Kinematics Analysis and Trajectory Planning of Dual-arm Pruning Robot

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Abstract. In order to overcome the disadvantages of manual pruning of tree branches, the dual-arm pruning robot is proposed in this paper. The structure of the dual-arm pruning robot is designed, and the three-dimensional model is established. Taking the dual-arm of the pruning robot as the study object, the D-H method is used to build the kinematics model so as to better research the process of the two arms cooperative pruning. The kinematics simulation is done by Matlab to verify the rationality of the D-H parameters. The workspace of the dual-arm is analyzed, as well as the trajectory planning in joint space. The torques of each joint are solved to determine the power of the driving motor. The research results provide the theoretical basis for the final prototype manufacturing.

Keywords: Dual-arm, pruning, robot.

1. Introduction
With the development of Informatization and intelligence in agricultural production, more and more new automation machinery has entered the field of agricultural production [1]. Pruning tool for the tree-branches close to electrical power lines is studied [2]. The urban landscape automatic pruning robot is designed and analyzed [3]. The key technology of the loquat pruning robot is addressed [4] and so on. By contrast, the automatic and intelligent operations of the pruning robot are more time-saving and convenient than the manual work of pruning tree branches. At present, comparing with the harvesting robots, the research and application of pruning robot are far from enough. Therefore, the development of pruning robots is necessary.

The human-like dual-arm pruning robot is addressed in this paper. The structure design of the robot is presented. The D-H mathematical model and simulation model of kinematics are studied to prove the accuracy of the structure. The workspace, the trajectory planning and the joint torque of the dual-arm are analyzed for solving the control problems.

2. Structure Design of Dual-arm Pruning Robot
Since the robot moves back and forth on the slope when pruning the branches of fruit trees, a chassis is needed for the robot that can support and drive the movement. Compared with the wheeled chassis, the turning radius of the crawler chassis is smaller. The ability to overcome obstacles is stronger, and the stability and reliability are higher. The body of the dual-arm pruning robot is installed on the crawler
chassis. The waist of the body is driven by a motor, which can rotate left and right. The arms of the body are the humanoid double arm structure, which are composed of shoulders, upper arms, lower arms, elbows and wrists. There are eleven joints including the waist and the dual-arm, and all the joints are rotary joints. Pruning is mainly realized by the movement of the dual-arm and waist, which can determine the position and orientation of the wrist end.

The ends of the two wrists are equipped separately with different pruning mechanisms. One of the end effector is a pruning plier, and the other is a pruning saw. The plier is composed of movable blade, fixed blade and laser sensor. The saw consists of ball screw, saw blade and laser sensor. The small branches can be trimmed directly with the pruning plier. The large branches can be pruned with plier and saw. In order to better identify the branches that need to be pruned, the vision module, obstacle avoidance module and other control systems are designed for accurate positioning.

The crawler chassis is controlled to move to the desired position in front of the trees, and then the branches that needed to be pruned are recognized by the camera. The relative position between the branches and the robot is determined by image acquisition and recognition. After that, the dual-arm is driven to exact location. When the branches are small, the laser sensor on the plier detects the branches, and the plier cut them off immediately. If there are large branches, the branches will be clamped by the plier, and then they are sawn off by the saw. A three-dimensional model of the dual-arm pruning robot is established, as shown in Fig. 1.

![Figure 1. 3D model of dual-arm pruning robot](image)

3. Kinematics Analysis

3.1. Kinematics Modeling

In order to better study how the dual-arm of the robot cooperate in the pruning work, the kinematics is analyzed. The forward kinematics problem of serial chain robot is to obtain the position and attitude of the end relative to the base, given all the joint positions and all the link parameters. The D-H method is applied to model the kinematics of robots. According to the four parameters of link length $a_n$, link offset $d_n$, link torsion angle $\alpha_n$, and joint angle $\theta_n$, the coordinate system and corresponding coordinate transformation are established in each joint, as well as the relationship between joint space and Cartesian space can be established. Each arm of the pruning robot is connected by five links through joints in sequence. The first link is the shoulder, and the last link is the wrist. The base coordinate system $O_0X_0Y_0Z_0$, the left arm base coordinate system $O_0X_0Y_0Z_0$, the left arm base coordinate system $O_0X_0Y_0Z_0$, and the right arm base coordinate system $O_0X_0Y_0Z_0$, are established. The established dual-arm coordinate system of the pruning robot is shown in Fig. 2.

Due to the symmetry of the dual-arm robot model, the kinematics solutions of the two arms are the same. Taking the left arm as the example, the D-H parameters are shown in Table 1. The solutions of kinematics are solved in formula (2) and formula (3).
Figure 2. Coordinate system distribution of dual-arm

Table 1. D-H parameters of left arm

| Link | \(a\) | \(d\) | \(\alpha\) | \(\theta\) |
|------|-----|-----|-----|-----|
| 1    | \(a_1\) | \(d_1\) | \(-90^\circ\) | \(\theta_1\) |
| 2    | \(a_2\) | 0   | 0   | \(\theta_2\) |
| 3    | \(a_3\) | 0   | 0   | \(\theta_3\) |
| 4    | 0   | \(d_4\) | 90°  | \(\theta_4\) |
| 5    | 0   | 0   | 90°  | \(\theta_5\) |

The homogeneous transformation matrix of the \(n\)th link coordinate system corresponding to the \((n-1)\)th link coordinate system is represented by \(^{n-1}T_n\):

\[
^{n-1}T_n = \begin{bmatrix}
\cos \theta_n & -\sin \theta_n & 0 & a_{n-1} \\
\sin \theta_n \cos \alpha_{n-1} & \cos \theta_n \cos \alpha_{n-1} & -\sin \alpha_{n-1} & -\sin \alpha_{n-1} d_n \\
\sin \theta_n \sin \alpha_{n-1} & \cos \theta_n \sin \alpha_{n-1} & \cos \alpha_{n-1} & \cos \alpha_{n-1} d_n \\
0 & 0 & 0 & 1
\end{bmatrix} 
\]

(1)

Multiply the transformation matrix between adjacent joints one by one to get the transformation matrix of the end coordinate system of the left arm relative to coordinate system of the base. The forward kinematics equation of the left arm is formula (2).

\[
^{0}T_5 = ^{0}T_1^{1T_1}^{2T_2}^{3T_3}^{4T_4}^{5T_5} = \begin{bmatrix}
5n & 5\alpha & 5a & 5p \\
0 & 0 & 0 & 1
\end{bmatrix} 
\]

(2)

Given end position and attitude of the left arm, the joint angles of the left arm are calculated by formula (3).

\[
(^{0}T_1)^{-1}^{0}T_1 = ^{2T_1}^{3T_2}^{4T_3}^{5T_4}
\]

(3)
3.2. Kinematics Simulation
The simulation model of the dual-arm is established by Matlab Robotics Toolbox, which can analyze the kinematics of robot intuitively. Simulation model of the dual-arm is shown in Fig.3. The simulation results show the correctness of the kinematics model of the dual-arm.

![Figure 3. Simulation model of the dual-arm](image)

3.3. Workspace Analysis
For the sake of studying the working area where the wrist end of the double-arm pruning robot can reach, the working space is discussed by Monte Carlo method [7]. When the two arms cooperate to prune, and the working space is the intersection of two single arm working spaces. Fig. 4 shows the workspace of the dual-arm. It shows that the workspace of the left and right arms of the robot have the overlapping parts, which mean that the two arms may collide. Therefore, algorithms are needed to control the movement of the dual-arm to prevent collisions.

![Figure 4. Workspace of the dual-arm](image)

4. Trajectory Planning

4.1. Trajectory Planning in Joint Space
S-curve interpolation is the method which can be used to analyze the trajectory planning of the dual-arm in joint space [8, 9]. According to the S-curve interpolation method, the simulation curves of motion
parameters of the dual-arm can be achieved by Matlab Robotics Toolbox. The curves of the six joints including the waist and the left arm of the robot are shown in Fig.5 to Fig.6. The curves of the six joints including the waist and the right arm of the robot are shown in Fig.7 to Fig.8. The joint position, velocity, acceleration are represented by $S$, $\dot{S}$ and $\ddot{S}$ respectively in the figures. From Fig.5 to Fig.8, it can be shown that the motion of dual-arm is smooth without mutation, which meets the design requirements.

**Figure 5.** Joint position curve and velocity curve of the waist and left arm

**Figure 6.** Acceleration curve of the waist and left arm

**Figure 7.** Joint position curve and velocity curve of the waist and right arm

**Figure 8.** Acceleration curve of the waist and right arm
4.2. Joint Torque
Given the initial position and termination position of the end effector, the initial joint angles and the target joint angles are obtained by using the iterative inverse kinematics algorithm in Matlab [10]. By setting the sampling time steps, the angles, angular velocities and angular accelerations of each joint are solved by using the S-curve interpolation method in joint space. According to the above data, the torques of each joint can be obtained. Fig. 9 shows the joint torques of each joint including the joints of the left arm and the waist. The simulation results show that the torques of each joint change smoothly. The prototype of the dual-arm pruning robot is shown in Fig. 10.

![Figure 9. Drive torques of left arm](image)

![Figure 10. Prototype of dual-arm pruning robot](image)

5. Conclusions
In this paper, the structure of the dual-arm pruning robot is designed. In order to verify the rationality of structure, the kinematics mathematical model of the dual-arm is analyzed, as well as the simulation
model. Then the workspace and the trajectory planning of the dual-arm in joint space are studied. The torques of each joint are solved. So the driving power of the motors are decided which can prove the control performance of the dual-arm. It is presented that the research lay a good foundation for further study of the dual-arm pruning robot.

Acknowledgments
This work was financially supported by Scientific Research Project of Intelligent Manufacturing Equipment Engineering Technology Research Center of GuangDong (Grant No. [2017] 1649).

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