WORKSPACE SIMULATION AND TRAJECTORY PLANNING FOR TOMATO SORTING DELTA ROBOT
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番茄分拣 DELTA 机器人作业空间和轨迹规划仿真

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DOI: 10.35633/INMATEH-58-19

***Keywords:** tomato sorting, delta parallel mechanism, MATLAB, workspace, trajectory planning*

ABSTRACT
Robotic simulations are an effective approach to validate various models and design schemes. A tomato sorting Delta parallel mechanism was validated in this study for the purposes of end-effector motion planning via simulation analysis. Real-world conditions of the robot as well as its forward and inverse kinematics were obtained, followed by simulation analysis to determine whether its workspace meets relevant operation requirements. The motion trajectory of the end-effector is planned according to the simulation results and the motion requirements for tomato sorting. A sine modified trapezoidal acceleration curve is applied as the motion law on the arc trajectory of the end-effector; said motion trajectory is found to be smooth and conducive to stable running of the robot based on MATLAB software analysis. A prototype was designed based on the simulation results and utilized to successfully complete 31 sorting tasks in one minute while smoothly and stably running.

摘要
机器人仿真是验证模型正确性和设计方案可行性的重要方法，为了验证番茄分拣 Delta 机器人尺寸的设计合理性，以及对机器人末端执行器进行运动规划，本文仿真分析了番茄分拣 Delta 机器人的作业空间，规划了末端执行器的运动轨迹。首先，分析番茄分拣 Delta 机器人实际的情况，求取 Delta 机器人末端执行器的运动学正解和逆解，仿真分析 Delta 机器人的作业空间，验证了其作业空间是否满足作业要求。然后，根据番茄分拣的运动要求，规划末端执行器的运行轨迹。在末端执行器的圆弧运动轨迹上，采用正弦修正梯形加速度曲线作为运动规律。采用 MATLAB 软件，仿真验证了番茄分拣 Delta 机器人末端执行器的运动轨迹平滑，运行平稳。基于仿真结果设计试验样机，并进行番茄分拣试验，结果表明该番茄分拣 Delta 机器人能够完成 31 次/min 的番茄分拣任务，且运行平稳。证明了将 Delta 机器人用于番茄分拣的可行性，以及作业空间和轨迹规划的合理性。

INTRODUCTION
Grading of agricultural products creates added value. In China, the annual yield of tomato products exceeds 34 million tons (*Qiao et al., 2014*), creating an urgent need for automatic tomato sorting machines (*Saber, 2018; Rupanagudi et al., 2014; Huang et al., 2018; Semary et al., 2015*). An automatic tomato sorting robot must have rapid speed, high precision, and stable operation for the lossless and accurate sorting of tomatoes. The Delta robot is compact in structure, fast, precise, and is widely used for sorting applications in today’s food and electron industries (*Feng et al., 2014; Kuo, 2016; Cheng and Li, 2018; Coronado et al., 2016*). Simulations are commonly used to assess research results and establish models *(Garg et al., 2018; Mukherjee, 2017)*; many scholars have investigated the Delta robot via simulation (*Zhou and Zhang, 2017; Kidokoro et al., 2015; Hou et al., 2017*). Jinzhao Du et al., for example, established a simplified dynamic model of the Delta robot and verified its effectiveness by simulation (*Du and Lou, 2017*).

Chi-Sheng Tsai et al. designed a fully operable rotating Delta robot and validated its kinematic model through simulation (*Tsai et al., 2016*). Jingjun Zhang et al. obtained a constraint equation and Jacobian matrix by analyzing the kinematic mechanism of a Delta robot based on ADAMS software simulations

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(*Zhang et al., 2009*). Tuong Phuoc Tho et al. used the adaptive neuro-fuzzy inference system to solve inverse kinematic problems of a Delta parallel robot; they verified the effectiveness of this method based on virtual reality technology and MATLAB software (*Tho et al., 2015*).

In the present study, MATLAB software was adopted to validate the workspace of a tomato sorting Delta robot and the effectiveness simulation-based trajectory planning. The system construction, kinematic analysis, and simulated end-effector workspace and trajectory are discussed below. An experiment conducted on a prototype robot built according to the simulation results is also discussed below.

MATERIALS AND METHODS

- **System construction**

The Delta robot-based tomato automatic sorting system is shown in Fig. 1. In this system, the visual sensor takes images of tomatoes on a conveyor belt, processes the images and sends detection results to the controller which drives the robot to classify the fruits into “excellent”, “good”, and “middle” categories.

The workspace of the tomato sorting Delta robot includes a section of conveyor belt and tomato collection zone, as shown in Fig. 2. The width of the belt face is 200 mm, and the dimension of the collection zone is 400 mm×150 mm. The bottom diameter of the cylindrical workspace must be larger than 420 mm and the height more than 60 mm to meet the relevant workspace requirements. The Delta robot has a “disc” which gathers and sorts tomatoes. Tomatoes of course are soft and relatively easily damaged – too fast suction or placing speed would harm the product. The sorting speed of the Delta robot can be safely set to 30 m/min.

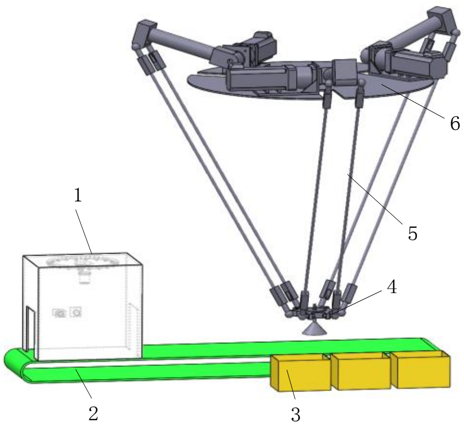


Fig. 1 - Components of automatic tomato grading system
1. Visual inspection box 2. Conveyor belt 3. Collection zone 4. Movable platform 5. Delta robot 6. Fixed platform

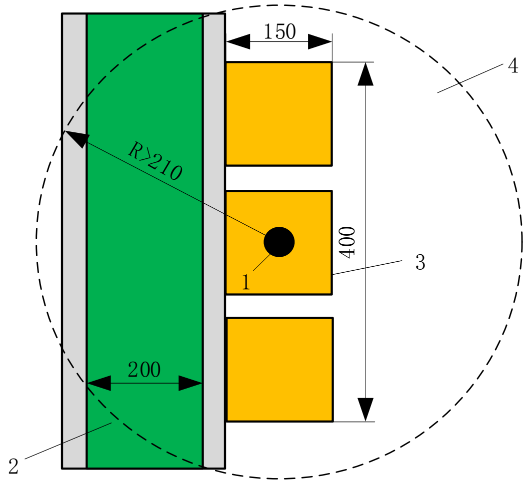


Fig. 2 - Workspace indication of robot
1. End-effector 2. Conveyor belt 3. Collection zone 4. Workspace

- **Simulation analysis of the workspace**

Inverse kinematics

The structure of the tomato sorting Delta robot can be simplified by neglecting the elastic deformation of the connecting rods, as shown in Fig. 3. Random arm 3 is composed of two parallel connecting rods. The two ends of the rods are connected by master arm 2 and fixed platform 4 through spherical hinges. The random arm can be simplified as a connecting rod for the purposes of kinematic analysis. The connecting rod moves *r* towards the centre. The movable platform is regarded as a point *P*. After simplification, the radius of the fixed platform is $e = R - r$; *r* is the radius of the movable platform.

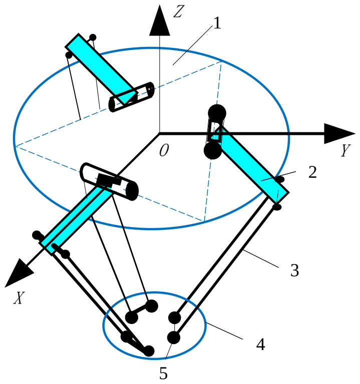


Fig. 3 - Structure of Delta robot

1. Movable platform 2. Master arm 3. Random arm 4. Fixed platform 5. Spherical hinge

The coordinate system *O-XYZ* of the tomato sorting Delta robot was established with central point *O* of the fixed platform as the origin of the reference system (Fig. 4). The *Z* axis is perpendicular to the fixed platform and the direction is upward. Beginning from origin *O*, the direction points to the connecting line between the master arm rod of the branch chain while the linking point of the fixed point is the positive direction of the *Y* axis. $A_iB_i = l_1$, $B_iP = l_2$. The central point between the branch chain master arms and connecting axis of the fixed platform $e_i = e(cos\,\beta_i \quad sin\,\beta_i \quad 0)^T$, where $\beta_i = \frac{(i-1)\times 2\pi}{3} - \frac{\pi}{6}$. The angle $\theta_i (i = 1,2,3)$ between A_iB_i and the face of the fixed platform is the rotation angle of the master arm. u_i and w_i represent the unit vector of the master arm rod and random arm rod respectively.

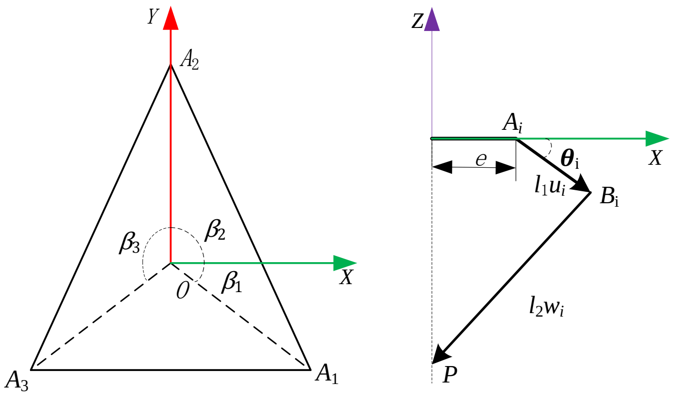


Fig. 4 - Space coordinates of Delta robot

The position of point *P* is $r = e_i + l_1u_i + l_2w_i$, that is, $r - e_i - l_1u_i = l_2w_i$. The two ends of the equation multiply with their own respective transpose variables. Substitute e_i, β_i, u_i, r, then after simplification:

$$F_i \cos\theta_i + E_i \sin\theta_i + G_i = 0, i = 1,2,3 \tag{1}$$

where, $F_i = 2l_1e - 2l_1x\,cos\,\beta_i - 2l_1y\,sin\,\beta_i$, $E_i = 2l_1z$, $G_i = (x - e\,cos\,\beta_i)^2 + (y - e\,sin\,\beta_i)^2 + z^2 + l_1^2 - l_2^2$.

Substitute $sin\,\theta_i = \frac{2\,tan\frac{\theta_i}{2}}{1+tan^2\frac{\theta_i}{2}}$ and $cos\,\theta_i = \frac{1-tan^2\frac{\theta_i}{2}}{1+tan^2\frac{\theta_i}{2}}$ into Equation (1) to solve. Thus, the inverse kinematics of the Delta robot is:

$$\theta_i = 2\arctan\frac{-E_i - \sqrt{E_i - G_i + F_i}}{G_i - F_i}, i = 1,2,3 \tag{2}$$

Forward kinematics

As shown in Fig. 4, points B_1, B_2 and B_3 are on a sphere with point P as the centre and the length of random rod l_2 as the radius. The coordinates of B_i are:

$$\begin{bmatrix} x_{B_i} \\ y_{B_i} \\ z_{B_i} \end{bmatrix} = \begin{bmatrix} e\cos\beta_i + l_1\cos\beta_i\cos\theta_i \\ e\sin\beta_i + l_1\sin\beta_i\cos\theta_i \\ -l_1\sin\theta_i \end{bmatrix}, i = 1,2,3 \tag{3}$$

and the relationship between B_i and point P $[x_p \quad y_p \quad z_p]^T$ is:

$$x_p{}^2 + (y_p - y_{B_2})^2 + (z_p - z_{B_2})^2 = l_2^2 \tag{4}$$

$$(x_p - x_{B_1})^2 + (y_p - y_{B_1})^2 + (z_p - z_{B_1})^2 = l_2^2 \tag{5}$$

$$(x_p - x_{B_3})^2 + (y_p - y_{B_3})^2 + (z_p - z_{B_3})^2 = l_2^2 \tag{6}$$

The forward kinematics of the tomato sorting Delta robot can be obtained after simplification as follows:

$$\begin{gathered} x_P = M_1 z_P + N_1 \\ y_P = M_1 z_P + N_2 \\ z_p = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \end{gathered} \tag{7}$$

where, $M_1 = -\frac{(z_{B3}-z_{B2})(y_{B1}-y_{B2})-(z_{B1}-z_{B2})(y_{B3}-y_{B2})}{(y_{B1}-y_{B2})x_{B3}-(y_{B3}-y_{B2})x_{B1}}$, $M_2 = -\frac{(z_{B3}-z_{B2})x_{B1}-(z_{B1}-z_{B2})x_{B3}}{(y_{B3}-y_{B2})x_{B1}-(y_{B1}-y_{B2})x_{B3}}$, $N_1 = 0.5\frac{(y_{B1}-y_{B2})O_2-(y_{B3}-y_{B2})O_1}{(y_{B1}-y_{B2})x_{B3}-(y_{B3}-y_{B2})x_{B1}}$, $N_2 = 0.5\frac{x_{B1}O_2-x_{B3}O_1}{(y_{B3}-y_{B2})x_{B1}-(y_{B1}-y_{B2})x_{B3}}$, $O_1 = x_{B_1}^2 + y_{B_1}^2 + z_{B_1}^2 - y_{B_2}^2 - z_{B_2}^2$, $O_2 = x_{B_3}^2 + y_{B_3}^2 + z_{B_3}^2 - y_{B_2}^2 - z_{B_2}^2$, $a = 1 + M_1^2 + M_2^2$, $b = 2(M_1N_1 + M_2N_2 - M_2y_{B_2} - z_{B_2})$; $c = N_1^2 + (N_2 - y_{B_2})^2 - z_{B_2}^2 - l_2^2$。

RESULTS

- **Simulation verification of robot workspace**

The simulation results of the tomato sorting Delta robot workspace are dependent on the correctness of the forward and inverse kinematics. A spiral curve can be constructed for this purpose as follows:

$$\begin{cases} x = 300\cos(\pi t) \\ y = 300\sin(\pi t) \\ z = -650 - 10t \end{cases} \tag{8}$$

Isometric sampling of the trajectory of point P was conducted in MATLAB software with a sampling distance of 200 mm. The space coordinates of the sampling points were plugged into Equation (2), then the inverse kinematics of the tomato sorting Delta robot was solved to obtain the corresponding master arm angle θ_i of all sampling points. θ_i was substituted into forward Equation (7) to obtain the trajectory generation point of the end-effector, as shown in Fig. 5.

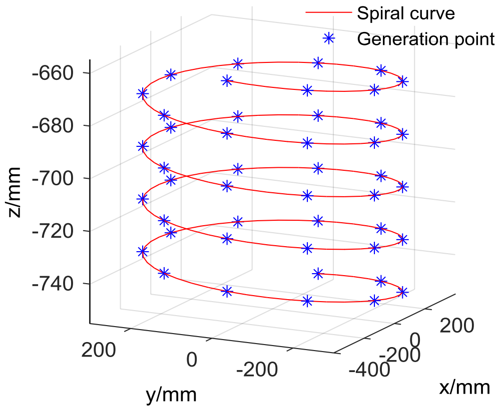
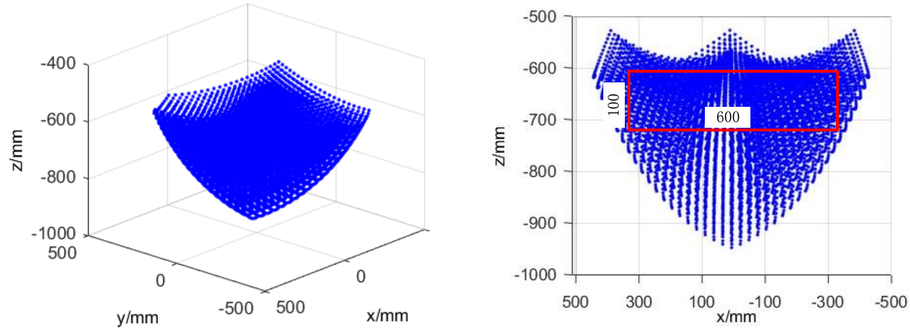


Fig. 5 - Comparison graph of involves and structure curve

The trajectory generation points of the end-effector basically overlap the spiral curve, which validates the forward kinematic analysis and inverse kinematic analysis of the Delta robot's end-effector.



(a) Workspace (b) Side view

Fig. 6 - Workspace simulation

With parameters of IRB360-1/800 type Delta robot as the reference, the master arm rod of the Delta robot was primarily set to l_1=240 mm, that of the random arm rod to l_2=800 mm, the radius of the fixed platform to R=200 mm, and the radius of the movable platform to r=50 mm. According to the forward kinematics of the Delta robot, the joint angle of the master arm was set to $\theta_i = [-45°, 45°]$. The simulation analysis of the tomato sorting Delta robot is as shown in Fig 6(a); Fig. 6(b) is a side view of the workspace. As discussed in Section 2, while grading, the Delta robot needs a cylindrical workspace with bottom diameter of 420 mm and height of 60 mm. As shown in Fig. 6(b), the real workspace of the Delta robot is a cylindrical zone with bottom diameter of 600 mm and height of 100 mm, which satisfies the requirements for tomato grading.

- **Motion trajectory planning and simulation**

The end-effector of the Delta robot usually adopts gate type trajectory and arc trajectory motion (*Zheng and Zhang, 2016; Su et al., 2018; Yang, 2017; Peng et al., 2017; Xie et al., 2015; Zhao et al., 2014*), as shown in Fig. 7. ABCDEFG represents the gate type trajectory, which is formed by straight line and arc trajectory. ADG is the arc trajectory, which is formed by a single arc. The end-effector of the tomato sorting Delta only moves between the conveyor belt and collection zone; thus both the arc trajectory and the gate type trajectory satisfy the relevant requirements. The total length of the arc trajectory is smaller than that of the gate type trajectory, so under the same motion law, the moving period of the arc trajectory is shorter. The arc trajectory was selected as the trajectory of the Delta robot end-effector in this study.

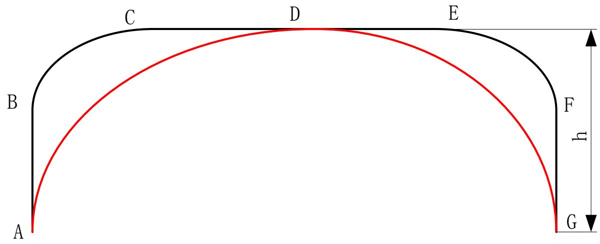


Fig. 7 - Tracking end of mechanism

Trajectory planning

Analysis is conducted based on the plane on which the arc trajectory is located. It is assumed that the arc trajectory is within the *XOZ*. The coordinates of trajectory initial point *A* are $(x_A \quad y_A \quad z_A)$, those of point *G* are $(x_G \quad y_G \quad z_G)$, and those of point *D* are $\left(\frac{x_A+x_G}{2} \quad \frac{y_A+y_G}{2} \quad z_A+h\right)$, thus the arc trajectory equation is:

$$\left(x-\frac{x_A+x_G}{2}\right)^2+\left(y-\frac{y_A+y_G}{2}\right)^2+\left(z-z_0\right)^2=R^2 \tag{9}$$

where, $z_0 = \frac{4h^2+8z_A h-(x_a-x_G)^2-(y_a-y_G)^2}{8h}$, $R = \frac{4h^2+(x_a-x_G)^2+(y_a-y_G)^2}{8h}$.

Rapid acceleration of the motor causes impact force on the robot which vibrates it. To eliminate the impact force, the motor is equipped with a sine modified trapezoidal acceleration curve (*Huang et al., 2015; Zhang et al., 2018; Li et al., 2017*). The displacement curve is expressed as follows:

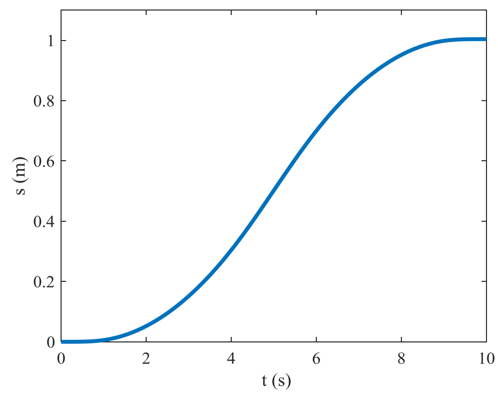
$$s(t)=\begin{cases} K\left\{27m\left[\cos(\frac{8\pi t}{T})-1\right]-n\left[\cos(\frac{24\pi t}{T})-1\right]\right\}+\frac{a_m t^2}{4} & (0\le t<\frac{T}{8}) \\ a_m(\frac{t^2}{2}-\frac{Tt}{16}+\frac{T^2}{256})-2K(27m+n) & (\frac{T}{8}\le t<\frac{3T}{8}) \\ -K(27mP_1+nP_2)+a_m T(\frac{5t}{16}-\frac{17T}{256}) & (\frac{3T}{8}\le t<\frac{5T}{8}) \\ a_m(-\frac{t^2}{2}+\frac{15Tt}{16}-\frac{67T^2}{256})+14K(27m+n) & (\frac{5T}{8}\le t<\frac{7T}{8}) \\ K(27mP_3+nP_4)+a_m(-\frac{t^2}{4}+\frac{Tt}{2}-\frac{18T^2}{256}) & (\frac{7T}{8}\le t<T) \end{cases} \qquad (10)$$

where, *T*- the moving period; a_m - the maximum acceleration of the end-effector; $K=\frac{a_m T^2}{55296\pi^2}$, $P_1=8\cos\left[\frac{4\pi(t-\frac{3T}{8})}{T}\right]-6$, $P_2=8\cos\left[\frac{12\pi(t-3T/8)}{T}\right]-6$, $P_3=\cos\left[\frac{8\pi(t-\frac{7T}{8})}{T}\right]+13$, $P_4=\cos\left[\frac{24\pi(t-\frac{7T}{8})}{T}\right]+13$, and $3m+n=48(m>0,n>0)$.

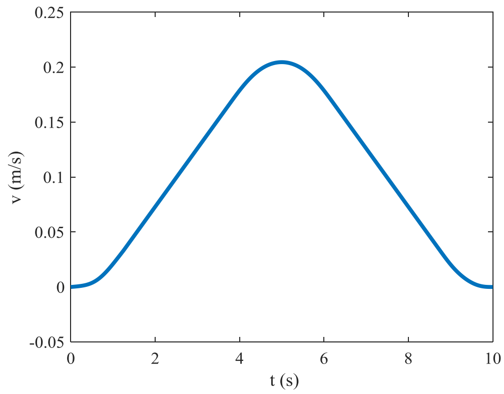
After one sorting process, the total travel of the end-effector is *L*. The relationship between *L* and *T* and a_m is:

$$T=\sqrt{\frac{L}{a_m(\frac{2+a}{192\pi^2}+\frac{23}{128})}} \qquad (11)$$

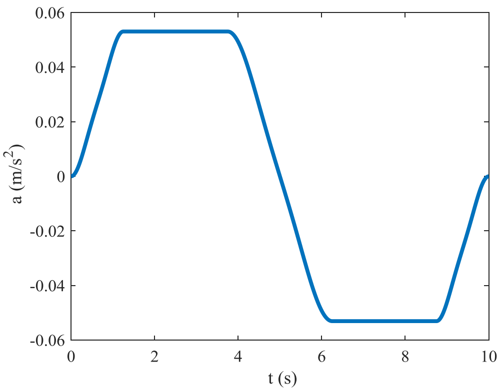
The minimum period $T\sqrt{\frac{5.287\cdot L}{a_m}}_{min}$ can be obtained through Equation (11). The change curve of the displacements, speed *v*, acceleration *a*, and jerk *j* of the end-effector of the robot with time can be obtained through said motion law as shown in Fig. 8.



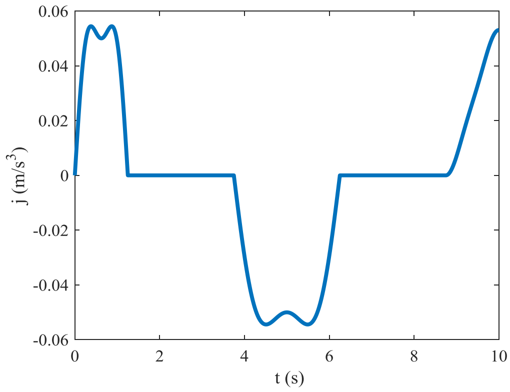
(a) Displacement curve



(b) Speed curve



(c) Acceleration curve



(d) Jerk curve

Fig. 8 - Curve of end-effector motion pattern

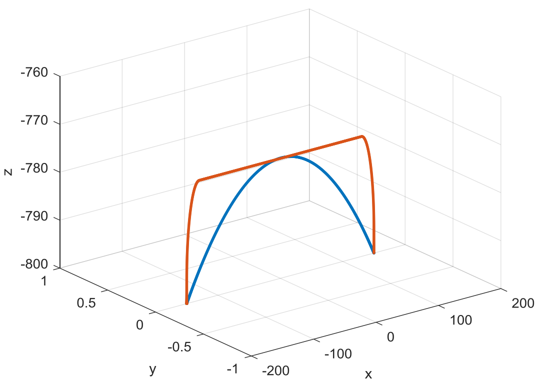
As shown in Fig. 8, after adopting the sine modified trapezoidal acceleration curve, the speed and acceleration curves of the end-effector are continuous and smooth. There is no mutation at the beginning or end of the jerk curve, which satisfies the high speed of the tomato sorting Delta robot.

Trajectory simulation

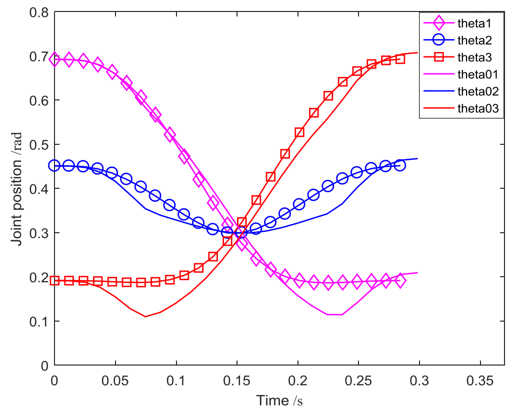
The smoothness of the end-effector trajectory is connected with the kinematic characteristics of robot joints. Kinematic characteristics include joint angle curve, angular velocity curve, and angular acceleration curve. MATLAB software was adopted in this study, as discussed above, for simulation analysis of the kinematic characteristics of the Delta robot and to verify the rationality of the end-effector's arc trajectory.

Assume the coordinate of point *A* is (-100, 0, -800), that of point *G* is (100, 0, -800), and *h* = 25 mm; the arc trajectory can be defined according to Equation (9). Determine the gate type trajectory based on same starting point and end point and set the excessive arc radius to 15 mm. Simulations were run here by adopting the sine modified trapezoidal acceleration curve motion law with a maximum acceleration of a_m = 20 m/s^2. The motion trajectory of the end-effector with sample points on the motion trajectory of the end-effector at sampling time of 0.001 s are shown in Fig. 9(a). After substituting coordinates of sampling points into the inverse kinematics of the Delta robot, the angle trajectory curves of the three joints were obtained as shown in Fig. 9(b). After derivation of the joint angle trajectory curve, the angular velocity curves of the three joints were obtained as shown in Fig. 9(c). After derivation of the angular velocity curve, the angular acceleration curves of the three joints were obtained as shown in Fig. 9(d). The kinematic characteristics curves of the joints obtained after analyzing the arc trajectory are theta1, theta2, and theta3. The kinematic characteristics curves of the joints obtained after analyzing the gate type trajectory are theta01, theta02, and theta03.

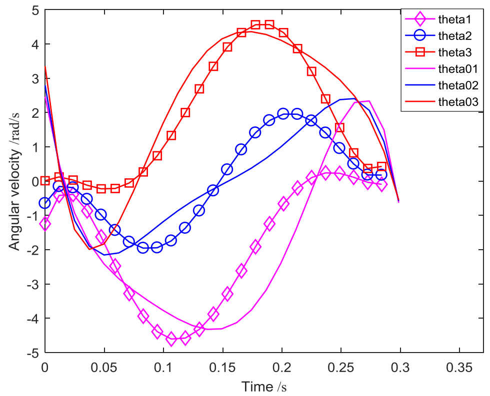
As shown in Fig. 9(b), the angular trajectory of the joints is smoother when adopting the arc trajectory rather than the gate type trajectory. As shown in Fig. 9(c), the change trends of the angular velocity curves obtained under the two trajectories are basically the same. However, the starting angular velocity of the three joints is smaller and the starting is more stable under the arc trajectory. Figure 9(d) also shows that while adopting arc trajectory, the change range of the angular velocity is smaller, the angular velocity change is smoother, and the running process is more stable than under the gate type trajectory. One period of the tomato sorting Delta robot takes 0.2842 s under the arc trajectory but takes 0.2985 s under the gate type trajectory. Under the same motion law, the motion period of the arc trajectory is also shorter.



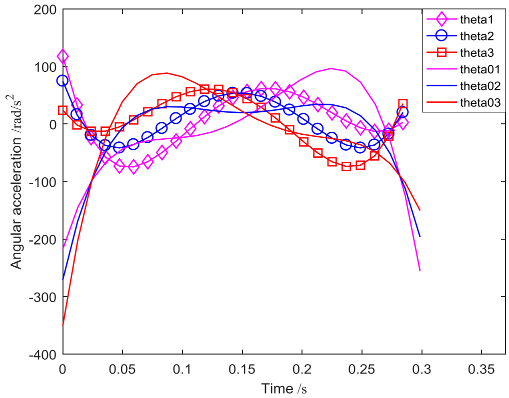
(a) End-effector motion trajectory



(b) Angular trajectory of three joints



(c) Angular velocity curves of three joints



(d) Angular acceleration curves of three joints

Fig 9 - Motion trajectory simulation curve

In order to verify the effectiveness of the sine modified trapezoidal acceleration curve motion law by comparison with isometric interpolation, the angular velocity curves of the three joints were obtained as shown in Fig. 10. While adopting the sine modified trapezoidal acceleration curve motion law, the acceleration curves obtained are theta1, theta2, and theta3; while adopting isometric interpolation, the angular velocity curves obtained are theta01, theta02, and theta03.

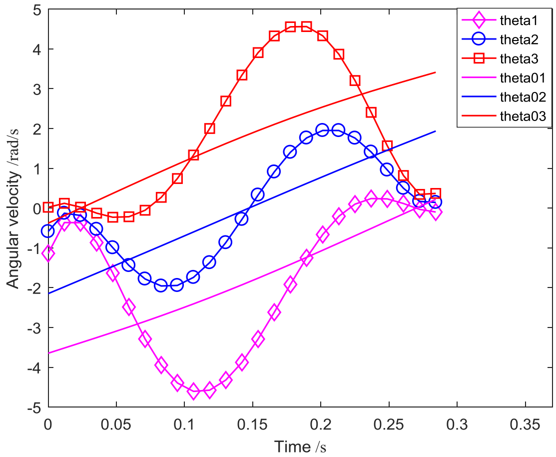


Fig 10 - Angular velocity curves of three joints

As shown in Fig. 10, while adopting isometric interpolation, the beginning angular velocities of theta1 and theta 2 as well as the ending angular velocities of theta 2 and theta 3 are larger compared to the sine modified trapezoidal acceleration curve motion law. The impact of the end-effector velocity is large and the motion is unstable under isometric interpolation, while the opposite is true under the sine modified trapezoidal acceleration curve motion law. The results shown in Fig. 9 and Fig. 10 together indicate that adopting an arc trajectory and sine modified trapezoidal acceleration curve motion law yields a smooth motion trajectory of the end-effector, stable system operation, and a short running period which satisfy the tomato sorting Delta robot's performance requirements.

- **Trial production of prototype**

A prototype of the tomato sorting Delta robot was constructed as shown in Fig. 11 based on the simulation results presented above. The main controller of the prototype is a STM32f407 and the motor is a 57HSE112-D25 type servo stepping motor. The tomato sorting Delta robot showed high speed and stable running throughout the experiment. It completed 31 tomato sorting tasks each minute on average, which satisfies the practical requirements for automatic tomato sorting.

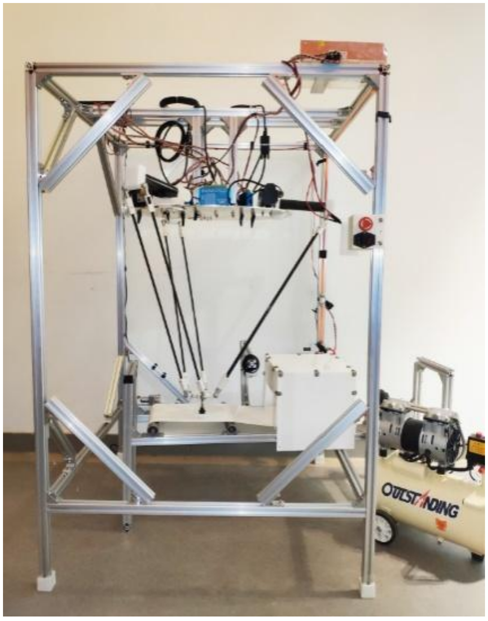


Fig. 11 - Tomato sorter Delta robot prototype

CONCLUSIONS

The dimensions of a tomato sorting Delta robot were determined in this study based on real-world workspace requirements. A trajectory planning simulation of the robot was then conducted according to the motion requirements for tomato sorting. A sine modified trapezoidal acceleration curve was selected as the motion law, and the condition of the end-effector was placed under arc trajectory conditions for simulation in MATLAB software. Under the simulated conditions, the system started smoothly, did not undergo excessive changes in angular velocity during operation, and showed a relatively short running period. In a tomato sorting experiment, a prototype Delta robot fabricated based on the simulation results ran rapidly and smoothly and completed 31 sorting tasks in one minute. In effect, the proposed tomato sorting Delta robot has strong kinematic performance and satisfies the relevant requirements for automatic, lossless tomato sorting including rapid speed, high precision, and smooth operation.

ACKNOWLEDGEMENT

This research has received support from the Fundamental Research Funds for the Central Universities (No. 2452016077), the Agricultural Science and Technology Innovation and Research project of Shaanxi Province (No. 2016NY-157). Students' Innovative Research Plan of Northwest A&F University (No. 2201810712385). The authors are also gratefully to the reviewers for their helpful comments and recommendations, which make the presentation better.

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