An Improved Control Method for Heavy-duty Truss Robot

Xin DING, Suo-huai ZHANG* and Meng-jie ZHU

College of Mechanical Engineering, Shanghai Institute of Technology, Shanghai 201418, China

*Corresponding author

Keywords: Heavy-duty robot, Dynamic characteristics, Control mode, Numeric simulation.

Abstract. The heavy-duty truss robot runs unsteadily, has large dynamic impact and low motion precision in the working process. In order to improve this phenomenon and work efficiency, an improved speed control method based on quintic function velocity curve is adopted and verified by numeric simulation software. The simulation results show that the quintic function velocity control curve has a gentler acceleration than the traditional S-curve and sinusoidal curve control method, and the acceleration value has been significantly reduced. The small change indicates that the truss robot based on this algorithm runs more smoothly and works more efficiently. In addition, the quintic function speed control curve has lower requirement for the required motor torque, which is also conducive to cost savings during object handling.

Introduction

Heavy-duty truss robot is one of industrial robots. Unlike ordinary industrial robots, truss robots are used to carry and place objects of high quality, with a weight of more than 1600 kg. At the same time of handling and placing heavy objects, the robot is required to have fast working efficiency, be able to accurately place heavy objects on the workstation, and the positioning accuracy is as high as possible.

When a truss robot completes a certain task, there are many ways of speed control, such as S-shaped speed curve, sinusoidal speed curve, quintic polynomial speed control curve [1-2]. The function of velocity curve is to determine the motion form between the starting and ending points in the actual motion process. Different velocity curves have different dynamic impact on the robot [3]. Because the dynamic impact has an important influence on the motion accuracy of the robot [4-6], the common velocity curves are compared in this paper. The dynamic impact of the robot in the motion process is expressed by acceleration, moment and other parameters [7-9].

Working Principle of Heavy-duty Truss Robot

The three-dimensional model of the heavy-duty truss robot is shown in Fig. 1. The heavy-duty truss robot has four degrees of freedom, which can move along the XYZ axis. At the same time, the end of the truss robot is equipped with a handling mechanical gripper, which can rotate along the Z axis. In addition, the gripper can move objects of different sizes by adjusting the distance between the two grippers. According to the requirements of the production line, the system should avoid the dynamic impact caused by the sudden change of acceleration as much as possible while moving objects quickly.

Because the span of X direction is too large, it is easy to be distorted and stuck in the course of moving, so two servo motors are installed on both sides of X direction to complete the movement of cross beam in X direction. Y direction can be achieved by using a servo motor, while Z axis expansion can be achieved by using the top mounted screw drive and the flank servo motor drive, which can reduce the "jitter" in the handling process, and the rotation of the gripper is driven by the servo motor. After startup, the system collects the specific position of the object to be carried by the upper computer, sends pulses to the X and Y direction servo motors, and then uses the gear and rack transmission structure to deliver the mechanical grasp to the object nearby, then lifts the Z axis, and then carries the object to the designated position, so that the whole process of handling is completed.
Motion Speed Control Mode

According to literature [10-12], the traditional truss robot moves independently on each axis, and then achieves the designated position through the speed combination of multiple steps. This method has the problems of long movement time and unstable motion. Therefore, the dynamic impact problem during the operation of the truss robot can be effectively avoided by using multi-axis linkage mode and simultaneously starting and stopping in multiple directions. In the process of multi-axis linkage of truss robot, the total running time is determined by the displacement of each direction and the maximum speed of each direction, namely:

\[ t = \max \left\{ \frac{L_x}{v_{x_{\text{max}}}}, \frac{L_y}{v_{y_{\text{max}}}} \right\} \]

Among them, \(L_x, L_y\) are displacement differences in two directions respectively.

Next, through several common speed control curves, the impact problem caused by multi-axis linkage process of truss robot is analyzed.

S-shaped Curve Speed Control

S-shaped curve is named for its shape similar to S-shaped curve in acceleration and deceleration stage. It is a commonly used speed control algorithm in current controllers. The acceleration and deceleration process of S-shaped curve is divided into seven stages, as shown in the following figure: \(t_0 - t_1\) in acceleration stage, \(t_1 - t_2\) in uniform acceleration stage, \(t_2 - t_3\) in deceleration stage, \(t_3 - t_4\) in uniform acceleration stage, \(t_4 - t_5\) in acceleration and deceleration stage, \(t_5 - t_6\) in uniform deceleration stage and \(t_6 - t_7\) in deceleration stage.

Assuming that the required distance of motion is \(L\), the upper limit of velocity is \(V_m\), the upper limit of acceleration is \(a_m\), the upper limit of acceleration is \(J_m\), the running time of constant acceleration is \(t_f\), the running time of constant acceleration is \(t_a\) and the running time of constant speed is \(t_v\).
From the definition, it can be seen that the time of acceleration change in seven segments has the following relationship:

\[ t_j = t_1 - t_0 = t_3 - t_2 = t_5 - t_4 = t_7 - t_6 \]
\[ t_a = t_2 - t_1 = t_6 - t_5 \]
\[ t_v = t_4 - t_3 \]

When \( t_0 < t < t_1 \) and \( t_0 = 0 \), the equations of displacement, velocity and acceleration are as follows:

\[ S(t) = \frac{1}{6} J_m t^3 \]
\[ V(t) = \frac{1}{2} J_m t^2 \]
\[ a(t) = J_m t \]

When \( t_1 < t < t_2 \), the equations of displacement, velocity and acceleration are as follows:

\[ S(t) = \frac{1}{2} J_m t_j (t - t_1)^2 + V(t_1)(t - t_1) + X(t_1) \]
\[ V(t) = J_m t_j (t - t_1) + V(t_1) \]
\[ a(t) = J_m t_j \]

When \( t_2 < t < t_3 \) the equations of displacement, velocity and acceleration are as follows:

\[ S(t) = -\frac{1}{6} J_m t_j (t - t_2)^3 + \frac{1}{2} a(t_2)(t - t_2)^2 + V(t_2)(t - t_2) + X(t_2) \]
\[ V(t) = -\frac{1}{2} J_m t_j (t - t_2)^2 + a(t_2)(t - t_2) + V(t_2) \]
\[ a(t) = -J_m t_j + a(t_2) \]

From this we can see that the velocity of each inflection point is:

\[ V(t_1) = \frac{1}{2} J_m t_1^2 \]
\[ V(t_2) = J_m t_j t_a + \frac{1}{2} J_m t_j^2 \]
\[ V(t_3) = -\frac{1}{2} J_m t_j^2 + J_m t_j t_a + V(t_2) = J_m t_j^2 + J_m t_j t_a \]

Then the maximum velocity at \( t_3 \) is the maximum velocity and the maximum velocity is:

\[ V_m = V(t_3) = J_m t_j^2 + J_m t_j t_a. \]

According to the symmetry of S-shaped curve, the expression of distance \( L \) is as follows:

\[ L = 2X(t_3) + S(t_v). \]

In the formula, \( S(t_v) \) represents the displacement in the uniform stage, and the velocity in the uniform stage is the maximum velocity \( V_m \) in the whole operation process. So the duration \( t_v \) of uniform motion is:

\[ t_v = L - (2J_m t_j^3 + 3J_m t_j^2 t_a + J_m t_j t_a^2) / V_m. \]

In summary, the relationship between distance \( L \) and \( J_m, t_j, t_a, t_v \) is as follows:

\[ L = J_m (2t_j^3 + 3t_j^2 t_a + t_j t_a^2 + t_j^2 t_v + t_j t_a t_v). \]

**Sinusoidal Acceleration and Deceleration Curve**

Acceleration equation:
\[ a(t) = \begin{cases} 
  a_m \sin \omega t & 0 \leq t \leq t_1 \\
  0 & t_1 \leq t \leq t_2 \\
  -a_m \sin \omega t & t_2 \leq t \leq t_3 
\end{cases} \]  \tag{9}

Among them, \( \omega \) is the undetermined coefficient, \( t_1 \) is the end time of sinusoidal acceleration, and \( t_2 \) is the start time of sinusoidal deceleration.

The velocity equation can be obtained by integrating the acceleration equation (9):

\[ v(t) = \begin{cases} 
  a_m (1 - \cos \omega t) / \omega & 0 \leq t \leq t_1 \\
  v_m & t_1 \leq t \leq t_2 \\
  a_m [1 + \cos \omega (t - t_2)] / \omega & t_2 \leq t \leq t_3 
\end{cases} \]  \tag{10}

Among them, \( v_m \) is the maximum velocity.

The displacement equation can be obtained by integrating the velocity equation (10):

\[ s(t) = \begin{cases} 
  a_m (t - \sin \omega t / \omega) / \omega & 0 \leq t \leq t_1 \\
  S_1 + v_m (t - t_1) & t_1 \leq t \leq t_2 \\
  S_1 + S_2 + a_m (t - t_2) - \sin \omega (t - t_2) / \omega & t_2 \leq t \leq t_3 
\end{cases} \]  \tag{11}

Among them, \( S_1 = \frac{a_m t_1}{\omega} \), \( S_2 = v_m (t_2 - t_1) \).

By definition: \( \omega t_1 = \pi \), and \( t = t_1 \),

\[ \omega = \frac{2a_m}{v_m}, \ t_1 = \frac{\pi}{\omega} = \frac{\pi v_m}{2a_m}, \ S_1 = \frac{\pi v_m}{4a_m}, \]

Critical state: \( t_1 = t_2 \), i.e. non-uniform stage, at which the maximum velocity \( v_{set} \) obtained satisfies \( S_1 = \frac{L}{2} \).

Then: \( v_{set}^2 = \frac{2a_m L}{\pi} \)  \tag{12}

In the formula, \( L \) is the total displacement of operation.

According to the symmetry of sinusoidal acceleration and deceleration motion, we can see that:

\[ T = 2t_1 + \frac{L - 2S_1}{v_m}, t_2 = T - t_1. \]

Finally, the relationship between total displacement, velocity and planning time can be obtained:

\[ T = t_1 + \frac{L}{v_m}. \]  \tag{13}

In the formula, \( T \) is the total running time.

**Quintic Function Curve**

Displacement equation:

\[ S(t) = k_5 t^5 + k_4 t^4 + k_3 t^3 + k_2 t^2 + k_1 t + k_0, \]

\[
\begin{align*}
  k_0 &= x_0 \\
  k_1 &= v_0 \\
  k_2 &= a_0 / 2 \\
  k_3 &= (20x_1 - 20x_0 - 8v_1 T - 12v_0 T - 3a_0 T^2 + a_1 T^2) / (2T^3) \\
  k_4 &= (30x_1 - 30x_0 + 14v_1 T + 16v_0 T + 3a_0 T^2 - 2a_1 T^2) / (2T^4) \\
  k_5 &= (12x_1 - 12x_0 - 6v_1 T - 6v_0 T - a_0 T^2 + a_1 T^2) / (2T^5)
\end{align*}
\]  \tag{14}
Among them, $x_0$ and $x_1$ are the starting and ending speed, $a_0$ and $a_1$ are the starting and ending acceleration, and $T$ is the total running time; $t \in [0, T]$.

Constraint $S(T) = L$, $S'(0) = 0$, $S'(T) = 0$, $S''(0) = 0$, $S''(T) = 0$.

Formula (14) can be changed to

$$\begin{cases}
    k_0 = 0 \\
    k_1 = 0 \\
    k_2 = 0 \\
    k_3 = \frac{10L}{T^3} \\
    k_4 = -\frac{15L}{T^4} \\
    k_5 = \frac{6L}{T^5}
\end{cases}$$

Then the displacement equation of the quintic function is:

$$S(t) = \frac{10L}{T^3} t^3 - \frac{15L}{T^4} t^4 + \frac{6L}{T^5} t^5. \quad (15)$$

**Simulation Analysis**

The truss robot is modeled by NX three-dimensional software. The movement of X and Y direction is accomplished by servo motor with reducer as power system and gear rack as transmission system respectively. The total length of X direction is 12m, and the total span of Y direction is 8m. In actual working conditions, the displacements of X direction and Y direction are 7.68m and 3.78m respectively, and the total running time is 10s.

In order to compare the influence of three speed control methods on the smooth operation of truss robots, the three-dimensional model is imported into ADAMS software for simulation analysis and comparison. Adding gear pairs and corresponding motion in XY direction respectively, the control function of motion is completed by new SPLINE text. Since the model imported directly is a pure rigid body model, only one motion function in X direction is retained. According to the above analysis, the velocity (or displacement) equations of the three speed control modes are as follows:

1) S-shaped curve:

- **X direction:**
  $$v(t) = \begin{cases}
    2t^2 & 0 \leq t \leq 0.3 \\
    0.18 + 1.2(t - 0.3) & 0.3 \leq t \leq 0.7 \\
    0.66 + 1.2(t - 0.7) - 2(t - 0.7)^2 & 0.7 \leq t \leq 1 \\
    0.84 & 1 \leq t \leq 9, \\
    0.84 - 2(t - 9)^2 & 9 \leq t \leq 9.3 \\
    0.66 - 1.2(t - 9.3) & 9.3 \leq t \leq 9.7 \\
    0.18 - 1.2(t - 9.7) + 2(t - 9.7)^2 & 9.7 \leq t \leq 10
  \end{cases}$$

- **Y direction:**
  $$v(t) = \begin{cases}
    t^2 & 0 \leq t \leq 0.3 \\
    0.09 + 0.6(t - 0.3) & 0.3 \leq t \leq 0.7 \\
    0.33 + 0.6(t - 0.7) - (t - 0.7)^2 & 0.7 \leq t \leq 1 \\
    0.42 & 1 \leq t \leq 9. \\
    0.42 - (t - 9)^2 & 9 \leq t \leq 9.3 \\
    0.33 - 0.6(t - 9.3) & 9.3 \leq t \leq 9.7 \\
    0.09 - 0.6(t - 9.7) + (t - 9.7)^2 & 9.7 \leq t \leq 10
  \end{cases}$$

2) Sinusoidal curve:

- **X direction:**
\[ v(t) = \begin{cases} 
0.42(1 - \cos \pi t) & 0 \leq t \leq 1 \\
0.84 & 1 < t \leq 9 \\
0.42[1 + \cos \pi(t - 9)] & 9 < t \leq 10 
\end{cases} \]

Y direction:

\[ v(t) = \begin{cases} 
0.21(1 - \cos \pi t) & 0 \leq t \leq 1 \\
0.42 & 1 < t \leq 9 \\
0.21[1 + \cos \pi(t - 9)] & 9 < t \leq 10 
\end{cases} \]

3) Quintic function curve:

X direction:

\[ S(t) = 4.536 \times 10^{-4} \times t^5 - 1.134 \times 10^{-2} \times t^4 + 7.56 \times 10^{-2} \times t^3 \quad 0 \leq t \leq 10, \]

Y direction:

\[ S(t) = 2.268 \times 10^{-4} \times t^5 - 0.567 \times 10^{-2} \times t^4 + 3.78 \times 10^{-2} \times t^3 \quad 0 \leq t \leq 10. \]

The results of ADAMS simulation are as follows:

Figure 3 shows the output torque diagram of the cross-beam gear. By measuring the torque of the cross-beam gear and utilizing the transmission ratio relationship, the actual output torque of the motor and the power of the motor can be deduced. It can be seen from the graph that the required torque of truss robot motor is reduced by one third by using quintic function speed curve control mode. In the first five seconds, the acceleration increases first and then decreases, which leads to the increase and then decreases of the torque. In the second five seconds, the acceleration is negative, and the change mode is the same as the first five seconds, but the motor is in the deceleration state, and the deceleration setting is carried out through the built-in brake.

![Torque Diagram of Cross Beam Gear](image)

Figure 3. Torque figure of cross-beam gear.

Figures 4 to 6 show the acceleration, acceleration and velocity contrast diagrams at the end of the claw respectively. The above parameters can better reflect the stability of the truss robot during operation. In Fig. 4, the quintic function speed curve control method has a maximum acceleration of about 450mm/s$^2$ during the operation of the truss robot. Compared with the other two methods, the acceleration value has been significantly reduced and the transition is smoother. At the same time, there is no "jitter" phenomenon in acceleration, so the vibration performance of truss robot has been greatly improved.
Summary
Aiming at several speed control modes commonly used in motor at present, through ADAMS simulation experiments, it can be seen that quintic function speed curve mode can improve the stability of truss robot in the whole operation process, reduce the rigid impact caused by sudden acceleration change, ensure the smoothness of the trajectory of truss robot, and improve the motion accuracy of truss robot. The maximum torque of external motor is reduced by one third. Therefore, the motor with smaller power can be selected to save the cost.
Acknowledgement

This research was financially supported by the National Natural Science Foundation of China. (Projection No. 51475311)

Reference

[1] Yang Chao, Zhang Dongquan. Acceleration and deceleration control of stepping motor based on S-curve [J]. Mechatronics Engineering, 2011, 28 (7): 813-817.

[2] You Wenhui, Wang Xiufeng, Lu Wenqi, et al. Design of trajectory planning interpolation system for industrial manipulators [J]. Mechatronics Engineering, 2019, 36 (2): 190-196.

[3] Zhang Li, Yang Dongsheng, Wang Yunsen, et al. NURBS interpolation forward-looking control algorithm based on cubic polynomial acceleration and deceleration [J]. Modular machine tools and automation processing technology, 2014 (3): 1-8.

[4] Li Hongbin, Xu Yichen, Lu Zhan. Trajectory optimization of packing and palletizing robot based on S-curve [J]. Packaging Engineering, 2018, 39 (17): 187-191.

[5] Pan Haihong, Yang Wei, Chen Lin, et al. Adaptive piecewise NURBS curve interpolation algorithm for acceleration and deceleration control of full S-curve [J]. China Mechanical Engineering, 2010, 21 (2): 190-195.

[6] Mu Haihua, Zhou Yunfei, Yan Sijie, et al. Research on 4-order trajectory planning algorithm for Ultra-precision point-to-point motion [J]. China Mechanical Engineering, 2007, 18 (19): 2346-2354.

[7] Du Qiaolian, Chen Xuhui, Shu Baihe. An improved trajectory planning method for robots [J]. Mechanical design, 2017, 34 (3): 31-35.

[8] Zhang Bin, Fang Qiang, Colin. Optimal time trajectory planning for large rigid body attitude adjustment system [J]. Journal of Mechanical Engineering, 2008, 44(8): 248-252.

[9] Haddad M, Khalil W, Lehtihet H E. Trajectory Planning of Unicycle Mobile Robots with a Trapezoidal-velocity Constraint [J]. IEEE Transactions on Robotics, 2010, 26 (5): 954-962.

[10] Peng Fang, Li Ping, Zhou Wenhui. Research on multi-axis path planning of rectangular coordinate manipulator [J]. Modular machine tools and automatic processing technology, 2012 (7): 71-74.

[11] Fu Yunzhong, Wang Yongzhang, Fu hongya, et al. Multi-axis linear interpolation and its "S acceleration and deceleration" programming algorithm [J]. Manufacturing Technology and Machine Tools, 2003, 11 (3): 375-382.

[12] Shi chuan, Zhao Tong, Ye Peiqing, et al. Planning of acceleration and deceleration control for S-curve of CNC system [J]. China Mechanical Engineering, 2007, 18 (12): 1421-1425.