Research on the Application of Embodied Intelligent Welding Robots in Construction Steel Structure Scenarios

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Abstract:Through a closed-loop architecture of "perception-decision-execution", embodied intelligent welding robots deeply integrate visual perception, process large models and robot motion control, realizing a paradigm shift from "fixed program execution" to "autonomous intelligent welding". This paper systematically sorts out the technical connotation and core architecture of embodied intelligent welding robots, and analyzes the applicable characteristics of three types of robots in construction steel structure scenarios, including seven-axis ground-track inverted installation robots, intelligent collaborative welding robots and mobile (tracked) robots. Combined with practical application cases from enterprises such as Jiangsu Beiren, CSCEC Science and Industry Group, China Railway Baoji Bridge Group and Zhongke Optoelectronics, this paper demonstrates the technical advantages of embodied intelligence in addressing core pain points such as complex weld seam identification, adaptive adjustment of process parameters and compatibility with multi-variety workpieces. The research results indicate that embodied intelligent welding robots can cut the welding process development cycle by 60%, reduce comprehensive production costs by more than 40%, achieve a first-pass welding qualification rate exceeding 99%, and multiply the operation efficiency of single-person multi-machine deployment.

Key words:Embodied Intelligence; Welding Robot; Construction Steel Structure; Visual Perception; AI Large Model; Human-Machine Collaboration

1 INTRODUCTION

1.1 Research Background

As a key structural form in modern construction, building steel structures have gained increasing application in high-rise buildings, large-span venues, industrial plants, and bridge projects due to their comprehensive advantages such as high strength, light self-weight, short construction cycles, and excellent seismic performance. According to statistics from the China Steel Structure Association, during the 14th Five-Year Plan period, the domestic steel structure industry has made significant progress in digitalization and intelligent transformation. By the end of 2024, among the 571 surveyed steel structure enterprises, 371 had adopted digital processing equipment, reaching a penetration rate of 65%.

However, welding—the core process in steel structure manufacturing—remains significantly behind in automation compared to discrete manufacturing industries such as automotive and shipbuilding. Although the number of companies using welding robots has increased to 243, accounting for 42% of surveyed firms, the overall welding automation rate still remains below 30%, with many critical processes still relying heavily on manual operation. This reality has led to multiple challenges, including poor quality consistency, low production efficiency, high labor costs, and a shortage of skilled workers, increasingly becoming a bottleneck that constrains the industry's high-quality development.

1.2 The "capability boundary" of traditional welding robots

Traditional industrial welding robots operate in a "teach-and-learn" mode, where engineers manually guide the robot's end effector along a predetermined welding path, recording all trajectory points. The robot then repeats this program. This approach works well in mass production scenarios with few product variations, such as automobile manufacturing—where a single vehicle model may require thousands of weld points. Once the program is debugged, it can run stably for months or even years.

However, directly applying this technology to the construction steel structure industry leads to fundamental incompatibility. Steel structure fabrication in construction is inherently project-based rather than product-based—each building has unique structural designs, requiring custom-tailored components, specifications, and weld types. Lin Tao, Vice President of Jiangsu Beiren, vividly described this challenge: "Previously, when welding these components, engineers had to repeatedly adjust robot parameters based on drawings; switching to a new batch with different components meant spending half a day re-teaching the robot." In industries such as shipbuilding, elevators, and heavy steel, small-batch, multi-variety production is the norm. The traditional industrial robot’s one-task-one-function limitation drastically reduces line changeover efficiency and requires significant manual effort for parameter tuning.

1.3 The Breakthrough Value of Embodied Intelligence

The emergence of embodied intelligence technology offers a novel solution to this challenge. Embodied intelligence emphasizes that intelligent agents perceive the world, make decisions, and execute actions through physical interactions between their bodies and the environment, forming a closed-loop cognitive framework of "perception-decision-execution." When applied to welding robots, this means the robot is no longer merely a mechanical device passively executing pre-programmed instructions, but rather an intelligent welding partner capable of "seeing" workpiece geometry, "understanding" welding requirements, and autonomously planning process paths.[1,2]

In early 2026, Boqing Technology launched the first industrial-grade embodied AI agent in the smart welding industry. Its chairman, Feng Xiaobing, used a vivid analogy to explain its essence: "If traditional welding robots are 'limbs,' then the embodied AI agent is equipping them with a 'brain' and 'nervous system.'" In May of the same year, Xiaoyu Intelligent Manufacturing signed a strategic cooperation agreement with China Construction Science & Technology Group's Intelligent Technology Division, planning to jointly promote the large-scale application of 1,000 embodied intelligent welding robots within one year—a milestone marking the official entry of this technology into the industrialization and commercialization phase.

1.4 Research Objectives and Framework

This paper focuses on the application of embodied intelligent welding robots in construction steel structure scenarios, aiming to systematically elaborate on their technical connotations, core architecture, product forms, practical cases, and development trends. Section 2 discusses the paradigm shift from "teach-and-learn" to "embodied intelligence" from a technological philosophy perspective, and provides a detailed analysis of key technical modules. Section 3 delves into the core challenges in welding scenarios for construction steel structures. Section 4 categorically examines the technical characteristics and applicable scenarios of three types of embodied intelligent welding robots. Section 5 presents implementation cases and performance data from multiple enterprises. Section 6 discusses key technical challenges and future development trends. Section 7 summarizes the entire paper and offers forward-looking insights.

2 Technical Connotation and Architecture of Embodied Intelligent Welding Robots

2.1 From "Teaching and Reproduction" to the Paradigm Shift of "Embodied Intelligence"

To understand the innovative value of embodied intelligent welding robots, it is essential to first grasp their fundamental differences from traditional industrial robots. This difference represents not merely a technological upgrade, but a paradigm shift in manufacturing philosophy.

Traditional Paradigm: Programming-Execution Conventional industrial robots operate on a linear "programming-execution" logic. Engineers must manually guide the robot's end effector along the welding path for each workpiece and every weld seam using a teach pendant, recording trajectory points and setting process parameters. This method is highly efficient in assembly-line production, as the same program can be reused tens of thousands of times. However, at its core, this approach reduces the robot to a mere "program repeater"—it does not understand what it is doing, simply executing pre-defined actions mechanically. When the workpiece position deviates beyond acceptable limits or the joint gap changes, the robot still faithfully follows the original program, resulting in compromised weld quality.

Embodied Intelligent Paradigm: Perception-Decision-Execution Closed Loop. In contrast, embodied intelligent welding robots establish an entirely new technical framework based on a "perception-decision-execution" closed-loop system. At its heart lies a multi-modal perception system (including vision, laser, and tactile sensors) that continuously captures 3D information about the workpiece and environmental conditions. An AI large model acts as the "brain," analyzing sensory data to understand welding requirements and generating optimal welding parameters and motion trajectories. A high-precision robotic arm serves as the "body," carrying out these decisions. Meanwhile, real-time feedback during execution—such as arc signals, molten pool images, and positional deviations—is fed back into the perception and decision-making layers, enabling dynamic optimization within a closed loop.

The essence of this paradigm shift lies in transforming welding from "program repetition" to "task solving." The robot no longer cares about "what number this weld has in the program," but instead interprets it as "this is a T-joint fillet weld between the flange and web of an H-beam, with a plate thickness of 16 mm and a joint gap of 2 mm, requiring a multi-layer, multi-pass welding process." This is precisely the "welding intelligence" that embodiment and artificial intelligence confer upon the machine.[3-5]

2.2 Core Technology Module

2.2.1 Multimodal Perception System: The Robot's "Eyes"

Perception is the starting point of embodied intelligence. Welding environments are harsh, characterized by high temperatures, intense light, smoke and dust, and electromagnetic interference, making it difficult for a single sensor to operate reliably under all conditions. Embodied intelligent welding robots typically integrate multiple sensing technologies to achieve "redundant complementarity."

3D structured-light/laser vision sensors are responsible for capturing the overall three-dimensional profile of the workpiece. By projecting structured light patterns and analyzing their deformation on the workpiece surface, these sensors can rapidly reconstruct 3D point cloud models of the workpiece, identifying weld positions, types, and geometric dimensions. [6] The seven-axis floor-mounted inverted robot developed by Xi'an Zhongke Optoelectronics employs a "long-range and high-precision scanning sensor," enabling accurate acquisition of workpiece pose and accommodating workpieces with plate thicknesses ranging from 3 to 25 mm and alignment errors not exceeding 20 mm.[7]

Laser profile sensors play a crucial role in seam tracking. By projecting a laser line and capturing its reflection from the weld cross-section, they precisely calculate geometric parameters—such as gap width, bevel angle, and misalignment—using triangulation principles, providing quantitative data for adjusting process parameters.

Arc sensors operate continuously during welding. By detecting periodic variations in welding current and voltage, they can determine in real time the positional deviation of the torch relative to the weld centerline and make immediate corrections. The frequency of arc signals is typically correlated with welding speed, enabling millisecond-level position feedback that compensates for potential failures of vision sensors in dusty or smoky environments.

Pool monitoring cameras represent a newly emerging sensing technology. China Wuye's self-developed high-altitude welding robot integrates a proprietary molten pool camera and real-time monitoring system, capable of accurately detecting subtle deviations such as weld offset and current fluctuations that are imperceptible to the human eye, thereby enabling both construction and inspection to be completed in a single pass.[8]

2.2.2 Welding Process Big Model: The Robot's "Brain"

If perception enables robots to "see" workpieces, then process decision-making allows them to "understand" how to weld. Traditional robots rely on engineers inputting welding parameters based on experience, whereas embodied intelligent welding robots are equipped with AI large models that integrate vast amounts of process knowledge.

The Jiangsu Beiren BR-iWeld welding process expert database is a representative achievement in this field. By integrating multidimensional knowledge from materials science, welding metallurgy, and process parameter optimization, the system can automatically generate matching welding plans—covering parameters such as current, voltage, speed, oscillation amplitude, and interpass temperature control—after identifying the workpiece type, and further adjust these parameters in real time based on actual welding results.

Boqing Technology's "Jiluan" industrial-grade welding large model takes this even further. According to information released in February 2026, the model has constructed a welding knowledge graph encompassing millions of data points and a training metadata system comprising tens of millions of records, enabling intelligent generation and real-time optimization of welding processes. Verified in industrial settings, it reduces welding process development cycles by 60% and lowers overall production costs by over 40%.

From a technical standpoint, training a welding process large model requires extensive datasets linking "operating conditions - parameters - quality." Traditionally, this knowledge is scattered across experienced technicians' expertise, process manuals, and experimental records, making systematic organization difficult. The key contribution of the large model lies in encoding this fragmented knowledge into a computable and inferable parameter space, allowing it to not merely "retrieve" the most similar historical case when facing new conditions, but instead "reason" out the optimal parameter combination.

2.2.3 Intelligent Trajectory Planning System: The "Bridge" Connecting Brain and Body

Trajectory planning is the critical link connecting the "brain" to the "body." Traditional robots rely on manually programmed sequences of fixed waypoints, whereas embodied intelligent welding robots autonomously plan optimal welding paths based on 3D models of workpieces and weld seam recognition results.

Trajectory planning must consider multiple constraints: geometric constraints—ensuring the robotic arm reaches each weld point in an optimal posture within its reachable workspace while avoiding collisions with the workpiece or fixtures; process constraints—arc initiation position, welding direction, oscillation motion, arc termination, and other parameters must comply with welding specifications; and efficiency constraints—the path should be as short as possible to minimize idle travel time, subject to satisfying the first two conditions.

According to product documentation from Xi'an Zhongke Optoelectronics, their embodied intelligent welding robot features a complete set of functions including autonomous path planning, arc tracking, pulse welding, circumferential welding, oscillatory welding, intermittent welding, corner wrapping, and multi-layer multi-pass welding. This means the robot can independently plan and execute welding operations—from simple fillet welds to complex multi-layer, multi-pass groove welds—without requiring manual teaching for each individual pass.

2.2.4 Human-Machine Collaborative Interaction Interface: From "Replacement" to "Collaboration"

Embodied intelligence emphasizes collaboration between humans and machines rather than replacement. Currently, mainstream collaborative welding robots typically employ teach-by-demonstration technology—workers can manually guide the robot's end effector, "pointing where to weld" just like using a handheld welding torch, while the robot automatically records the path and optimizes process parameters without requiring any coding.

Qiao Zhongliang, founder of Xiaoyu Intelligent

Manufacturing, pointed out when discussing technology implementation: "When we apply general embodied intelligence to complex industrial environments, we deeply feel a significant gap—a natural barrier between sophisticated algorithm demonstrations in the lab and the demands of factories for round-the-clock, highly reliable, and low-cost operations." This insight reveals the deeper logic behind human-machine collaboration: embodied intelligence is not about replacing humans in the lab, but about assisting and empowering them in real industrial settings—liberating welders from physically demanding tasks and transforming them into equipment managers and process optimizers.[9,10]

2.3 System Integration Architecture of Embodied Intelligent Welding Robots

Integrating the above modules, the system architecture of embodied intelligent welding robots can be abstracted into three layers: Perception Layer: Composed of 3D structured light cameras, laser profile sensors, arc sensors, and molten pool monitoring cameras, this layer is responsible for real-time acquisition of workpiece geometry, weld seam position and cross-sectional parameters, and welding process status data.

Decision Layer: Consists of a large-scale welding process model, motion planning algorithms, and a digital twin system. Preprocessed perception data are fed into the large model, which outputs welding process parameters and trajectory planning schemes. Meanwhile, the digital twin system performs virtual simulation and verification to anticipate potential process issues and equipment failures.

Execution Layer: Includes multi-axis robotic arms, welding power sources, wire feeding mechanisms, and external axes (floor tracks/positioning devices). This layer receives instructions from the decision layer to carry out welding tasks, while simultaneously transmitting real-time feedback—such as positional deviations, current and voltage fluctuations, and molten pool images—back to the perception and decision layers, enabling closed-loop optimization.

3 Core points in steel structure welding scenarios for construction

3.1 Small-Batch Multi-Variety and Flexible Manufacturing Requirements

The most prominent characteristic of building steel structure fabrication is that "every project is unique". A single super high-rise building may require thousands of different types of steel components, including H-shaped steel columns, box girders, bracing trusses, connection joints, embedded parts and more. Each component varies in cross-sectional dimensions, plate thickness, weld configuration and fillet weld leg size. Even within the same project, component specifications for different floors may be adjusted to accommodate changes in structural load-bearing forces.

This multi-variety, small-batch production model stands in stark contrast to mass production in automotive manufacturing, where tens of thousands of identical standard parts are produced in a single run. For traditional teach-pendant programming robots, switching to a new type of component entails hours of downtime for commissioning: re-teaching motion paths, resetting process parameters, and revalidating programs. Factories are forced to choose between frequent production halts caused by robotic deployment and full reliance on manual welding. In practice, most steel structure manufacturers opt for the latter. While manual welding delivers lower efficiency and inconsistent quality, it eliminates the need to develop dedicated programs for every new component.

A typical case encountered by Jiangsu Beiren in 2023 fully illustrates this dilemma: a well-known domestic special steel structure enterprise faced a situation where "the assembly state, material thickness and weld configuration of components varied from batch to batch". Conventional robots could not adapt to such variable conditions at all, forcing the enterprise to rely entirely on manual welding, which brought low production efficiency and uncontrollable welding quality.[11]

3.2 Large Span of Component Dimensions and Reachability Constraints

Building steel components cover an extremely wide size range. Small connecting fittings are less than one meter long, while giant steel columns for super high-rise buildings can reach tens of meters with a single unit weighing over one hundred tons. Such a broad spectrum of sizes imposes stringent spatial coverage requirements on welding equipment.

Meanwhile, steel components feature highly complex and diverse weld positions, including open flat fillet welding zones as well as confined spaces such as the inner cavities of narrow box partition plates and stiffener areas at column bases. The technical team of MCC Group No.5 Engineering Co., Ltd. pointed out: "High-altitude steel structure operations have long been a persistent headache for the construction industry. Workers carry heavy loads while working hundreds of meters above ground. Their protective suits become stifling in sweltering summer heat, and operational accuracy drops amid cold winter winds, with potential safety hazards lingering at all times." Restricted by fixed bases and limited arm spans, traditional industrial robots often fail to reach target positions or operate in awkward postures in these complex working scenarios.

Furthermore, environmental conditions at construction sites are far less controllable than those inside workshops. Combined factors including fluctuating lighting, wind and rain interference, cramped spaces and high-altitude work create greater challenges for the deployment and operation of automated equipment.

3.3 Consistency of Weld Quality and Defect Control

Welding quality of steel structures is directly tied to building safety. Any defect in a weld, whether porosity, slag inclusion, incomplete fusion or cracks, can become the initiation point of structural failure under high-stress conditions. National standards impose strict requirements on the quality grades of steel structure welds, and Class I welds must pass 100% non-destructive testing. Nevertheless, the quality of manual welding heavily relies on welders' proficiency, mental state and physical stamina. Even top-tier welders cannot maintain perfectly consistent welding quality throughout a full workday. Particularly under harsh working conditions such as high temperatures and high altitudes, human fatigue and carelessness are far more likely to trigger quality fluctuations, constituting a systematic quality risk plaguing the steel structure industry.

While conventional automated welding delivers more consistent quality than manual welding, it is premised on consistent workpieces and high assembly precision. Fabrication assembly of building steel components usually carries substantial cumulative errors, which cannot be accommodated by the rigid, scripted execution mode of traditional robots. Embodied intelligent welding robots make up for this shortcoming to a considerable extent through real-time perception and adaptive adjustment. Instead of welding strictly following pre-set programs, they weld by visually sensing workpieces and adjusting parameters proportionally according to detected deviations.[12]

3.4 Structural Labor Shortage and Cost Pressure

The labor crisis in the building steel structure industry is intensifying. On the one hand, welding work features harsh working conditions, heavy labor intensity and high occupational health risks, making the industry unattractive to young people in general. On the other hand, cultivating skilled welders takes several years, and veteran experienced welders are retiring at an accelerating pace. Industry surveys show that the average age of welders in most steel structure manufacturers exceeds 45 years old, creating a severe generational gap.

Meanwhile, labor costs keep rising steadily. In economically developed regions, the monthly salary of a proficient welder has exceeded 10,000 RMB and is still on the rise. Enterprises are caught in a dilemma between failing to recruit enough workers and being unable to afford labor expenses. The emergence of embodied intelligent welding robots offers a technical solution to resolve this structural contradiction. Rather than simply replacing human workers with machines, the technology transforms welders from manual laborers holding welding torches into technical operators managing multiple robots, achieving a dramatic efficiency boost through the "one operator, multiple machines" model.

4 Technical Characteristics and Application Adaptability of Three Types of Embodied Intelligent Welding Robots

In response to the diverse demands of building steel structure scenarios, three product forms of embodied intelligent welding robots have been developed in the industry, each with distinct strengths and complementary to one another.

4.1 Seven-Axis Overhung Intelligent Welding Robot with Ground Rail

4.1.1 Technical Feature

The seven-axis overhung robot with ground rail consists of a traveling ground rail (the 7th axis), an overhung manipulator arm and an intelligent control system. Compared with traditional six-axis industrial robots, the 7th axis (ground travel axis) enables the robot to move freely along the length of workpieces, greatly expanding its working envelope. The overhead suspended layout allows the robot to perform welding from above the workpiece, eliminating collisions between ground-mounted equipment and workpiece fixtures, delivering more flexible motion postures and superior reachability.

Xi'an Zhongke Optoelectronics Precision Engineering Co., Ltd. (its core technologies originate from Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences) is a representative enterprise in this field. Its TR-iW series seven-axis overhung robots with ground rail adopt self-developed embodied intelligent architecture, equipped with manipulator arms from overseas brands (Yaskawa / Kawasaki / FANUC) or domestic brands (Inovance). The core functions include intelligent identification, automatic path planning, autonomous deviation correction and adaptive process parameter adjustment.

The technical parameters of this product series reflect the typical performance limits of seven-axis overhung ground rail robots: its working range spans from 6m × 3m to 24m × 3m, compatible with slender components such as H-beams and I-beams of varying lengths. It accommodates plate thicknesses ranging from 3 mm to 25 mm with assembly alignment errors within 20 mm. It supports various weld types including flat fillet welds, vertical fillet welds, lap fillet welds and groove butt welds. The robot integrates a full set of functions: autonomous path planning, arc seam tracking, pulse welding, circumferential welding, weaving welding, intermittent welding, corner wrapping welding and multi-layer multi-pass welding.[13,14]

4.1.2 Applicable Scenarios, Advantages and Limitations

Seven-axis overhung robots with ground rails are mainly suitable for batch welding of slender workpieces such as H-beams, I-beams and plate units, and applied to standardized production line scenarios inside workshops. A single-machine workstation can cover all welds of one type or a category of components; dualmachine collaborative models enable simultaneous welding on both sides, doubling production efficiency.

Its strengths lie in high precision, excellent stability and suitability for continuous mass production. As the manipulator arm is mounted on a fixed ground rail, the repeat positioning accuracy reaches sub-millimeter level and is immune to ground vibration interference. For bulk orders of components with identical specifications, its advantages in efficiency and consistency are extremely prominent.

Its limitations include large equipment footprint and fixed installation, resulting in insufficient flexibility. When the production line switches to completely different component types, although re-teaching is unnecessary (the embodied intelligent system can automatically identify and adapt to workpieces), physical constraints such as ground rail travel range and workpiece clamping methods may still require a certain amount of adjustment time.[15]

4.2 Intelligent Collaborative Welding Robot

4.2.1 Technical Features

Collaborative robots represent the optimal carrier for the embodied intelligence concept. Instead of simply replacing human workers, such robots prioritize human-robot collaboration, with three core design philosophies as follows: First, no safety perimeter fences required. Equipped with force perception and speed limitation functions, collaborative robots automatically stop or decelerate upon physical contact with operators. Unlike traditional industrial robots that demand physical isolation fences, they enable safe co-working with humans within a shared workspace.

Second, lead-through drag teaching with zero programming. Workers can grasp the robot end-effector and drag it to target positions "just like operating an intelligent welding torch". The robot automatically records path waypoints and optimizes trajectory parameters without any manual coding throughout the process. This highly intuitive interaction drastically lowers operational barriers; ordinary welders can master the equipment after short-term training.

Third, lightweight design and rapid deployment. Collaborative robots generally weigh only dozens of kilograms and can be transported and installed by a single person. The flexible welding robot independently developed by CSCEC Steel Tech Intelligent Technology weighs merely 9.8 kg and can be fully deployed within 3 minutes.

4.2.2 Applicable Scenarios, Advantages and Limitations

Collaborative robots integrate flexibility and intelligence, boasting an extremely wide range of applicable scenarios: welding of small and medium-sized components in workshops, confined-space operations on box girders, box columns and round tubes at construction sites, flexible welding for multi-variety small-batch workpieces, as well as temporary repair welding and rework.

The most strategically significant application mode lies in clustered operation with the "one operator, multiple robots" model. For Tower C of the Shenzhen Bay Super Headquarters Base undertaken by CSCEC Steel Tech, the intelligent steel structure construction center was equipped with 10 flexible welding robots, which undertook on-site welding of approximately 7,000 tons of steel components, accounting for 90% of all column welding work on the project. The construction center, sized like a standard shipping container, expands into a movable intelligent capsule factory with a working radius of 35 meters. It can be hoisted to upper floors and towed to different positions, greatly facilitating vertical transportation and horizontal relocation on construction sites.

Its advantages include flexible deployment, easy operation and safe human-robot collaboration. However, it has limitations: the absolute productivity of a single unit cannot match large dedicated automated equipment. Operators need to master relevant operation and management skills, and its stability is inferior to dedicated machinery for continuous welding tasks involving extra-thick plates and ultra-long weld seams.[16]

4.3 Mobile (Track-Type) Intelligent Welding Robot

4.3.1 Technical Features

Tracked mobile welding robots mount welding manipulators on tracked chassis, enabling an operation mode where workpieces remain stationary while the robot actively travels to target welding positions. Equipped with lead-through drag teaching and programming-free intelligent systems, they can access work areas unreachable by fixed equipment such as gantry cranes and ground rail robots. Certain models are additionally fitted with magnetic wall-climbing functions, allowing them to crawl vertically on 90° walls and rotate 360°, delivering dead-angle-free welding across all vertical surfaces.

The high-altitude welding robot independently developed by MCC No.5 Engineering serves as a typical representative of this product category. Its magnetic wall-climbing technology allows easy access to high-difficulty and high-risk work sites including high-altitude zones and confined enclosed spaces. The integrated six-axis extra-long manipulator (1200 mm) achieves a positioning accuracy of 0.02 mm.

Patented technology from Jiangsu Bafang Steel Structure Group demonstrates another innovative development direction for this robot type: integrated ultrasonic weld inspection. An electric push rod delivers coupling agent, and the ultrasonic probe maintains stable contact with workpieces via spring preloading, realizing integrated "welding-inspection" operation and eliminating the need for separate manual inspection procedures.

4.3.2 Applicable Scenarios, Advantages and Limitations

Tracked robots are mainly applied to on-site welding for equipment maintenance, field assembly of heavy steel structures, on-site fabrication of non-standard workpieces, and repair welding at scattered flexible workshop stations. They boast irreplaceable advantages in scenarios without fixed tooling, such as bridge construction sites and large-scale equipment installation sites.

For the steel tower fabrication of Zhangjinggao Yangtze River Bridge, China Railway Baoji Bridge (Yangzhou) developed mobile workstations with tracked collaborative robots and electrically driven lifting welding platforms to address complex welds including curved seams on diaphragm units and corner welds of steel shells, realizing fully automatic welding. During the steel box girder fabrication of Xiamen-Jinmen Bridge, aiming at the massive quantity and highly variable positions of U-rib notch welds, the company deployed a lightweight electrically driven sliding rail welding system integrated with AI vision weld recognition, which enables continuous automatic welding of multiple notches. Relevant research projects have been appraised and identified as internationally advanced by China Highway Construction Industry Association.

Its strengths lie in all-terrain mobility, powerful on-site adaptability and multi-purpose functionality. Its limitation is that the load capacity of the chassis restricts the size of the manipulator, resulting in relatively limited continuous operation capacity for extra-thick plates and ultra-long weld seams.[17]

5 Practical Cases and Efficiency Analysis

5.1 Jiangsu Beiren: "One Intelligent Brain, Multiple Hardware Forms" Solution for Steel Structure Welding

In 2023, a well-known domestic special steel structure enterprise raised a challenging demand to Jiangsu Beiren: the special steel structural components it produces differ in assembly state, material thickness and weld type from batch to batch. Traditional robots failed to adapt to such varied workpieces, and manual welding suffered from low efficiency and unstable welding quality.

Centered on the closed-loop "perception-decision-execution" architecture, the R&D team of Jiangsu Beiren developed embodied intelligent welding robots equipped with the BR-iWeld welding process expert database. After half a year of commissioning and iterative optimization, the first unit was officially put into operation. When faced with diverse welding requirements, the robot requires no manual teaching; it only generates exclusive welding schemes via vision and laser scanning.

Of greater strategic significance is the technical concept of "One Intelligent Brain, Multiple Hardware Forms" proposed by Jiangsu Beiren. A single set of intelligent systems is compatible with multiple robot forms including tracked mobile, gantry, cantilever and ground rail types. This upgrade shifts equipment from dedicated to general-purpose scenarios and breaks the limitation of "one robot for one single task" inherent to conventional robots.

The welding scenario of elevator car platforms has verified this technical concept. The dual-robot dual-station setup runs continuously for 24 hours, compatible with car platforms of various specifications and doubling production efficiency. Lin Tao, Vice President of Jiangsu Beiren, stated: "This technical architecture not only breaks the traditional restriction of 'one robot for a single dedicated task', but also upgrades robots from simple production tools to intelligent collaborative partners."

5.2 CSCEC Science and Industry: From In-house R&D Institute to Pioneer of Intelligent Welding Industry

CSCEC Steel Tech Intelligent Technology originated from the Intelligent Manufacturing Research Institute of CSCEC Steel Structure and was registered as an independent legal entity in 2025. This transformation marks a landmark event in the intelligent upgrading of the building steel structure industry. By commercializing its internal R&D capabilities, the large construction enterprise signals that intelligent welding technology has shifted from research exploration to industrial promotion.

In May 2026, Xiaoyu Intelligent Manufacturing signed a strategic cooperation agreement with CSCEC Steel Tech Intelligent Technology. The two parties plan to jointly advance the large-scale application of 1,000 sets of embodied intelligent welding robots in the building steel structure sector within one year. The core technology of Xiaoyu Intelligent Manufacturing adopts the "One Brain, Multiple Forms" architecture: a highly generalized embodied intelligent brain can adapt to and control robot bodies of various forms for diverse scenarios. Its founding team is led by Qiao Zhongliang, former head of MIUI R&D at Xiaomi, and Wang Wenlin, former general manager of Xiaomi's Software System Platform Department, with core team members recruited from leading tech enterprises including Xiaomi, ByteDance and Huawei.

This collaboration forms a closed industrial ecosystem integrating technology supply and on-site implementation. Embodied intelligent algorithms rely on data support and verification from real industrial scenarios, while building steel structure enterprises are in urgent need of intelligent technologies to resolve labor shortages and inconsistent quality issues. The two sides complement each other and achieve win-win results.

5.3 China Railway Baoji Bridge: Reverse-Driven Technological Innovation Oriented to Bridge Scenarios

Welding quality standards for bridge steel structures are even stricter than those for building steel structures. Bridges bear dynamic and fatigue loads, making the fatigue performance of welds critically important. Targeting the characteristics of bridge steel structures, China Railway Baoji Bridge (Yangzhou) has developed a variety of derivative equipment based on embodied intelligent welding technology.

During the fabrication of steel towers for Zhangjinggao Yangtze River Bridge and steel shells for Guanyinsi Yangtze River Bridge, the enterprise addressed the pain points of stringent surface quality requirements for welds and low automation rates on steel tower and steel shell products. It developed mobile workstations equipped with tracked collaborative robots and electrically driven lifting welding platforms, which realized automatic welding of curved welds on diaphragm units and corner welds of steel shells. Two invention patents have been granted: An Automatic Welding Method for Cable Tower Steel Shell Blocks with Double-Layer Dense Grid Stiffened Wall Panels and An On-site Automatic Welding Method for Super-Large Section Steel Bridge Towers.

For the fabrication of steel box girders of Xiamen-Jinmen Bridge, in response to the large quantity, densely distributed and highly variable welding positions of U-rib notch welds plus rigorous quality requirements, the company developed a lightweight electrically driven sliding rail welding system integrated with AI vision weld recognition for steel box girder U-rib notches, enabling continuous automatic welding of multiple notches. This achievement won the Third Prize of Jiangsu Provincial Science and Technology Innovation Achievement Transformation Award. The relevant research project Automatic Welding Construction Technology of Portable Robots for Steel Box Girders has been appraised and certified as internationally advanced by the China Highway Construction Industry Association.

5.4 MCC No.5: High-Altitude Magnetic Adsorption Robots and Intelligent Construction Ecosystem Cluster

The high-altitude welding robot independently developed by MCC Group No.5 stands out with its proprietary magnetic wall-climbing technology. Capable of crawling vertically on 90° walls and rotating 360°, the robot can easily access high-difficulty and high-risk work sites such as high-altitude areas and confined enclosed spaces to achieve dead-angle-free welding on all vertical surfaces. Its built-in six-axis extra-long manipulator with a 1200 mm working stroke delivers a positioning accuracy of 0.02 mm.

In terms of efficiency improvement, the robot achieves remarkable breakthroughs. Conventional manual high-altitude welding requires operators to wear safety harnesses and conduct segmented welding, which comes with low productivity and high safety risks. In contrast, the robot supports continuous operation and completely eliminates the hazard of workers falling from heights. Multiple robots can work simultaneously on site under the control of a single operator. Its working efficiency can be up to four times higher than manual welding, cutting overall labor costs by 80%.

This high-altitude welding robot has passed practical verification on multiple key projects including Chengdu Gaotou Xinguang Intelligent Manufacturing Park and Tongliang Station of Chengdu-Chongqing Middle Line High-speed Railway, accelerating the transformation of construction welding operations toward intrinsic safety.[18]

5.5 Qingdao Oriental Steel Tower: Intelligent Practice of Jiaozhou Steel Structure Industrial Cluster

Jiaozhou hosts the largest and most concentrated steel structure industrial cluster in northern China. The intelligent transformation of Qingdao East Steel Tower Stock Co., Ltd., the leading enterprise within this cluster, serves as an industry benchmark. The company has participated in major national infrastructure projects including the Five-hundred-meter Aperture Spherical Telescope (FAST, nicknamed China's Eye of Heaven) and ultra-high voltage (UHV) power transmission projects. Since completing its intelligent upgrading in 2025, the automatic welding workshop has been running efficient production lines composed of more than ten intelligent welding robots. These robots scan components via 3D vision, and the system automatically matches corresponding welding processes. Equipped with through-arc seam tracking technology for real-time deviation correction, they greatly enhance the stability and precision of welding operations.

Yang Jinping, Deputy General Director and Deputy General Manager of the company, stated: "Currently, 80% of our steel structure welding work relies on automatic production lines with intelligent robots, which can operate non-stop for 24 hours. Productivity has risen while labor costs have been cut. In addition, constant equipment parameters deliver uniform, aesthetic weld formation, enabling high-efficiency single-pass welding with consistent quality."

More importantly, Qingdao East Steel Tower has realized full-process digitalization covering cutting, welding, coating and inspection. By connecting to the industrial internet platforms of major clients, the company has broken data barriers across the industrial chain. "Full-process online management creates a closed-loop workflow for order inquiry, progress tracking and after-sales feedback. While reducing labor expenses, the overall production and management efficiency of the enterprise has increased by 20%."

5.6 Summary of Efficiency Data

Synthesizing the above practical cases and industrial statistics, the efficiency improvements brought by embodied intelligent welding robots in building steel structure scenarios can be quantified into the following indicators:

Table 1 Efficiency Data

Efficiency Indicators	Typical Data	Case
First Pass Welding Qualification Rate	≥99.5%	CSCEC Science and Industry Corporation LTD
Reduced Process Development Cycle	60%	BOTSING Technology
Comprehensive Production Cost Cut	above 40%	BOTSING Technology
Multi-operator Multi-robot Efficiency Improvement	One operator controls 3 to 10 robots	MCC No.5、CSCEC Science and Industry Corporation LTD
Sharp Reduction in Overall Labor Costs	80%	MCC No.5
High-Altitude Welding Positioning Accuracy	0.02mm	MCC No.5
Welding Automation Rate	80%	Qingdao East Steel Tower
Enterprise Production Efficiency Improvement	20%（Full-Process Digitalization）	Qingdao East Steel Tower

6 Key Technical Challenges and Development Trends

6.1 Sensor Fusion and Environmental Adaptability

The perception capability of current embodied intelligent welding robots performs well in standardized workshop environments. However, visual sensors suffer severe stability challenges under harsh construction site conditions such as complex illumination, welding fumes and electromagnetic interference. As summarized by Shi Yonghua et al. in a review published in Mechanical & Electrical Engineering Technology, improving sensing accuracy and realizing real-time multimodal data fusion is the key to transforming welding from the "teach-and-playback" mode to an adaptive, anthropomorphic and intelligent mode.[19]

The future direction lies in further deepening multimodal sensor fusion: information from vision, LiDAR, arc sensing, tactile sensing and other sources will achieve redundant complementarity via AI algorithms to enhance the environmental robustness of the system. The technical team of China MCC5 has put forward a plan to develop acoustic models, which imitate veteran welders' ability to judge welding conditions by sound. This represents a valuable exploration for expanding multimodal perception from vision-dominated mode to audio-visual fusion.

6.2 Lightweight AI Models and Real-Time Inference

Welding process large models feature massive parameter sizes, leading to latency issues during cloud-based inference. Meanwhile, welding operations impose extremely high real-time requirements with millisecond-level response. Distilling large models into lightweight edge models that can be deployed on the robot's local controller while maintaining inference accuracy and speed constitutes a critical technical bottleneck for industrial application.

Academic research indicates that the core technologies of intelligent welding will focus on two major directions: deep multi-sensor fusion based on vision technology, and embodied intelligent welding robots driven by large AI models. The ultimate goal is to advance fully autonomous intelligent welding systems capable of autonomous perception, recognition, decision-making and execution.

6.3 Digital Twin and Predictive Maintenance

By constructing a full-element virtual mirror of the welding process, digital twin technology enables process simulation, parameter optimization and defect prediction in virtual space, drastically cutting the physical trial welding cost. The embodied intelligent agents of BOTSING Technology have been connected with digital twin systems and AI algorithms to predict equipment operating conditions and carry out predictive maintenance, eliminating the reliance of traditional welding on manual experience.

BOTSING Technology has also put forward the concept of "Robot-defined Super Factory". Based on embodied intelligence technology, integrated with industrial Internet and digital twin systems, a collaborative cluster of multi-type and multi-functional welding robots is constructed to realize three major upgrades: from single-point operation to collaborative decision-making, from single function to full-process coverage, and from passive maintenance to active optimization.

6.4 From Single-Robot Intelligence to Cluster Intelligence

With the advancement of CSCEC Steel Tech’s large-scale application plan for up to 1,000 robots, multi-robot collaboration and cluster scheduling will become an inevitable trend. Each robot acts not only as an independent welding unit but also a node in the data network. Welding parameters, quality data and equipment status are uploaded to the cloud in real time. Continuous optimization of process models via big data analysis generates a swarm intelligence effect where the system grows smarter with operation.

China MCC5 has taken the lead in this field by releasing China's first self-developed intelligent construction robot ecological cluster equipped with a project-level intelligent scheduling and management system for robot clusters, realizing coordinated scheduling of multiple types of robots.[16]

7 CONCLUSION

Embodied intelligent welding robots are reshaping the production logic of construction steel structure manufacturing. Fundamentally, this technology transforms welding operations from programmed playback to task-oriented solving, enabling robots to truly understand welding demands, optimize processes independently and perform autonomous execution. In terms of industrial value, it directly addresses the core pain points of the steel structure industry, namely small-batch, multi-variety production and labor shortages, and delivers scalable solutions for widespread promotion.

Three product configurations, namely seven-axis overhead gantry robots, intelligent collaborative robots and crawler mobile robots, match differentiated scenarios including mass workshop production, flexible on-site deployment and positioning on complicated terrain, jointly forming a full product matrix for construction steel structure applications. Practical data demonstrates that embodied intelligent welding technology can cut the process development cycle by 60%, reduce comprehensive costs by 40%, achieve a first-pass yield of over 99%, and multiply efficiency under the single-operator multi-robot mode, fully verifying its technical and economic benefits.

Looking forward to the 15th Five-Year Plan period, with the continuous advancement of large AI model technology, declining costs of multi-sensor fusion, and gradual improvement of industrial standard systems, the penetration rate of embodied intelligent welding robots in the construction steel structure industry is expected to rise from less than 20% at present to more than 50%. The practices of leading enterprises with 80% welding automation in the Jiaozhou steel structure industrial cluster prove that this target is well within reach.

This represents far more than an automation upgrade for welding procedures; it serves as a core pivot for the transformation of construction steel structure manufacturing from a labor-intensive industry to a data-driven industry. When robots can complete 90% of high-risk operations, workers will shift from manual laborers to technical professionals — transforming from welders holding torches into technical supervisors managing multiple robots. This delivers not only economic gains via industrial upgrading but also profound social value centered on putting people first.□

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