Research on the Planning Method of Robot Terminal Speed Based on Task Characteristics

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Abstract. In order to study the speed planning of the industrial robots trajectory end under different tasks, the three speed planning methods of the third degree polynomial, the fifth degree polynomial and the five-segment S-curve are compared and studied. Analyze the stability and positioning accuracy of the robot’s end motion process in different occasions, and combine the speed and acceleration changes of the three speed planning methods, and recommend the end speed planning method for common tasks such as palletizing, loading and unloading, and grinding. Taking specific tasks as an example, the simulation results verify the rationality of the recommended method.

1. Introduction
With the rapid development of the robot industry, many manual tasks in the field of industrial production have been replaced by industrial robots. Industrial robots can perform many complex tasks that cannot be performed by humans with their accuracy, flexibility and high efficiency[1]. Among them, the trajectory planning technology of industrial robots has gradually become one of the hotspots in the field of robot research at home and abroad, and has also become the key to robot application and research and development[2]. Among them, the trajectory planning of industrial robots is very important, and trajectory planning is the key link for robots to complete their tasks[3]. Considering the environment during the movement and the working performance of the robot, the expected movement trajectory of the robot actuator is assigned to solve the change of the movement amount of the robot end effector over time, including displacement, velocity, acceleration, etc[4]. For tandem robots, trajectory planning can be divided into joint space trajectory planning and Cartesian space trajectory planning. Whether it is trajectory planning in joint space or in Cartesian space, it is ultimately reflected in the displacement, velocity, and acceleration images of the robot's trajectory movement process to ensure the continuous and smooth motion of the robot[5].

In order to ensure the continuous and stable motion of the robot during operation, it is necessary to constrain the robot motion speed and acceleration, which is called speed planning. Speed planning is one of the important contents of trajectory planning research. The quality of speed planning determines the performance of robots. The use of different speed planning schemes for different operating situations can greatly improve the productivity of modern industrial robots and reduce the burden on workers[6]. Among them, the speed planning directly affects the robot trajectory and affects the quality of work[7]. If, when the variable acceleration occurs a sudden change in the planning, the robot will have an impact, which will affect the robot control accuracy[8].

This article intends to conduct a comparative study on three commonly used speed planning methods to provide a reference for the selection of robot end speed control under different tasks.
2. Cubic polynomial velocity planning

2.1 Cubic polynomial velocity planning algorithm
The cubic polynomial speed planning is suitable for the situation where the initial position and speed, the end position and speed of the trajectory are known[9]. Let the cubic polynomial have the form:

\[ S(t) = a_0 + a_1t + a_2t^2 + a_3t^3 \]  

(1)

Obviously, the velocity function can be obtained by first-order derivative:

\[ \dot{S}(t) = a_1 + 2a_2t + 3a_3t^2 \]  

(2)

The acceleration function can be obtained by second-order derivative:

\[ \ddot{S}(t) = 2a_2 + 6a_3t \]  

(3)

In order to obtain a smooth motion curve, at least four constraints are required. Regarding the two adjacent points of the trajectory as the starting point and the end point of a short section of displacement, represented by \( S_0 \) and \( S_f \) respectively, the constrained starting velocity is \( V_0 \) and the ending velocity is \( V_f \):

\[
\begin{align*}
S(t_0) &= S_0 = a_0 \\
S(t_f) &= S_f \ \\
\dot{S}(t_0) &= v_0 \\
\dot{S}(t_f) &= v_f
\end{align*}
\]

(4)

Substituting constraint conditions into Eq.(1), Eq.(2) and Eq.(3), the coefficients can be obtained:

\[
\begin{align*}
a_0 &= S_0 \\
a_1 &= v_0 \\
a_2 &= \frac{3}{t_f^2} (S_f - S_0) - \frac{1}{t_f} (2v_0 + v_f) \\
a_3 &= \frac{2}{t_f^3} (S_0 - S_f) + \frac{1}{t_f^2} (v_0 + v_f)
\end{align*}
\]

(5)

2.2 Analysis of cubic polynomial speed planning curve
In the simulation verification of the cubic polynomial speed planning algorithm, it is assumed that the acceleration period and the deceleration period have the same time and the same displacement length. Considering the actual situation, there will be two situations: the maximum speed reaches the expected speed and the expected speed is not reached. Among them, the expected speed is divided into maximum speed higher than expected speed and lower than expected speed.

2.2.1 Can reach the expected speed. Assuming that the expected maximum speed is \( V_{\text{max}} = 25 \text{mm/s} \), the starting point of the displacement \( S_0 = 0 \text{mm} \), the end point \( S_f = 180 \text{mm} \), the constrained starting speed is \( V_0 = 0 \text{mm/s} \), and the ending speed is \( V_f = 0 \text{mm/s} \).

The running result is shown in ‘figure 1’:
Figure 1. Can reach the expected speed

It can be seen from ‘figure 1’ that the time required to reach the maximum speed is 5s, and the constant speed period of movement at the maximum speed is 4s, and the total time is 14s.

2.2.2 Cannot reach the expected speed

When the displacement is short, the expected maximum speed may not be reached during the speed planning process and the speed needs to be decelerated.

Figure 2. Cannot reach the expected speed

The cubic polynomial speed plan can be seen from ‘figure 2’ when it fails to meet expectations, ‘figure 2(a)’ has a maximum speed of 25mm/s and a displacement of only 80mm. When it accelerates to the expected speed, it starts to decelerate immediately. There is no uniform speed process in the middle, and the total time is 10s. In ‘figure 2(b)’, because the total displacement is only 40mm, the maximum speed is only 15mm/s, which is lower than the expected maximum speed of 25mm/s, and the total time is 8s. It can be seen from the comparison of ‘figure 1’ and ‘figure 2’ that when the displacement is large enough, the maximum speed of the speed plan can reach the expected speed and there is a uniform speed section; when the displacement is gradually reduced, the uniform speed section gradually becomes shorter to disappear, and even the maximum speed cannot reach The expected speed starts to decelerate.

It can be seen from the simulation results that the speed curve obtained by the cubic polynomial speed planning has obvious inflection points at the segment connection, and the acceleration curve will change suddenly at the junction of each segment, which will affect the stability and positioning accuracy of the robot during the movement. This method can be used in robot palletizing and material handling tasks. These tasks do not require high stability and positioning accuracy of the robot.
movement, and some deviations are allowed.

3. Quintic polynomial velocity planning
In order to obtain a motion curve with continuous acceleration, the position and velocity need suitable initial and final conditions, as well as appropriate initial and final acceleration values. There are six boundary conditions in this way, so it is necessary to use quintic polynomial trajectory interpolation, and simulate the quintic polynomial velocity planning to obtain the velocity and acceleration functions[10].

3.1 Quintic polynomial velocity planning algorithm
Suppose the quintic polynomial has the following form:

\[
S(t) = a_0 + a_t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5
\]

(6)

Its velocity function expression is:

\[
\dot{S}(t) = a_1 + 2a_2t + 3a_3t^2 + 4a_4t^3 + 5a_5t^4
\]

(7)

The acceleration function expression is:

\[
\ddot{S}(t) = 2a_2 + 6a_3t + 12a_4t^2 + 20a_5t^3
\]

(8)

3.2 Analysis of the quintic polynomial velocity planning curve
Assuming that the acceleration period and the deceleration period have the same time, the expected maximum speed is \(v_{\text{max}}=25\text{mm/s}\), and the starting point of the displacement \(S_0=0\text{mm}\); the constrained start speed is \(v_0=0\text{mm/s}\), and the end speed is \(v_f=0\text{mm/s}\);

3.2.1 Can reach the expected speed. It can be seen from ‘figure 3’ that it took 5s for the speed to go from 0 to the expected maximum speed, and the uniform speed was maintained for 5s. When the total time is determined, the total displacement is 220mm.

![Figure 3. Can reach the expected speed](image)

3.2.2 Cannot reach the expected speed. As with the cubic polynomial speed planning, when the displacement is gradually reduced, the uniform speed section may disappear and the expected speed may not be reached. The simulation result is shown in ‘figure 4’:

![Figure 4. Cannot reach the expected speed](image)
When the fifth-order polynomial fails to meet expectations, it can be seen from ‘figure 4(a)’ that when the displacement is reduced to 95mm, the maximum speed can also reach 25mm/s, and the total time is 10s. When the displacement is further reduced, as shown in ‘figure 4(b)’, the displacement is only 70mm, and the maximum speed is lower than the expected maximum speed. The maximum speed is only 17mm/s, and the total time is only 8s.

From the simulation results, the fifth-order polynomial velocity curve is excessively smooth at the joints of each section, and there is no obvious inflection point. The acceleration curve is also a continuous curve, and there is no sudden change. It can significantly improve the stability and positioning accuracy of the robot’s motion, and is suitable for tasks requiring stable robot motion, such as the loading and unloading of presses, and the assembly of workpieces. These tasks require the robot to maintain stability during the motion process, and require the robot to have high positioning accuracy during the motion process.

4. Five-segment S-curve speed planning

The acceleration function curve of the five-segment S-curve speed planning is also continuously changing. Its advantage is that the acceleration can be controlled so that the acceleration of the robot during the movement process meets the requirements of the acceleration range.

4.1 Five-segment S-curve speed planning algorithm

The five stages are divided into acceleration, acceleration and deceleration, uniform speed, deceleration and deceleration. Assuming that except for the constant speed section, the time of the rest four sections is equal to $T_a$, the total time is $T$, the speed of the constant speed section is $v_s$, the slopes of the four variable speed sections are all $A$, the total displacement of the entire trajectory is $L$, and the acceleration section displacement $L_1$, Acceleration and deceleration section displacement $L_2$.

Then the expressions of each period of time function and total time function are:

$$
T_a = \frac{v_s}{\sqrt{A}} \\
L_1 = \frac{1}{6} A T_a^3 \\
L_2 = \frac{5}{6} A T_a^3 \\
T = 4T_a + \frac{L - 2L_1 - 2L_2}{v_s}
$$

(9)

Its acceleration piecewise function is:
Integrate the acceleration piecewise function to get the velocity piecewise function:

\[
a(t) = \begin{cases} 
  A(t), & (0 \leq t \leq T_a) \\
  -A(t-2T_a), & (T_a \leq t \leq 2T_a) \\
  0, & (2T_a \leq t \leq T-2T_a) \\
  -A\left(t-(T-2T_a)\right), & (T-2T_a \leq t \leq T) \\
  A(t-T), & (T-T_a \leq t \leq T) 
\end{cases}
\]  

(10)

Integrate the acceleration piecewise function to get the velocity piecewise function:

\[
v(t) = \begin{cases} 
  \frac{1}{2} At^2, & (0 \leq t \leq T_a) \\
  -\frac{1}{2} A(t-2T_a)^2 + A T_a^2, & (T_a \leq t \leq 2T_a) \\
  \frac{1}{2} A(t-T+2T_a)^2 + A T_a^2, & (T-2T_a \leq t \leq T) \\
  \frac{1}{2} A(t-T)^2, & (T-T_a \leq t \leq T) 
\end{cases}
\]  

(11)

4.2 Analysis of Five-Segment S-curve Speed Planning Curve

The five-stage S-curve speed planning also has the two situations of the above two speed planning methods. Suppose the expected maximum speed is \(v_{\text{max}}=25\text{mm/s}\), the starting point of the displacement \(S_0=0\text{mm}\), the end point \(S_f=200\text{mm}\); the constrained starting speed is \(v_0=0\text{mm/s}\), the end speed is \(v_f=0\text{mm/s}\); the shift section slope \(A=3\).

4.2.1 Can reach the expected speed. Enter the given constraints, the simulation results are shown in ‘figure 5’:

![Figure 5. Can reach the expected speed](image)

Figure 5. Can reach the expected speed

It can be seen from ‘figure 5’ that the uniform speed section takes 6s, and the remaining four sections each take 2s. The total time is 14s, and the maximum acceleration can reach 10\text{mm/s}^2.

4.2.2 Cannot reach the expected speed. Two situations where the expected speed is not reached, the simulation results are shown in ‘figure 6’:
It can be seen from ‘figure 6(a)’ that keeping the slope and time of the shifting section unchanged, reducing the displacement to 150mm, the maximum speed can still reach the expected maximum speed of 25mm/s, and the time is reduced to 12s. It can be seen from ‘figure 6(b)’ that keeping the slope of the shifting section unchanged, and further reducing the displacement to 70mm, the maximum speed will not reach the expected maximum speed. The maximum speed is only 15mm/s, and the shifting section time will also be reduced. The total time is reduced to 9.5s.

The five-segment S-curve speed planning method can control the slope of the variable speed section, and realize the control of the movement speed by controlling the acceleration time, and the stability during the movement is also guaranteed. This speed planning method can be used in special tasks such as laser cutting and polishing. These tasks not only require the robot to move smoothly, but also require the robot to have a good control over the speed of movement.

5. Simulation experiment and result analysis

5.1 Simulation
Aiming at the above three speed planning methods, the ER_factory software developed by EFT Intelligent Equipment Co., Ltd. is used for offline programming simulation, and the ER3A robot model independently developed by EFT is selected. Taking linear trajectory motion as an example, set the same maximum speed and acceleration/deceleration time to verify the above three speed planning methods.

Set the absolute speed to 150mm/s and the movement time to 3s. During the experiment, the 20 points passed by the linear motion were recorded, the interval time of each point was 0.15s, and the coordinates of each point were output.

The robot end position coordinate data obtained by the simulation experiment is analyzed and calculated, and the displacement, velocity, and acceleration images of the three speed planning methods are drawn, as shown in ‘figure 7’ The experimental results are basically consistent with the expected results.
5.2 Selection of robot speed planning for specific tasks

As shown in ‘figure 8’, the robot takes the material from point A and places it in the four discharge positions of B, C, D and E. This process does not require high speed control and stability of the robot. The simulation results show that the third degree polynomial The speed planning method meets the requirements of this task.

‘Figure 9’ shows the loading and unloading of the press. The robot is required to take the material from A and B and feed it to C in the press, and then take out the good model from C and place it at D. During the process, the robot is required to move smoothly and accurately pick and place materials. The five-order multiple speed plan is selected, and the simulation experiment results show that the stability of the robot is guaranteed during the movement, and the positioning accuracy can also meet the requirements when picking and unloading materials.
As shown in ‘figure 10’, the robot uses a laser cutter to cut the steel plate, and the black line on the steel plate is the cutting path. The cutting process requires precise control of the trajectory and speed of the robot’s end. This task requires the use of a five-segment S-curve speed planning method. The simulation experiment results verify the feasibility of this method. During the movement, not only can the speed of the robot be controlled, but also the positioning accuracy during the movement can be guaranteed.

6. Conclusion
The article compares the speed and acceleration characteristics of the three kinds of speed planning, and concludes that different speed planning methods can be used in different robot tasks. It is verified by simulation experiments that selecting an appropriate speed planning method for specific tasks can improve positioning accuracy and stability, and lay a foundation for further research on robot speed planning in the future.

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