Path Planning Simulation of 6-DOF Manipulator

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Abstract. With the development of automation and intelligence in manufacturing industry, industrial robots have become an important part of intelligent chemical plants. In practical application, all functions implemented are realized by manipulator. Facts have proved that reasonable path planning for the manipulator is helpful to reduce the loss and impact of mechanical parts during operation, greatly improve the service life of the manipulator, and also help to improve the control accuracy of the manipulator of the robot. In this paper, the six-degree-of-freedom manipulator is taken as the research object, and the motion path planning scheme of the manipulator is designed, which is verified by PVDF material grabbing simulation experiments. The results show that the motion path of the manipulator designed in this paper takes less time than the shortest path to grab materials, and the operation accuracy is higher.

Keywords: Manipulator, Dynamic Simulation, Path Planning

1. Introduction
In recent years, with the proposal of "Industry 4.0" and "Made in China 2025" plans, the manufacturing industry is developing towards intelligence. Industrial robots have become indispensable equipment in modern intelligent factories, mainly suitable for fast, accurate and repetitive work [1,2]. The trajectory of the manipulator determines the quality of production and manufacturing. In order to make the robot move as expected in the unknown working environment and complete the work efficiently and stably, the operation accuracy of the manipulator needs to be improved [3-5]. This paper takes the six-degree-of-freedom manipulator as the research object and uses MATLAB software to carry out simulation planning research on its motion path.

2. Kinematic Analysis of 6-DOF Manipulator
During the forward and reverse movements of the manipulator, the coordinate system changes, and it is necessary to perform rotation, translation and other processing along the X axis and Z axis to obtain a new coordinate system and solve it using the homogeneous change matrix [6]. The following is the conversion from \( \{O_{i-1}\} \) coordinate system to \( \{O_i\} \) coordinate system, the conversion sequence is as follows:

(1) Use \( Z_{i-1} \) as the axis to rotate the coordinate system, the rotation angle is \( \theta_i \), and the X axis direction remains unchanged before and after the change;
(2) Use $Z_{i-1}$ as the axis to do coordinate system translation processing, the moving distance is $d_i$, and the X axis direction remains unchanged before and after the same change;

(3) Translate along the direction of the $X_i$ axis, the moving distance is $a_i$, the origin of the $\{O_{i-1}\}$ coordinate system and the origin of the $\{O_i\}$ coordinate system before processing coincide;

(4) The coordinate system is rotated with $X_i$ as the axis, the rotation angle is $\alpha_i$, and the Z axis direction remains unchanged before and after the change.

After processing according to the above steps, the $\{O_{i-1}\}$ coordinate system is converted to the $\{O_i\}$ coordinate system, and the resulting homogeneous transformation matrix is as follows:

$$
_{i-1}^{i}T = \begin{bmatrix}
c_{\theta_i} & -s_{\theta_i} & 0 & a_{i-1} \\
s_{\theta_i}c_{\alpha_{i-1}} & c_{\theta_i}c_{\alpha_{i-1}} & s_{\alpha_{i-1}} & -s_{\alpha_{i-1}}d_i \\
s_{\theta_i}s_{\alpha_{i-1}} & c_{\theta_i}s_{\alpha_{i-1}} & c_{\alpha_{i-1}} & c_{\alpha_{i-1}}d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(1)

The D-H parameters of the 6-DOF manipulator studied in this paper are shown in Table 1.

| Number of joints | $\theta_i$ | $a_{i-1}$ | $d_i$ | $a_{i-1}$ |
|-----------------|------------|-----------|-------|-----------|
| 1               | $\theta_1$ | 90        | 160   | 0         |
| 2               | $\theta_2$ | 0         | 350   | 0         |
| 3               | $\theta_3$ | 90        | 130   | 0         |
| 4               | $\theta_4$ | -90       | 0     | 425       |
| 5               | $\theta_5$ | 90        | 0     | 0         |
| 6               | $\theta_6$ | 0         | 0     | 133.5     |

The parameters in Table 1 are substituted into the homogeneous transformation matrix, and the product of the adjacent joint transformation matrix is calculated to obtain the forward motion value of the manipulator.

$$
_{0}^{T} = \begin{bmatrix}
n_x & o_x & a_x & p_x \\
n_y & o_y & a_y & p_y \\
n_z & o_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(2)

The principle of reverse motion solution is the same as that of forward motion solution. Through coordinate conversion processing, the parameter values are substituted to obtain them, which will not be described here too much.

3. **Trajectory Planning of Manipulator**

The planning of the trajectory of the manipulator can use the joint angle formed by the motion of the starting point and the ending point as the analysis object, and expand the description by constructing an interpolation function [7]. For example, set four constraint conditions to constrain the starting point and ending point of joint motion to ensure that the formed trajectory is continuous. Generally, the following cubic polynomial is used for description.

$$
\theta(t) = a_0 + a_1t + a_2t^2 + a_3t^3
$$

(3)
Derivation of formula (3) can obtain the speed and acceleration of the movement of the manipulator, and the obtained results are substituted into the initial conditions to obtain the various parameter values, thereby obtaining the motion trajectory function.

The cubic polynomial trajectory planning is relatively simple and suitable for use when the workpiece gripping type is relatively single. Due to the many types of workpieces involved in the processing and manufacturing of some projects, this paper studies the motion trajectory of the joint space of the manipulator, introduces the cycloid curve planning method, and plans the spatial motion trajectory for the more complicated working conditions [8]. The running trajectory generated by the planning method is relatively stable, and there is no jitter. In the limited interval, if the target point is at the end position, the resulting acceleration and speed are both 0, which greatly reduces the difficulty of planning the trajectory [9]. The starting point and the focus are the key planning objects, and the planning of the intermediate motion process is reduced.

4. Simulation Experiment of 6-DOF Manipulator PVDF Bar Grasping Motion Path Planning

This article takes PVDF bar grabbing movement as an example to carry out simulation experiment research on the motion path planning of the manipulator. According to the requirements of bar manufacturing and handling, design material handling tasks, clarify the robotic arm gripping motion tasks, plan the motion path, and simulate the motion path of the robotic arm on the built simulation platform. By observing the simulation results, it is judged whether the path planning scheme can effectively control the manipulation of the manipulator to complete the material grabbing task.

4.1 Grab Task

In this simulation experiment design, two grabbing tasks were deployed, namely grabbing a single target material and multiple target materials, and the "shortest path" method was used as a control group.

1) Single target material grabbing task

Select PVDF bar as the grab target material, hang the material to 10 different positions respectively, fix the space position of the manipulator, and simulate the time spent by the manipulator to grab these 10 target materials.

2) Multiple target material grabbing tasks

Select PVDF bar as the grab target material, and the space position of the manipulator is fixed. Five sets of test experiments are designed. The number of materials is 2,3,4,5,6 in order, and the average grabbing time and average grabbing time of a single PVDF material are simulated and tested.

4.2 Motion Path Planning

During the processing and manufacturing of PVDF bar, the manipulator may face multiple grasping tasks. In order to improve the operation efficiency of the manipulator, it is necessary to ensure that the joint angle weighted value is the minimum [10]. Therefore, the experimental path planning is based on the principle of joint angle weighted minimum, and the corresponding motion path function is designed. Using mathematical language to describe the movement of PVDF bar machining and manufacturing manipulator: if the manipulator is in the position \((x_0, y_0, z_0)\) when carrying out the grab task, the number of materials to be grabbed is \(n\), and the space position of materials to be placed is marked as \((x_0', y_0', z_0')\), respectively, calculate the six degree of freedom joint space variables, according to the principle of minimum energy consumption of the mechanical arm, plan the material grabbing sequence, and complete the grabbing of all materials according to the grabbing sequence.

The generation of the optimal grasping path is based on the premise that the total value of the rotation angle of the manipulator is the smallest, and the objective function of the minimum time consumption and energy consumption of a single joint is obtained. Ignoring other factors, the minimum energy consumption is the least time-consuming, and the accumulated time-consuming results of multiple joints to complete the grasping operation are obtained [11]. The following is the best function of material grabbing path planning:
In formula (4), $P$ represents the objective function, reaction energy consumption; $n$ represents the number of space points passed; $m$ represents the number of joints; $w_i$ represents the energy consumption; $\theta_{i,j}$ represents the joint angle.

### 4.3 Experimental Platform

In this experimental study, build the experimental platform, as shown in Figure 1. Then, the coordinate system of the manipulator is constructed, and the relative position between the manipulator and the frame coordinate system is determined. The material objects are suspended at different positions, and the material grabbing situation of the manipulator is tested and simulated by MATLAB platform.

![Figure 1. Experimental platform](image)

### 4.4 Analysis of Simulation Results

In this simulation test and analysis, the manipulator is applied to a single PVDF material grabbing and multiple material grabbing environment to test the reliability of the manipulator grabbing motion path planning scheme. Place the manipulator at the initial position, hang the PVDF rod material by cable, calculate the material grabbing posture according to the fifth joint segmentation method, complete the material grabbing operation along the above motion path, and generate the time-consuming data of grabbing material on the simulation interface.

(1) Single PVDF material grab simulation test

In this experiment, the materials were placed in different space positions to test whether the manipulator can accurately grasp the materials, and to test the time of each material grabbing and the average grabbing time of 10 experimental materials. Table 2 shows the simulation test results of single PVDF material grabbing.

| test | Material location(m) | Grab or not | Grab time(s) | test | Material location(m) | Grab or not | Grab time(s) |
|------|----------------------|-------------|--------------|------|----------------------|-------------|--------------|
| 1    | (0.61,0.31,0.50)     | yes         | 27.3         | 6    | (0.31,-0.3,0.69)     | yes         | 25.7         |
| 2    | (0.49,0.31,0.52)     | yes         | 25.5         | 7    | (0.41,-0.24,0.6)     | yes         | 21.6         |
| 3    | (0.22,-0.5,0.49)     | yes         | 22.2         | 8    | (0.21,0.49,0.60)     | yes         | 27.9         |
| 4    | (0.59,0.0,0.64)      | yes         | 24.6         | 9    | (0.11,-0.49,0.7)     | yes         | 23.6         |
| 5    | (0.21,0.59,0.39)     | yes         | 28.6         | 10   | (0.40,0.49,0.49)     | yes         | 27.8         |
According to the statistical results in Table 2, it can be known that the robotic gripping material movement path designed in this study can accurately grasp the material, and the time-consuming range is 21.6s to 28.6s, and the average time is 25.48s. Therefore, this research program meets the grasping of single workpieces in manufacturing.

(2) Multiple PVDF material grab simulation test

For multiple material grabbing simulation experiments, the "shortest path" method is also selected as the control group. With the increase of the number of materials, the average grabbing time and average grabbing time of a single PVDF material are compared and observed. The results are shown in Table 3.

**Table 3. Simulation test results of multiple PVDF material grabbing**

| Number of PVDF materials | Average grabbing time of single PVDF material(s) | Average grabbing time(s) |
|--------------------------|-----------------------------------------------|--------------------------|
|                          | The research method in this paper | "Shortest Path" method | The research method in this paper | "Shortest Path" method |
| 2 pcs                    | 19.24                                        | 19.24                    | 38.6                                 | 38.6 |
| 3 pcs                    | 18.58                                        | 18.66                    | 55.7                                 | 56.1 |
| 4 pcs                    | 17.24                                        | 17.56                    | 69.1                                 | 70.3 |
| 5 pcs                    | 16.39                                        | 16.85                    | 81.9                                 | 84.3 |
| 6 pcs                    | 16.21                                        | 16.57                    | 97.2                                 | 99.4 |

By comparing the statistical results in Table 3, it can be seen that the time of grasping motion path of the manipulator proposed in this study is relatively short, and the average grasping time of a single PVDF material or with the increase of material quantity is less than that of the "shortest path" method.

In order to mine the characteristics of the grab material of the manipulator proposed in this study, the time-consuming data of the grab path of the manipulator in this study are separately counted and plotted into a graph as shown in Figure 2.

**Figure 2. Relation between the time-consuming of grabbing materials by manipulator and the increase of material quantity**

In Figure 2, the abscissa represents the number of PVDF materials, with values of 1, 2, 3, 4, 5, 6, and the ordinate represents the average pick-up time of a single PVDF material. According to the trend of the curve in Figure 2, as the number of PVDF materials increases, the time it takes for the manipulator to grab a single PVDF material gradually decreases. When the number of grabbed materials reaches 5, the time-consuming curve is gradually flat, with a small change. Therefore, in this study, the manipulator has high efficiency when grabbing 5-6 PVDF materials. When the number of materials is small, the advantage of the motion path designed in this paper is not significant. In practical applications, the movement path of the manipulator needs to be designed according to the actual situation.
5. Conclusion
In this paper, the kinematic analysis of the six degree of freedom manipulator is made, and the motion path of the manipulator to grasp the workpiece material is planned. Simulation test results show that the planned motion path in this study takes less time than the "shortest path" motion path when there are more materials to be grabbed. With the increase of the number of materials to be grabbed, the average time-consuming is less. When the number of materials to be grabbed reaches 5, the time-consuming of the manipulator to grab materials is no longer reduced.

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