Kinematics Analysis and Simulation Research of Fruit and Vegetable Picking Arm Based on MATLAB

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Abstract: In order to understand the reliability and stability of the fruit and vegetable picking arm during its operation, a simulation design of the fruit and vegetable picking arm grabbing design was designed. This article mainly takes the picking arm as the research object, adopts the improved D-H method to establish the coordinate system of each joint, establishes the kinematics equation, and solves the kinematics. Using the robotics toolbox of MATLAB software, mathematical modeling and simulation of picking process are carried out. The simulation results show that the operation of the fruit and vegetable picking arm is very stable, which has certain practical significance for further research on picking robots.

1. Preface

With the continuous advancement of science and technology, the continuous improvement of the national economic level, and the improvement of the quality of life that the people increasingly pursue, the output of the fruit and vegetable industry continues to expand. Stepping up to increase the output of fruits and vegetables has become a necessary contradiction at the moment. In the fruit and vegetable production process, we pay close attention to the fruit and vegetable harvesting process, and of course it is also the most important. Fruit and vegetable production has the characteristics of strong seasonality, short cycle, high labor intensity, high labor cost but low picking efficiency. The labor used in fruit and vegetable harvesting accounts for about 35% to 45% of the entire fruit and vegetable production process, which severely restricts China's fruit and vegetable industry. Further development of automation[1]. Therefore, the emergence of automatic picking robots can partially solve the labor shortage, liberate labor, and make outstanding contributions to the fruit and vegetable industry. From the current status of fruit and vegetable research, picking robots are generally composed of vision systems, control systems, mobile systems, picking systems, etc. Although my country's agricultural science and technology has achieved certain results in fruits and vegetables, it has not yet fully autonomously reached the point of replacing human picking tasks. This article does some simulation verification and analysis on whether the operation of fruit and vegetable picking robot is stable. And the use of matlab robotics related software to simulate the operation process of the fruit and vegetable picking arm designed to reduce the cost of the experiment, further research in the picking robot has certain practical significance.
2. The kinematic equation of fruit and vegetable picking arm

2.1 D-H coordinate system and connecting rod parameters

The D-H parameter method is a matrix method proposed by Denavit and Hartenberg in 1995 to establish a coordinate system for each member of the multi-joint link. The D-H parameter method is to abstract the relationship of each coordinate system from the complex mechanical structure [2]. The research object of this paper is the execution part of the fruit and vegetable picking robot-the picking arm. The model is RE6-730-MI. The execution part is a linkage mechanism with 6 rotating joints connected in series. According to a joint axis between two adjacent links, the coordinate system is established with the central axis of each joint as the origin of the coordinate system. The coordinate system \( \{i\} \) is fixedly connected to link 1. Figure 1 shows the picking arm of the key parts of fruit and vegetable picking. Table 1 shows the D-H parameter table of the fruit and vegetable picking arm. The connecting rod parameters of the picking arm determined according to the D-H parameter method are shown in Table 1.

![Figure 1 The picking arm of the key parts of fruit and vegetable picking](image1)

| Link | Link length \( a_i \) | Corner \( \alpha_i \) | Setover \( d_i \) | Twist angle \( \theta_i \) |
|------|-------------------|----------------|---------|-------------------|
| 1    | 0                 | 0             | 0       | \( \theta_1 \)    |
| 2    | 330               | \( \pi/2 \)   | 0       | \( \theta_2 \)    |
| 3    | 950               | 0             | 0       | \( \theta_3 \)    |
| 4    | 200               | \( \pi/2 \)   | 800     | \( \theta_4 \)    |
| 5    | 0                 | \(-\pi/2\)    | 0       | \( \theta_5 \)    |
| 6    | 0                 | \( \pi/2 \)   | 0       | \( \theta_6 \)    |

Method of establishing joint coordinate system:
1. The origin of the coordinate system \( \{i\} \) on the intersection of \( X_i \) and \( Z_i \).
2. The \( z \)-axis of the coordinate system \( \{i\} \) coincides with the \( i \)-axis and points to any point.
3. The \( X \)-axis of the coordinate system \( \{i\} \) coincides with the common normal from the \( i \)-axis to the \( i+1 \)-axis.
4. The \( Y \)-axis of the coordinate system \( \{i\} \) depends on the right-hand rule. The setting rules of the linkage coordinate system are shown in Figure 2.

![Figure 2 Link coordinate system](image2)
2.2 Forward kinematics of fruit and vegetable picking arm

For the forward kinematics analysis of the fruit and vegetable picking arm, the parameters of each joint are known, and then the pose of the end effector relative to the base coordinate system is calculated[3]. The D-H representation of the kinematic equation of fruit and vegetable picking arm is to use a homogeneous transformation matrix a to describe the relationship between the coordinate system of link \( l-1 \) and the coordinate system of link \( l \). After determining all the connecting rod parameters, you can follow the steps below to establish the relationship between two adjacent connecting rods \( i \) and \( i-1 \):

1. \( Z_{i-1} \)-axis: the connecting shaft between the \( i \) link and the \( i-1 \) link.
2. \( X_i \)-axis: along the \( Z_{i-1} \)-axis and the common perpendicular of the \( Z_i \)-axis point to the \( Z_i \)-axis;
3. \( Y_i \)-axis: satisfy the right-hand principle
4. Rotate the \( X_i \)-axis around the \( Z_{i-1} \)-axis by an angle of \( \theta_i \), so that the \( X_{i-1} \)-axis and the \( X_i \)-axis are in the same direction;
5. Translate the coordinate system \( \{i-1\} \) along the \( Z_i \)-axis \( d_i \), so that the \( X_{i-1} \)-axis and the \( X_i \)-axis are on the same line.
6. Move the coordinate system \( \{i-1\} \) along the axis by a distance \( a_i \), so that the origin of the coordinate system coincides with the origin of the coordinate system \( \{i\} \).
7. Rotate the coordinate system \( \{i\} \) around the \( X_i \)-axis by \( \alpha_i \), so that the \( Z_{i-1} \)-axis and the \( Z_i \)-axis are on the same straight line.

\[
A_i = \begin{bmatrix}
\cos \theta_i & -\sin \theta_i & \sin \theta_i & 0 & a_i & 0 \\
\sin \theta_i & \cos \theta_i & \cos \theta_i & 0 & a_i \sin \theta_i & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \tag{1}
\]

In order to make calculation simple, first substitute the values of the connecting rod rotation angle \( \alpha \) and the offset distance \( d \) of 0 in the D-H parameter table 1 into the formula (1) to obtain the rotation matrix of the six joint coordinate systems

\[
^0T = A_i = \begin{bmatrix}
\cos \theta_i & 0 & \sin \theta_i & 0 & a_i & 0 \\
\sin \theta_i & 0 & -\cos \theta_i & 0 & a_i \sin \theta_i & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \tag{2}
\]

\[
^iT = A_i = \begin{bmatrix}
\cos \theta_i & 0 & \sin \theta_i & 0 & 0 & 0 \\
\sin \theta_i & 0 & -\cos \theta_i & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix} \tag{5}
\]

By performing some mathematical operations on the above homogeneous transformation matrices, the answer to the forward kinematic equation of the fruit and vegetable picking arm can be obtained.

2.3 Inverse kinematics solution of fruit and vegetable picking arm

The inverse kinematics of the fruit and vegetable picking arm is actually to know the position of each joint to inversely derive the angle of each joint. Compared with the forward kinematics of the fruit and vegetable picking arm, the inverse kinematics analysis is relatively more complicated. Because inverse
kinematics is not the only solution, it has multiple solutions, infinite solutions or even no solutions. This paper uses analytical method to solve the inverse kinematics equation of fruit and vegetable picking arm. In the inverse calculation of the robotic arm, it is known that the forward kinematic transformation matrix of the robotic arm and the transformation matrix out of each adjacent link can be obtained by the identity transformation. The formula is as follows:

\[
0T = \frac{1}{2} T^T \frac{2}{T} \frac{2}{T} T = \frac{1}{3} T
\]

(8)

The inverse of the transformation matrix formula (2) and equation (7) of the manipulator is obtained, and the formula (9) and equation (10) are obtained:

\[
0T^{-1} = \begin{bmatrix}
\cos \theta_1 & \sin \theta_1 & 0 & 0 \\
0 & 0 & 1 & -d_1 \\
\sin \theta_1 & -\cos \theta_1 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(9)

\[
2T^{-1} = \begin{bmatrix}
\cos \theta_6 & \sin \theta_6 & 0 & 0 \\
-\sin \theta_6 & \cos \theta_6 & 0 & 0 \\
0 & 0 & 1 & -d_6 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(10)

Formula (8), (9) and (10) can be combined to obtain the analytical equation (11) for three corners.

\[
\begin{align*}
d_4 &= (a_x \cos \theta_1 - a_z \sin \theta_1) d_6 - \left(p_y \cos \theta_1 - p_x \sin \theta_1\right) \\
\cos \theta_4 &= -(a_x \cos \theta_1 - a_z \sin \theta_1) \\
\sin \theta_4 &= (a_y \cos \theta_1 - a_z \sin \theta_1) \sin \theta_6 - (n_y \cos \theta_1 - n_z \sin \theta_1) \cos \theta_6
\end{align*}
\]

(11)

Then calculate the analytical formulas of \( \theta_1, \theta_5, \theta_6 \) as follows:

\[
\theta_1 = \arctan 2(m,n) - \arctan 2(d_4 \pm \sqrt{m_1^2 + n_1^2 - d_4^2})
\]

(12)

Among them, \( m_1 = d_4 a_y - p_y, \quad n_1 = d_4 a_z - p_z \)

\[
\theta_5 = \pm \arccos(a \sin \theta_1 - a_y \cos \theta_1)
\]

(13)

\[
\theta_6 = -\arctan 2\left(\frac{n_2}{\sin \theta_5}, \frac{m_2}{\sin \theta_5}\right)
\]

(14)

Among them, \( m_2 = n_2 \sin \theta_1 - n_3 \cos \theta_1, \quad n_2 = a_z \sin \theta_1 + a_y \cos \theta_1 \)

In the same way, the analytical formula for \( \theta_2, \theta_3, \theta_4 \) can be calculated as follows:

\[
\theta_2 = \pm \arccos\left(\frac{m_1^2 + n_1^2 - a_z^2 - a_z^2}{2a_x a_y}\right)
\]

(15)

Among them, \( n_3 = (a_x \cos \theta_1 + n_3 \sin \theta_1) d_6 - a_y d_6 - d_4 + p_z \)

\[
m_y = (n_3 \cos \theta_1 + n_4 \sin \theta_1) \sin \theta_3 d_4 + (a_y \cos \theta_1 + a_z \sin \theta_1) \cos \theta_3 d_4
\]

\[
-\left(a_x \cos \theta_1 + a_z \sin \theta_1\right) d_6 + \left(p_y \cos \theta_1 + p_z \sin \theta_1\right)
\]

\[
\theta_3 = \arctan 2(m_4,n_4)
\]

(16)

\[
m_4 = \frac{(a_y \cos \theta_1 + a_z \sin \theta_1) n_3 - a_z \sin \theta_3 m_4}{a_z^2 + a_z^2 + 2a_z a_5 \cos \theta_3}
\]

\[
m_4 = (m_3 + a_3 \sin \theta_3 m_4) / (a_z \cos \theta_3 + a_y)
\]

\[
\theta_4 = \arctan 2(m_1,n_5) - \theta_5 - \theta_6
\]

(17)

\[
m_5 = -\left(n_1 \cos \theta_1 + n_5 \sin \theta_1\right) \sin \theta_6 - \left(a_x \cos \theta_1 + a_y \sin \theta_1\right) \cos \theta_6
\]

After a series of mathematical derivation, we calculated the joint angle of each link. But after our calculations, we can find that each joint pose can calculate eight different joint angles, and there are even other solutions. This shows that our fruit and vegetable picking arm will pick targets from various angles when picking. But this will reduce the efficiency of picking operations. So we need to restrict it. Through its inverse kinematics analysis, it has a guiding significance for the fruit and vegetable picking arm when picking operations.
3. Kinematics simulation of fruit and vegetable picking arm

3.1 Forward kinematics simulation of fruit and vegetable picking arm
In Robotics Toolbox, the starting position and ending position of the end effector of the fruit and vegetable picking arm are defined as point a and point B in turn. Then the motion simulation of the fruit and vegetable picking arm model is carried out. Figure 3 shows the starting position of the fruit and vegetable picking arm. Figure 4 shows the end position of the fruit and vegetable picking arm. Figure 5 shows the spatial movement track of the end position of the fruit and vegetable picking arm[4].

![Figure 3](image1.png)  ![Figure 4](image2.png)

Figure 3 shows the starting position of the fruit and vegetable picking arm. Figure 4 shows the end position of the fruit and vegetable picking arm.

![Figure 5](image3.png)

Figure 5 shows the spatial movement track of the end position of the fruit and vegetable picking arm. The simulation shows that in theory, the operation of the joints and moving parts of the fruit and vegetable picking arm is smooth.

3.2 Inverse kinematics simulation of fruit and vegetable picking arm
The inverse kinematics simulation of fruit and vegetable picking arm refers to the process of solving the angle value of each joint when the posture of the end effector of the fruit and vegetable picking arm is known. Next, the inverse kinematics of fruit and vegetable picking arm is simulated with MATLAB software, and the correctness of inverse kinematics solution is verified by the known joint data[5]. The specific process is shown in Figure 6:
Firstly, the driving functions of the six joints of the fruit and vegetable picking arm are given as formula (18). Then, the end posture of fruit and vegetable picking arm is obtained by kinematics analysis.

\[
\begin{align*}
\theta_1 &= 85 \sin(x) \\
\theta_2 &= 55 \sin(x) \\
\theta_3 &= 65 \sin(x) - 45 \\
\theta_4 &= 92.5 \sin(x) \\
\theta_5 &= 60 \sin(x) \\
\theta_6 &= 180 \sin(x)
\end{align*}
\]

(18)

The interval of simulation verification is \([0, \frac{2\pi}{2}]\), and the forward step length is 0.1, which is equivalent to inverse kinematics verification on more than 60 sets of test data. Draw the change curve of the driving joint function, as shown in Figure 7. It is known that the given joint angles are all within the range of movement of the picking arm. Then the kinematics method is used to solve the end posture of the picking arm, and the solution program of joint angle is compiled according to the inverse kinematics equation. The solution result is shown in Figure 8.

Calculating the error of each set of data, it is found that the inverse kinematics solution result is correct by comparing the data obtained by simulation and the angle data obtained by the inverse kinematics analytical method.

4. Trajectory planning of the fruit and vegetable picking arm operating process

The trajectory optimization of the fruit and vegetable picking arm can further improve the performance of the planned trajectory and meet actual needs. The trajectory optimization can shorten the movement time of the fruit and vegetable picking arm, reduce energy consumption. At the same time, unnecessary shaking and shock can be avoided, and the stability of the picking process can be increased. Therefore, it is necessary to optimize the trajectory of the fruit and vegetable picking arm.
Joint space trajectory planning is to transform the joint variables of the fruit and vegetable picking arm into a function of joint angle changes over time[6]. The Cartesian space trajectory planning is to transform the displacement, acceleration and acceleration of the fruit and vegetable picking arm end effector in Cartesian space into a functional relationship that changes with time. The two functions in Robotics Toolbox used in MATLAB software for trajectory planning and simulation of fruit and vegetable picking arms are ctraj function and jtraj function. Then use these two functions to plan the trajectory of the Cartesian space coordinate system and the joint space trajectory.

4.1 Cartesian trajectory planning of fruit and vegetable picking arm

The position of the object is when the space is orthogonal to each other and the posture is in accordance with any one of the space descriptions. We call this space Cartesian space or work space. The advantage of joint space trajectory planning is that it is simple, convenient and not prone to singularities. At the same time, the amount of calculation is small and it is easy to control in real time, but the disadvantage is that the end trajectory is not intuitive. Cartesian space trajectory planning is more intuitive. Cartesian trajectory planning is to give the interpolation points and find the inverse solution, and calculate the corresponding angles of each joint when the initial and final attitude are known. Cartesian trajectory planning is carried out with robotics toolbox in MATLAB software, and then the curves of position, speed and acceleration of the end actuator of fruit and vegetable picking arm with time are obtained, as shown in Figure 9.

4.2 Joint space trajectory planning of fruit and vegetable picking arm

The advantage of trajectory planning in joint space is that there is no need to solve the inverse or positive solution of fruit and vegetable picking arm. The disadvantage is that the trajectory of the corresponding operation space cannot be predicted, which increases the possibility of collision between the fruit and vegetable picking arm and the environment[7]. The basic joint space trajectory planning is usually used without end path requirements, which belongs to point-to-point motion. Generally, we need to know the beginning and end position of the joint, and then use different interpolation algorithms for interpolation fitting. When there are special requirements, we also need to pass the specified intermediate node. When there are special requirements, you also need to pass the designated intermediate nodes. Therefore, trajectory planning is transformed into an interpolation fitting problem. Knowing the beginning and ending positions of the joints and the corresponding joint angles of the intermediate nodes, the continuous trajectory is obtained by interpolation[8]. The fifth order polynomial interpolation law is used to draw the trajectory of fruit and vegetable picking arm.
Based on the robotics toolbox of MATLAB software, joint space trajectory planning is carried out, and the relationship curves of angle, velocity, acceleration and time of each joint are obtained.

Figure 10 Curves of the joint angles of the six joints over time
Figure 11 The curve of the angular velocity of the six joints over time
Figure 12 The curve of angular acceleration of six joints over time

Through joint trajectory planning simulation simulation, the joint angle, angular velocity and angular acceleration of each joint of the fruit and vegetable picking arm are obtained with time. It can be seen from Figure 10, Figure 11, and Figure 12 that the joint angle, angular velocity, and angular acceleration of the fruit and vegetable picking arm are all smooth curves. It shows that the joints and moving parts of the fruit and vegetable picking arm can run smoothly during actual operations.

5 Conclusion
According to the structural characteristics of the fruit tree picking robot, this paper establishes a kinematic model, and simulates the movement of the fruit and vegetable picking arm through MATLAB Robotics Toolbox. The secondary development of the robot toolbox enables it to simulate complex continuous space curves. The trajectory of the end effector of the fruit and vegetable picking arm is obtained by simulation. Then, the Cartesian space trajectory simulation and joint trajectory space simulation of the fruit and vegetable picking arm are performed to obtain the curve of the position, speed and acceleration of the end effector of the fruit and vegetable picking arm over time. At the same time, the motion characteristic curves of the angle, angular velocity and angular acceleration of each joint during the movement of the fruit and vegetable picking arm are also obtained. The simulation results show that the position, velocity and acceleration curves of each joint of fruit and vegetable picking arm, as well as the curves of angle, angular velocity and angular acceleration, are smooth under the constraint conditions of the head and end points of the trajectory. Therefore, the
reliability and stability of the operation process of the fruit and vegetable picking arm are demonstrated, which provides a certain theoretical basis for the further research of the picking robot.

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