Optimization of the Operating Trajectory for Elevated Picking Robotic Arms

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Abstract

A trajectory optimization method based on improved particle swarm optimization (PSO) algorithm and 3-5-3 segmented polynomial interpolation is proposed to address the problems of low efficiency and large shaking of the robotic arm in the elevated picking scene. Establish a kinematic model using the UR10 robotic arm and optimize interpolation parameters using an improved PSO algorithm to achieve trajectory planning in the shortest possible time. The simulation results show that the optimized running time is reduced by 11%, and the trajectory smoothness is significantly improved, which verifies the effectiveness of the method.

Keywords

Running Trajectory; Trajectory Optimization; Polynomial Interpolation Method; Particle Swarm Optimization Algorithm; D-H Method; MATLAB.

1. Introduction

With the rise in labor costs, traditional manual picking methods are unable to meet the demands of the fruit industry. The application of robotic arms in harvesting can significantly improve efficiency, but existing trajectory planning methods have problems such as low efficiency and poor stability in complex environments. Therefore, this study proposes a trajectory optimization method based on improved PSO algorithm and 3-5-3 segmented polynomial interpolation, aiming to improve the motion performance of the robotic arm in elevated picking.

In recent years, with the rapid development of facility agriculture, the elevated planting mode has gradually become popular[1,2]. In this mode, the fruits are distributed at different levels of the elevated structure, and traditional manual picking is not only inefficient, but also poses safety hazards. The application of automated harvesting robotic arms has become the key to solving this problem. However, the trajectory planning of robotic arms in elevated environments faces many challenges, including obstacle avoidance in complex foliage environments, path optimization of multi-objective points, and smoothness of motion.

The main contribution of this study is:An improved PSO algorithm has been proposed, which significantly enhances the global search capability and convergence speed of the algorithm through adaptive inertia weights and dynamic learning factors; By combining the 3-5-3 piecewise polynomial interpolation method, the smoothness and efficiency of the robotic arm trajectory have been achieved. The effectiveness of the method has been verified through simulation experiments, providing theoretical support for the practical application of elevated picking robotic arms[3,4].

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2. Kinematic Analysis

2.1 Robot Arm D-H Model

Establish a kinematic model of the UR10 robotic arm using an improved Denavit Hartenberg (D-H) method[5]. The relative posture relationship of each joint is described by a homogeneous transformation matrix, and the parameters are shown in Table 1.

Table 1. Three Scheme comparing

Joint Numble i	a_{i-1}/mm	α_{i-1}/(°)	d_i/mm	θ_i
1	0	0	175	θ_1
2	0	90	0	θ_2
3	615	0	0	θ_3
4	570	0	17	θ_4
5	0	90	115	θ_5
6	0	-90	120	θ_6

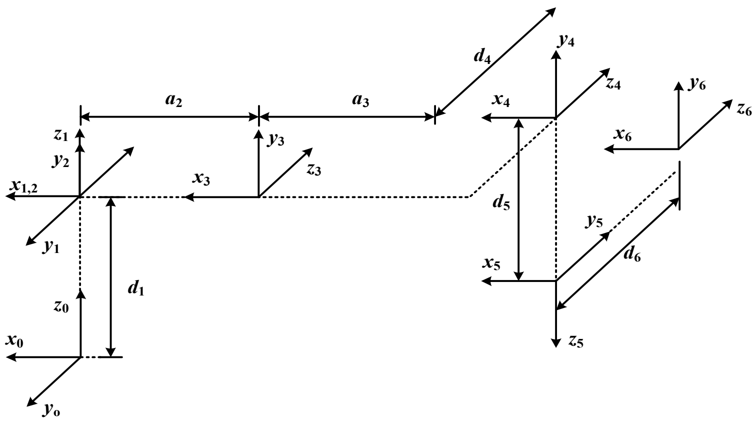

Figure 1. Coordinate system of each joint

2.2 Forward Kinematics

Establish forward kinematics equations through the D-H parameter table and derive the transformation matrix of the robotic arm from the base to the end effector:

$$ {}^0_6T = {}^0_1T\,{}^1_2T\,{}^2_3T\,{}^3_4T\,{}^4_5T\,{}^5_6T = \begin{pmatrix} n_x & o_x & q_x & p_x \\ n_y & o_y & q_y & p_y \\ n_z & o_z & q_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1} $$

Among them, n, o, and q are the pose matrix components, and p is the position component.

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Forward kinematics analysis is the foundation of trajectory planning for robotic arms. By using the D-H parameter table, the relative positional relationship between the joints of the robotic arm can be accurately described, providing theoretical support for subsequent trajectory planning.

2.3 Reverse Kinematics

The correctness of the model was verified by solving inverse kinematics problems using MATLAB Robotics Toolbox[6].

Reverse kinematics analysis is a crucial step in trajectory planning for robotic arms. Through inverse kinematics, the target position of the end effector can be converted into the angle values of each joint, thereby achieving precise trajectory control[7,8].

3. Trajectory Planning and Optimization

3.1 Polynomial Interpolation Method

Use 3-5-3 piecewise polynomial interpolation method to plan trajectories, ensuring continuity of joint position, velocity, and acceleration. The picking process is divided into three stages: rapid approach, slow approach to the target fruit, and moving to the placement point.

Polynomial interpolation is one of the commonly used methods in trajectory planning for robotic arms[9]. By using piecewise polynomial interpolation, the motion trajectory of the robotic arm can be effectively controlled, ensuring its smoothness and continuity during the motion process.

3.2 Trajectory Optimization Problem Description

Optimize the operating efficiency of the robotic arm with the shortest time as the objective function:

$$f(t) = \min(t_{i1} + t_{i2} + t_{i3}) \tag{2}$$

Simultaneously satisfying the constraints of joint velocity and acceleration:

$$\begin{cases} \left|\dot{S}_{i1}(t)\right| \le v_{\max} \\ \left|\dot{S}_{i2}(t)\right| \le v_{\max} \\ \left|\dot{S}_{i3}(t)\right| \le v_{\max} \end{cases}, \begin{cases} \left|\ddot{S}_{i1}(t)\right| \le a_{\max} \\ \left|\ddot{S}_{i2}(t)\right| \le a_{\max} \\ \left|\ddot{S}_{i3}(t)\right| \le a_{\max} \end{cases} \tag{3}$$

The core of trajectory optimization problem lies in how to achieve efficient operation of the robotic arm while satisfying kinematic constraints. By optimizing the objective function, the operating time of the robotic arm can be effectively shortened and the picking efficiency can be improved.

3.3 Improved Particle Swarm Optimization Algorithm

To address the issue of standard PSO algorithm[10,11] being prone to getting stuck in local optima, the following improvements are proposed:

Adaptive inertia weight:

$$\omega=\begin{cases}\omega_{\max}-\left(\omega_{\max}-\omega_{\min}\right)\bullet\left(1+\cos\left(\dfrac{m}{M_{\max}}\pi\right)\right), m\leq 0.6M_{\max}\\ \omega_{\min}+\left(\omega_{\max}-\omega_{\min}\right)\bullet\left(1+\cos\left(\dfrac{m-0.6M_{\max}}{M_{\max}}\pi\right)\right), m>0.6M_{\max}\end{cases} \tag{4}$$

Dynamic learning factor:

$$c_1=2\sin^2\left(\frac{\pi m}{2M_{\max}}\right) \tag{5}$$

$$c_2=2\cos^2\left(\frac{\pi m}{2M_{\max}}\right) \tag{6}$$

The improved PSO algorithm significantly enhances the global search capability and convergence speed of the algorithm through adaptive inertia weights and dynamic learning factors. In the trajectory optimization of robotic arms, the improved PSO algorithm can more effectively search for the optimal solution and improve the operational efficiency of the robotic arm.

4. Simulation Experiment and Result Analysis

4.1 Experimental Setup

Simulate the UR10 robotic arm using MATLAB. Set four position nodes and convert them into joint angle values (Table 2).

Table 2. The joint angle corresponding to the position point

Position	Joint 1/rad	Joint 2/rad	Joint 3/rad	Joint 4/rad	Joint 5/rad	Joint 6/rad
Start position	0.1745	0.2618	0.7854	0.0873	0.1745	0.1047
Middle point 1	1.3090	0.4363	2.0944	1.0472	0.5236	0.6981
Middle point 2	2.2689	-0.7854	0.2618	1.9199	-1.0472	1.3963
Termination position	1.7453	-1.2217	-0.1745	0.3491	0.1745	-0.1745

4.2 Optimal Results

Compare the optimization performance of standard genetic algorithm (GA), PSO algorithm, and improved PSO algorithm (Table 3).

Table 3. The joint angle corresponding to the position point

Algorithm	Optimal time/s	Average time/s	Convergence times	Optimization percentage
GA	5.5026	5.63024	35.6	31%
PSO	5.4753	5.57074	34.2	28%
Improve PSO	5.3606	5.56705	24.7	-

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From the above optimization results, it can be seen that GA algorithm and PSO algorithm have slower convergence speed and are prone to getting stuck in local optima, while the improved PSO algorithm has faster convergence speed, fewer iterations than the other two algorithms by 28% to 31%, and shorter average optimization time. The results indicate that the improved PSO algorithm has more significant advantages in 3-5-3 polynomial interpolation trajectory planning.

The effectiveness of the improved PSO algorithm in optimizing the trajectory of robotic arms has been verified through simulation experiments. The optimized trajectory not only shortens the running time, but also significantly improves the smoothness and stability of the motion.

5. Conclusion

This study proposes a trajectory optimization method based on an improved PSO algorithm and 3-5-3 segmented polynomial interpolation, which significantly improves the operational efficiency and stability of the elevated picking robotic arm. In the future, further research can be conducted on multi robotic arm collaborative operations and trajectory planning problems in complex environments.

6. Discussion

The results of this study indicate that the improved PSO algorithm has significant advantages in optimizing the trajectory of robotic arms. However, there are still some limitations that need further exploration:

Algorithm complexity: Although improving the PSO algorithm has improved the optimization effect, its computational complexity is relatively high. In the future, it can be further optimized through parallel computing or hardware acceleration.

Practical application scenarios: Simulation experiments are conducted in ideal environments, and there may be more uncertain factors in actual picking scenarios, such as changes in lighting and fruit occlusion, which require further validation of the algorithm's robustness.

Multi objective optimization: Current research focuses on minimizing time as the objective function, and in the future, multi-objective optimization can be considered, such as minimizing energy consumption and maximizing harvesting success rate.

In addition, the method proposed in this study is not only applicable to elevated harvesting robotic arms, but can also be extended to other fields such as industrial assembly, warehousing and logistics. By further optimizing algorithms and hardware design, it is expected to achieve automated tasks in more scenarios.

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