Kinematics Modeling and Simulation of Gantry Ship Welding Manipulator with Hybrid Structure

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Abstract. The existing gantry ship welding robot mechanism is mostly in series, which has the problems of large motion inertia at the end and joint error accumulation. A kind of ship welding robot with hybrid structure is designed. The platform control mechanism and rotary mechanism adopt the form of planar parallel mechanism, which can effectively increase the rigidity and error compensation ability of the actuator. And the adjusting mechanism of welding torch adopts series structure and keeps the flexible output ability. The kinematics model of the welding actuator is established by combining the closed-loop vector method, complex vector method and D-H four-parameter method. The positive solution of the mechanism is given, and the velocity and acceleration are analyzed based on it. Through simulation analysis, we get the workspace and kinematic characteristics curve of some components under given trajectories to verified the feasibility of the proposed mechanism.

1. Introduction

Welding technology has become a necessary technology to accelerate the shipbuilding cycle, improve the quality and process, and promote the rapid development of China's shipbuilding industry [1-2]. Much attention has been paid to the research of welding robots, such as: Y K Liu established three intelligent fusion algorithms of welding robots for the development of intelligent welding robots in GTA welding, and their advantages were verified by simulation [3]; N K Ku developed an embedded controller and control software for autonomous mobile welding robot of ships and enabled it to move and perform welding tasks in a double-shell structure [4]; K Wang introduced the dynamic model identification of robot's axial force during friction stir welding [5]. However, almost all the ship welding robots use the joint mechanism with series structure, so it leads to heavy weight, large inertia and poor dynamic performance of each robot arm. And accumulative errors will occur along with the motor superposition at each joint, which will affect the welding accuracy and is not suitable for high-strength, large-scale shipbuilding welding.

Therefore, a new type of welding mechanism is designed to meet the increasing demand of welding by combining the multi-degree-of-freedom controllable mechanism [6-8]. Combining closed loop vector method, complex vector method, D H four parameter method [9] to conduct Kinematics modeling of mechanism, the positive solution of the mechanism is given, and the velocity and acceleration are analyzed based on it. Through simulation analysis, we get the workspace and kinematic characteristics curve of some components under given trajectories.

2. Configurations
Figure 1 is a ship welding robot with hybrid structure which is based on two side guide ways and figure 2 is the schematic diagram of its actuator. The welding mechanism is divided into three parts: mechanism of platform control, rotary mechanism and adjusting mechanism of welding gun. The IJDE and DKGC linkage mechanisms consisting of two degrees of freedom closed-chain five-bar linkage and two groups of parallelograms are used to keep the CFG level of the moving platform at all times. The top A, E and I are hinged on the frame, and the A and E points are respectively equipped with servo motors for driving. DKJ is a tripod and D is a compound hinge. Among them, all kinematic pairs are rotary pairs. The axis HQ is welded vertically to the center point H of the platform FG. MN is an active rotating link driven by a servo motor to rotate around the axis HQ. The NO is an electric telescopic cylinder with two ends connected to the rotating disk and the swing arm respectively. The point P on the swing arm OR is connected to the rotating sleeve QP, and OR can rotate along the rotating rod MN. The entire MNOPQ mechanism always rotates around the shaft HQ in the same plane. The link RS of the adjusting mechanism of the welding torch is hinged at the R point of the swing arm, driven by a small servo motor at R, and S is the end welding torch.

3. The Positive Solution Of Position

3.1. Mechanism of Platform Control
As shown in Figure 2, a reference coordinate system is established. The base coordinate system is fixed at point A of the base, and the moving coordinate system is established on each member respectively. The vector of each component is defined as \( \vec{l}_1, \vec{l}_2, \vec{l}_3, \vec{l}_4, \vec{l}_5 \), the positive angles between the vectors and the X axis are \( \theta_1, \theta_2, \theta_3, \theta_4 \). By the closed loop vector method, we have

\[
\vec{l}_1 + \vec{l}_2 = \vec{l}_3 + \vec{l}_4 + \vec{l}_5
\]

(1)

do the following operations

\[
(\vec{l}_1 + \vec{l}_2 - \vec{l}_3 - \vec{l}_4) \cdot (\vec{l}_1 + \vec{l}_2 - \vec{l}_3 - \vec{l}_4) = \vec{l}_1 \cdot \vec{l}_1
\]

(2)

then, we obtain

\[
A + B + C \cos \theta_2 + D \sin \theta_2 = 0
\]

(3)

Where

\[
A = l_1^2 + l_2^2 + l_3^2 + l_4^2 - l_5^2, \quad B = 2l_1l_4 \cos \theta_4 - 2l_1l_4 \cos \left( \theta_4 - \theta_0 \right) - 2l_1l_5 \cos \theta_1,
\]

\[
C = 2l_1 \left( l_1 \cos \theta_1 - l_4 \cos \theta_4 - l_5 \cos \theta_4 - \theta_0 \right), \quad D = 2l_1 \left( l_1 \sin \theta_1 - l_4 \sin \theta_4 - \theta_0 \right)
\]

When \( x_i = \tan(\theta_i / 2), \quad \sin \theta_2 = 2x_i / (1 + x_i^2), \quad \cos \theta_2 = (1 - x_i^2) / (1 + x_i^2), \) in the formula (3) we can
obtain $x_i = -D \pm \sqrt{D^2 - (A + B - C)(A + B + C)} / (A + B - C)$, namely, $\theta_2 = 2 \arctan(x_i)$.

In the same way, $x_i = -D \pm \sqrt{D^2 - (A + B - C)(A + B + C)} / (A + B - C)$, $\theta_3 = 2 \arctan(x_i)$, of which $A = l_1^2 + l_2^2 + l_3^2 - l_2^2$, $B = 2L_1 l_2 \cos \theta_1 - 2L_2 l_2 \cos \theta_1 - 2L_3 l_2 \cos (\theta_2 - \theta_1)$, $C = 2L_1(l_2 \cos \theta_1 - l_2 \cos \theta_2 + l_3)$, $D = 2L_2 l_2 \sin \theta_1 - l_1 \sin \theta_1$

The height of the moving platform is $l$, so the point coordinates of H is

$$\begin{align*}
x_H &= l \cos \theta_1 + l \cos \theta_2 \\
y_H &= l \sin \theta_1 + l \cos \theta_2 + l
\end{align*}$$

(4)

3.2. Rotary Mechanism

The rotary mechanism, as is shown in Fig. 2, is to achieve flexible welding trajectories in its workspace, which can also be regarded as a six-bar closed-chain mechanism, of which $L_1$ and $L_2$ can be regarded as movable connecting rods. By complex vector method, we obtain

$$L_e e^{i \theta} + L_e e^{i \theta} = L_e e^{i \theta} + L_e e^{i \theta} + L$$

(5)

Separation of real part and imaginary part based on Euler formula

$$\begin{align*}
L_a \cos \theta_6 &= L_a \cos \theta_7 + L \\
L_a + L_2 \sin \theta_6 &= L_3 \sin \theta_7 + L
\end{align*}$$

(6)

In the from $(a^2 + b^2) \sin^2 \theta_7 - 2bc \sin \theta_7 + c^2 - a^2 = 0$, we obtain

$$\theta_7 = \arcsin[(bc \pm \sqrt{b^2 - c^2}) / (a^2 + b^2)]$$

(7)

Of which $\theta_5 = \theta_6 = \pi / 2$, $L_2$ is a variable, $a = 2L_1 a$, $b = 2L_2 (L_1 - L_2)$, $c = l_2^2 - l_2^2 - (l_2 - l_2)^2$, we get

$$\theta_6 = \arcsin[(L_3 \sin \theta_7 + L_4 - L_4) / L_2]$$

(8)

Combining $\theta_6 = 3 \pi / 2 - \theta_7$ and formula (7)-(8) we can know the connection between $\theta_6$, $\theta_7$, $\theta_8$.

3.3. Adjusting Mechanism of Welding Gun

We can split the link OR into two parts like OP and PR as shown in Figure 3. The base coordinate system of the rotating part is set up at H point of the moving platform, the $Z_1$ and $Z_H$ are coincident. The origin of the coordinates of the end link is located at the end point S in the post coordinate system.

Starting from the connecting link HQ, the transformation matrix is $T_1$:

$$T_1 = \begin{bmatrix}
c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\
s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\
0 & s\alpha_i & c\alpha_i & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(9)

We can acquire the pose transformation matrices of the components by combining with table 1 and formula (9), they are $T_0$, $T_1$, $T_2$, $T_3$.
Figure 3. Sketch of rotating mechanism

Table 1. D-H parameters

| Serial number | $\alpha_i$ | $a_i$ | $d_i$ | $\theta_i$ |
|---------------|------------|-------|-------|------------|
| 0             | 0          | 0     | $L+d$ | $\theta$   |
| 1             | $\pi/2$    | $L_i$ | 0     | $\theta$   |
| 2             | 0          | $L_s$ | 0     | $\theta_9$ |
| 3             | 0          | $L_b$ | 0     | $\theta_{10}$ |

The transformation matrix of the series part end welding torch point S relative to the moving platform coordinate system $\{H\}$ is $^HST=T_0^1T_1^2T_2^3$. Therefore, the pose matrix of the H point base coordinate system relative to the fixed coordinate system $\{A\}$ is

$$^AT_A=Trans(x_H,y_H,0)Rot(x,90^\circ)$$

So the final pose matrix of the welding mechanism’s end S relative to the fixed coordinate system is

$$^AT_S=^HT_H^ST_S$$

Where $\theta_b=3\pi/2-\theta$. And formula (10) is the position positive solution equation of the position of S at the end of the welding mechanism.

4. Velocity and Acceleration Analysis

Coordinate system based on mobile platform $\{H\}$, the position equation of the S point for the rotation part as follows

$$\begin{align*}
x_i &= (L_4 + L_6c\theta_6 + L_6c\theta_6\theta_{10})\cos^2\theta - L_6s\theta_6\theta_{10}
y_i &= 2(L_4 + L_6c\theta_6 - L_6s\theta_6\theta_{10})\cos\theta + L_6c\theta_6\theta_{10}
z_i &= L + d + L_6s\theta_6 + L_6c\theta_6\theta_{10}
\end{align*}$$

The positive solution equation for the end of the welding mechanism on the moving platform is
obtained by the first order derivative and (11).

\[ \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \left[ \begin{bmatrix} \mu G_s \\ 0 \\ 0 \end{bmatrix} \right] \left[ \begin{bmatrix} \partial_4 \\ \partial_5 \\ \partial_6 \end{bmatrix} \right] \]

Similarly, if \{A\} is the basic coordinate system, combined formula (10), obtain

\[ \begin{bmatrix} \dot{x}_{sa} \\ \dot{y}_{sa} \\ \dot{z}_{sa} \end{bmatrix} = \left[ \begin{bmatrix} \lambda G_s \\ 0 \\ 0 \end{bmatrix} \right] \left[ \begin{bmatrix} \partial_1 \\ \partial_4 \\ \partial_5 \end{bmatrix} \right] \]

\[ \left[ \lambda G_s \right] \] is the first-order motion influence coefficient of the whole welding mechanism and the velocity Jacobian matrix of the end effector of the welding mechanism. The forward solution equation of the acceleration can be obtained by continuous derivation of the velocity positive solution equation.

5. Simulation Analysis of Numerical Example

**Table 2.** Scale parameter of link

| Link /Scale parameter | Link     | l_1 | l_2 | l_3 | l_4 | l_5 | l  | L+d | L_1 | L_2 |
|-----------------------|----------|-----|-----|-----|-----|-----|----|-----|-----|-----|
| Length(mm)            |          | 200 | 300 | 300 | 200 | 100 | 40 | 200 | 90  | 56~150 |
| Link                  | L_3      | L_4 | L_5 | L_6 | l_{B}=l_{D} | l_{J}=l_{4} | l_{K D}=l_{G} | l_{K G}=l_{3} | LDK |
| Length(mm)            |          | 140 | 40  | 140 | 160 | 36  | 200| 63  | 300 | 113° |

**Figure 4.** Given trajectory diagram

The length of each Link is shown in Table 2. Equipped with a welding torch device, the track shown in Figure 4 can also be completed at the motor A and E two at the top of the driving mechanism. The acceleration, velocity and displacement curves of the AB bar, the DE bar and the end point S under the given driving function are shown in Figure 5a, 5b, 5c, respectively.

The simulation results show that the overall workspace of the mechanism can satisfy the requirements of the ship welding task. As shown in figs 5a and 5b, the velocity and acceleration curves of the two active bars change slightly at three times, which is actually caused by the change of the driving direction of the active bars or the movement to the singular position. A sudden change in the corresponding curve of the terminal point S will occur, as shown in Figure 5c and it is not conducive to smooth welding work, but in addition, there is no obvious mutation in the rest of the curve. Therefore, the whole mechanism can achieve smooth welding, in the actual programming drive and dimension synthesis should try to make the mechanism work within its singular range, in the welding torch welding operation to ensure the stability of the active drive input.
6. Conclusions
Based on the engineering practice, this paper designs a hybrid structure ship welding manipulator in the field of shipbuilding welding, which not only increases the rigidity and error compensation ability of the actuator, but also keeps the flexible output ability. The kinematics model of the mechanism is established by using closed-loop vector method, complex vector method and D-H parameter method, and the positive position solution is given. The velocity and acceleration of the mechanism are analyzed based on the forward position solution equation. The kinematics characteristics of the active input and output are analyzed by the given trajectory simulation, we can obtain the ship welding mechanism is feasible. Such innovative design examples can also provide reference for the development and design of other construction machinery products.

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