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A New Trajectory Planning Method of 6-DOF Apple Picking Manipulator

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Abstract

In order to control the 6-DOF apple picking manipulator to complete the picking task accurately and safely, a new trajectory planning method of 6-DOF apple picking manipulator is studied. Based on the mathematical model of the 6-DOF apple picking manipulator, the pose information and arm shape information of the forward and reverse motion of the manipulator are analyzed. On the basis of the obstacle avoidance method for the apple picking manipulator based on the improved artificial potential field, the obstacle model is constructed to obtain the obstacle distribution information. Through the two-way planning algorithm of the manipulator obstacle avoidance based on the improved artificial potential field method, the pose information and arm shape of the forward and reverse motion of the manipulator are controlled. On this basis, the trajectory planning control method of 6-DOF apple picking manipulator based on sliding mode PID control is used to control the manipulator to pick apples accurately and safely. After testing, the 6-DOF apple picking manipulator can realize the safe picking of apples according to the set picking position and speed.

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Keywords: 6-DOF; Apple picking; Picking; Manipulator; Trajectory planning.

1. Introduction

As the representative of contemporary high-tech industry, robot industry began in the 1960s. The rapid development of robotics and robotics industry benefits from the emergence and rapid development of microcomputer technology. At present, millions of robots have been applied in various fields, especially in manufacturing systems [1].

Big data, cloud computing and mobile Internet technology, which are familiar to us, promote the development of robot technology. Their integration with robot technology makes the degree of artificial intelligence of robots higher and higher. Military UAVs, autonomous cars, home service robots and so on have been realized, and even common [2]. In the world, many media generally believe that it is no exaggeration to use "The Pearl at the top of the crown" to describe the position of robots in the manufacturing industry. Now an important sign to measure the level of a country's high-end manufacturing industry is the R & D, manufacturing and application of robots. With the wave after wave of industrial revolution, we have moved from automation to informatization and then to robotics. It has to be admitted that the emergence of robots has greatly improved the production efficiency of industrial production. In modern life, the situation that robots gradually replace people to take the post of physical labor or even mental labor has been slowly accepted by people [3].

With the high development of productivity, the accuracy and stability of motion put forward high requirements for robots. How to improve the working efficiency of the robot and minimize the error caused by the movement process is the key problem to be solved in its application, because the most important index to measure the performance of the robot is the working efficiency and quality of the robot. Therefore, more in-depth research on robot system is the basis of robot design and development [4]. The research on manipulator trajectory planning is the premise and foundation to solve the problem.

The so-called trajectory planning is to discuss the method of calculating trajectory. The trajectory can reflect the motion path of the manipulator in space. Those who know something about the robot system know that the smoothness and stability of the motion process of the manipulator (avoiding the sudden change of displacement, speed and acceleration as much as possible) is a principle that must be followed in the motion process of the robot system. In fact, abrupt motion requires a lot of power, which is difficult to provide due to the physical limitations of the motor[5,6]. Therefore, this reflects the importance of motion trajectory planning. Using simple technology to plan the motion of the robot can make its motion smooth and stable, and produce less impact and vibration, which basically ensures the long-term and stable operation of the system. However, the vibration of rigid body and the sudden change of motion are difficult to be guaranteed [7]. Therefore, we have to deeply study the trajectory planning

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of robot in order to meet the increasing performance requirements.

The technology of trajectory planning is also developing and improving with the improvement of productivity and tracking accuracy[8]. There are many performance optimization indexes of robot trajectory planning algorithm, such as optimal time and optimal impact. The most studied is the robot trajectory planning algorithm in the optimal time. This most studied trajectory algorithm is indeed a very active research field in the past ten years [9].

ZHENG C-E et al. proposed the trajectory planning method of the apple picking manipulator based on the deep deterministic policy gradient algorithm (DDPG) of stepwise migration strategy. The progressive space constraint of DDPG was used to train the strategy step by step, and the transfer learning idea was used to transfer the trained strategy to the promiscuous obstacle scene. Finally, the DOF apple picking manipulator was simulated. This method can improve the training efficiency in the process of trajectory planning training, but it is difficult to ensure that the apple picking robot arm can safely and accurately pick the target apple during the picking process [10]. LIU X-F et al. designed a stretchable, fixed torque, self-transporting efficient apple picking manipulator based on a variety of mechanical structures. This mechanical arm not only improves the picking efficiency, but also reduces the cost of picking apples, which can ensure personal safety to a certain extent. However, this mechanical arm is difficult to pick apples accurately according to the set apple picking position, and its accuracy needs to be improved [11]. FAN Z-Y et al. proposed a trajectory planning method for camellia fruit picking manipulator based on the improved Gray Wolf algorithm. The kinematics and working space of the manipulator were analyzed, and the trajectory fitting planning was carried out. The gray Wolf algorithm was improved based on the analysis of Wolf writing and hunting, and the improved gray Wolf algorithm was used to carry out the trajectory optimization simulation experiment of the manipulator picking operation. This method can obtain the trajectory planning results with optimal time, but ignores the security and accuracy of picking operations [12]. SI G-B et al. designed a path planning method for agricultural picking manipulator based on cloud platform and Q-learning algorithm. This paper analyzes the application of Q learning algorithm in the path planning of agricultural picking manipulator, introduces the working mode of cloud platform and calculates the path planning, designs the control system of agricultural picking manipulator, and realizes the path planning of picking manipulator. This method can better avoid the obstacles in the environment, and the path deviation of the overall motion curve is small, but its picking accuracy is difficult to be guaranteed [13].

There are many kinds of trajectory planning algorithms. Its development has experienced a process from low-level to high-level, simple to complex. Its interpolation accuracy is higher, and the interpolation speed is faster. Classical interpolation algorithms include straight line, arc, helix and so on. Straight line interpolation and arc interpolation are the two most basic interpolation algorithms. At present, the most studied algorithms are parametric curve algorithms, such as B-spline curve, NURBS curve and so on. Combined with the current research data, this paper puts forward a new trajectory planning method of 6-DOF apple picking manipulator. This method can not only accurately realize apple picking according to the specified information, but also has good obstacle avoidance effect.

2. Methods

2.1. Mathematical model of 6-DOF apple picking manipulator

To study the motion of the manipulator, it must firstly establish the kinematic equation. When studying the 6-DOF apple picking manipulator, the corresponding coordinate system should be established on each corresponding manipulator link. In order to understand the motion of the manipulator, the relationship between the link coordinate systems must be established [14]. In order to determine the translation vector of the connection between the coordinate systems and the direction of each link coordinate system, this paper uses the D-H parameter method to reflect the relative position of the adjacent links for the multi degree of freedom manipulator.

2.1.1. Forward kinematics model

The forward motion pose ${}_6^0H'$ of the 6-DOF apple picking manipulator is constructed as follows:

$$ {}_1^0H' = \begin{bmatrix} YX\alpha_1 & -XX\alpha_1 & 0 & 0 \\ XX\alpha_1 & XY\alpha_1 & 0 & 50 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

$$ {}_2^0H' = \begin{bmatrix} YX\alpha_2 & -XX\alpha_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -XX\alpha_2 & -YX\alpha_2 & 1 & 425 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

$$ {}_3^0H' = \begin{bmatrix} YX\alpha_3 & -XX\alpha_3 & 0 & 0 \\ XX\alpha_3 & YX\alpha_3 & 1 & 0 \\ 0 & 0 & 1 & 50 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

$$ {}_4^0H' = \begin{bmatrix} YX\alpha_4 & -XX\alpha_4 & 0 & 0 \\ 0 & 0 & 1 & 425 \\ -XX\alpha_4 & -YX\alpha_4 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

$$ {}_5^0H' = \begin{bmatrix} YX\alpha_5 & -XX\alpha_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ XX\alpha_5 & YX\alpha_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

$$ {}_6^0H' = \begin{bmatrix} YX\alpha_6 & -XX\alpha_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -XX\alpha_6 & YX\alpha_6 & 0 & 100 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6} $$

Where, YX and XX are cosine function and sine function in turn. The product of six transformation matrices between adjacent joints is the forward kinematics solution.

2.1.2. Reverse kinematics model

The reverse motion pose of the 6-DOF apple picking manipulator is:

$$ {}_{j}^{0}H = {}_{1}^{0}H(\alpha_1)\,{}_{2}^{0}H(\alpha_2)\,{}_{3}^{0}H(\alpha_3)\,{}_{4}^{0}H(\alpha_4)\,{}_{5}^{0}H(\alpha_5)\,{}_{6}^{0}H(\alpha_6) \quad (7)$$

To solve each joint variable α_j, due to the particularity of the 6-DOF apple picking manipulator, the 6-DOF apple picking manipulator can have different postures at the same point, resulting in the multiplicity of joint variables of the 6-DOF apple picking manipulator, because α_1 and α_3 have two solutions, and their combination makes α_2 have four groups of solutions. And the wrist joint "flipping" will get another four solutions:

$$\alpha_4 = \alpha_4' - 180^{o} \quad (8)$$

$$\alpha_5' = -\alpha_5 \quad (9)$$

$$\alpha_6 = \alpha_6' - 180^{o} \quad (10)$$

Where, α_4', α_5' and α_6' are the angles of joint connecting rod after the turnover of the 4th, 5th and 6th wrist joints respectively. Therefore, there are 8 sets of solutions for inverse kinematics. That is, there are 8 groups of joint angles, which can meet the same posture from the end of the 6-DOF apple picking manipulator. However, due to mechanical constraints, not all of these 8 sets of solutions can be achieved [15].

In the trajectory planning of 6-DOF manipulator, it is one of the important works to determine the unique inverse solution. Otherwise, the shape of the manipulator at the end of the manipulator is uncertain during the movement, which will be very dangerous [16]. Therefore, the arm shape parameters should be introduced here:

$$rr = \begin{cases} rr > 0 & \text{Left shoulder} \\ rr < 0 & \text{Right shoulder} \end{cases} \quad (11)$$

$$cr = \begin{cases} cr > 0 & \text{High elbow} \\ cr < 0 & \text{Low elbow} \end{cases} \quad (12)$$

$$vr = \begin{cases} vr > 0 & \text{High wrist} \\ vr < 0 & \text{Low wrist} \end{cases} \quad (13)$$

Where, rr, cr and vr are the shape parameters of the shoulder, elbow and wrist of the manipulator respectively.

2.2. Obstacle avoidance method of apple picking manipulator based on improved artificial potential field

Based on the posture information and arm shape information of the forward and reverse motion of the 6-DOF apple picking manipulator mastered in Section 2.1, through the obstacle avoidance method of the apple picking manipulator based on the improved artificial potential field, the obstacle model in the operating environment of the apple picking manipulator is constructed to obtain the obstacle distribution information, and the obstacle avoidance of the manipulator is realized through the two-way planning algorithm of the manipulator based on the improved artificial potential field method.

2.2.1. Obstacle model

Because the obstacles such as fruit trees and branches generally have irregular shapes, it is difficult to describe them accurately. In this paper, the spherical envelope of the obstacles is used to approximate the modeling. Although this modeling method expands the obstacle region to a certain extent, it simplifies the description of the obstacle region and the calculation of the spherical envelope approximation method, effectively improves the planning efficiency and ensures the safety of path planning [17].

The spherical envelope of the obstacle can be described as $N(q_0, s_n)$, as shown in Figure 1, in which the maximum and minimum values of the vertex coordinates of the obstacle are (x_a, y_a, z_a) and (x_b, y_b, z_b) in turn, the coordinate of the ball center in the base coordinate system is $q_0(x_0, y_0, z_0)$, and the radius of the surrounding ball is s_n.

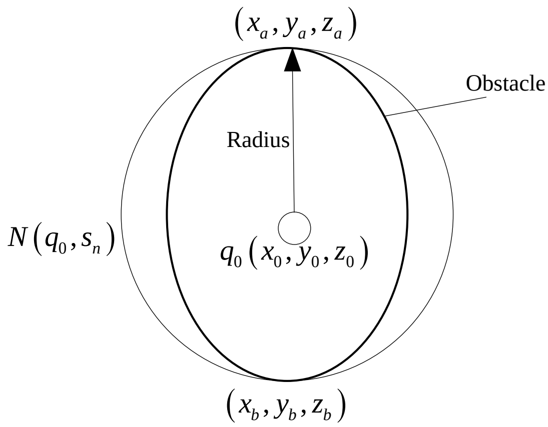

Figure 1. Model of obstacles spherical envelope

$$s_n = \frac{(x_a - x_b)^4 + (y_a - y_b)^4 + (z_a - z_b)^4}{2} \quad (14)$$

The bounding sphere is defined as:

$$S = \left\{ (x, y, z)^T \right\} \quad (15)$$

Where x_a, y_a and z_a are the maximum values of x axis coordinates, y axis coordinates and z axis coordinates of obstacles; x_b, y_b and z_b are the minimum values of x axis coordinates, y axis coordinates and z axis coordinates of obstacles; T stands for transpose.

2.2.2. Bi-directional planning algorithm for obstacle avoidance of manipulator based on improved artificial potential field method

The 6-DOF apple picking manipulator belongs to the research category of picking robot. The artificial potential field method is widely used in the path planning of mobile robot. Its basic idea is to regard the 6-DOF apple picking manipulator as a particle and establish an artificial potential field composed of gravitational field $V_{att}(p)$ and repulsive field $V_{rep}(p)$ in its workspace. The gravity $G_{att}(p)$ and repulsive force $G_{rep}(p)$ generated by them act on the joint target point of the 6-DOF apple picking manipulator. The principle of artificial potential field method is shown in Figure 2.

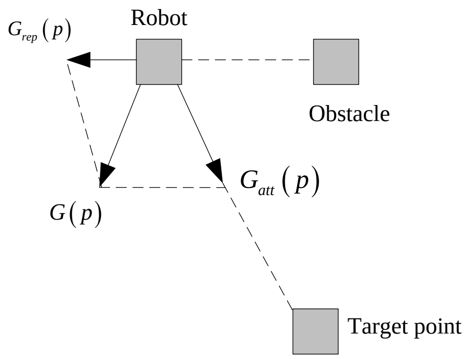

Figure 2. Principle of artificial potential field method

Assuming that the current pose of the 6-DOF apple picking manipulator is p, $p={}_j^0H+{}_j^0H'$, and the sum of rr, cr and vr is referred to as the morphological parameter rcv, the resultant force exerted by the artificial potential field on the manipulator is:

$$G(p)=SG_{att}(p)rcv+SG_{rep}(p)rcv \tag{16}$$

When planning the path of the manipulator with the artificial potential field method, we should not only ensure that the end of the manipulator reaches the target point, but also consider the possible collision between the connecting rod of the manipulator and the obstacle [18]. In this paper, an appropriate artificial potential field is established in the workspace of the manipulator, and the artificial potential field method is improved from three aspects: oscillation problem, algorithm efficiency and local minimum point.

In order to better apply the artificial potential field method to the path planning of manipulator, the gravitational field and repulsive field are established in joint space and Cartesian space respectively. The gravitational field exists between the manipulator and the target position. The farther away from the target position, the greater the gravity, and the generated gravity pulls the manipulator to the target position [19].

When planning the path of multi degree of freedom manipulator in Cartesian space, the inverse kinematics solution needs to be carried out continuously, which often leads to the emergence of singular solutions [20]. In order to avoid this problem, the gravitational field $V_{att}(p)$ is established in the joint space of the manipulator.

$$V_{att}(p)=\begin{cases} rcv\left\|\frac{p\theta}{2}-\frac{p_{goal}\theta}{2}\right\| & \|p-p_{goal}\|\le e \\ rcv\|\theta ep-\theta ep_{goal}\|-\frac{1}{2}\theta e^2 & \|p-p_{goal}\|>e \end{cases} \tag{17}$$

Where, p_{goal} is the pose of the apple, which belongs to the desired pose of the manipulator; θ is the gravitational gain. The distance threshold e is set to prevent the robot arm from obstacle avoidance failure due to excessive gravity.

It can calculate the negative gradient of the gravitational field $V_{att}(p)$ to obtain the gravitational force:

$$G_{att}(p)=\begin{cases} rcv\|-\theta p+\theta p_{goal}\| & \|p-p_{goal}\|\le e \\ -e\cdot rcv\frac{\theta(ep-ep_{goal})}{\|ep-ep_{goal}\|} & \|p-p_{goal}\|>e \end{cases} \tag{18}$$

The repulsion field exists between the manipulator and the obstacle. The generated repulsion force $G_{rep}(p)$ keeps the manipulator away from the obstacle, and its size is inversely proportional to the shortest distance $\gamma(p)$ between the manipulator and the obstacle.

It is very complex to establish the repulsive force field in the joint space, so it is necessary to calculate the minimum $\gamma(p)$ in all the manipulator attitudes P_{obs} in the collision. Therefore, it is easier to calculate $\gamma(p)$ and establish the repulsion field of the manipulator in Cartesian space.

Since the manipulator cannot be regarded as a particle, several control points are defined on the manipulator as the force points of the manipulator in the repulsion field. Select the coordinate origin O_1, O_2 and O_3 of the 3th, 5th and 6th joints of the manipulator as the control points, as shown in Figure 3.

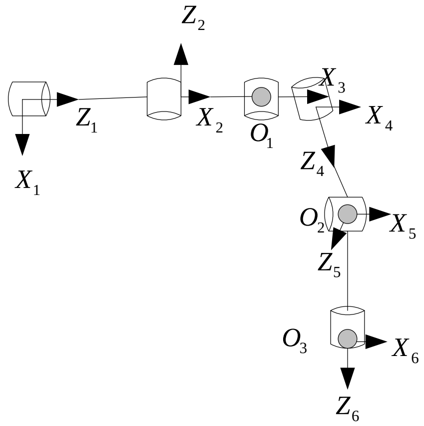

Figure 3. Manipulator control points

Let $b_j(p)$ as the coordinate of the control point O_j when the manipulator is in position and attitude p, and there is repulsive potential energy for the control point O_j:

$$V_{rep}^j(p)=\begin{cases} \frac{\partial_j}{2}\left(\frac{rcv}{\gamma(b_j(p))}-\frac{rcv}{\gamma_0}\right)^2 & \gamma(b_j(p))\le\gamma_0 \\ 0 & \gamma(b_j(p))>\gamma_0 \end{cases} \tag{19}$$

Where ∂_j is the repulsion gain of control point O_j; $\gamma(b_j(p))$ is the shortest distance from O_j to the obstacle; γ_0 is the maximum distance of the repulsion of the obstacle to O_j.

The further repulsive force O_j can be applied on:

$$G_{rep}^j(p)=\begin{cases} rcv\left(\frac{\partial_j}{\gamma(b_j(p))}-\frac{\partial_j}{\gamma^2(b_j(p))}\right)\frac{\gamma(b_j(p))}{\gamma^2(b_j(p))} & \gamma(b_j(p))\le\gamma_0 \\ 0 & \gamma(b_j(p))>\gamma_0 \end{cases} \tag{20}$$

Finally, the gravity $G_{rep}^j(p)$ in the operating environment of the manipulator in Cartesian space is converted into joint force $G_{rep}(p)$:

$$G_{rep}^j(p)=G_{rep}(p)/\sum_{j=1}^{3}I_{v,j}(p)rcv \tag{21}$$

Where, $I_{v,j}(p)$ is the part of the central line velocity of the Jacobian matrix of the manipulator.

At some positions in the repulsion area, the manipulator will appear alternately with $G_{att}(p) > G_{rep}(p)$ and $G_{att}(p) < G_{rep}(p)$. Under the action of such potential field force, the manipulator will move back and forth, resulting in oscillation of obstacle avoidance path [21].

In this regard, the repulsive variable gain coefficient ε is introduced to make the repulsive gain decrease gradually in the oscillation stage, reduce the ratio of repulsive gain to gravitational gain, avoid the sudden change of resultant force direction, and realize a relatively smooth track, as follows:

$$\partial_j = \varepsilon \cdot \partial_0 \tag{22}$$

Where ∂_0 is the initial repulsion value.

In order to further improve the search efficiency of the algorithm, an adaptive step size strategy is introduced in the process of path search.

The next pose p_{next} of the manipulator is determined by the gradient descent direction. Set the current pose of the manipulator as p, including:

$$p_{next} = rcv \cdot \varepsilon\rho + \frac{\sigma G(p)}{\|G(p)\|} \tag{23}$$

$$\|p_{goal} - p\| > \rho \tag{24}$$

Where σ and ρ are the search step size and the maximum allowable error respectively.

The algorithm adaptively modifies the step size according to the distance between the control point of the manipulator and the obstacle. When the obstacles are far away, large step size is adopted to improve the search efficiency of obstacle avoidance path [22]; When the obstacle is close, reduce the step size to ensure the accuracy of the algorithm, as follows:

$$\sigma = \sigma_0 + rcv \cdot \sum_{j=1}^{3} \varepsilon\mu_j \gamma\left(b_j(p)\right)/3 \tag{25}$$

Where σ_0 is the initial step size; μ_j is the weight coefficient of the manipulator control point O_j.

Aiming at the problem that the path planning by artificial potential field method is easy to fall into local minima, a two-way planning algorithm based on artificial potential field method is proposed. The specific manifestation of the local minimum point is: when the manipulator is searching for the obstacle avoidance path, the resultant force of the gravity and repulsion received by the manipulator at a certain position is just at a minimum point. At this time, the change of any joint angle will lead to the increase of the resultant force, the manipulator will move repeatedly at this position, the manipulator will fall into the local minimum, and the algorithm will fail [23]. Bi directional planning is to use the artificial potential field method to plan two opposite paths from the initial point and the target point respectively. The target point of each search for the obstacle avoidance path will be updated, and the gravity of the manipulator will change accordingly, avoiding the emergence of local minimum points to a certain extent [24]. Finally, the two paths are spliced into the final path.

The specific steps of two-way planning are as follows:

1. From the initial point of the end of the 6-DOF apple picking manipulator in Cartesian space and the apple picking target point, the initial value and target value of the obstacle avoidance trajectory of the manipulator in joint space are obtained [25].
2. The initial value of the obstacle avoidance trajectory of the 6-DOF apple picking manipulator in the joint space is planned forward, and the initial target is p_{goal}. For p_{goal}, the initial target of the obstacle avoidance trajectory becomes p_{start}.
3. After the calculation of the improved artificial potential field method, the current position of the 6-DOF apple picking manipulator is updated to p_j^f and p_j^r by forward and reverse programming respectively. The position planning result includes the pose and arm shape of the 6-DOF apple picking manipulator. These two values will be set as the target point for the next search.
4. Repeat step (3) until after i times of search, when the 6-DOF apple picking manipulator moves forward and backward, the result of obstacle avoidance path planning meets the following conditions, and the algorithm ends.

$$\begin{cases} \|p_j^f - p_j^r\| < F \\ \|p_j^f - p_j^r\| < E \end{cases} \tag{26}$$

Where, F and E are the maximum allowable errors of joint quantity and space quantity.

2.3. Trajectory planning control method of 6-DOF apple picking manipulator based on sliding mode PID control

Based on the basic knowledge of the picking obstacle avoidance of the manipulator realized in Section 2.2, in order to ensure the stability and success of the 6-DOF apple picking manipulator, the error model of the 6-DOF apple picking manipulator is set as follows:

$$\psi_t = p_j^f \cdot p_j^r\left(\psi_{t+1} + h_1 + h_0\right) \tag{27}$$

Where h_1 and h_0 are the design parameters of sliding mode PID controller. When $\psi^2 + h_1\psi + h_0 = 0$, the 6-DOF apple picking manipulator is stable. ψ is the damping ratio, t is the picking time, and ψ_{t+1} is the damping ratio of the manipulator at time $t+1$.

The design process of sliding mode PID controller is divided into two steps. Firstly, a sliding mode surface function is defined, and then an appropriate control law is designed to make the system reach and maintain the desired sliding mode surface $\lambda = 0$.

$$\lambda = p_j^f \cdot p_j^r\left(\psi_{t+1} - \psi_t\right) \tag{28}$$

If the desired sliding surface exists, $\lambda = 0$ can be made. Let $\psi_{t+1} = \psi_t$, introduce equation (28) into equation (27), then:

$$h_1\psi_{t+1} + h_0\psi_t = 0 \tag{29}$$

Equation (29) as time increases, the error of the 6-DOF apple picking manipulator when picking apples will eventually converge to 0.

The control input vc of the 6-DOF apple picking manipulator is designed as follows:

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$$vc = p_j^f \psi_{PID} \cdot p_j^r \psi_{PID} \tag{30}$$

Where, ψ_{PID} is the control parameter output value of sliding mode PID control of 6-DOF apple picking manipulator.

The gain of traditional PID controller is generally fixed, which can not meet the control quality requirements of manipulator under forward and reverse changing conditions [26]. Therefore, the three control gains ψ_P (proportional), ψ_I (integral) and ψ_D (differential) designed in this paper can be obtained by online learning of the following adaptive law, where $\zeta_j > 0$ represents the adaptive learning rate.

$$\psi_{PID} = -\zeta_j 1 \cdot \psi_t \tag{31}$$

Where 1 is a symbolic function. Using this formula, three control gains ψ_P, ψ_I and ψ_D can be obtained through online learning, and the mechanical arm can be dynamically controlled to complete apple picking accurately and safely under forward and reverse changing working conditions [27].

3. Experimental analysis

In order to verify the feasibility of this method, simulation experiments are carried out in MATLAB 7.0 environment. The experimental environment information is shown in Table 1.

Table 1. Experimental environment information

Name	Working space
Spatial range	[-200,200]mm×[-200,200]mm
Unit size	20mm×20mm
Number of obstacle units / piece	5

In the experimental environment shown in Table 1, the obstacle avoidance effect of the 6-DOF apple picking manipulator when performing the picking task under the use of the method in this paper is tested. The effect diagram is shown in Figure 4.

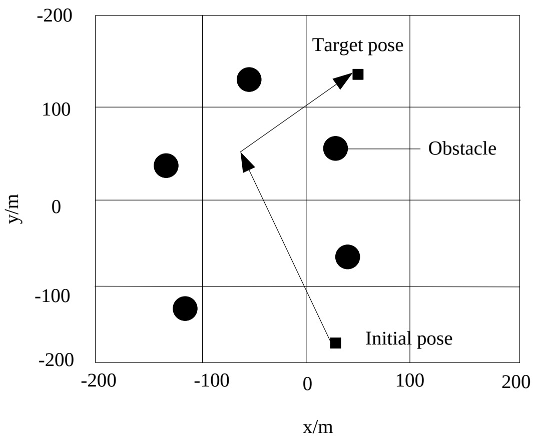
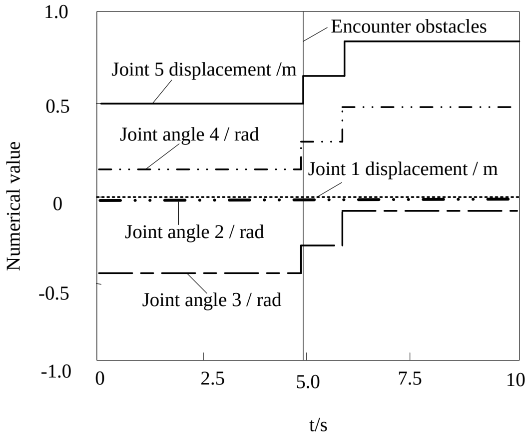


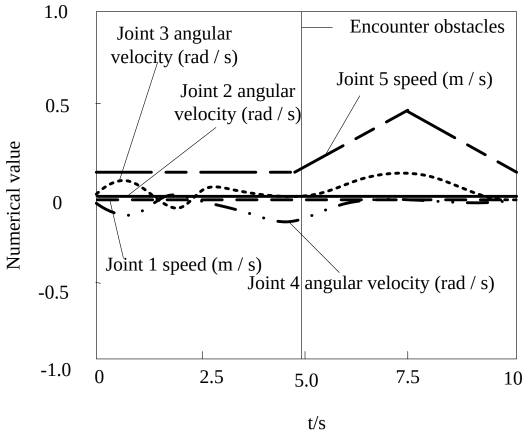
Figure 4. Obstacle avoidance effect of 6-DOF apple picking manipulator during picking task

As shown in Figure 4, the manipulator moves from the initial pose to the target pose, and there is no collision with the obstacles in the workspace in this process, and the obstacle avoidance effect passes the test.

During the obstacle avoidance movement of the manipulator, the variation curves of the motion angle and angular velocity parameters of each joint are shown in Figure 5.



(a) Movement change state of each joint angle

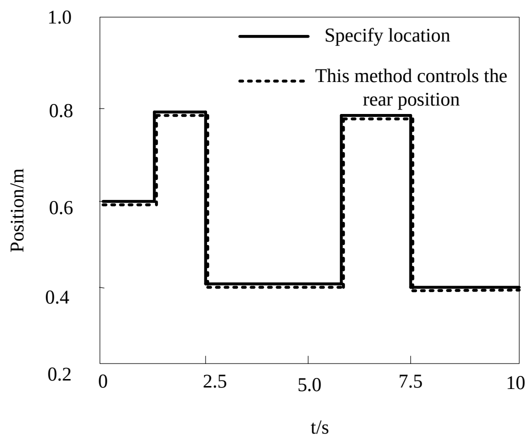


(b) Angular velocity motion change state of each joint

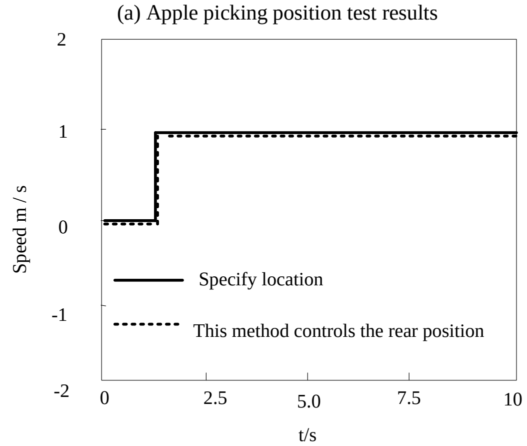
Fig 5. Motion parameters of manipulator joints

Because the joint 1 and rotating joint 2 of the 6-DOF apple picking manipulator are set on the motion carrier where the manipulator is located, the two joints did not act in the experiment, so the motion parameter curves of joints 1 and 2 coincide. It can be seen from the analysis of Figure 5 that the movement of joint 3, joint 4, joint 5 and joint 6 is stable. When approaching the obstacle each time, the angular velocity of the joint decreases. After completing obstacle avoidance, the speed increases rapidly, so as to shorten the time of the whole movement process. The control time of the whole obstacle avoidance process of the manipulator is less than 10s, the movement process of the manipulator is stable and the speed is continuous, which shows the effectiveness of this method.

Under the use of the method in this paper, the picking effect of 6-DOF apple picking manipulator is shown in Figure 6.



(a) Apple picking position test results



(b) Apple picking speed test results

Figure 6. Picking effect of 6-DOF apple picking manipulator

As shown in Figure 6, under the control of the method in this paper, the 6-DOF apple picking manipulator can pick according to the set value of the apple picking target position, and the picking speed also meets the set value, indicating that this method is effective.

4. Discussion

The 6-DOF apple picking manipulator belongs to the research category of fruit tree picking robot. Combined with the research content of this paper, the existing problems of fruit tree picking robot are discussed, and the control suggestions are given.

4.1. Problems of fruit and vegetable picking robot

At present, the picking robot has achieved remarkable results in strawberries, cucumbers, oranges and other fruits and vegetables, but it has not really met the requirements of replacing human beings to complete the picking task. In the development process of the picking robot, there are still some key factors restricting its development. The author believes that the existing problems are as follows.

1. The identification and positioning efficiency of fruit and vegetable robot is not high

In order to complete the picking operation, the picking robot must first have the function of accurately identifying the types of fruits and vegetables, and be able to distinguish the differences between mature and immature fruits and vegetables. At present, gray threshold method, shape feature method and color chroma method are mainly used. Gray threshold method and color chroma method judge fruits and vegetables based on spectral reflection characteristics. The image obtained in this way is easy to be affected by light and produce image noise, which affects the recognition accuracy; Shape feature method is a positioning method based on the condition that the shape of fruits and vegetables can form a complete boundary. In the process of operation, affected by the growth environment of fruits and vegetables, fruits and stems and leaves often coincide together. Therefore, it is very difficult to capture the complete boundary and cannot effectively distinguish the specific shape features of fruits and vegetables. It can be seen that the identification and positioning of fruits and vegetables by the picking robot is the key factor affecting the grasping efficiency.

2. The obstacle avoidance and picking rate of fruit and vegetable robot is not high

In the process of grasping fruits and vegetables, the picking robot is in an unstructured picking environment. The fruits not only overlap each other, but also are covered by branches and leaves. The degree of freedom and flexibility of the picking manipulator and manipulator are the key factors to determine whether they can successfully avoid obstacles. In addition, affected by the motion control program, image processing algorithm, mechanical structure and other aspects, the picking efficiency of most fruit and vegetable robots is low. For example, the picking robot can harvest 5 strawberries, 6 oranges, 3 cucumbers, 8 tomatoes and 6 apples in one minute. How to improve the working efficiency is one of the key problems in the development of picking robot.

3. The manufacturing and maintenance cost of fruit and vegetable robot is high

Compared with industrial robots, the working environment of fruit and vegetable robots is more complex and diverse. Affected by the weather and crop growth environment, its mechanical structure, control system and walking device are more complex, the manufacturing cost is higher, and the research and development cycle is also very long. As a kind of intelligent agricultural equipment with high precision, high intelligence and high technology, the technical level and cost of equipment maintenance are very expensive. How to reduce the development cycle and maintenance cost is one of the key problems in the development of picking robot.

4.2. Control countermeasures of fruit and vegetable picking robot

1. The motion control and path planning methods of the apple picking manipulator were studied to improve the obstacle avoidance ability and harvesting efficiency of the fruit and vegetable picking robot. The motion control and path planning of the picking manipulator should be determined according to the characteristics of the manipulator, the position of the apple and the picking requirements. Firstly, the kinematics and dynamics of the apple picking manipulator should be modeled. Through the forward motion model, the forward motion posture of the manipulator should be constructed, and the reverse motion posture of the manipulator should be constructed by the reverse motion model, so as to determine the manipulation scheme of the picking manipulator for apple under the six degrees of freedom. In the actual apple picking

process, environmental factors will have a great impact on the operation of the manipulator, so it is necessary to establish an obstacle model. According to the improved artificial potential field method, this paper proposes a bidirectional obstacle avoidance planning algorithm for the manipulator. The optimization of model parameters was verified by motion simulation analysis, and the path tracking control algorithm was studied to timely compensate the problem of target position offset in the process of robot motion, ensure the position tracking error in a reasonable range, and finally improve the success rate of obstacle avoidance and fruit harvest rate of fruit and vegetable picking robot.

2. Research and develop modular open control system to improve the expansion flexibility of fruit and vegetable picking robot and reduce the development cost. At present, the picking robot adopts special mechanical structure, control system and program language. This closed way is not conducive to the expansion and extension of robot function. Therefore, the functions of the picking robot can be subdivided, and the control device with module as the sub unit can be constructed according to the unified norms and standards, so as to adapt to different types of fruits and vegetables by replacing the mechanical parts or control devices with different degrees of freedom. It can be seen that this method with good universality and expansibility can not only quickly build a new robot picking control system, but also greatly reduce the development cost and maintenance cost, and greatly improve the flexibility and flexibility of the picking robot. The device is suitable for different types of fruits and vegetables. It can be seen that this method with good universality and expansibility can not only quickly build a new robot picking control system, but also greatly reduce the development cost and maintenance cost, and greatly improve the flexibility and flexibility of the picking robot.

The trajectory planning method of 6-DOF manipulator studied in this paper can be used as a reference for the research of fruit and vegetable picking robot， which has reference value.

5. Conclusions

Nowadays, as the agricultural production in the process of picking manipulator of the application of common equipment has been heavily promoted, but because in the present agricultural picking, picking manipulator's high cost, low accuracy picking, picking low efficiency, poor security were picking process problems, in this paper, the trajectory planning method of six degrees of freedom mechanical arm were studied. The mathematical model of the 6-DOF apple picking manipulator was established. Based on the forward and reverse motion models of the manipulator, the pose information and arm shape information of the manipulator were analyzed. On the basis of the improved artificial potential field method, the obstacle model is constructed, which is convenient for the manipulator to obtain the obstacle information more accurately in the process of picking and avoid the obstacle according to the planned path. Through the obstacle avoidance bidirectional planning algorithm, the control and trajectory planning of the manipulator are completed in the process of apple picking. The application effect of the method proposed in this paper is tested by experiments, and the following conclusions are drawn:

1. Under the application of this method, in the process of the manipulator moving from the initial pose to the target pose, there is no collision with obstacles in the workspace, indicating that the manipulator has a good effect of obstacle avoidance under the method in this paper;
2. In the process of apple picking, the joint motion of the manipulator is stable. When the manipulator is close to the obstacle, the joint angular velocity will become smaller. After the obstacle avoidance is completed, the speed can be rapidly improved and the time consumed in the whole movement process of the manipulator is shortened. And the control time of the manipulator in the whole obstacle avoidance process is less than 10s, indicating that the manipulator motion process is stable and the speed is continuous, which proves that this method is effective;
3. Under the control of the method, the 6-DOF apple picking manipulator can accurately pick apples according to the set target position, and the picking speed also meets the set requirements, indicating that the method in this paper can accurately pick apples and meet the safety requirements.

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