adjust welding paths and pressure parameters (600–900 N), and increase the welding qualification rate from 94% of traditional special machines to 98.5%, reducing the defect rate by 42%.

4.2.2. Engine compartment welding

The welding of the engine compartment needs to deal with the dual challenges of high temperature environment and complex materials such as aluminum alloy and high-strength steel. A certain car manufacturer adopts a six axis welding robot with high-temperature protection design, which ensures continuous operation stability in environments above 80 °C through a water-cooled circulation system and ceramic coated welding gun [8]. Case data shows that in the welding of engine brackets, the robot uses pulse MIG welding technology with a welding current of 180–220 A, a stable penetration depth of 1.8–2.2mm, a heat affected zone width of ≤ 0.3mm, and a tensile strength of 520 MPa, which is 18% higher than manual welding. In another example, a domestic car company introduced a laser arc hybrid welding robot in turbocharger welding, which monitors the temperature field of the weld seam in real time through infrared thermal imaging, dynamically adjusts the laser power (3–4kW) and wire feeding speed (8–12 m/min), controls the welding deformation within 0.15 mm, improves the yield to 99.2%, and has an annual failure rate of less than 0.5 times.

5. Technical challenges and optimization strategies for the application of workstation robots

5.1. Main technical challenges currently faced

5.1.1. Identification and adaptive control of complex welds

The identification and adaptive control of complex welds are the core difficulties in workstation robot welding, mainly due to material diversity, geometric irregularity, and dynamic working condition interference. In the welding of dissimilar materials between aluminum alloy and carbon steel, due to the difference in thermal conductivity (aluminum alloy 237 W/m · K vs. carbon steel 50 W/m · K), traditional visual systems are difficult to stably recognize the weld boundary. A study shows that a weld recognition system based on multispectral imaging can improve the positioning accuracy to ± 0.2mm, but the algorithm processing delay still reaches 120ms, which is difficult to meet the real-time requirements of high-speed welding. In terms of adaptive control, in a welding case of a new energy battery box, the robot needs to dynamically adjust the laser power (1.5–3kW) and welding speed (0.8–1.5m/min) to compensate for thermal deformation. However, due to the mismatch between the sensor sampling frequency (≤ 1 kHz) and the controller response bandwidth, the fluctuation range of weld penetration depth reaches ± 0.15 mm, resulting in 10% of batches requiring secondary welding [9].

5.1.2. Communication and scheduling problems in multi robot collaborative welding

Multi robot collaborative welding faces dual challenges of communication delay and task allocation conflicts. When deploying 8 welding robots for collaborative operation on a white body production line of a certain car company, the probability of robot motion trajectory conflicts reached 0.3 times/hour due to the time synchronization error (± 5 ms) of the Ethernet communication protocol, and the average fault recovery time reached 12 minutes. Research data shows that using time sensitive networks (TSN) can control communication jitter within ± 1 μs, but requires an additional 15% hardware cost. At the task scheduling level, when a chassis welding station adopts a centralized scheduling algorithm, the computational complexity increases exponentially with the number of robots (O(n^3)), and the path planning of 6 robots in collaboration takes up to 45 seconds, which cannot meet the production cycle of 60 seconds per vehicle. Although the introduction of distributed reinforcement learning algorithms compresses the planning time to 8 seconds, the collaborative accuracy drops to ± 0.25mm and the yield loss is 2.7%.

5.2. Process optimization and system upgrade strategy

5.2.1. Intelligent optimization of welding parameters based on machine learning

Machine learning technology achieves dynamic optimization of welding parameters and defect prediction by mining multi-source data correlations in the welding process. A research team constructed a random forest model for pulse MIG welding of aluminum alloys. By inputting current, voltage, wire feed speed, and molten pool image features, the accuracy of predicting weld depth and porosity reached 92%, reducing process validation time by 60% compared to traditional empirical tuning modes [10]. In a practical case, a new energy vehicle company adopted deep reinforcement learning algorithm to dynamically adjust laser power and welding speed through real-time collection of force thermal signals (sampling rate 1kHz) by welding robots, reducing the fluctuation range of weld penetration depth of battery trays from ± 0.12mm to ± 0.05mm and reducing the defect rate to 0.3%. In another example, a welding quality prediction system based on LSTM network can identify the risk of insufficient penetration 10ms in advance, trigger parameter correction instructions, and increase the first pass rate of welding a commercial vehicle frame from 96.4% to 98.8%.

5.2.2. Application of digital twin technology in welding simulation

Digital twin technology achieves pre validation and dynamic optimization of welding processes through multi physics coupling simulation and virtual real interaction. A German car company has established a digital twin model for white body welding, integrating a thermal mechanical structural coupling analysis module with a simulation accuracy of over 95%, resulting in a welding deformation prediction error of ≤ 0.1mm and a 40% reduction in process debugging cycle. Case data shows that a chassis welding production line simulated the influence of different fixture stiffness on weld quality through a twin system. After optimizing the fixture layout, the welding stress concentration area was reduced by 23% and the fatigue life was increased by 15%. In another application, a laser welding robot utilizes a twin system with real-time data synchronization to simulate complex path planning schemes in a virtual environment, successfully reducing the actual welding trajectory error from ± 0.25mm to ± 0.08mm and improving the overall equipment efficiency (OEE) by 12%.

5.3. Development path of human computer collaboration and intelligence

5.3.1. Innovative mode of collaborative robot (Cobot) in welding

The collaborative robot (Cobot) achieves safe collaborative operations in welding scenes through force feedback control and human-machine interaction interface. A certain independent brand car company has deployed a seven axis collaborative robot in the welding of small batch customized car models, equipped with tactile sensors and dynamic collision detection algorithms. After manual assistance in positioning, it automatically completes the welding of door hinges, reducing the production cycle time from 120 seconds to 75 seconds per piece, and the human-machine safety distance can be reduced to within 0.5 m. A research case shows that a new energy vehicle battery pack welding station uses a dual arm collaborative robot to achieve adaptive fitting between the welding gun and the workpiece through visual force fusion technology. The welding pressure control accuracy reaches ± 3N, reducing the porosity of the aluminum alloy weld from 1.2% to 0.4% and reducing the frequency of manual intervention by 80%.

5.3.2. Remote monitoring and maintenance of 5G and edge computing drives

The integration of 5G network and edge computing technology provides the welding robot with low delay and high reliability remote control capability. A joint venture car company has deployed a 5G private network (end-to-end delay ≤ 8ms) in the welding workshop, which analyzes welding current, voltage, and vibration data in real-time (sampling rate 2kHz) through edge servers, achieving millisecond level response to abnormal working conditions. Case data shows that a certain body welding line transmits welding quality characteristic data to a cloud AI platform through 5G, which improves the accuracy of fault diagnosis to 96% and shortens the average repair response time from 45 minutes to 8 minutes. In another example, an overseas factory uses edge computing nodes for predictive maintenance of welding robots. The LSTM model trained based on historical operating data can give an early warning of reducer failure 72 hours in advance, reduce the replacement cycle of spare parts by 40%, and reduce the annual maintenance cost by 25%.

6. Conclusion

Workstation robots have significant value in automotive welding, with multi axis motion control and other technologies increasing welding efficiency to over 5000 weld points per hour, accuracy within ± 0.1 mm, and a quality pass rate of over 99%, reducing the risk of manual intervention. In the future, the construction of intelligent welding system is the key point, which needs to integrate adaptive algorithms, digital twins and 5G edge computing to achieve dynamic optimization of parameters, multi robot collaboration and quality traceability. Green manufacturing technology is equally crucial, such as laser arc hybrid welding which can reduce energy consumption by 15–20%. The industry should accelerate the development of welding process standards, improve the technical training system, break through technical bottlenecks through cross disciplinary innovation, and promote the development of automobile manufacturing towards efficiency, flexibility, and sustainability.

Disclosure statement

The author declares no conflict of interest.

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