A robot off-line programming system for welding intersecting pipe

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Abstract. In order to meet the requirements of welding intersecting line welds, an off-line programming system is designed. The off-line programming system is developed with SolidWorks API functions, includes kinematics analysis, trajectory planning, off-line simulation and other modules. The system is applied to an ABB welding robot with six revolute joints. The welding experiment of the robot cylindrical intersecting pipe is carried out, and the experimental results verify the system.

1. Introduction

In the actual processing, the welding technology is called the industrial "tailor". Manual welding can be flexibly used in various occasions, but it can not guarantee stable welding quality and takes a long time. Therefore, robot welding as a new mode of welding technology development, it avoids the disadvantages of manual welding, more to meet the needs of the production.

The control system of welding robot can be divided into teaching programming and off-line programming[1]. Instructional programming refers to that workers manually operate the robot instructional device, drive the welding tool to reach each welding point of the workpiece in turn according to a certain trajectory, adjust the position and attitude of the robot, and manually carry out welding through the instructions recorded by the instructional device. Instructional programming robot welding production is very common. In some pressure vessels and petrochemical pipeline engineering, tube-pipe, ball-pipe and other intersecting line welds are the common typical welding forms[2]. These spatial welding curves have high welding strength, so it is difficult to ensure welding quality and efficiency by using instructional programming. In contrast, the off-line programming system can carry out off-line simulation before actual welding, and can carry out more accurate trajectory planning, saving production time and improving work efficiency.

The research of off-line programming technology started in the 1970s, and some countries, led by the United States, Japan and Germany, have carried out preliminary research on the development of off-line programming system. For example, AutoWeld system[3] of the university of Webster in Canada, WRAPS system[4] of loughborough university in Britain, IGRIP system[5] of Dened Robotics...
company in the USA and so on. However, these systems are not perfect in motion planning, collision detection and parameter setting, so they are not put into commercial use on a large scale. With the development of commercialization of industrial robots, some robot manufacturers have developed specialized off-line programming systems, such as ABB’s RobotStudio system and Motoman’s MotoSim system. But these systems are expensive and designed only for their own robots.

In order to meet the requirements of welding intersecting line welds, an off-line programming system which can automatically output robot welding program is designed. The off-line programming of robot using CAD system is a hotspot in recent years. Therefore, this system takes SolidWorks2017 as the platform, aims at ABB IRB1410 type 6-dof arc welding robot, uses the API interface of SolidWorks to complete the development of off-line programming system for robot, and realizes kinematics analysis, trajectory planning, off-line simulation and other functions.

2. Robot CAD modeling
The off-line programming system in this paper carries out three-dimensional CAD modeling based on SolidWorks, and uses DH coordinate system[6] to analyze the structure of ABB IRB1410 robot, which mechanical structure is shown in Fig 1.

![Figure 1. Mechanical structure of ABB IRB1410 robot](image)

According to this coordinate system, the connecting rod parameters are shown in Table 1.

| Link | ai  | αi | di  | θi  | θi range  |
|------|-----|----|-----|-----|-----------|
| 1    | 150 | -90| 475 | θ1  | -170~170  |
| 2    | 600 | 0  | 0   | θ2 (-90) | -65~70    |
| 3    | 120 | -90| 0   | θ3  | -65~70    |
| 4    | 0   | -90| 720 | θ4 (+180) | -150~150  |
| 5    | 0   | 90 | 0   | θ5  | -115~115  |

Robot modeling in SolidWorks requires multiple steps. First of all, draw the sketch, according to the size of the specific parts of the drawing in detail. Then, according to the sketch of the parts, the feature operation is carried out, and the model of the parts is saved after the parts are completed. According to this step, multiple parts are generated repeatedly, and then cooperation is added between parts to complete the modeling of robot assembly. Finally, the base coordinate system of the robot is established at the base of the assembly, and the coordinate calibration of the robot assembly is completed. The flow is shown in Figure 2.
Figure.2. Schematic diagram of robot CAD modeling

The robot model built according to this process is shown in Figure.3.

Figure.3. ABB IRB1410 robot CAD modeling

3. Kinematic analysis

Kinematics analysis[7] of welding robot is the premise of robot graphics modeling and trajectory planning, and also the basis of off-line programming system. Robot kinematics analysis refers to describing the relationship between robot connecting rod parameters, motion variables and robot pose (position and posture). Forward kinematics solution is a method to solve the end-effector pose with known joint variables and connecting rod parameters of the robot.

Given, the transformation matrix formula of the adjacent two connecting rods of the robot is:

\[ ^{i-1}T_i = \text{Rot}(Z, \psi_i) \text{Trans}(0,0,d_i) \text{Rot}(X, \alpha_i) \]

According to the above formula, the transformation matrix of adjacent connecting rod can be calculated as follows:

\[ ^{i-1}T_i = \begin{bmatrix}
    \cos(\psi_i) & -\sin(\psi_i) & 0 & a_i \\
    \sin(\psi_i) \cos(\alpha_i) & \cos(\psi_i) \cos(\alpha_i) & -\sin(\alpha_i) & -d_i \sin(\alpha_i) \\
    \sin(\psi_i) \sin(\alpha_i) & \cos(\psi_i) \sin(\alpha_i) & \cos(\alpha_i) & d_i \cos(\alpha_i) \\
    0 & 0 & 0 & 1
\end{bmatrix} \]

According to the connecting rod parameters of ABB IRB1410 robot, the relation matrix of adjacent connecting rods can be calculated:

The transformation matrix of each adjacent connecting rod is multiplied successively to obtain the transformation matrix of its end-effector coordinate system with respect to the coordinate system of the base. The kinematics equation(3) is as follows:

\[ ^{1}T_6 = ^{5}T(\theta_5)\cdot^{4}T(\theta_4)\cdot^{3}T(\theta_3)\cdot^{2}T(\theta_2)\cdot^{1}T(\theta_1) \]

The inverse kinematics is a method to solve the joint Angle given the end-effector pose and connecting rod parameters.
In this system, ABB IRB1410 robot inverse kinematics is solved by Screw Theory [8]. A total of 8 solutions can be obtained by applying the inverse kinematics algorithm. This system selects one of the 8 solutions as the optimal solution according to the actual welding needs.

4. Trajectory planning

Robot trajectory planning refers to the process of selecting appropriate welding parameters to generate the optimal welding seam according to the actual welding needs. This system will extract the track information of welding seam through the SolidWorks API function, and carry out track planning on this basis.

It is necessary to obtain the equation of the surfaces of the two welds in the workpiece coordinate system if the surface information of the weld is provided in the curve weld planning. It is assumed that the welding surface information is known, and the following equation (4) can be obtained:

\[
\begin{align*}
F_1(x, y, z) &= 0 \\
F_2(x, y, z) &= 0
\end{align*}
\]

The discrete point coordinates of the curved seam in the workpiece coordinate system are:

\[
\begin{align*}
x_i &= p_i(\theta) \\
y_i &= p_i(\theta) \\
z &= p_i(\theta)
\end{align*}
\]

Then, the tangent vector of the discrete welding seam points is:

\[
V(p) = [p_i'(\theta) \quad p_i'(\theta) \quad p_i'(\theta)]
\]

The normal vector of the welding surface equation (7) is as follows:

\[
\begin{align*}
\vec{n}_1 &= \left(\frac{\partial F_1}{\partial x}, \frac{\partial F_1}{\partial y}, \frac{\partial F_1}{\partial z}\right) \\
\vec{n}_2 &= \left(\frac{\partial F_2}{\partial x}, \frac{\partial F_2}{\partial y}, \frac{\partial F_2}{\partial z}\right)
\end{align*}
\]

Then the z-axis direction of the coordinate system of the discrete point of the weld is the angular bisector vector of the two normal vectors of the discrete point of the weld:

\[
\vec{m}(p_i) = \frac{\vec{n}_1(p_i)}{||\vec{n}_1(p_i)||} + \frac{\vec{n}_2(p_i)}{||\vec{n}_2(p_i)||}
\]

The auxiliary coordinate system of the discrete points of the weld is:

\[
\begin{align*}
\vec{e}_i &= \frac{\vec{V}(p)}{||\vec{V}(p)||} \\
\vec{e}_i &= \frac{\vec{m}(p)}{||\vec{m}(p)||} \\
\vec{e}_i &= [e_x \quad e_y \quad e_z]
\end{align*}
\]

The transformation matrix of the auxiliary coordinate system of the discrete weld points in the workpiece coordinate system is shown as follows:

\[
\begin{bmatrix}
0 & 0 & 0 & 1 \\
e_x & e_y & e_z & 0 \\
e_x & e_y & e_z & 0 \\
e_x & e_y & e_z & 0
\end{bmatrix}
\]

5. Off-line simulation experiment

This paper will verify the feasibility of the off-line programming system for the simulation experiment of ABB IRB1410 robot for cylindrical intersecting pipe welding. The off-line simulation interface of the off-line programming system is shown in Fig.4.
The experimental steps are as follows:
Step 1: Open the off-line programming system and import model.
Step 2: Coordinate system calibration of tools and workpieces according to 6-point method and 3-point method.
Step 3: Select the welding path, and use the program to extract the welding path information.
Step 4: Select the interpolation method and establish the auxiliary coordinate system of discrete points. Modify the pose information to optimize the welding trajectory.
Step 5: Convert trajectory planning information into robot language and output program.
Step 6: Import the output program into the robot control cabinet, and operate the demonstrator to complete the welding.

The experimental process is shown in Fig.5.

This program is used for welding experiment of cylindrical intersecting pipe. The generated robot language program is shown in Fig.6.
system, $e$ is the offset distance, and $\theta$ is the rotation Angle of the oblique branch pipe around the $Y_B$ axis.

Where point $p0$ is the initial point of motion, and tool1 is the coordinate of welding tool. The position coordinates of point P1~P41 are shown in Table 2:

| n  | $\theta_i$ | X       | Y       | Z       |
|----|------------|---------|---------|---------|
| 1  | 0          | 8.0000  | -34.3445| 65.0096 |
| 2  | $pi/20$   | 15.8217 | -34.0956| 63.5604 |
| 3  | $2pi/20$  | 23.4508 | -32.8431| 61.1581 |
| ...| ...        | ...     | ...     | ...     |
| 40 | $39pi/20$ | 0.1783  | -33.5759| 65.4998 |
| 41 | $40pi/20$ | 8.0000  | -34.3445| 65.0096 |

Offline welding simulation with SolidWorks is shown in Fig. 7.

![Figure 7. Off-line simulation experiment](image)

Import the program into ABB robot control cabinet and run the welding program. The welding experiment of cylindrical intersecting pipe is shown in Fig. 8.

![Figure 8. Actual welding experiment](image)

6. Conclusion

Based on SolidWorks platform, the SolidWorks API interface was used for secondary development, and the off-line programming system development for ABB IRB1410 arc welding robot was completed. The modules of kinematics analysis, trajectory planning and off-line simulation are completed. This system verifies the welding experiment of robot cylindrical intersecting pipe.

7. References

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