Research on Control System Errors of Welding Robots

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Abstract. In the context of the rapid development of intelligent manufacturing, industrial robots represented by intelligent welding robots are being increasingly applied in production. However, with the continuous improvement of manufacturing precision requirements, welding robots face more stringent challenges in weld precision control. How to improve their control precision has become a research focus in this field. This paper, starting from various key aspects, including the path planning errors in welding robots and the recognition errors of sensors, conducts an in-depth exploration of the analysis of the operation errors of welding robots and strategies for reducing these errors. Besides, sorting out the control system of welding robots and the theories related to their errors, and integrating error-causing factors, such as sensor precision and control algorithms scattered in many other studies. The paper summarizes the research progress of error theory under the coupling effect and aims to improve the knowledge framework of the precision control of welding robots. Additionally, this essay provides a solid foundation for subsequent theoretical research, promoting the development of welding robot technology toward higher precision and greater intelligence.

Keywords: Intelligentized Welding Robot, End-Effector, Operating System Error, Error Reduction

1 Introduction

With the technology development,the field of intelligent robots is becoming a major focus of scientific research. Among them, the optimization of control errors in welding robots has gradually emerged as one of the core challenges in the R & D process of this field. Welding robots with higher precision can not only significantly improve the pass - rate of conventional industrial products but also be suitable for welding tasks in complex or harsh environments, expanding their application scope in the high - end manufacturing field. Moreover, high - precision welding robots can, to a certain extent, avoid the problem of unstable quality caused by human fatigue during manual welding. This helps to enhance production efficiency and welding quality, thereby further promoting the development of intelligent manufacturing. Therefore, welding, as a labor-intensive position, is now facing unprecedented changes and transformations.

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China's intelligent welding robots were initially widely applied due to the demand for the mass production of automobiles. In recent years, with the continuous development of industrial automation technology, the application of intelligent welding robots in the field of industrial welding has been gradually extended to multiple industries such as machinery manufacturing, steel structure manufacturing, and shipbuilding [1]. In today's industrial welding industry, intelligent robots have become one of the key technologies and play an important role in fields such as industry, aerospace, and electronics and electrical appliances. The automation, flexibility, intelligence, and precision of the welding process have become an inevitable trend in the development of welding technology [2].

Zhao Wenguang and others pointed out when studying the intelligentized welding robot that, while welding robots are widely applied, there are still certain challenges in the field of improving the precision of welding robots, which restricts the development of welding robots to a certain extent [2]. In addition, due to the differences in manufacturing processes, equipment calibration, and error compensation among different enterprises, there are still inevitably certain errors in the practical application of welding robots. This not only affects the stability of the welding quality but also poses higher requirements for the intelligent control of welding robots. The errors mainly come from three aspects, namely, positioning errors, path planning errors, and errors caused by different sensors. This paper proceeds from multiple perspectives to analyze the control errors of intelligent welding robots, including Welding path planning errors of welding robots,Multi-sensor cooperative errors, and the disadvantages of sensor design. In addition, by analyzing the error-causing factors of welding robots, this paper provides valuable insights for manufacturers to optimize the design and operation of welding robots. Ultimately, this study contributes to the overall development of the field of welding robots and propels industrial production towards a more efficient and precise direction [3].

2 Path Planning Error

The operating system errors generated by intelligent welding robots mainly occur when the welding torch of the welding robot reaches the specific weld seam position. After the welding robot obtains the specific environmental position information, the algorithm will further construct its two - dimensional environmental map and calculate and design the optimal path to reach the weld seam position. However, a large number of path planning algorithms with different working purposes and characteristics are involved in the path planning process. Therefore, how to achieve the complementary advantages and disadvantages of the algorithms of the welding robot and coordinating multiple path planning algorithms is the main strategy for reducing the errors generated during the path planning process.

2.1 The Path Trajectory of the Robot

The path planning of welding robots is mainly divided into global path planning and local path planning. The objective of global path planning is to find the shortest path for the welding robot to reach the weld seam position while ensuring there are no obstacles in the way. The specific purpose of local path planning, on the other hand, is to avoid dynamic obstacles. Generally speaking, for a welding robot to reach a specific target weld seam, it needs to rely on the joint "cooperation" of local path planning and global path planning. As indicated by Sun Zhiqiang et al., currently, the algorithms used for global path planning of welding robots are the mainstream algorithms such as the Dijkstra algorithm, A* algorithm, Genetic Algorithms (GA), and Rapidly Exploring Random Tree (RRT) [4]. The path planning represented by the rectangle is a regular path planned based on the form of a single point-to-point route. This type of path planning has the advantages of minimizing time cost, path distance, and machine operating energy consumption. However, it also reveals its inevitable limitations, that is, this planning method is only applicable to tasks with low difficulty levels [4]. Nevertheless, it is worth noting that the errors caused by this type of path are almost negligible. In addition, there is circular path planning. Its basic principle is to design an interval within which the robotic arm can rotate in place from 360 degrees to 180 degrees. Correspondingly, to some extent, it will be at the cost of the operating speed and efficiency of the robotic arm [5]. Similarly, the errors generated by this type of path are significantly smaller compared to the irregular path planning represented by the curves mentioned below. When the robot executes irregular path tasks, the path shapes of the welding robot mainly manifest as regular trajectories such as rectangles and circles, as well as irregular paths like curves. Compared with regular paths such as rectangles, irregular paths of the curve type are relatively more difficult to design, and they will also bring about greater errors when specific tasks are executed. Specifically, the main errors faced are manifested as sudden acceleration and deceleration during the driving process, and it is difficult to ensure the stability of the robot when turning. In order to avoid the errors caused by the path design mainly based on arcs, some researchers have found that Bezier curves can more effectively reduce the errors caused by path execution [5]. A Bezier curve refers to a mathematical curve applied in two-dimensional graphics applications, which is a vector curve. This type of curve is shown in Figure 1 and Figure 2 [5]. This type of curve can be roughly divided into two types: the right diagonal planning curve and the left diagonal planning curve. This curve has the characteristics of a continuous trajectory and smooth path, and it can reduce the problems mentioned above to a greater extent.

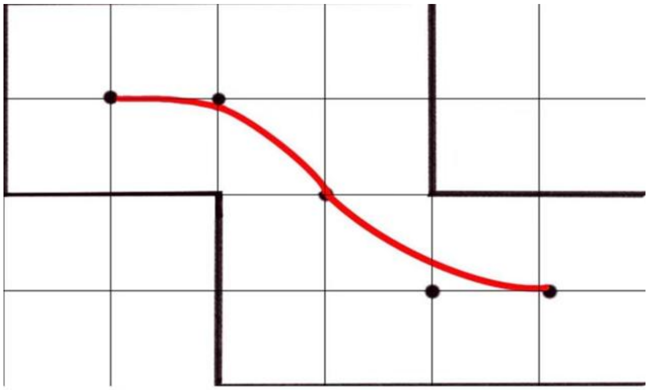

Fig. 1. Left diagonal programming curve [5]

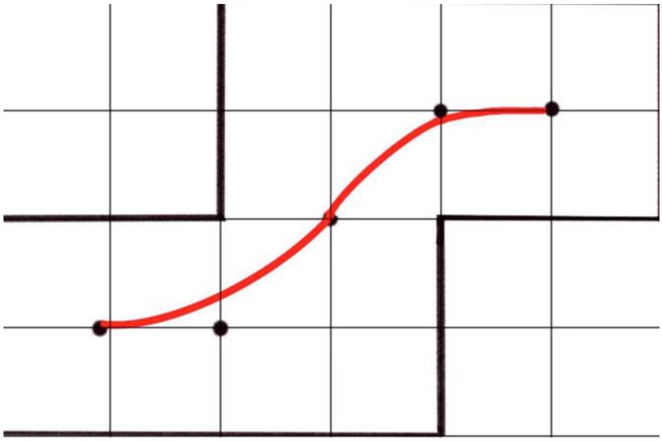

Fig. 2. Right diagonal programming curve [5]

2.2 The Algorithm Principle of Path Planning

The path planning of welding robots refers to the ability of such robots to independently find routes to reach the task - performing area by relying on specific algorithms when completing specific welding tasks, and it needs to be highly efficient and safe simultaneously. The underlying logic of its operation is to reasonably segment the acquired image data, process it into a map, and "inform" the robotic arm in the form of tasks. Currently, the mainstream algorithms used for robot path planning are the A* algorithm, the Dijkstra algorithm based on graph theory, and the artificial potential field algorithm. The essential principle of the A* algorithm is that the computer first calculates the f - cost for each node (where $f(n)=g(n)+h(n)$, $g(n)$ is the actual cost from the starting point to the current node, and $h(n)$ is the estimated cost from the current node to the target node). Then, it determines the square with the minimum f-cost around the starting point and selects all squares with such characteristics as the optimal route to the destination. For the heuristic function f(n)=g(n)+h(n) of the A* algorithm, common calculation methods for h(n) include Manhattan distance, Euclidean distance, and Chebyshev distance. In the implementation process of the A* algorithm, an open list is usually used to store squares that can be explored, and a closed list is used to store squares that have been traversed. In relevant diagrams (as shown in Table 1 and Figure 3), the number in each square represents the f-cost corresponding to that square. Green represents paths that are explored but not selected, and yellow represents selected paths. Suppose that in the relevant scenario, the side length of a grid is 10, and this setting is used for specific operations such as the calculation of relevant distances and costs.

Table 1. Algorithm exploration list of six-by-six two-dimensional map

Open list	Closed list
(3,2)=60,A	(4,3)=40,A
(4,1)=60,A	(4,4)=30,(4,3）
(5,2)=60,A	(4,5)=20,(4,4)
(3,3)=50,(4,3)	(4,6)=10,(4,5)
(5,3)=50,(4,3)	
(3,4)=40,(4,4）	
(5,4)=40,(4,4)	
(3,5)=30(4,5)	
(5,5)=30,(4,5)	

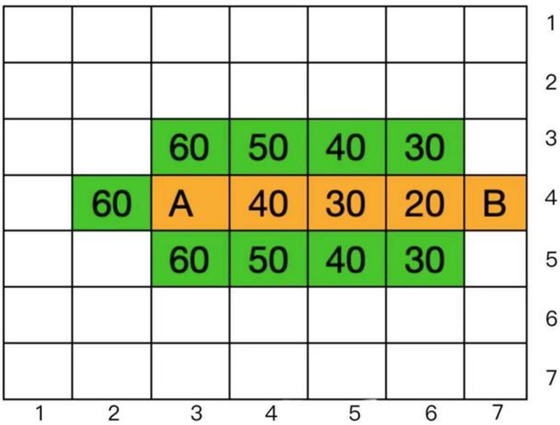

Fig. 3. The six by six two-dimensional grid map (Picture credit: Original)

The Dijkstra algorithm is an algorithm used to solve the single - source shortest path problem in a weighted directed graph. Essentially, it operates based on a greedy strategy. Each time, it selects a point that is closest to the source node from any unvisited node and finally achieves the goal of finding the shortest path [6]. Therefore, the two algorithms mentioned above are mainly used for the global path planning of welding robots. Local path planning means that during the movement of the robot, according to the real - time acquired local environmental information (such as the distance and position of obstacles detected by sensors in real - time), the movement path within a short period of time is planned and adjusted online. Compared with global path planning which focuses on finding the shortest path, local path planning focuses on enabling the welding arm of the welding robot to avoid obstacles in real - time, adapt to dynamic environments, and explore the local optimal path. Local path planning mainly relies on the artificial potential field algorithm. The artificial potential field algorithm mainly refers to regarding the three - dimensional space where the robot or moving object is located as a space filled with a virtual force field. In this space, the target point generates an attractive force on the moving object, attracting it to approach; the obstacle generates a repulsive force, preventing the object from approaching. Under the combined action of these attractive and repulsive forces, the moving object moves along the direction of the resultant force, thus planning a path that avoids obstacles and tends towards the target point. The research by Wang Qunpeng et al. shows that although the artificial potential field algorithm is a relatively traditional local path planning algorithm, it has the advantages of simple principle, easy implementation, and strong operability, so it can be widely applied in the field of robot path planning [7].

2.3 Improvement of the Path Planning Algorithm

The A* algorithm is a traditional algorithm relying on a heuristic search. This algorithm calculates and compares the total cost from any node to the target node to obtain the optimal path. Compared with other algorithms, the A* algorithm is more concise, but its limitations cannot be ignored. In practical applications, due to improper selection of the heuristic function, sub - optimal routes may occur. Specifically, the defect factors are mainly reflected in two aspects: the design defect of the heuristic function and the inaccuracy of dynamic environmental information during welding. Firstly, there is a defect in the design of the heuristic function. When applying this algorithm to welding robots, it may happen that the estimated value in the heuristic function is greater than the actual value. At this time, the welding robot will choose a route that seems better on the surface but actually has a much longer distance. As a result, when performing welding tasks, the robot may travel a lot of unnecessary distances and even take the wrong route. Secondly, the inaccuracy of dynamic environmental information during welding is also one of the causes of algorithm errors. The A* algorithm is based on simplifying the environment faced by the welding robot during task execution into a static two - dimensional map. If new obstacles appear to block the welding robot from performing tasks, this algorithm may not be able to update the information in time and will continue to plan the path based on past "outdated" information, ultimately leading to collisions with obstacles. When the welding robot performs specific welding tasks, if the above problems are not effectively solved, they will become one of the main factors contributing to errors. In addition, the Dijkstra algorithm based on graph theory is also worth mentioning. The Dijkstra algorithm describes how to start from the current set in a weighted graph and traverse all the nodes in the graph to obtain the shortest path from any node to the remaining nodes [7]. Compared with the more concise A* algorithm, a complete Dijkstra algorithm has limitations in terms of the inability to achieve lightweight storage space and high computational complexity [8]. The basic principle of the RRT algorithm is to continuously and rapidly expand a random tree until a complete and feasible path is obtained [9]. Although this algorithm is significantly faster in planning relatively simple paths when the welding robot is actually performing welding work, it still has limitations: when there are concave obstacle areas on the welding workpiece itself, the number of searches of this algorithm will increase significantly, the speed will slow down, and the path quality will deteriorate [9]. Zhang Chenwei et al. proposed integrating a dynamic weighting method on the basis of the original algorithm to reduce the number of nodes that the algorithm needs to explore, thereby reducing the possibility of sub - optimal paths and reducing algorithm errors [8]. Researchers such as Wang Pengjie pointed out that by purposefully expanding the traditional RRT algorithm, the blindness problem in node expansion of the original algorithm can be avoided, and it is expected to greatly improve search efficiency [9]. They used a mobile welding robot - Advantech industrial computer equipped with the ubuntu18.04 system, using SICK lidar and Gmapping mapping algorithm, and a two - dimensional grid map as the experimental scenario, and effectively proved that the weld - seam robot using such an improved RRT algorithm has higher stability during movement.

3 Welding Image Recognition Errors

In conclusion, after the welding robot has determined its arrival at the execution position of the specified welding task, it needs to leverage the technologies in the field of robot vision to achieve accurate identification of the weld seam position. For a welding robot, the sensor is a necessary condition for it to perform tasks correctly and precisely. The robot relies on the sensor to obtain information and then execute specific tasks. Therefore, the sensor is not only the main factor causing the manipulation errors of the welding robot but also a major indicator for measuring the precision of the robot.

3.1 The Basic Working Principle of Welding Seam Position Positioning

Currently, the related technologies of robot vision have been widely applied in aspects such as autonomous driving in the automotive field, weld seam position tracking and weld seam identification of intelligent welding robots. The whole process of the welding robot's positioning of the weld seam position can be divided into three major modules, as shown in Figure 4 below. When the robot identifies the weld seam position, just like humans, it needs to go through three major steps: image acquisition, image transmission, and image processing. Among them, there are various image processing methods for welding robots. Currently, the main methods include the TOF (Time of Flight) method, the triangulation measurement method, and the structured light method. The essence of these methods is to rely on light waves to draw point cloud images and then obtain the three-dimensional position information of the weld seam. After obtaining the position information of the weld seam, it enters the image transmission stage. In essence, this process is to convert the weld seam position information collected by the welding robot from an optical signal into an electrical signal. Finally, there is the processing of weld seam information. Researchers such as Zhang Weijie have pointed out that when the welding robot processes the weld seam information, its essence is to perform classification, that is, how to "screen out" the positions where there are weld seams from the collected images [10]. When using computer vision for defect detection, currently, the main methods include the template matching method, the Blob analysis method, and the deep learning method.

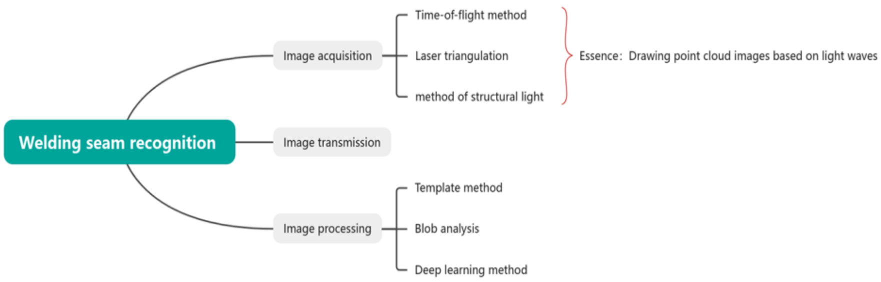

Fig. 4. : Weld identification process. (Picture credit: Original)

3.2 Analysis and Comparison of Various Industrial Cameras

Su Cimin et al. indicated that the image acquisition function of the high-precision weld seam tracking system of the robot is the basis for achieving high-precision weld seam tracking [11]. Sun Lingshuo proposed that there are mainly three technical schemes for obtaining the three-dimensional position information of the workpiece: the binocular stereo vision method, the structured light method, and the Time of Flight (TOF) method [12]. Firstly, the binocular stereo vision method adopts the parallax principle. Two imaging devices are used to collect two images of the measured target from different positions. Then, a stereo matching algorithm is used to match the corresponding points on the two images, and further, the position deviation between the corresponding points is calculated to achieve the purpose of measuring the three-dimensional point cloud data of the target object [9]. If a camera based on this principle is applied to a welding robot, due to its relatively large calculation amount and high requirements for the algorithm, the error will be amplified. The structured light method is based on the triangulation measurement principle. The projector projects light with certain structural characteristics onto the surface of the object, and a second camera is set at the other end to collect the image of the structured light on the surface of the object. When the relative position between the projector and the camera is fixed, through the triangular relationship between the image and the object, the three-dimensional point cloud data of the surface of the target object can be calculated by using the coordinates of the distorted two-dimensional light stripe image. However, the limitations of this testing method are also obvious: under the influence of a strong light environment, its measurement accuracy will decrease, especially when the measurement distance is relatively long. Finally, there is the Time of Flight method. This method utilizes the principle that the speed of light in a vacuum remains constant. A light pulse is emitted towards the observed object, and then the light pulse reflected back from the object is received. The distance between the measured object and the camera is calculated by detecting the flight time of the light pulse. Its limitation lies in the more stringent requirements for the performance of the equipment. For example, there are problems such as high energy consumption and high requirements for the accuracy of time measurement.

4 Conclusions

The generation of errors in welding robots is based on multiple factors. This paper takes the path planning of welding robots, weld seam position recognition, and sensors as the entry points, and comprehensively analyzes the errors of welding robots, filling the gap in this field. In terms of path planning algorithms, it has been clarified that the design defect of the heuristic function in the A* algorithm, as well as the situation that the Dijkstra algorithm cannot adapt to concave workpieces, are the main sources of errors. In the research on the errors of sensor-based welding position recognition, it has been determined that different types of industrial cameras are prone to be affected by error factors such as complex environments and excessive computational loads of the cameras themselves during the process of weld seam recognition. This paper analyzes the operating system errors of welding robots, which can provide a scientific basis for the optimization of the mass production process and the improvement of product quality in the industrial welding field. Based on the methods of literature search and literature analysis, this paper comprehensively and elaborately analyzes how to reduce the operating system errors generated when welding robots perform specific tasks. However, in the existing research in this field, under complex and changeable environments, the dynamic adaptability of welding robots to environmental disturbances needs to be enhanced. In addition, the research on the error coupling mechanism and the overall compensation strategy when multiple welding robots perform collaborative welding is still relatively weak.

Acknowledgements

All the authors contributed equally and their names were listed in alphabetical order.

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