Research on Motion Path Planning of Six Degrees of Freedom Robot Based on Fuzzy Control Algorithm

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Abstract. Aiming at the trajectory planning problem of six-degree-of-freedom industrial robot in fixed space, this paper extends the trajectory optimization to the actuator control optimization of each joint of industrial robot. At the same time, the control algorithm of each joint steering gear of the robot under the specified path is given. Finally, the whole control strategy is simulated by the software of matlab, and the simulation results are good. The trajectory planning method of six-degree-of-freedom industrial robots proposed in this paper can be used for reference in general industrial process control.

1. Introduction
Throughout the history of mankind, every industrial innovation marks the development of the times. The replacement of human manual labor from tools and machine-substitute tools has greatly increased productivity, all of which demonstrate that industrial technology innovation is the most effective and convenient means of improving people's living standards. With the rapid advancement of "Made in China 2025", industrial robots have been widely used. With the improvement of intelligence, the traditional hand-held recorder recording method has become increasingly unable to meet the demand for mechanical arm path control in industrial production[1]. In the complex and variable implementation space, the path of the robot arm needs to be improved at any time for safe production. The traditional method requires multiple use of the hand-held device to change the path of the robot arm, which greatly reduces the efficiency of industrial production. Moreover, due to the complicated construction environment, it is not conducive to the safe production of engineering personnel.

2. Robotic kinematics model
The robots in the general industrial field are generally articulated robots. The main body is an articulated robot arm designed like a human upper limb. An independent drive motor is installed inside each joint. Each motor is called an axis of the robot, also called a degree of freedom of robot[2]. The six-degree-of-freedom robot arm of a certain brand selected in this paper consists of a rotating base, three parallel links, and a rotating fingertip actuator, which can simulate human lumbar rotation, arm flexion and extension, wrist rotation and pitch, and palm execution[3]. The specific structure is shown in Figure 1.
According to the specific parameters of the robot and our control requirements, the simplified diagram is extracted as shown in Figure 2. In this paper, the D-H parameter method is used to determine the motion trajectory of the robot arm by the spatial pose of the mechanical arm's coordinate system in space\(^4\). Robotic kinematics mainly studies the movement of robots, including the posture of the robotic arm mechanism and the discipline of the robotic arm. The main research of two types of problems is to give the angle of each joint of the robot arm, the position and posture of the actuator at the end of the robot is required, which is called the kinematics positive problem, and the other is to know the position and posture of the end effector. The robot corresponds to the entire joint angle of this position and attitude, called the kinematic inverse problem.

The D-H method is to describe the spatial geometric relationship of each link relative to the fixed reference frame by homogeneous transformation, and describe the spatial relationship of the adjacent two links by a fourth-order homogeneous transformation matrix, so as to derive the "end-end actuator coordinate system". "Based on the equivalent homogeneous coordinate transformation matrix of the "base coordinate system", the equation of motion of the industrial robot is established.

In the Cartesian coordinate system, a homogeneous matrix can be used to represent the translation (as shown in formula 1) and rotation (as shown in formula 2) transformation of the joint on the X, Y, and Z axes.

\[
\text{Trans}(x, a) = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{Trans}(y, a) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{Trans}(z, a) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

\[
\begin{align*}
R(x, \theta) &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta & 0 \\ 0 & \sin \theta & \cos \theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
R(y, \theta) &= \begin{bmatrix} \cos \theta & 0 & \sin \theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \theta & 0 & \cos \theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
R(z, \theta) &= \begin{bmatrix} \cos \theta & -\sin \theta & 0 & 0 \\ \sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{align*}
\]

The transformation \(A_{i-1}^{i-1}\) of the coordinate system \{i\} relative to \{i-1\} can be regarded as the product of four sub-transforms, namely:

1. Rotate \(b_{i-1}\) around \(X_{i-1}\);
2. Moved \(a_{i-1}\) along \(X_{i-1}\);
3. Rotate \(\theta_i\) around \(Z_{i-1}\);
4. Moved \(d_i\) around \(Z_{i-1}\).

It can be expressed as:
\[ A_{i-1} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & b_{i-1} \\ \sin \theta_i \cos \alpha_{i-1} & \cos \theta_i \cos \alpha_{i-1} & -\sin \alpha_{i-1} & -d_i \sin \alpha_{i-1} \\ \sin \theta_i \sin \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & \cos \alpha_{i-1} & d_i \cos \alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \] (3)

For industrial robots with \( n \) joints, \( n \) coordinate systems can be established, and the base point of the last coordinate system is the fingertip coordinate system of the manipulator. Obviously, for industrial robots with \( n \) joints, there exists \( n+1 \) rotation matrix: \( A_{n-1} \), \( A_{n-2} \), \ldots, \( A_0 \). Among them, \( A_0 \) is the conversion of the first coordinate system to the basic coordinate system, and the conversion of the second coordinate system to the basic coordinate system is as follows:

\[ A_0^0 = A_2^2 \times A_0^0 \] (4)

Therefore, for a six-degree-of-freedom industrial robot, the position conversion relationship between the end joint and the basic coordinate system can be obtained by backstepping the position of the end joint.

\[ A_6^0 = A_5^5 \times A_4^4 \times \cdots \times A_0^0 = \begin{bmatrix} a_x & b_x & c_x & d_x \\ a_y & b_y & c_y & d_y \\ a_z & b_z & c_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \] (5)

Finally, the forward kinematics equation of the industrial robot is obtained.

The inverse kinematics problem of a six-degree-of-freedom industrial robot is to solve the specific joint variable \( \theta_1, \theta_2, \ldots, \theta_6 \) when the position and attitude of the manipulator are known, i.e. when the upper formulas \( a, b, c \) and \( d \) are known, and the inverse kinematics problem is solved by calculating. Usually, we can get many sets of solutions. We can further use the actual needs to limit the conditions of solutions to eliminate redundant solutions, such as the rotation angle of each joint, the limitation of spatial obstacles and so on. The main parameters of industrial robots presented in this paper are shown in Table 1.

| Axis | Rotation angle (angle) | Maximum speed of rotation (angle/s) |
|------|------------------------|-----------------------------------|
| A1   | \( \pm 185 \)          | 105                               |
| A2   | +70/-140               | 101                               |
| A3   | +155/-120              | 107                               |
| A4   | \( \pm 350 \)          | 292                               |
| A5   | +125/-122.5            | 258                               |
| A6   | \( \pm 350 \)          | 284                               |

3. Fuzzy control algorithm
Fuzzy control is an algorithm for real-time optimization of controlled objects according to fuzzy logic and certain fuzzy rules. The main process of fuzzy control includes three steps: object fuzzification, establishment of fuzzy rules and anti-fuzziness. In this paper, a fuzzy control algorithm is used to control the motion process of the manipulator[5].

3.1. Fuzzification
Firstly, we collect the current angle of the steering gear and compare it with the set value to get the deviation \( E \) and the difference \( E_c \) between the current deviation and the last deviation. Then we need to fuzzify the two values. The deviation we collect has a certain range of variation (i.e. the range of maximum and minimum), we divide the range into eight parts, and group them. Nine points in the eight parts are defined as NB (negative big), NM (negative middle), NS (negative small), ZO (zero), PS (positive small), PM (positive middle), PB (positive big). Let's take \( E \) as an example and assume that the value of \( E \) is in the interval of PB and PM. At this time, \( E \) corresponds to PB and PM with two
membership degrees, the ratio of E membership to PM is $a = \frac{(E-PM)}{(PB-PM)}$, and the ratio of E membership to PB is $\left(\frac{PB-E}{PB-PM}\right) = (1 - a)$. Similarly, we can also fuzzify EC.

3.2. Fuzzy Reasoning
We will fuzzify the calculated E and EC. After deducing their respective membership degrees, we can find out the corresponding membership degrees of the output values according to the fuzzy rules table. The selected table of fuzzy rules is shown in Table 2[6].

We assume that the two membership degrees of E are PM and PB, and the membership degrees of E belong to PM are $a$ ($a < 1$), while the membership degrees of E belong to PB are $(1 - a)$. Assuming that the two membership degrees of Ec are NB and NM, and the membership degree of EC belongs to NM is $b$, the membership degree of Ec belongs to NB is $(1 - b)$. Under the assumption that E belongs to PM with a degree of membership and Ec belongs to NB with a degree of membership $(1 - b)$, the output value belongs to ZO with a degree of membership $(1 - a)$.

Similarly, we can conclude that when the output value belongs to ZO, the other two membership degrees are $a \times b$, $(1-a) \times b$, and the output value belongs to NS, the membership degree is $(1-a) \times 1 - b$.

| E | Ec |
|---|---|
| PM | ZO |
| PB | NSA |
| NS | ZO |
| ZO | NS |
| PS | ZO |
| PM | ZO |
| PB | ZO |

3.3. Ambiguity resolution
For the output value, we also adopt the method of giving membership degree. We also divide the interval of output value into eight parts, namely 7 membership values NB, NM, NS, ZO, PS, PM, PB. The blurring is solved by the method of gravity center. The formula of gravity center method is as follows:

$$Z_0 = \frac{\sum_{i=0}^{n} \mu_c(Z_i) \cdot Z_i}{\sum_{i=0}^{n} \mu_c(Z_i)}$$

In the formula,
$Z_0$ is the exact value of the output of the Fuzzy Controller after it is defuzzified;
$Z_i$ is the value in the universe of fuzzy control variables;
$\mu_c(Z_i)$ is the membership value of $Z_i$.

Where,
$$\mu_c(Z_i) \cdot Z_i = [a \times b + a \times (1 - b) + (1 - a) \times (1 - b)] \times Z0 + (1 - a) \times b \times NS$$

And the sum of $\mu_c(Z_i)$ is the sum of membership degree of output value. In other words:
$$a \times b + a \times (1 - b) + (1 - a) \times (1 - b) + (1 - a) \times b = 1$$

So far, the whole process of ambiguity is over.

4. Conclusion
In summary, given the requirement of the end pose of the robot, the axis motion of the robot can be obtained by backstepping the kinematics model of the robot. After the optimal trajectory is obtained...
by restricting the motion conditions of the robot with certain rules, the motion of the rudder is controlled by the fuzzy control algorithm, and then the robot is controlled to move to the target point. For the motion process of the robot, we use Robot tools of the MATLAB toolbox to simulate, and the simulation results are shown in Figure 3 below. The model of the robot, the trajectory of linear motion, the change of position, velocity and acceleration in the course of motion are given.

![Simulation results](image)

Figure 3. Simulation results

Appendices
1. Jilin Science and Technology Innovation Development Plan Project (201750244)
2. Major Science and Technology Projects of Jilin Institute of Chemical Technology (2018017)
3. Major Science and Technology Projects of Jilin Institute of Chemical Technology (2016033)

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