International Journal of Robotics and Automation (IJRA)
Vol. 6, No. 2, June 2017, pp. 112~120
ISSN: 2089-4856, DOI: 10.11591/ijra.v6i2.pp112-120

Delta Parallel Robot Based on Crank-Slider Mechanism

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Article Info

Article history:

Received Feb 6, 2017
Revised Apr 20, 2017
Accepted May 5, 2017

Keyword:

Crank-slider mechanism
Delta parallel robot
Force transmission
Pick-and-place operation

ABSTRACT

A three-degree-of-freedom Delta parallel manipulator driven by a crank-slider mechanism is proposed. In Cartesian space, a gate-shaped curve is taken as the path of the pick-and-place operation, combining with the inverse kinematics theory of the Delta robot, and a mathematical model of robot statia force transmission is established. The force and the output torque of the robot-driven joint are taken as the main performance indexes, and the value of the crank-slider mechanism applied to Delta robot is further measured. The simulation results show that the delta robot driven by the crank slider mechanism can reduce the force and output torque of the driving joint during the picking and discharging operation, and has good practical application value.

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1. INTRODUCTION

The Delta mechanism with three-degree-of-freedom has been proposed by Dr. CLAVEL since 1985[1]. It is widely used in electronics, food, medicine and other fields with the advantages of high bearing capacity, high positioning accuracy, simple structure, easy to achieve high-speed movement, etc[2-4]. At present, the Delta series of robots institutions developed by Pierrot team include H4 I4, Heli4 and Par4 and so on[5-7] in which industrial acceleration reaches 12g and experimental acceleration reaches 20g of Par4. Adept company developed a four degree of freedom high-speed SCARA parallel robot based on the prototype[8] of Par4 robot. And the robot claims to be the fastest in the world. Huang Tian[9] simplified Delta mechanism as Planar mechanism Diamond and invented TJU-Delta manipulator.

Nowadays, the stimulation from the huge demand of Delta series robot in industry, it is particularly important to improve the precision, stability and rigidity of Delta robot's high-speed， high-frequency and pick-and-place operation. To further improve the accuracy, stability and stiffness of the high-speed, high-frequency and pick-and-place operation, the present ways cover two aspects: reducing the inertia of moving parts by lightweight design, improving the dynamic performance index by scale integrated[9]; reducing the deviation between the actual pose and the pose of the command using high speed and high precision control system[10]; making a good path planning of pick-and-place operation of end effector to shorten the cycle and reduce the structural vibration[11-13].

The research results[14-15]and related advantages of rotary drive Delta robots and linear drive Delta robots were absorbed.Therefore, it put forward Delta parallel robot driven by crank-slider mechanism with three-degree freedom as show in Figure 1 to reduce the force and output torque of the external rotation pair of Delta robot, then improve the movement accuracy, stability and stiffness and the research focus on the most important operation mode pick-and-place operation [13].

By planning the movement trajectory of the robot pick-and-place operation, the input of the driving joint is solved by using the inverse kinematics theory of Delta parallel mechanism.Finally, the static transfer model of robot pick-and -place operation is constructed to analyze the force transfer performance of the mechanism, and under the virtual prototype software the model is designed to prove its practical value.

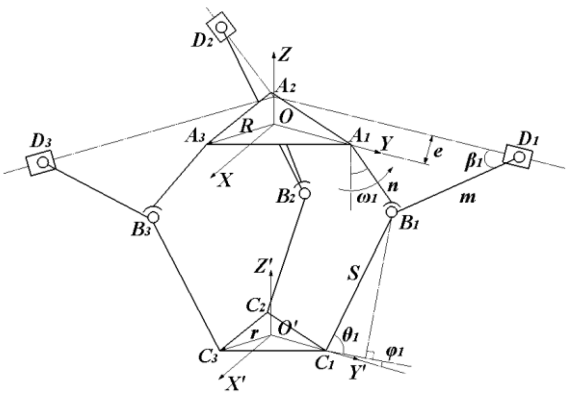


Figure 1. Sketch diagram of Delta mechanism

2. RESEARCH METHOD

2.1 Path planning of pick-and-place operation

The pick-and-place operation consists of three parts, including vertical-horizontal-vertical, as shown in Figure 2. The robot's ending part moves from point A at the time of t = 0, completes the entire pick-and-place operation at point D, and divides the whole motion process from A to D into N parts according to time shown in equation (1) Sequence, [13]which is analyzing the position coordinates, velocity and acceleration information about the robot's ending part relative to the time variable t.

$$t_i = T \cdot \frac{i}{N}(i = 0,1,\cdots,N) \tag{1}$$

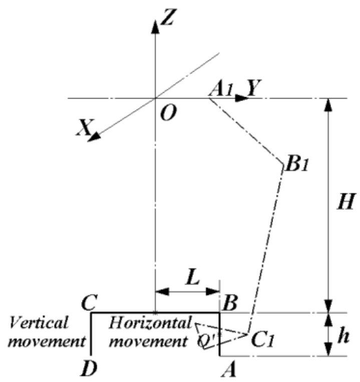


Figure 2. Pick and place operation track

The robot moves along the vertical axis from point A to point B when $0 \leq S_{AB}(t_i) \leq h$, during this process, the position coordinates, velocity and acceleration about t_i are as follows (2)

$$\begin{cases} \boldsymbol{S_{AB}} = (0 \quad L/2 \quad -S_{AB}(t_i) - H)^T \\ \boldsymbol{V_{AB}} = \left(0 \quad 0 \quad -S'_{AB}(t_i)\right)^T \\ \boldsymbol{A_{AB}} = \left(0 \quad 0 \quad -S''_{AB}(t_i)\right)^T \end{cases} \tag{2}$$

When $-L/2 \le S_{BC}(t_i) \le L/2$, the robot's ending part moves from point B to point C in the horizontal direction. At this time, the motion path height z remains unchanged, the position coordinates, velocity and acceleration about t_i are as follows (3)

$$\begin{cases} \boldsymbol{S_{BC}} = (0 \quad S_{BC}(t_i) \quad -H)^T \\ \boldsymbol{V_{BC}} = (0 \quad S'_{BC}(t_i) \quad 0)^T \\ \boldsymbol{A_{BC}} = (0 \quad S''_{BC}(t_i) \quad 0)^T \end{cases} \tag{3}$$

Finally, the robot's ending part moves from point C down to point D along the vertical axis to complete the entire pick-up process when $0 \le S_{CD}(t_i) \le h$. At this time, the position coordinates, velocity and acceleraion about t_i are as follows (4)

$$\begin{cases} \boldsymbol{S_{CD}} = (0 \quad -L/2 \quad -S_{CD}(t_i) - H)^T \\ \boldsymbol{V_{CD}} = \left(0 \quad 0 \quad -S'_{CD}(t_i)\right)^T \\ \boldsymbol{A_{CD}} = \left(0 \quad 0 \quad -S''_{CD}(t_i)\right)^T \end{cases} \tag{4}$$

Through the above equations (2) ~ (4), you can ensure the position coordinates S, speed V, acceleration A that are relative to the changing of t about the robot's ending part movement in the entire pick-up cycle.

2.2 Input solution of driving joints of Delta mechanisms

After solving the motion position of coordinate S about the robot's ending part in the base, the input of the driving joint can be solved by using the Delta parallel mechanism inverse theory[16].From Figure 1, the vectors position A_i and B_i in the coordinate system $O - XYZ$ are shown below (5-6).

$$\begin{bmatrix} \boldsymbol{A_{1O}} \\ \boldsymbol{A_{2O}} \\ \boldsymbol{A_{3O}} \end{bmatrix}^T = \begin{bmatrix} 0 & -\frac{\sqrt{3}R}{2} & \frac{\sqrt{3}R}{2} \\ R & -\frac{R}{2} & -\frac{R}{2} \\ 0 & 0 & 0 \end{bmatrix} \tag{5}$$

$$\boldsymbol{B_{iO}} = \begin{bmatrix} \cos\eta_i\,(n\sin\omega_i + R) \\ \sin\eta_i\,(n\sin\omega_i + R) \\ -n\cos\omega_i \end{bmatrix} \tag{6}$$

$\eta_i = (4i - 1)\pi/6$ $(i = 1,2,3)$.

It is also known that the vector position C_i in the coordinate system $O' - X'Y'Z'$ is as follows (7)

$$\begin{bmatrix} \boldsymbol{C_{1O'}} \\ \boldsymbol{C_{2O'}} \\ \boldsymbol{C_{3O'}} \end{bmatrix}^T = \begin{bmatrix} 0 & -\frac{\sqrt{3}r}{2} & \frac{\sqrt{3}r}{2} \\ r & -\frac{r}{2} & -\frac{r}{2} \\ 0 & 0 & 0 \end{bmatrix} \tag{7}$$

As can be seen from the above, the vector $\overrightarrow{OO'}$ can be expressed as an equation (8) in the $O - XYZ$ coordinate system.

$$\begin{bmatrix} \boldsymbol{S_{AB}} \\ \boldsymbol{S_{BC}} \\ \boldsymbol{S_{CD}} \end{bmatrix} = \begin{bmatrix} 0 & L/2 & -S_{AB}(t_i) - H \\ 0 & S_{BC}(t_i) & -H \\ 0 & -L/2 & -S_{CD}(t_i) - H \end{bmatrix} \tag{8}$$

Assuming that S $(S_{AB}, S_{BC}, S_{CD}) = (x, y, z)$; then the vector $\overrightarrow{B_iC_i}$ can be expressed as the following equation (9).

$$\overrightarrow{B_iC_i} = \boldsymbol{C_{iO'}} + \boldsymbol{S} - \boldsymbol{B_{iO}} \tag{9}$$

Therefore, according to $\left|\overrightarrow{B_iC_i}\right| = S$, we can deduce the following equation (10-12)

$$x^2 + (r + y - n\sin\omega_1 - R)^2 + (z + n\cos\omega_1)^2 = S^2 \quad (10)$$

$$\left(x - \frac{\sqrt{3}}{2}r + \frac{\sqrt{3}}{2}n\sin\omega_2 + \frac{\sqrt{3}}{2}R\right)^2 + \left(y - \frac{1}{2}r + \frac{1}{2}n\sin\omega_2 + \frac{1}{2}R\right)^2 + (z + n\cos\omega_2)^2 = S^2 \quad (11)$$

$$\left(x + \frac{\sqrt{3}}{2}r - \frac{\sqrt{3}}{2}n\sin\omega_3 - \frac{\sqrt{3}}{2}R\right)^2 + \left(y - \frac{1}{2}r + \frac{1}{2}n\sin\omega_3 + \frac{1}{2}R\right)^2 + (z + n\cos\omega_3)^2 = S^2 \quad (12)$$

Assuming that $k_i = \tan\left(\frac{\omega_i}{2}\right)$ （$i = 1,2,3$）, (10-12) can be simplified as a quadratic equation as follows (13):

$$R_i k_i^2 + P_i k_i + Q_i = 0 \ （i = 1,2,3） \quad (13)$$

By the root of the formula can be solved k_i

$$k_i = \frac{-P_i \pm \sqrt{P_i^2 - 4R_iQ_i}}{2R_i}$$

The R_i, P_i, Q_i are all known quantities. Therefore, to achieve the planned pick and place operation trajectory, the corresponding joint drive input control angle should be as the formula (14).

$$\omega_i = 2arc\tan k_i \quad （i = 1,2,3） \quad (14)$$

2.3 Static transmission mathematical model of the Delta mechanism

2.31 The establishment of force transfer model

After ensuring the joint drive input angle has been controlled, this essay will use the Delta parallel robot driven by the crank-slider to analyze the force transmission performance of the mechanism[17]. Assuming that the load of the moving platform in the Delta parallel robot pick-up operation is G, the force of the three branches on the moving platform is shown in Figure 3. According to the dynamic platform vertical and horizontal force balance, we can get the following formula (15).

$$\begin{cases} \sum_{i=1}^{3} f_i \sin\theta_i = G \\ \sum_{i=1}^{3} f_i \cos\theta_i \cos\varphi_i = 0 \\ \sum_{i=1}^{3} f_i \cos\theta_i \sin\varphi_i = 0 \end{cases} \quad (15)$$

θ_i is the angle between the connection of the moving platform and the moving platform plane, and φ_i is the angle between the plane of the moving platform and the x' axis.

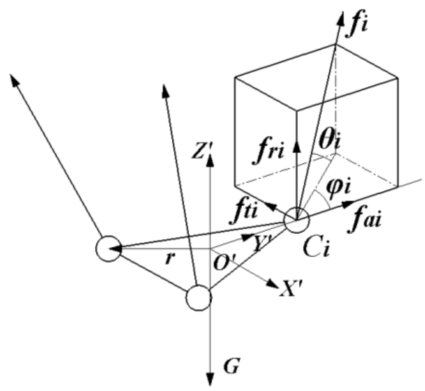


Figure 3. Force diagram of Delta platform

According to the force and the reaction force is equal, then $f_i = F_i$ (16), the force decomposition of F_i is shown in Figure 4.

$$\begin{cases} F_{ai} = F_i \cos\gamma_i \cos\alpha_i \\ F_{ti} = F_i \cos\gamma_i \sin\alpha_i \\ F_{ri} = F_i \sin\gamma_i \end{cases} \tag{16}$$

Assuming that the plane of the crank-slider mechanism is π , it is easy to obtain the equation (17) after the orthogonal decomposition is done on the π plane.

$$\begin{cases} F_{Ai} = F_{ai} + F_{Di} \sin(\omega_i - \beta_i) \\ F_{Di} \cos(\omega_i - \beta_i) = F_{ti} \end{cases} \tag{17}$$

According to corresponding geometric relationship, it can be derived as the following formula (18).

$$\tan\beta_i = \frac{e + m\cos\omega_i}{n} \tag{18}$$

At this time, the driving arm AB is subjected to the force M_i perpendicular to the π plane (19).

$$M_i = F_{ri} \times m \tag{19}$$

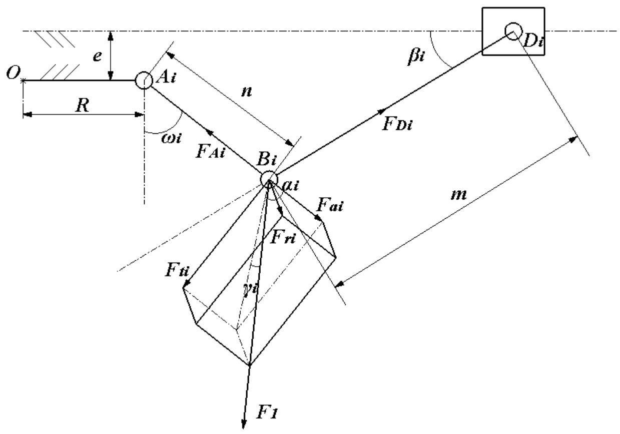


Figure 4. Force diagram of Delta platform

2.32 The effect of the crank-slider on the drive joint

After orthogonal force decomposition of the Delta parallel mechanism, which is not driven by the crank-slider mechanism, it is easy to obtain the following formula (20).

$$F'_{Ai} = F'_{ai} = F'_i \cos\gamma'_i \cos\alpha'_i \tag{20}$$

The driving arm AB is subjected to the force M'_i perpendicular to the π plane and the firce M''_i on a π plane (21).

$$\begin{cases} M'_i = F'_{ri} \times m \\ M''_i = F'_{ti} \times m \end{cases} \tag{21}$$

On the impact of the force on the drive joints (22)

$$\Delta F_{Ai} = F_{Ai} - F'_{Ai} \tag{22}$$

Therefore, the equations (23) can be solved by combining the above equations (16) to (18) and (20).

$$\Delta F_{Ai} = F_i \sin\gamma_i \cdot \frac{\tan\omega_i - \frac{e+m\cos\omega_i}{n}}{1+\frac{\tan\omega_i(e+m\cos\omega_i)}{n}} \tag{23}$$

$|\omega_i|$, $|\gamma_i| \in (0, \pi/2)$.

When$\Delta F_{Ai} < 0$, the crank-driven Delta parallel mechanism in the pick-and-place operation make the joint bear the smaller force. On the impact of the output coupling torque of the joint (24)

$$\Delta M_i = M_i - \sqrt{(M_i')^2 + (M_i'')^2} \tag{24}$$

Through the formulas (20) and (22) we can draw the conclusion: $\Delta M_i = m\left(F_{ri} - \sqrt{(F'_{ri})^2 + (F'_{ti})^2}\right) < 0$, The crank-driven Delta parallel mechanism requires a smaller force output by the driving joint in the pick-and-place operation.

3. RESULTS AND ANALYSIS

The Delta robot prototype model was established by the virtual prototype software, as show in Figure 5. The corresponding parameters of Delta parallel mechanism was shown in Table 1, and the example analysis of the pick and place operation of the movement simulation trajectory was shown in Figure 2, the corresponding drive joint control The angle ω_i （$i = 1,2,3$） is shown in Figure 6.

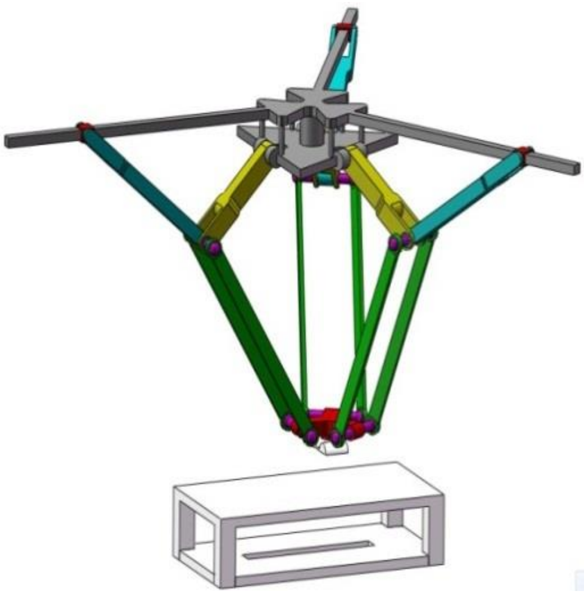


Figure 5. Virtual prototyping model of Delta robot

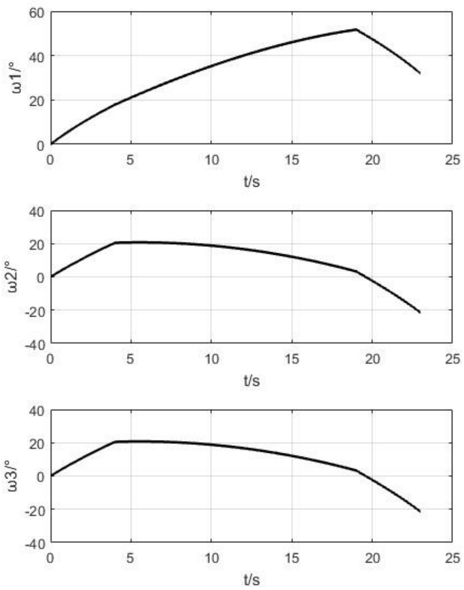


Figure 6. Opening angle ω_i of the drive joint

Table 1. Delta mechanism parameters

characteristic	R/mm	r/mm	n/mm	S/mm	m/mm	e/mm	h/mm	L/mm	point A-Coordinate/mm	G/N
parameter	$\frac{200\sqrt{3}}{3}$	40	120	240	200	40	40	75	0, 75, -317	10

3.1 The driving joint force analysis

According to the formula (23),$|\omega_i|$, $|\gamma_i| \in (0, \pi/2)$, We can assume that the function $f(\omega_i)$ is as follows (25).

$$f(\omega_i) = \tan\omega_i - \frac{e+m\cos\omega_i}{n} \tag{25}$$

① When $\omega_i \in (-\pi/2,\ 0)$, $f(\omega_i) < 0$, it is easy to obtain $\Delta F_A < 0$, so driving joint of Delta parallel robot using crank-driven bears the smaller force in the pick-and-place operation.
②$\omega_i \in (0,\ \pi/2)$, To $f(\omega_i)$ for the guide.

$$f'(\omega_i) = \frac{1}{(\cos\omega_i)^2} + \frac{5}{3}\sin\omega_i > 0$$

$f(\omega_i)$ is monotonically increasing in $\omega_i \in (0,\ \pi/2)$ (26). Combining Figure 6 we can know that the input drive joint controls the range of angle ω_i.

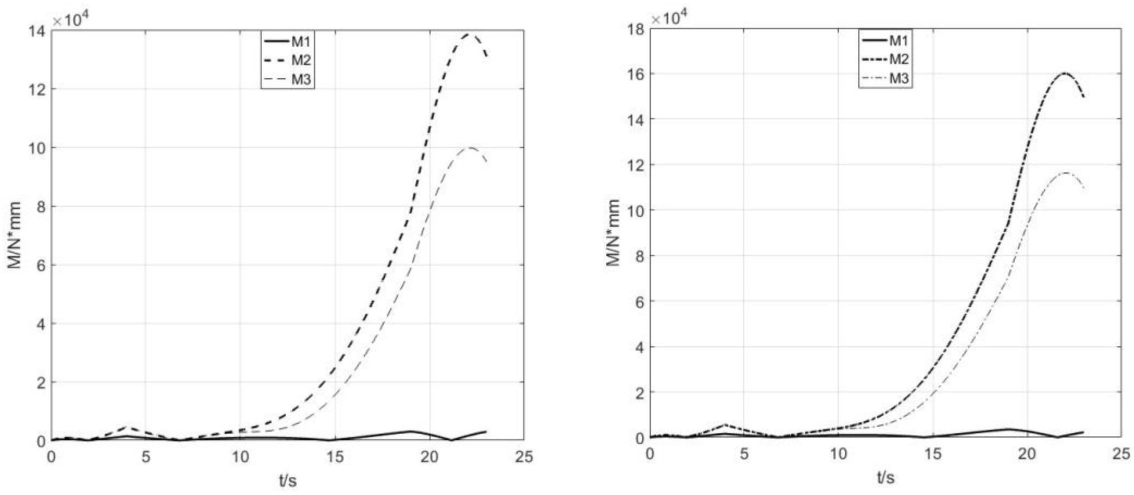
$$\begin{cases} 0.23^{\circ} \le \omega_1 \le 51.71^{\circ} \\ 0^{\circ} \le \omega_2 \le 20.77^{\circ} \\ 0^{\circ} \le \omega_3 \le 20.77^{\circ} \end{cases}$$
$$\begin{cases} f(\omega_1) \le f(51.71^{\circ}) = -0.099 < 0 \\ f(\omega_2) \le f(20.77^{\circ}) = -1.512 < 0 \\ f(\omega_2) \le f(20.77^{\circ}) = -1.512 < 0 \end{cases} \quad (26)$$

If $\omega_i \in (0,\ \pi/2)$ is satisfied, $\Delta F_A < 0$ established.

In combination ① and ②, when the input joint controls the opening angle ω_i as shown in Figure 6 , the driving joint will bear the smaller force than the Delta parallel robot not driven by a crank-slider in the pick-up operation .

3.2 Simulation Analysis of Driver 's Driving Torque

The Delta parallel robot driven by the crank- slider mechanism and not driven by the crank-slider, the changing torque of their three driving joints are shown in Figure 7.



(a). The output torque driven by the crank-slider mechanism

(b). The output torque driven doesn't by the crank-slider mechanism

Figure 7. Two different types of the output torque driven

Defining the optimal objective function M_t of the Delta robot driven joint output torque is shown in equation (27). The M_t is the sum of the three driving joint output moments at time of t_i during pick-and-place operation [13].

$$M_t = M_{1t} + M_{2t} + M_{3t} \quad (27)$$

It can be obtained that the total torque M_t of the Delta parallel robot using the crank-slider mechanism and without using the crank-slider during the pick-and-place operation under equal load conditions are shown in Figure 8 below. Obviously, the use of the crank slider mechanism will reduce the total torque of the Delta parallel robot during the entire pick-and-place operation.

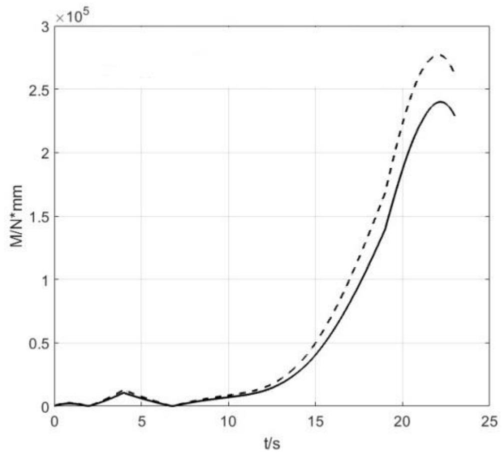


Figure 8. The total drive torque of the drive joint output

4. CONCLUSION

In this paper, it present the crank-slider mechanism applied to Delta Parallel Robot for the pick-and-place operation, motion simulation is carried out in the virtual prototype software, and the force and the output torque of the robot-driven joint are used as the main performance indexes.The research results verify that the delta robot driven by the crank slider mechanism can effectively reduce the force and output torque.

1. Path planning of pick-and-place operation. Determining the shape of the curve in Cartesian space, the position coordinates, velocity and acceleration of the robot are obtained according to the corresponding time series.
2. Input solution of each control angle of joint drive. Based on the inverse solution theory of Delta mechanism and planned robot end trajectory, each control angle of joint drive is solved.
3. Establishment of Static transmission mathematical model of the Delta mechanism. Make force transmission analysis for mechanism for using and not using crank-slider . And it is proved that Delta mechanism based on crank-slider mechanism can reduce the force and output torque.
4. Analysis of motion simulation is carried out in the virtual prototype software. Through the design of the prototype model, the motion simulation of pick-and-place operation, it can be decided that Delta mechanism based on crank-slider mechanism can reduce the force and output torque and have good practical application value.

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