Application of Intelligent Steel Bar Welding Robot Based on Image Tracking Technology

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Abstract: Most existing steel bar welding robots adopt a pre-programmed operation mode and lack dynamic adjustment capabilities. To promote the upgrading of welding robots from mechanical operation to intelligent operation, an intelligent steel reinforcement cage welding robot was developed based on image tracking technology through the optimization of tooling fixtures and integration of core systems. The robot utilizes a V-shaped integrated supporting and pressing tooling fixture and a three-axis linked gantry positioning system, which enables control of the longitudinal, transverse, and height deviations of upper-layer steel bars within 1.0 mm, with a repeat positioning deviation of less than 0.5 mm. An industrial-grade 3D structured light camera and a weld seam tracking system are integrated at the end of the robotic arm. A coordinate mapping between the camera and the robotic arm is established using the chessboard calibration method, forming a closed-loop technical process of photographing, recognition-3D modelling judgment, and dynamic correction, with a calibration error of < 0.1 mm. Tests show that the total time for a single welding spot of the robot, from positioning to welding, is ≤ 13.6 seconds, which is 45.6% more efficient than traditional pre-programmed robots. The welding qualification rate reaches over 98.7%. It can meet the high-efficiency and high-precision welding needs of mass production of steel reinforcement cages in intelligent beam yards.

Keywords: Welding Robot; Weld Seam; 3D Structured Light Camera; Tooling Fixture; Dynamic Correction; Intelligent Beam Yard

1. Introduction

In major infrastructure projects such as bridges and stadiums, steel reinforcement cages serve as core load-bearing structures. The welding quality of load-bearing structures directly determines the overall safety and durability of the projects [1]. With the promotion of technologies such as intelligent beam yards and prefabricated construction, projects have put forward higher requirements for the precision, efficiency, and intelligence level of steel reinforcement cage welding. The traditional operation mode relying on manual welding or single pre-programmed robots has been difficult to adapt to the construction rhythm and quality standards of modern engineering.

The technology of replacing manual welding with welding robots has reduced workers' physical labor and been widely applied in various industries [2-4]. Currently, most mainstream steel bar welding robots adopt a preset path operation mode, which has multiple technical bottlenecks. Firstly, the lack of dynamic adjustment capability: when steel bars undergo slight displacement due to transportation collision or placement deviation, the robot cannot perceive and correct it in real time, easily leading to weld misalignment and insufficient welding. Test data shows that the welding qualification rate of traditional pre-programmed robots is generally low, requiring manual repair welding, which significantly increases rework costs [5,6]. Secondly, poor environmental adaptability: arc radiation at the welding site is likely to interfere with detection components, and metal spatter can also cause damage to camera lenses, seriously restricting continuous operation efficiency [7-9].

To address the above problems, this study develops an intelligent steel reinforcement cage welding robot based on image tracking technology, combined with fixture optimization and core system integration. A V-shaped integrated supporting and pressing fixture is used to ensure stable steel bar positioning, and a 3D structured light camera and weld seam tracking system are integrated to construct a

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dynamic correction mechanism, coupled with a linked camera protection device, forming an intelligent operation scheme featuring precise positioning, real-time adjustment, and safety protection. The robot aims to improve welding precision and efficiency, enhance adaptability to complex environments, provide technical support for mass welding of steel reinforcement cages in intelligent beam yards, and promote the intelligent transformation of infrastructure welding operations.

2. Core Technical Framework

The core technical framework of the welding robot includes a mechanical system (hardware) and a control system (software), both of which adopt a modular design to realize the orderly combination of functions.

As shown in Figure 1, to meet the welding requirements of large size and multiple welding spots for capping beam steel reinforcement cages, the mechanical system adopts a coordinated layout of a gantry and a multi-axis robotic arm. A CM350 welding machine (rated power: 38 KW) is integrated at the end of the robotic arm mounted on the gantry, and flexible switching between the welding torch and detection components is achieved through a quick-change interface. Moreover, the guide rails of the gantry adopt high-precision linear slides, which are matched with a servo motor drive to ensure movement stability and positional accuracy during large-range operations.

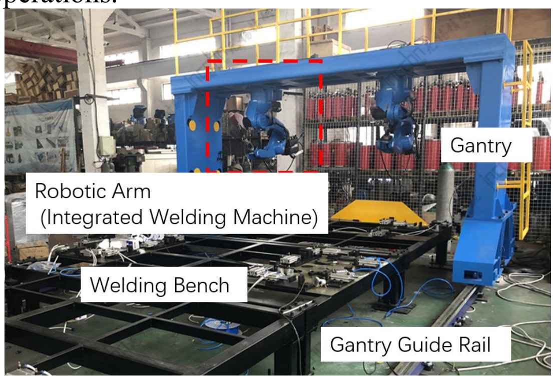

Figure 1. Mechanical system of the welding robot

The control system is divided into three functional modules (subsystems): motion control, data processing, and human-machine interaction.

(1) The motion control module is mainly responsible for the coordinated motion control of the gantry's X/Y/Z axes and the robotic arm's 7 axes. It supports preset path planning and real-time dynamic adjustment, and can realize multi-axis linkage logic through PLC programming.

(2) The data processing module receives real-time image data from the 3D structured light camera (resolution: 1280×960, frame rate: 30 fps), extracts weld seam feature points via image processing algorithms, and generates 3D coordinate data.

(3) The human-machine interaction module supports the setting of welding parameters (welding current, voltage, speed) and real-time monitoring of operating status. It also has data storage and export capabilities, which can record complete parameters and quality data of a single operation to facilitate subsequent traceability and analysis.

3. Control of Welding Precision

3.1 Image Tracking of Weld Seam

Weld seam image tracking is achieved through three steps: photographing with a 3D structured light camera, establishing a coordinate mapping model, and dynamic correction.

Based on the high-precision and anti-interference requirements of the welding scenario, an industrial-grade structured light camera is selected for the 3D structured light camera. Its technical parameters are as follows: resolution of 1280×960, 3D point cloud density ≥ 100 points/mm², measurement range of 300–1000 mm, and 3D measurement accuracy ≤ 0.08 mm, which can effectively identify subtle deviations at steel bar intersections.

The core of the coordinate mapping model between the camera and the robotic arm is to establish the conversion relationship between the camera coordinate system and the robotic arm coordinate system. In this robot design, a chessboard calibration method combined with multi-point verification is adopted to achieve a calibration error of < 0.1 mm.

First, a high-precision chessboard calibration target is placed on the welding platform. Then, the least squares method is used to fit the coordinate conversion matrix (including the rotation matrix and translation vector), and the coordinate conversion formula is established. Finally, 5 feature points not involved in calibration are selected for verification, and the deviation between the converted robotic arm coordinates and the actual coordinates is calculated. If the deviation > 0.1 mm, the parameters of the conversion matrix are re-

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optimized until the deviation of all verification points is ≤ 0.08 mm, ensuring a calibration error of < 0.1 mm.

Through this method, the weld seam position identified by the camera can be accurately converted into the motion coordinates of the robotic arm, providing a data foundation for subsequent dynamic correction.

Dynamic correction includes 3 step as fellow:

Step 1 is image capture and recognition.

Step 2 is 3D modelling and weldability judgment. Based on the 3D point cloud data of the camera, a 3D model of the welding spot area is constructed to calculate the intersection coordinates (weld seam positions) of longitudinal and transverse steel bars.

Step 3 is dynamic correction. If judged as "weldable", the deviation values (ΔX, ΔY, ΔZ) between the actual weld seam coordinates and theoretical coordinates are calculated. If the deviation ≤ 0.5 mm, welding is executed directly. If the deviation > 0.5 mm, the deviation values are transmitted to the motion control module, which drives the robotic arm to adjust its position according to ΔX, ΔY, and ΔZ.

Through this closed-loop process, issues such as steel bar deviation and installation errors can be addressed in real time, ensuring precise alignment between the welding trajectory and the weld seam, and significantly reducing the risks of insufficient welding and weld detachment.

3.2 Welding Precision

In accordance with the construction requirements for steel reinforcement cage welding, the robot's positioning accuracy is set as follows: (1) the positional deviation of the upper-layer steel bars in the longitudinal, transverse, and height directions ≤ 1.0 mm, and (2) the repeat positioning deviation < 0.5 mm.

As shown in Figure 2, the weldability prediction and dynamic correction functions of the weld seam tracking system can reduce unqualified welding spots caused by steel bar deviation and parameter deviation. According to the trial operation, the total time for a single welding spot from positioning, judgment to welding is 10–13 s, and the recognition efficiency is superior to that of traditional pre-programmed robots. For the average workload of 300 welding spots per single steel reinforcement cage of the capping beam, the welding time per single cage can be ≤ 75 min, meeting the mass production requirements of intelligent beam yards.

Moreover, to avoid steel bar displacement caused by contact between the welding machine and steel bars during the welding process, a V-shaped integrated clamping fixture for supporting and pressing is designed, which meets the design requirements for "fit degree" and "stability" in steel bar positioning. As shown in Figure 3, the core structure of the fixture consists of two parts: a fixed V-shaped supporting block at the lower part and a V-shaped pressing block with a guide rod cylinder at the upper part.

Figure 2. Weld Seam Tracking System

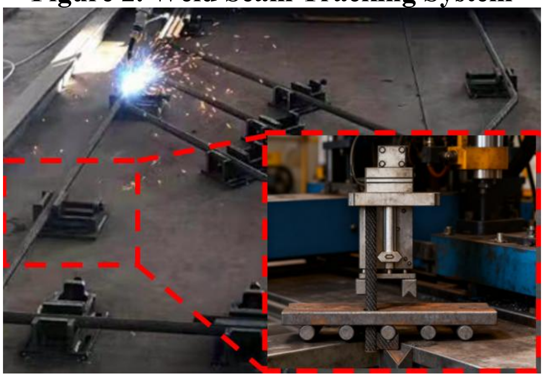

Figure 3. V-Shaped Integrated Clamping Fixture

4. Engineering Application in Intelligent Beam Yard

As shown in Figure 4, the developed steel bar welding robot has been applied to the intelligent beam yard of Section JGATJ-1 in the reconstruction and expansion project of the Beijing-Hong Kong-Macao Expressway.

On-site construction deployment is carried out around efficient collaboration and safety compliance. In terms of spatial layout, the robot is installed in the welding workshop. The distance between the welding platform (12000 mm × 6000 mm) and both the steel bar raw material storage area and finished product storage area is set to 5 m, facilitating steel bar transfer (using an electric hoist with a transfer time ≤ 3 min per frame). For the equipment power supply, a 380V industrial power supply is adopted, equipped with a dedicated distribution box (including overload protection and leakage protection functions) to avoid voltage fluctuations caused by sharing power with other equipment. Regarding safety protection, guardrails (height: 1.2 m) are installed around the robot's operating area, and arc shielding plates are equipped (to reduce the impact of arc light on surrounding operators). Emergency stop buttons are also installed to ensure a quick shutdown in emergency situations.

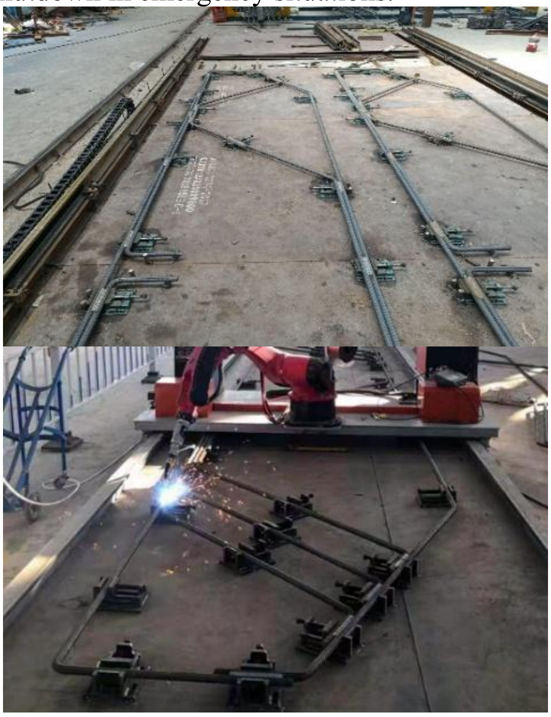

Figure 4. Operation of the Intelligent Welding Robot in Smart Beam Yard

5. Conclusions

To promote the upgrading of welding robots from mechanical operation to intelligent operation, an intelligent steel reinforcement cage welding robot has been successfully developed based on image tracking technology, through fixture optimization and system integration, and has been applied in intelligent beam yards. The main conclusions are as follows:

1) Through the synergistic effect of the V-shaped integrated supporting and pressing fixture and the three-axis linkage gantry positioning system, the robot can ensure stable steel bar fitting and qualified gaps, controlling the deviations of upper-layer steel bars in the longitudinal, transverse, and height directions within 1.0 mm, with a repeat positioning deviation of less than 0.5 mm.

2) Test results show that the total time for a single welding spot from positioning to welding is ≤ 13.6 s, representing a 45.6% improvement in welding efficiency compared to traditional pre-programmed robots (exceeding the 40% target value). The welding qualification rate reaches over 98.7%, and the dynamic correction function significantly reduces unqualified welding spots caused by steel bar deviation, accurately meeting the welding quality requirements.

3)The robot has been successfully applied in the intelligent beam yard of the Beijing-Hong Kong-Macao Expressway reconstruction project. A single beam yard can complete the welding of 8 steel reinforcement cages per day, which can efficiently match the project construction schedule and provide a reliable intelligent welding solution for the mass production of steel reinforcement cages in intelligent beam yards.

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