Advances in Multi-robotic Welding Techniques: A Review

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***Abstract*—Robotic welding techniques are a hotspot in the field of robotic welding. It has the characteristics of good environmental adaptability, wide spatial distribution, free cooperation, better system redundancy and robustness. In this paper, the research progress of multi-robotic welding techniques are reviewed, including weld seam tracking technology, remote welding technology, off-line programming and simulation technology, multi-robot cooperative welding technology. The technical problems are pointed out and the future development trend is prospected.**

***Index Terms*—welding, weld seam tracking, remote welding, off-line programming, multi-robot welding, review**

I. Introduction

Welding is one of the most fundamental processes in manufacturing and is used to fabricate products from desks to space stations. It is also a very physically demanding and dangerous profession. The welding process generates hazardous fumes, arc flash and heat, which could cause permanent damage to the eyes and respiratory system. The current shortage of skilled labor and increasing production demands in a competitive global market has given rise to increased opportunities for robotic welding. Robotic welding has been used successfully in industry for many years.

Welding robot is an industrial robot engaged in welding work. The welding gun is mounted on the mechanical interface of the last shaft of the welding robot through the connecting flange. The welding robot is an articulated robot and most of it has 6 axes. The use of welding robots can improve labor productivity, reduce labor intensity, improve product quality stability, facilitate product differentiation, and promote the upgrading of related industries [1]-[4].

Achieving stable, high-quality, and efficient welding is the significance of applying welding robots, and is also an important topic in the field of welding robots. Since welding is a highly nonlinear and multi-variable process, it is extremely difficult to control the quality of weld formation. In order to overcome the influence of the above factors on the welding quality, the robot welding field urgently needs to adopt multi-disciplinary knowledge such as computer technology, information sensing technology and artificial intelligence to realize automatic identification and tracking of weld seams, acquisition of dynamic characteristic information of weld pool, welding parameters are adaptively adjusted to improve welding quality and welding efficiency. In order to realize high-quality and high-efficiency welding of robots, the research on welding robots at home and abroad mainly focuses on the following aspects.

II. Weld Seam Tracking Technology

Due to errors in machining and assembly, as well as weld deformation caused by uneven temperature fields, the shape and position of the weld will change. Therefore, weld seam tracking technology is used to monitor the weld state in real time during the welding process to adjust the weld. The path is critical to ensure the quality of the weld [5]-[7]. At present, the weld seam tracking technology is mainly based on sensor and control technology. In the field of welding robot, the application of sensors is developing from single sensor to multi-sensor intelligent information fusion. In terms of control, fuzzy and hybrid control methods are well applied in the research of weld seam tracking technology. The combination of them makes the weld seam tracking technology have better control characteristics such as self-adaptation and self-learning.

A. Related Work

Li *et al*. [8] considered welding seam localization problem as visual target tracking and proposed a robust welding seam tracking algorithm. The weld seam tracking system is shown in Fig. 1. Prior to the beginning of welding, the seam is separated using a cumulative gray frequency, which is utilized to adaptively determine the initial position and size of the search window. Secondly, they propose a sequence gravity method for extracting a smoother center line of welding seam, which is able to reduce the impact of influence on the accuracy of feature point localization due to the intersection of seam and noise. Then, in order to improve the real-time performance and accuracy of the system, they use the double-threshold recursive least square method to fit the curve obtained by sequence gravity method. Finally, compared with other solutions for seam tracking and recognition through extensive experiments, the superiority of the propose algorithm is well demonstrated.

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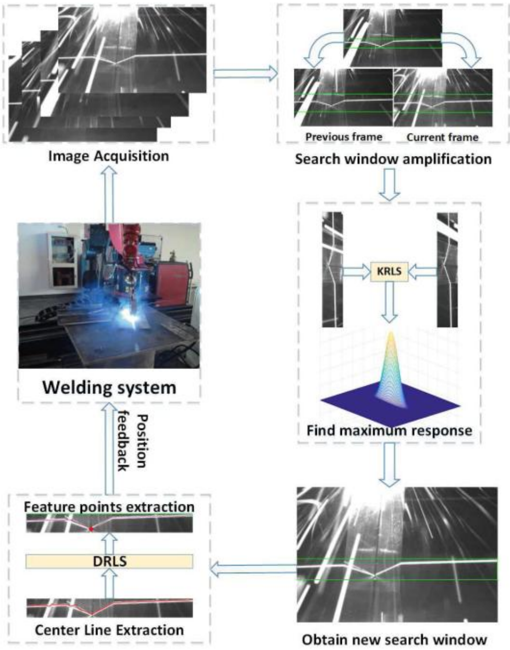

Figure 1. Illustration of the welding seam-tracking system [8].

Gu *et al*. [9] proposed the weld deviation recognition of a new type of deep penetration TIG welding. The principle is shown in Fig. 2. Firstly, they use a bilateral filter to remove the noises, and preserve the edge of the region of interest of images obtained by a high dynamic range CCD. Secondly, the improved Otsu algorithm is used to obtain accurate welding arc shape, weld pool and weld characteristics. Then, they propose canny algorithm to obtain a complete edge contour. Finally, the pixel coordinates of the midpoint of the weld and the arc center line are obtained using maximum curvature algorithm and parabolic, respectively. The experimental results show that the proposed algorithm can accurately obtain the welding seam coordinates and the deviation of the arc center line, which can meet the accuracy requirements of robotic welding, and realize the real-time correction function of the welding robot.

Figure 2. Principle of deep penetration TIG welding [9].

Gao *et al*. [10] proposed the predictive fuzzy control method for the curved weld seam tracking problem of wheeled welding mobile robot used in shipbuilding and large spherical tank welding. The main advantages of this predictive fuzzy controller include small tracking error and the availability of a linearized predictive model which reduces the computing complexity and improves the tracking quality. The experiment results demonstrate that the feasibility and advantages of this predictive fuzzy control on the curve weld seam tracking.

Hu *et al*. [11] analyzed the arc sensing system and obtained the information of seam deviation by characteristic harmonics method. Then, they designed a fuzzy controller to simulate and test, the results show that the control system can achieve seam tracking.

Mao *et al*. [12] presented a new welding robot system which based on rotating arc sensor as the seam tracking sensor. In this paper, they establish the kinematic model of system and design the parameter self-tuning fuzzy controller. Finally, the experimental results show that the robot system can achieve automatic large fillet welding seam tracking in narrow spaces.

Fan *et al*. [13] developed a welding control system for automatic pulsed gas tungsten arc welding of aluminum alloy with root pass. During welding, an image of the weld pool and its vicinity is captured when basic current of welding power. Then, the top-front side part image is processed to get gap size and welding direction for adjusting welding condition and seam tracking.

Zou *et al*. [14] studied a weld pool image processing algorithm based passive-light-vision. The experiment and analysis have illustrated that wavelet transform can effectively filter out the image noise, maintain the details of the image and prevent the boundaries blurred. This algorithm can be used in the seam tracking of welding robot.

Li *et al*. [15] proposed robust automatic welding seam identification and tracking method by utilizing structured-light vision. In this paper, the characters strings acquire from the object image are matched with those from the model, so that the position of the welding seam can be determined. Finally, the advantages of the new algorithm are testified and compared through several experiments.

Gao *et al*. [16] presented a novel method of detection of weld and seam tracking during gas tungsten arc welding. The effectiveness of the proposed algorithm in the presence of weld pool image noise has been tested by the computer simulations and actual welding experiments. Also, the results of experiments have demonstrated the robustness of weld position detection for seam tracking.

B. Summary

According to the above literature, great progress has been made in the research of welding seam tracking technology. Its future development trend is to adopt advanced technology, so that the system can obtain more useful information for tracking processing to increase the intelligence of the system. However, the seam tracking system based on image processing is difficult to process because of the large amount of image data, and there are many work to be completed. How to choose the most simple and refined algorithm to get high quality effect is an urgent problem we need to study.

III. REMOTE WELDING TECHNOLOGY

With the development of economy and science, the scope of welding operations is extending to the nuclear environment, underground, space, deep water, high temperature, extreme cold and other extreme environments. Under the condition of guaranteeing the welding quality, to maximize the comfort of human activities and reduce the danger of human activities is one of the development trends of welding robots nowadays. The emergence of remote welding technology effectively solves the above problems [17]-[20].

A. Related Work

Li *et al*. [21] presented supervisory control concept of telerobotic system for remote welding in unstructured environment (Fig. 3). Firstly, they present and implement three supervisory control strategies, which are namely laser vision sensing based teleteaching, graphics simulation based plan and control, and local autonomous control. Secondly, they integrate the three control modes into a multi-modal human-machine interface, which are effectively interacting with the human-machine interface. Finally, the experiments demonstrate that the three supervisory control modes improve the performance of arc welding telerobotic system, which are flexible enough to perform remote welding task in unstructured environment.

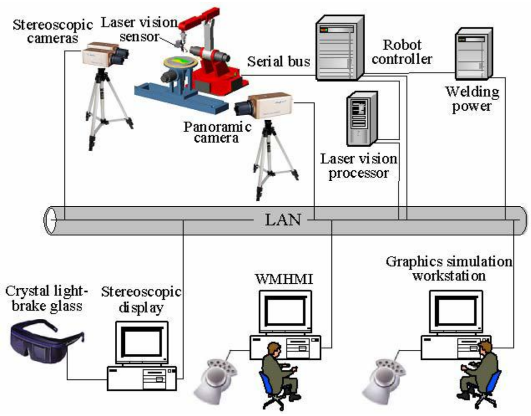

Figure 3. Hardware architecture of the arc welding telerobotic [21].

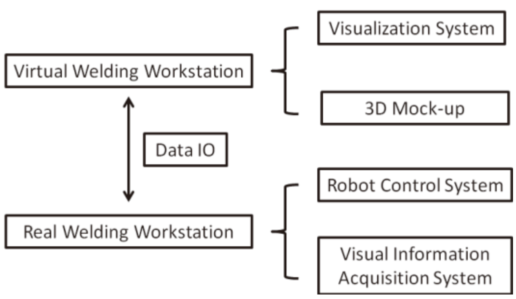

Figure 4. General structure of virtualized welding system [22].

Fu *et al*. [22] presented a novel hybrid reality system for tele-operated weld monitoring (Fig. 4). Firstly, they use 3D scanning techniques to create a digital model of objects to be welded. Secondly, a mock-up is constructed form a set of templates or 3D printed based on the model. Then, the welding process is captured by cameras and visualized on the 3D mock-up using projects. Therefore, the welder can monitor the welding process as if the welding is on the mock-up with proper spatial and 3D cues. Finally, user studies show that their HRD has reduced the mental workload and is preferred by welders.

Hiroi *et al*. [23] proposed a remote welding robot manipulation system by using multi-view images (Fig. 5). After the operator specifies a two-dimensional path on the images, the system transforms it into three-dimensional path and displays the movement of the robot by overlaying graphics with images. The accuracy of their system is enough to weld objects by combining with the touch sensor.

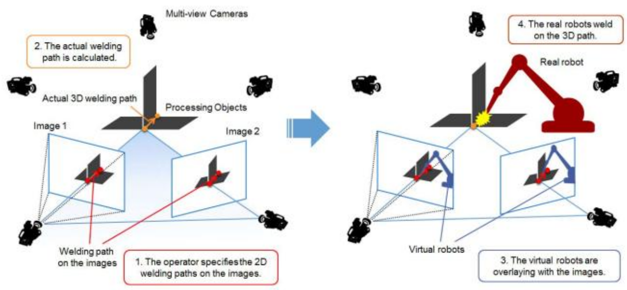

Figure 5. System overview [23].

Xi *et al*. [24] studied the image matching algorithm in remote welding. In this paper, they design the experiment and match the two-dimensional image of the welding target. It can be seen from the experimental results that the system can extract a relatively large number of feature points and provide corresponding image technology for the remote welding robot.

Zhang *et al*. [25] designed and implemented a remote monitoring system for welding machines based on B/S mode. This system realizes data acquisition and transmission by single-chip microcomputer system. The experiments show that the system can meet the need of the remote monitoring, and has a certain practical values.

Sun *et al*. [26] performed the Remote Welding Robot System (RWRS) experiment. The operator uses space ball to manipulate the robot in remote site approaching the welding seam by means of the stereo view and graphical simulation system. The experimental and simulative results show that the RWRS is high efficient, valuable and successful.

Liu *et al*. [27] brought forward human-simulation intelligent control strategy based on the force guiding by analyzing force error target track on the foundation of the PID control model. The experimental results show that the control process is characterized by relatively simple algorithm and fast computation compared with the PID control. It is more suitable for the on-line detecting and compensating the remote welding teleteaching.

Kim *et al*. [28] implemented the robot-based remote welding and investigated the welding characteristics. In this paper, the scanner-integrated system and the robot-based system are available to implement laser remote welding.

Tsoukantas *et al*. [29] developed and discussed a theoretical approach of the remote welding process. The study obtains numerically the melting boundaries of different heat source angles, based on an analytical calculation of the keyhole depth. Finally, the theoretical results present good agreement when compared with experimental data obtained from a remote welding system on lap welding of AISI 304 stainless steel, thin sheets.

Hatwig *et al*. [30] described advantages and challenges of remote laser beam weldingg. This leads to the highest quality welding seams and cutting edges by using task oriented programming the parameters of the process.

B. Summary

According to the above literature, the experts have mainly researched the modeling and calibration techniques of virtual environment in the field of remote welding technology, and achieved great progress in the research of it.

IV. Off-line Programming and Simulation Technology

At present, the welding programming method used in the field of robot welding production is mainly teaching programming, which has certain safety risks for programmers and welding robots. At the same time, the manufacturing of welding products is developing towards flexible manufacturing with multi-variety, small-volume and complicated flexible manufacturing. The welding programming workspace extends to extreme environments such as space, deep water and nuclear environment. These factors are not conductive to the implementation of teaching programming. The realization of off-line programming and simulation technology can effectively solve the above problems. Compared with on-line teaching programming, the off-line programming system can reduce robot downtime and improve the operator's programming environment.

A. Related Work

Shen *et al*. [31] developed a 3D visual off-line programming system of six degree of freedom robot based on the secondary development function of the 3D software UG (Fig. 6). With C++ programming language, the function and development tools provided by UG/OPEN, it realizes the function of system modeling, motion simulation, path planning, off-line programming, state monitoring and so on. The system is able to meet the off-line programming requirements for the six degree of freedom robot in vehicle door welding process.

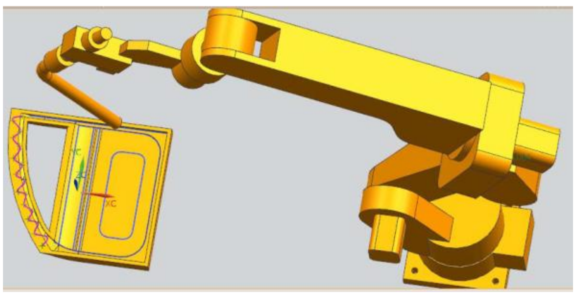

Figure 6. The motion simulation of welding robot [31].

Bruccoleri *et al*. [32] proposed an off-line programming approach for welding robots. The approach is based on the integration of a software tool for robot simulation and a user–friendly interface for automatic generation of the control program. The user can graphically arrange the components in a robotic work-cell and simulate the movements and operating sequences in controller-specific tasks (Fig. 7). This methodology guarantees high level of flexibility of the robotic system when high variety of work-pieces needs to be welded. The approach has been implemented and tested in a real welding work-cell.

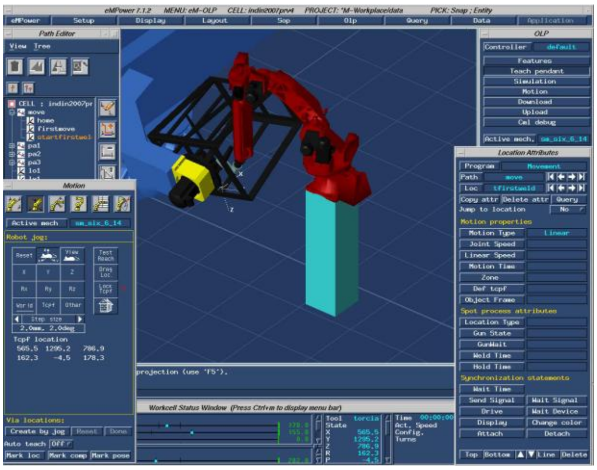

Figure 7. Using OLP to acquire paths and positions for workcell [32].

Kim *et al*. [33] proposed a PC-based off-line programming method for welding robots in shipbuilding. In this paper, they explain the methodology of 3D simulations for new type robotic OLP system. The strength of the developed OLP system lies in its flexibility in handling the changes in the robot's target objects. In addition, the operator can generate robot programs very easily and quickly by using of the developed OLP system.

Konukseven *et al*. [34] designed and implemented man machine interface software for the ABB industrial robot. The main aim of this software is to provide features which would facilitate on-line/off-line programming of the robot. The software provides a three dimensional graphical simulation of the robot and its environment, which also allows loading custom designed objects into the simulated environment.

Berger *et al*. [35] proposed an approach based on a programming tool. It is used to enable the automatic generation of robot trajectory paths from different free forming surfaces of existing 3D-CAD models by means of the linear and circular interpolation.

Wang *et al*. [36] proposed a study of the interference simulation based on robot welding of the radar pedestal by using the KUKA Sim Pro simulation software and off-line program technology. It is helpful to use the simulation method to guide the actual robot welding so as to protect robot from impacting and reduce the weld defects.

Chen *et al*. [37] developed the off-line programming system for MOTOMAN-UP series robots by using Visual C++ and OpenGL. In this paper, they describe the composition and function of the system and its design method. It can plan the motion path and posture of welding gun for any saddle-shape weld, and display the workpiece on the interface synchronically in proportion. Finally, the test results show that the system is feasible.

Liu *et al*. [38] developed a universal off-line programming system of arc welding robot station to replace the previous way of teaching and replaying the robot. It is composed of seven modules, being able to build the 3D feature-based model of weld workpiece, recognize and convert the geometric and technical information of welding seams, plan the welding process, load the workpiece onto robot simulation circumstance and simulate the processes of executing welding operations.

Zhang *et al*. [39] developed the software based on the programming platform SolidWorks API. The main function of this software is planning the posture of characteristic coordinate frame of weld. Combined with the inverse kinematic resolution of robot and automatic posture planning, all joint rotating angles can be obtained. The results could be sent in COSMOS Motion a plug-in package of SolidWorks and be used in the simulations of robot welding.

B. Summary

According to the above literature, the experts are very mature in the research of off-line programming and simulation technology. In foreign countries, the welding off-line programming software has the disadvantages of high price and unopen source code. On the contrary, it developed in China relies heavily on SolidWorks, UG and other three-dimensional software, which takes a lot of time and high cost to run in practice.

V. MULTI-ROBOT COOPERATED WELDING TECHNOLOGY

Because the robustness of a single welding robot can hardly be improved to a certain level, which forces some welding tasks to be completed by the cooperation of multiple welding robots, so the research on path planning of multi-robot cooperative welding is very important. Multiple welding robots cooperate with each other to complete the welding task that can't be achieved by a single welding robot. In addition, the configuration requirements are higher if the complex welding task is completed by a single welding robot, and the requirements of each welding robot in the multi-welding robot system are lower if the complex work is decomposed into two or more welding robots with simple functions [40], [41].

A. Related Work

Zhou *et al*. [42] studied the cooperated welding trajectory planning problem of multi-robot system without gripper tools. In this paper, they propose a multi-robot cooperated trajectory planning approach based on the closed kinematic chain model by taking a master-slave dual robots cooperated welding system as the research object. Firstly, they analyze the orientation and position constraints between weld seams and the welding gun. Secondly, they create a general closed kinematic chain of multi-robot welding workstation based on the coupled optimization principle of multi-robot cooperative motion with ship welding. Then, they establish the corresponding cooperative motion models, which are applied to plate-to-plate (Fig. 8), tube-to-plate, and tube-to-tube welding scenarios of cooperated dual-robot welding systems. Finally, the simulations results show the effectiveness and feasibility of the method.

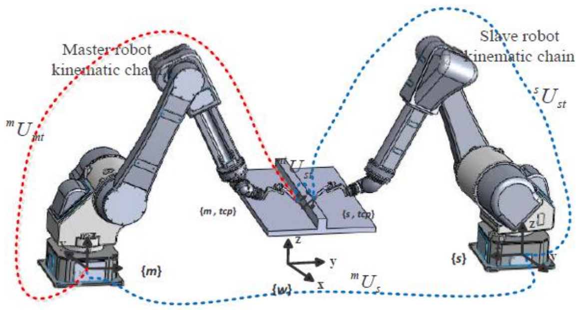

Figure 8. Plate-to-plate welding case [42].

Yahui *et al*. [43] explored the kinematic relations between cooperated robots both in couple motion and overlay motion. In this paper, they firstly propose a new trajectory teaching method based on conclusions of the analysis in kinematic cooperation relation (Fig. 9). Then, they use a Matlab Robotic Toolbox to carry out numerical simulations involved two Puma560 robots. Finally, the simulation results demonstrate that conclusions of the kinematic cooperation analysis are correct and the proposed trajectory teaching method is effective to solve the problem of trajectory teaching for multiple robots cooperation system.

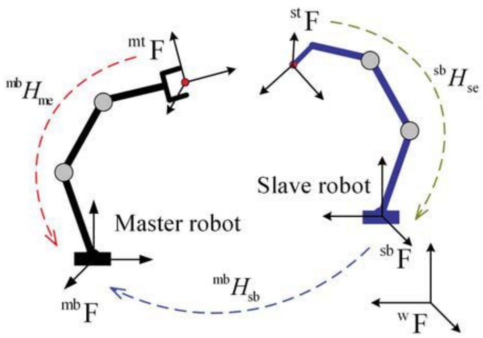

Figure 9. Schematic diagram of two robots cooperation system for welding [43].

Zhang *et al*. [44] proposed the two-robot welding coordination of complex curve seam which means one robot grasp the workpiece, the other hold the torch, the two robots work on the same workpiece simultaneously. Firstly, they build the dual-robot coordinate system (Fig. 10) and present three point calibration method of two robot's relative base coordinate system. Secondly, they choose the non-master/slave scheme for the motion planning. Then, down hand welding is employed which can guarantee the torch and the seam keep in good contact condition all the time during the welding. Finally, the simulation results demonstrate that the welding process can meet the requirements of down hand welding.

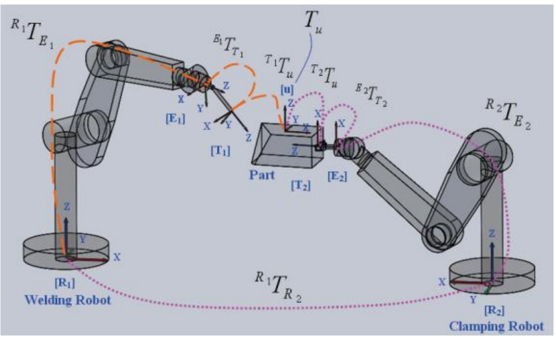

Figure 10. Dual-robot coordinates system [44].

Wu *et al*. [45] considered the problem of coordinating multiple motion devices for welding. They focus on the problem of coordinating a three-axis positioning table and a six-axis manipulator. Their approach to the coordination problem is based on a subdivision of tasks and their method of redundancy coordination is superior to pseudo-inverse techniques, for it is more global and accurate.

Meng *et al*. [46] analyzed the trajectory constraint relation of the cooperative robots and proposed a practicable teaching method based on the relative motion between the pose of cooperated multi-robot end-effectors, the trajectory constraint relation of the cooperative robots. Finally, two-robot cooperation system for welding is set up, using which the constraint relation is testified and the teaching method proposed is validated.

Yang *et al*. [47] surveyed on modeling and controlling of welding robot system based on multi-agent. It describes the ways of modeling based on BDI theory and Petri net, then the communication ways, middleware technologies and the cooperation methods are discussed respectively in the part of controlling.

Zhao *et al*. [48] put forward completely construction levels of communication system, and gave effective solution to solve the communicating problem of cooperated multi-robot's work.

Zhai *et al*. [49] proposed a trajectory optimization method of two cooperative welding robot arms. An experiment is set up to compare the welding trajectory of the optimal start point with those of other feasible points. With analysis in each joint's average angular velocity, the volatility and peak of the angular velocity and total welding time, it is verified effective for the trajectory optimization method.

Gan *et al*. [50] investigated the problem of how to emulate a manual welding process by two cooperative robotic manipulators. Mathematic model of trajectory planning for two cooperative robots doing a welding task is in a constrained optimization form. A Genetic Algorithm solve has been adopted to solve such an optimization problem. Pipe-connect-pipe welding experiment has been carried out at the end of the paper and the weld results verified the effectiveness of their method.

B. Summary

According to the above literature, scholars at home and abroad have studied the multi-robot cooperated welding technology more mature. Most of them used intelligent algorithm to solve the path planning problem of it.

VI. Conclusion and Discussion

As an important symbol of the development of manufacturing industry, welding robot technology will occupy a high position in the current and future industrial development. In recent years, many experts and scholars have studied welding robots in weld seam tracking technology, remote welding technology, off-line programming and simulation technology, and multi-robot cooperative welding technology. However, there are still some technical problems and theoretical limitations, especially the visual control technology, virtual reality technology and intelligent cooperative control technology of welding robot will be the main research direction in the future. With the continuous development of these technologies, welding robots will enter a new stage of development.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Jie Xu, Gong Zhang conducted the research and wrote the paper, the others analyzed the data; and all authors had approved the final version.

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