Design and Coordinated Motion Control of a Welding Robot for Large Scale Workpieces

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Abstract. In order to meet the demands of the welding of large scaled workpieces, a welding robot is designed with 9 motion joints and 6 degrees of freedom. Two groups of macro and micro motion mechanisms are adopted for large travel and high positioning precision. The welding trajectory is taught grossly in Cartesian space, and the motion of joints is planned in joint space with the kinematics model of the welding robot. A method of motion control of macro and micro joints is presented for stability and precision in seam tracking. Experimental results verified the effectiveness of the mechanisms of welding robot and the control system.

Keywords: Welding robot, Motion control, Visual servo, Welding automation.

1 Introduction

The devices and intelligent technology for weld of large scale workpieces are widely applied in mechanical manufacturing industry, especially in pressure vessel and pipe construction. Nowadays the devices commonly used in weld industry include welding manipulators, rollers, positioning machines, tumbling machine, special welding machine and welding robot station, etc. For large workpieces welding, the devices are commonly in gantry structure or based on walking mechanisms, combining with other auxiliary mechanisms. As to welding technology, auto submerged arc welding widely adopted for large workpieces weld for its high productivity and quality. With the development of equipment manufacturing and control technology, welding devices feature in mechanism maximization and precision[1]. There are some significant trends that more and more application of welding robot with high precision and reliability, and the application of digital intelligent control technology for advanced control system for extreme manufacturing.

Although more and more welding robots and advanced control technology have been introduced to weld industry, there are still some challenges for the welding of large scale workpieces in mechanism and control, which include the large workspace of the robot with high positioning precision, the open robot controller, coordinated motion control of multi-axis, and macro- micro motion control.

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Firstly, the mechanisms of welding manipulators commonly structured gantry[3] and walking mechanisms[4] for large scaled workpieces welding. A specific mechanisms was presented for boiler pipes welding[5]. In the process of the workpieces welding, the mechanisms with long travel and high precision are needed for the weld seam. That improves the cost of the welding equipments, so the applications of automatic welding are limited, especially for the small enterprises of weld manufacturing. Secondly, the controller of welding robot used to be designed for specific equipments, thus it is difficult to meet the need of generality and openness of controller. Xu designed a real time open robot controller for a standard industrial welding robot system SIASUN-GRC[6], and the general robot controller for welding manipulators should be studied further. Compared to precisely teaching and offline programming[7], it is convenient to online tracking control base on few grossly teaching points. Then the third issue is the coordinated motion control of macro and micro mechanisms for the stablity and precision in process of seam tracking.

The remainder of this paper is organized as follows. Firstly, the structure of mechanisms of welding robot is introduced in Section 2, and the kinematics model of the robot is calcuted. Then, the system functions and control architecture are discribed in Section 3. In Section 4, the method of teaching and planning of the motion of the robot is developed, and the motion control for the coordination of macro and micro mechanisms is given. Experiments of seam tracking are conducted to verify the effectiveness of the mechanisms of welding robot and the control system in section 5. Finally, the paper is concluded in Section 6.

2 Mechanism Design and Kinematics Model

The overall welding robot system is composed of the robot body, welding system, a host computer, a console, motion control and driving device, and vision sensors mounted on the welding torch for monitoring, etc.

2.1 Mechanism Design

A robot is designed with 9 joints and 6 degree of freedom for large scaled workpieces welding. The prototype structure of welding robot is shown in figure 1. The robot is structured in gantry. In order to enlarge workplace of the robot, there are two groups of orthogonal translational mechanisms with 6 translational joints for positioning. Thus the macro and micro motion mechanisms are composed of redundant joints in same directions. One group of macro joints can move with large travel, and the other group micro joints can position with high precision. In the process of multi-axis motion of the welding robot, the micro joints can compensate positioning precision by intelligent sensing and control. Furthermore, three rotational joints are installed on the gantry structure of translational joints to adjust the pose of the weld torch. Welding equipments are integrated with the gantry and joints of the robot.

The travel and resolve of the joints of welding robot are shown in Table 1. The 3 joints of macro mechanisms provide large travel with low resolution of 1mm. Correspondingly, the 3 joints of micro mechanisms provide small travel with higher resolves of 0.01mm.

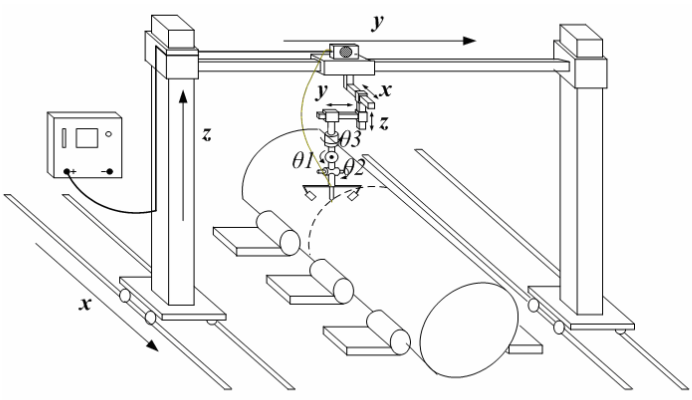

Fig. 1. The prototype structure of welding robot

Table 1. The travel and resolution of the joints of welding robot

	Travel	Resolution
X	3000mm	1mm
Y	1000mm	1mm
Z	1200mm	1mm
x	200mm	0.01mm
y	200mm	0.01mm
z	100mm	0.01mm
α	120°	0.05°
β	120°	0.05°
γ	180°	0.05°

2.2 Kinematics Model

The definition of the coordinates frame of welding robot is shown in Figure 1. The origin point of the coordinates of world frame is defined as the intersections of the two axes of roll and yaw rotational joints when every joint is at zero position. Then the transformation matrix for the robot is as (1):

$$ {}^{0}T_{6} = \begin{bmatrix} c2s3 & c2c3 & -s2 & a_2c2c3 - a_3s2 + a_1s2 + x \\ -s1s2s3 - c1c3 & -s1s2c3 + c1s3 & -s1c2 & a_2(c1s3 - s1s2c3) + (a_1 - a_3)s1c2 + y \\ c1s2s3 - s1c3 & c1s2c3 + s1s3 & c1c2 & a_2(c1s2c3 + s1s3) + a_3c1c2 - a_1c1c2 + z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

where ci is the abbreviation for $cos\theta_i$, and si for $sin\theta_i$; x, y and z are the variables of translational joints, and θ_1, θ_2, and θ_3 are the angles of 3 rotational joints; a_1, a_2, a_3 are the parameters of the 3 rotational joints.

The inverse kinematics model of the welding robot can be deduced by formula (1). The variables of translational and rotational joints θ_1, θ_2, θ_3, x, y and z can be calculated as follows.

$$\theta_1 = -\arcsin\left(\frac{a_y}{\cos\theta_2}\right) \tag{2}$$

$$\theta_2 = -\arcsin a_x \tag{3}$$

$$\theta_3 = \arcsin\left(\frac{n_x}{\cos\theta_2}\right) \tag{4}$$

$$x = p_x - a_2 c2c3 + a_3 s2 - a_1 s2 \tag{5}$$

$$y = p_y - a_2(c1s3 - s1s2c3) - (a_1 - a_3)s1c2 \tag{6}$$

$$z = p_z - a_2(c1s2c3 + s1s3) - a_3 c1c2 + a_1 c1c2 \tag{7}$$

Note that the variables of micro translational joint are redundant to macro ones, so they need not be calculated in the inverse kinematics of the robot.

3 System Functions and Control Architecture

The welding robot provides positioning and motion of weld torch to meet the demands in process of welding, which are implemented by corresponding function modules and control system.

3.1 System Functions

There are some system functions for the welding process, which include teaching, planning, multi-axis linkage, motion control, monitoring, human-compute interface, and manual manipulation function.

a) Teaching function. Precisely teaching for complicated weld seam of workpieces is a tedious work either online manipulating or offline programming. It is convenient to teach few points grossly to obtain approximate track of seam for automatic manufacturing in weld industry. Therefore, the grossly teaching mode is adopted for the welding robot to sample weld seam. For example, it is sufficient to teach only two or three points; for complicated weld seam for simple beeline seam; for girth weld seam of pipe, the parameters of the girth seam (e.g. circle or ellipse), or the boundaries are needed.

b) Multi-axis linkage. As the external axis of welding robot, some auxiliary mechanism such as rollers or positioning machines will be controlled for multi-axis linkage. The motion and velocity of the external axis are sampled and controlled to estimate the position and pose of workpieces, and the amount of feed of weld torch can be calculated with relative position and pose between weld seam and the weld torch.

c) Motion control. Coordinated motion control of the macro and micro mechanisms is realized by intelligent algorithms in this function, which will be discussed in the next section.

d) Monitoring and human-compute interface. A stereo cameras and structured light vision sensor are mounted on the end-effector of the robot. The position of weld seam can be visually measured by the structured light vision sensor for seam tracking in process of weld; the relative pose of wed torch and workpieces is inspected by the stereo cameras for the alignment of the torch. The images of workplace are shown on the console in real time, and the results of image process and features extraction are shown to monitor the status of weld. The welding parameters and the welding devices can be managed in the function module.

e) Manual manipulation. The pose and position of the weld torch can be adjusted by manual control with 6 translational joints and 3 rotational ones. By manual function, the torch and vision senor can reach desirable pose, and the torch are moved near the initial weld position. Manual function is also needed when debugging and maintenance of devices.

3.2 Control Architecture

Control system of welding robot is designed with multi layers, which include the interactive and intelligent layer, motion planning layer, motion control and servo control layer. The Control architecture of welding robot is shown in Figure 2. Concretely, an industrial PC is employed for the host computer; two motion control cards plan the multi-axis linkage; servo drivers and servo motors with the rotary encoders comprise driving control units. The functions of top two layers are implemented by the host computer, and bottom two layers are implemented by the motion control cards, the servo drivers and the motors.

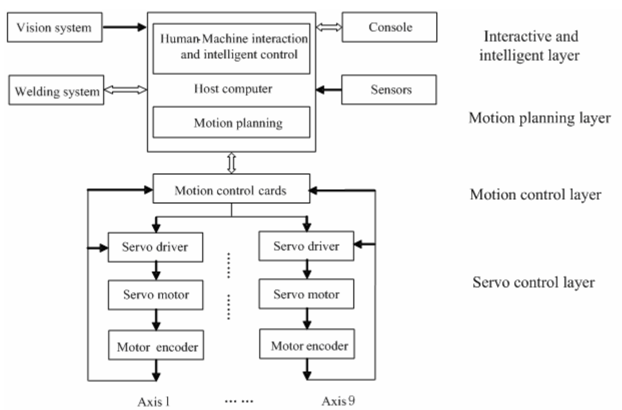

Fig. 2. Architecture of Control System

The top layer is interactive and intelligent layer, which provides the management functions, including human-machine interaction, task planning, control of welding system, the signal processing of field sensors and vision sensors, monitoring and intelligent control. In the layer, the welding system is started or closed via the communication interface of the host computer, teaching task is accomplished, and the control variables of weld torch are calculated by intelligent algorithms.

The second layer is motion planning. According to the control variables or the desirable pose of weld torch given by top layer, the motion of the weld torch are planned in Cartesian space, and the variables of the joints are calculated in joint space by inverse kinematics of the welding robot.

Given variables of the joints in motion planning layer, the analog signal output is calculated in the motion control layer, with the feed back of the encoder of the motors. The close loop control is implemented by the motion control cards for multi-axis linkage. The commands of motion control are buffed in motion planning layer, and the synchronization and coordination of translational joints and rotational ones is also realized in the layer.

The bottom layer is for servo control. The velocities of the motors are controlled by the servo drivers with the feed back of the encoder signals of the joints.

4 Motion Planning and Control

4.1 Teaching and Planning

According to the teaching sample points of welding robot and the prior knowledge of seam groove, the trajectory of weld seam is generated with B-spline or high degree polynomial. The pose and position of welding torch are planned in Cartesian space. Then the joint motion is planned in joint space with inverse kinematics for solution of joint coordinates. As shown in figure 3.

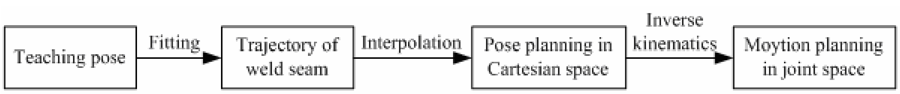

Fig. 3. Teaching and motion planning of the welding robot

4.2 Motion Control of Macro and Micro Mechanisms

The motion control of macro and micro mechanisms aim at large workplace, high accuracy and stability for seam tracking. In the process of planning motion, the joints with macro motion provide main motion trajectory, and the motion of micro mechanisms compensates the accuracy of positioning. Concretely, the motion of macro mechanism is given by teaching path, and micro motion is automatically adjusted by intelligent algorithms with vision sensing information. Furthermore, since the travel of micro mechanism is small, the two groups of translational joints are linked in synchronization to ensure the smoothing trajectory of the welding torch, when the micro mechanisms are limited. According to the position of the micro mechanisms, the expected offset of the macro mechanisms is calculated, which is implemented by the coordination module of motion control. The motion of macro mechanisms is introduced to the motion control as feed forward signal for the motion stability and the coordination of two groups of joints in the process of seam tracking. The control block diagram of welding robot is shown in figure 4.

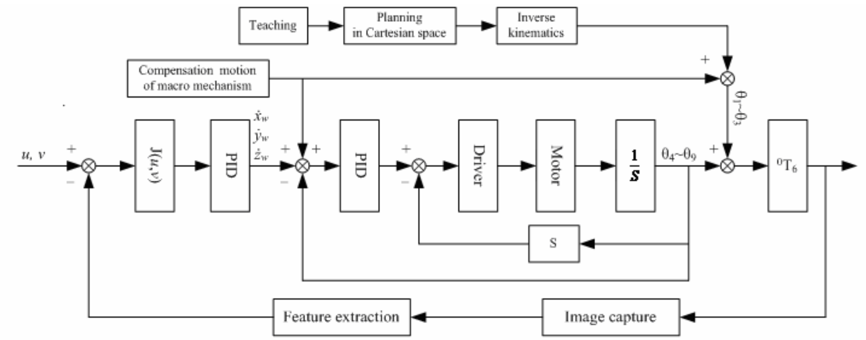

Fig. 4. Control block diagram of welding robot

5 Experimental Results

According to the design of the welding robot, a prototype of the welding robot was manufactured with 9 joints and 6 degree of freedom. The mechanism of the robot is shown as in figure 5, composed of the joints, servo motors, the sensors and welding equipments.

The experiments of teaching and the motion control of seam tracking were conducted with the designed mechanisms of the welding robot and the motion control system. A workpiece with preprocessed S-shaped weld groove was employed for seam tracking. There are two experiments conducted for comparison. Firstly, the motion of weld torch was taught with 20 points, and the trajectory of welding torch was generated with B-spline. Then using the same workpiece, the motion of weld torch was taught grossly with 4 points, and the trajectory was generated with linear interpolation in Zigzag weld groove. The seam tracking control and the coordinated control of macro and micro mechanisms were investigated in two cases.

The Motion of macro and micro mechanisms in the first experiment is shown in figure 6, and the tracking error is shown in figure 7; the unit of the coordinates is mm.

Fig. 5. The mechanisms of welding robot

In the process of seam tracking control, the two groups of joints move in synchronization, and micro joints provide the motion compensation in high precision. As a result, the error of tracking is less than 1mm, and the average error is less 0.5mm.

In the second experiment, although the welding seam trajectory was taught grossly, the desirable results of seam tracking control were still obtained. As shown in figure 8 and figure 9, the weld groove was repeated precisely, and the average error is less 0.5mm. The twice experimental results verify the effectiveness of the mechanisms of welding robot and the motion control with synchronization and coordination.

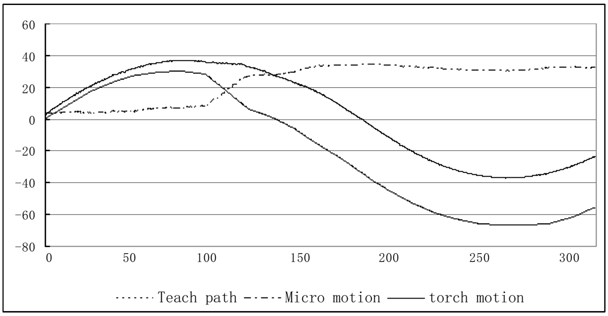

Fig. 6. Motion of macro and micro mechanisms in the first experiment

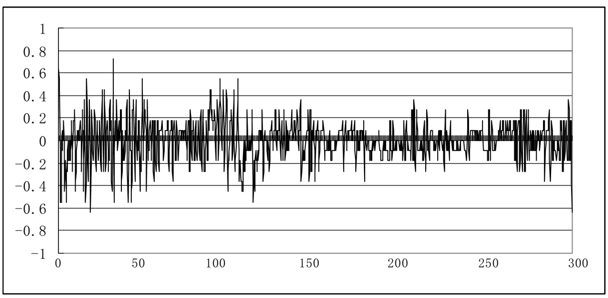

Fig. 7. The tracking error of weld torch in the first experiment

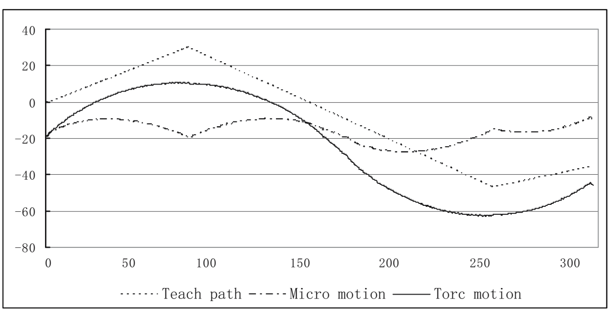

Fig. 8. Motion of macro and micro mechanisms in the second experiment

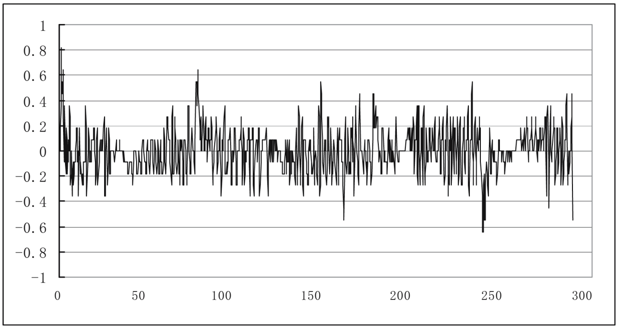

Fig. 9. The tracking error of weld torch in the second experiment

6 Conclusions

In this paper, a welding robot was designed for large scaled workpieces. The two groups of macro and micro translational mechanisms provide large travel with high positioning precision for weld manipulation. The given welding trajectory can be grossly taught and planned in Cartesian space, and then the variables of the joints are planned in joint space via the inverse kinematics of the welding robot. The motion control of micro and macro joints is presented, by which the precision was compensated by the visual servo of micro joints based on feed back of visual sensing. The performance of seam tracking control of the welding robot is robust to the teaching trajectory in advance. Experimental results verified the effectiveness of the mechanisms of welding robot and the control system.

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