Control and Dynamic Simulation of Wire-Driven Precise Spray Robotic Arm

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Abstract. The spraying of citrus to kill insects is a necessary part of the citrus planting process. Most of the currently used sprayers are cover sprays, which cannot achieve accurate and low-consumption spraying. Causing a lot of pesticide waste and environmental pollution. Aiming at the difficulty of precise spraying of citrus leaves, this paper proposes a soft spraying manipulator with good bending characteristics and flexible operation ability. The robotic arm consists of 6 joints and 2 arm segments. The two arm segments of the robotic arm are driven by two wire ropes and move in two orthogonal planes respectively. The PD controller design is designed. The joint state observers are constructed to predict joint angles, angular velocities, and other information. The dynamic simulation experiment is carried out, and the relationship between the wire rope tension and the spring elastic force changes with time, and the relationship between each joint angle changes with time. These make the wire-driven precise spray robotic arm potentially useful in agricultural spraying.

1. Introduction
Spraying is one of the important links in orchard operations. The traditional farming methods make crop spraying equipment always require manpower to maintain, and it is difficult to achieve precise spraying. This results in the waste of pesticides and pollutes the ecological environment. Multiple spraying operations have high requirements on machinery, but crop spraying equipment is relatively backward in China[1].

Many areas still use traditional machinery for spraying operations. Citrus trees are easy to spray and pick after dwarfing. However, citrus trees have many branches and leaves and the fruits are hidden in the canopy, so it is impossible to accurately spray the bottom of the leaves and the inside of the plant using traditional spraying machines. Traditional robots have limited freedom of movement and are suitable for structured environments. In comparison, flexible robotic arms can be regarded as many kinematic joints, so flexible robotic arms can flexibly reach any position in the workspace[2]. Using flexible robotic arms can be better in orchard spraying.

Flexible robots are widely used due to increasing industrial productivity, reducing the weight of robots and the need for low energy consumption[3-4]. It’s a cable-embedded silicone arm that mimics the motions octopuses use when crawling[5]. A framework for flexible robot structure modeling, making it more accurate for predictive maintainence, energy efficiency optimization and other work fields[6]. For the working environment in closed and dangerous areas, a variety of wire-driven snake-shaped flexible...
manipulators have been applied in aerospace and nuclear energy\cite{7}. Due to its dexterous structure, it is widely used in the field of surgery\cite{8,9}. Some of the common designs of these robots are tendon and wire driven\cite{10-11}.

Compared with the traditional manipulator, the flexible robot has the advantages of smaller size and lighter weight\cite{12-13}, the agricultural field has also begun to apply the flexible robot. The proposed snake bone-armed robot has high degree of freedom and low cost, which is more feasible than the rigid robotic arm.

In this paper, a wire-driven flexible robot for agricultural orchard spraying is designed, which has a smaller diameter and a long length of the robotic arm. The high degree of freedom can realize the task of precise spraying of citrus trees.

2. Wire-driven Precise Spray Robotic Arm

As shown in Figure 1, it is a flexible wire-driven concentric robotic arm. The mechanical arm is an open-loop kinematic chain structure composed of multiple rotating pairs. It’s composed of a motor box, a first arm segment and a second arm segment. The robotic arm is driven by 4 steel wire ropes and has 2 motors as the power source. Each motor is respectively connected to a terminal plate in the forward and reverse directions, and the forward and reverse rotation of the motor realizes the control of two ropes with opposite winding directions to drive the bending motions in the horizontal plane and the vertical plane respectively. Under the constraints, the manipulator is divided into two arm segment, and the workspace of the manipulator can be expanded through such active constraints\cite{14}. The three tandem joints of the first arm segment realize the bending motion of the manipulator in the horizontal plane, and the joints of the second arm segment realize the bending motion in the vertical plane. The first and the second arm branches are both connected by three joints, each branches have three degrees of freedom, and both have basically the same structure. The telescopic motion of the wire ropes make the branches of the robotic arm bend, and the adjacent links are connected by a spring and a hinge structure, so that the adjacent links which belong to each branches have the same joint angle. Moreover, this structural design reduces the number of drive motors while ensuring the flexibility of motion.

Equipped with the end effector of the spray system at the end of the robotic arm. The spray system is variable flow, and the spray distance of the spray head can be adjusted. As shown in Figure 2, precise spraying is performed when the nozzle is aimed at the target.
3. Control System

Since the wire-driven robotic arm is a nonlinear compensation system, the open-loop control cannot guarantee the stability of the manipulator's motion. Therefore, in order to reduce the motion control error of the mechanism during the movement process, this paper adopts a closed-loop control system based on PD regulator to perform closed-loop control of the joint. At the same time, a joint state observer is introduced into the system feedback to predict the actual joint motion state. The predicted joint angle, angular velocity and other information are fed back to the PD regulator to form a closed-loop control of the entire system. The block diagram of joint closed-loop control is shown in figure 3.

![Block diagram of control](image)

3.1. PD Controller

In order to obtain the relationship between the joint torque and joint displacement, velocity and acceleration of the joint. The joint space dynamic equation is established by the Newton-Euler method, and the general structural formula of its closed form is:

\[ H\ddot{q} + C\dot{q} + G = \tau \]  

Where, \( H \) is inertia matrix, \( C \) is Coriolis matrix, \( G \) is equivalent gravity, \( \dot{q} \) is joint angular velocity. \( \ddot{q} \) is angular acceleration, \( \tau \) is the driving torque produced by the rope tension. By calculating the moment, the rope force Jacobian \( J_Tf \) can be expressed as:

\[ \tau = Hv + C\dot{q} + G \]  

In the equation, \( v \) is the control quantity to be designed. From Equation (1) and Equation (2) we have:

\[ \ddot{q} = v \]  

According to the PD control theory, the PD controller is designed as:

\[ v = K_p e_q + K_d \dot{e}_q + \ddot{q}^d \]  

Where, \( e_q = q - q^d \) is joint position error, \( \dot{e}_q = \dot{q} - \dot{q}^d \) is joint velocity error, \( K_p \) and \( K_d \) is gain matrix which is the diagonal matrix. From Equation (1), Equation (2) and Equation (4), we can get:

\[ \ddot{e}_q + K_d \dot{e}_q + K_p e_q = 0 \]  

Where, \( \ddot{e}_q = \ddot{q} - \ddot{q}^d \) is joint acceleration error.

Only use the PD controller for open-loop control can produce large errors. As the number of joints increases, the accumulated error of the joints will make the end motion error larger and cannot reach the
working position. Therefore, only using PD open-loop control cannot guarantee the performance of the system.

3.2. Joint State Observer
The single joint motion space of the wire-driven manipulator is very small. In the agricultural spraying environment, it is necessary to increase the range of motion of the joints to improve the working space of the sprayer. Since pesticides spilled on the robotic arm will corrode the electronic components, no angle sensors are installed at the joint corners. In order to obtain the joint angle and angular velocity required by the system, a state observer is selected to estimate the joint state.

The system state equation can be expressed as:

\[ \dot{x} = Ax + Bu \]

Where, \( A \) is system state matrix, \( B \) is system input matrix, \( u \) System input vector.

The output equation of the system is expressed as:

\[ y = cx \]

Where, \( c \) is system output matrix.

The joint state observer is constructed as:

\[ \dot{x} = (A - Lc)x + Bu + Ly \]

Where \( L \) is the feedback matrix of the observer. Therefore, the eigenvalues of the coefficient matrix all have negative real parts by setting \( L \), so that the estimated value of the joint state gradually approaches the real value.

After adding a joint state observer to the feedback, the observer can estimate the joint angle and angular velocity. It gives the feedback information to the controller to control the motor to act, so that the end effector can reach the position required by the job.

4. Kinematics and Dynamics Simulation Experiments

4.1. Spring force and wire rope tension
The torque on the motor is:

\[ M = F \cdot R \]

Where, \( M \) is motor torque, \( F \) is the wire rope tension, \( R \) is the wire rope winding radius.

Dynamic simulation of the first arm segment. In the case of no external load, the force of the spring at each joint of the branches and the change of the joint angle are only affected by the tension and friction of the wire rope. As shown in Figure 4, the force of each spring and wire rope is represented by different color curves. In the figure, red represents the spring force at the first joint, pink represents the spring force at the second joint, black represents the spring force at the third joint, blue represents the tension of the wire rope of the first arm section. The maximum tensile force of the wire rope is 52.917N, and the motor torque is 2.223N*m at this time.

![Figure 4](image)

Figure.4  Variation curve of the wire rope and spring force of the first arm section

Do the same dynamic simulation for the second arm segment as first arm segment. The spring force and the change of the joint angle at each joint of the branches are mainly affected by the wire rope tension and gravity. As shown in Figure 5, the force of each spring and wire rope is represented by different color curves. In the figure, red represents the spring force at the four joint, blue represents the spring force at the third joint, blue represents the tension of the wire rope of the first arm section. The maximum tensile force of the wire rope is 52.917N, and the motor torque is 2.223N*m at this time.

![Figure 5](image)
of the wire rope of the second arm section. The maximum tensile force of the wire rope is 52.863 N, and the motor torque is 2.220 N \cdot m at this time.

![Figure.5](image)

**Figure.5** Variation curve of the wire rope and spring force of the second arm section

This robotic arm is a cantilever structure. The simulation results show that the influence of friction can be ignored, the influence of gravity cannot be ignored, and the first arm segment is more sensitive to the driving force than the second arm segment. This indicates that static friction does not need to be included in the dynamic model, and in subsequent studies, the structure needs to be optimized to minimize the weight of the robotic arm. Within 0.5 s of the start of movement, the elastic force of the springs at each joint fluctuates. In 0.5 s to 2 s, the elastic force of the spring is linear with time. Which indicates that the robotic arm does not move smoothly within 0.5 s, and the movement is smooth from 0.5 s to 2 s.

4.2. **Constant Curvature Theory Verification Experiment**

The wire rope moves for two seconds at a speed of 20 mm/s. As shown in figure 6, the joint angle of the first arm segment is \( \theta_1 = 23.77^\circ, \ \theta_2 = 22.83^\circ, \ \theta_3 = 22.21^\circ \). As shown in figure 7, the joint angle of the second arm segment is \( \theta_4 = 22.13^\circ, \ \theta_5 = 22.70^\circ, \ \theta_6 = 21.58^\circ \). At this time, the maximum difference between the three joint angles of the first arm segment is 1.56 \( ^\circ \), and the maximum difference between the three joint angles of the second arm segment is 1.12 \( ^\circ \). Therefore, the constant curvature theory can be used to construct the kinematic model of this wire-driven flexible robotic arm. The constant curvature assumption is widely used in flexible robot modeling and has been proven to be accurate enough under small load conditions\(^{[15]}\).

![Figure.6](image)

**Figure.6** Change curve of each joint angle of the first arm segment

It can be seen from the simulation results that compared with the second arm segment, the mechanical structure of the first arm segment overcomes the effect of gravity. Therefore, the change of the joint angle is only affected by the friction force and the rope tension, the size of each joint angle is closer, and the slope of the joint angle change curve is more the same. With the increase of the joint angle of the first arm segment, the difference of each joint angle gradually decreases, and the motion accuracy
of the arm segment gradually decreases. With the increase of the joint angle of the second arm segment, the difference of each joint angle gradually increases, and the motion accuracy of the arm segment gradually increases.

5. conclusion

In this paper, a wire-driven segmented linkage concentric robotic arm is proposed and dynamic simulation is performed. Based on the PD control system, the joint is closed-loop controlled and a joint state observer is constructed to predict the joint angle, angular velocity and other information. The flexible robotic arm is composed of multiple rotating pairs and has 6-DOF, so it has high underactuated. Its diameter, length and mass are 73mm, 670mm and 935.08g respectively. It can be nimbly inserted between the branches to achieve precise spraying of citrus trees. Without considering the load at the end of the manipulator, the parameters of each joint spring are obtained through dynamic analysis when the manipulator is in a state of constant curvature. The elastic force of each spring in the arm segment is similar, and the experiment proves that the mechanical arm moves smoothly, and the elastic force of the spring does not vibrate significantly. This spraying robotic arm can be installed on a mobile robot for spraying operations to reduce labor burden. It is expected to be applied to precise spraying of citrus fruit trees.

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