Manipulator Trajectory Control Combined with Moving Average Filtering Algorithm

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Abstract: To solve the problem of abnormal angular velocity and angular acceleration in manipulator trajectory motion controlled by quintic spline interpolation algorithm, a manipulator trajectory control algorithm combined with moving average filtering algorithm was proposed. Based on the quintic spline interpolation algorithm, the moving average filtering algorithm was used to clean the abnormal data under the quintic spline interpolation. And the recursive forward dynamics model based on joint space motion was used to design the trajectory motion control of the manipulator. The simulation results show that the manipulator trajectory control algorithm combined with the moving average filtering algorithm has strong constraint ability of diagonal velocity and angular acceleration, and 67% of the maximum velocity and maximum acceleration of the joint axis of the designed manipulator trajectory are significantly reduced, and the curve is smoother.

Keywords: Quintic spline interpolation; Mechanical arm; Moving average filtering algorithm; Joint space motion; Forward dynamics

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1 Introduction

In the environment of rapid development of intelligence, robotic arms have been developed to a considerable extent in various fields [1-3] due to the advantages of economic manual costs and safety for automated operations. Thus, accurate trajectory planning for robotic arms is particularly important in this case.

The common algorithms for robot arm trajectory

motion are joint space motion and Cartesian space motion, etc. To study the trajectory motion of the robot arm for the joint space, the maximum velocity and maximum acceleration of the joint in the motion should be as small as possible, the acceleration at the beginning and end position should be 0 and the angular velocity and angular acceleration should be smoothly over [4,5]. Segmented linear interpolation has good stability and curve convergence, but the smoothness of the curve cannot be guaranteed; Bessel curve [6] does not satisfy the second-order derivative continuity and the interpolation curve does not pass through the path point; B-spline interpolation [7] has an interpolation curve that satisfies the second-order derivative continuity but also does not pass through the path point; polynomial interpolation [8] requires certain constraints to be configured in each segment interval, and when the number of nodes is too The calculation is more complicated when the number of nodes is too large, where the acceleration mutation phenomenon exists in the three-sample interpolation, and the five-sample interpolation curve is smooth and does not have the mutation value, but there is still deviation.

In [9], Zhang Liangan et al improved the flexibility and stability of the robotic arm, however, the automation and accuracy of the robotic arm was low, and the footprint was large. Liu Bao and Di Xin [8] reduced the residual vibration of the joint axis using cubic spline trajectory planning, but the pulsation was discontinuous. Li J [10] utilized a spline function and an improved genetic algorithm to solve the problem of generating singular structure points in motion, as well as improved the local optimum problem, but the reliability of the results was poor. A new adaptive control method for a multi-joint flexible robotic arm was proposed by Rahmani B et al. in [11],

which solved the trajectory tracking problem by using stable inverse control of the robotic arm dynamics. Van Pham C et al. focused on the problem of tracking control manipulator with radial basis function neural network periodic motion and predetermined trajectory of the control dual linkage at joint position, and proposed a robust adaptive control method based on radial basis function neural network in [12]. Generally, some defects exist in the approaches mentioned above, such as the non-smooth motion of the robotic arm, incoherent acceleration trajectories and discontinuous pulses. Therefore, this paper proposes a robotic arm trajectory control algorithm combined with sliding average filtering algorithm, which is used to effectively reduce the joint angular acceleration jumps and achieve smoother angular velocity and angular acceleration curves.

2 A five spline interpolation algorithm combined with a sliding average filtering algorithm

2.1. A five spline interpolation algorithm

Assuming that the interval $[\theta_0, \theta_n]$ is a robotic arm joint node, the definition of the five times spline interpolation is in the interval $[\theta_0, \theta_n]$, and the joint split is given as $\theta_0 < \theta_1 < \dots < \theta_{n-1} < \theta_n$. a_0 、 a_1 、 a_2 、 a_3 、 a_4 、 a_5 are six undetermined coefficients of the quintuple polynomial. The angles, angular velocities and angular accelerations of the beginning and end joints are also constrained, where joint angles satisfy equation (1).

$$\begin{cases} \theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \\ \dot{\theta}(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4 \\ \ddot{\theta}(t) = 2a_2 + 6a_3 t + 12a_4 t^2 + 20a_5 t^3 \end{cases} \quad (1)$$

The two adjacent points are then treated as the start and end points of a trajectory, which satisfies

equation (2).

$$\begin{cases} \theta(t_0) = \theta_0 = a_0 \\ \theta(t_f) = \theta_f = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \\ \dot{\theta}(t_0) = \dot{\theta}_0 = a_1 \\ \dot{\theta}(t_f) = \dot{\theta}_f = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4 \\ \ddot{\theta}(t_0) = \ddot{\theta}_0 = 2a_2 \\ \ddot{\theta}(t_f) = \ddot{\theta}_f = 2a_2 + 6a_3 t + 12a_4 t^2 + 20a_5 t^3 \end{cases} \quad (2)$$

Equation (3) can be obtained by taking equation (2) into equation (1), which gives the trajectory of the robot arm under the five spline interpolation algorithm.

$$\begin{cases} a_0 = \theta_0 \\ a_1 = \dot{\theta}_0 \\ a_2 = \ddot{\theta}_0 / 2 \\ a_3 = \frac{20\theta_f - 20\theta_0 - (8\dot{\theta}_f + 12\dot{\theta}_0)t_f - (3\ddot{\theta}_0 - \ddot{\theta}_f)t_f^2}{2t_f^3} \\ a_4 = \frac{30\theta_f - 30\theta_0 - (14\dot{\theta}_f + 16\dot{\theta}_0)t_f + (3\ddot{\theta}_0 - 2\ddot{\theta}_f)t_f^2}{2t_f^4} \\ a_5 = \frac{12\theta_f - 12\theta_0 - (6\dot{\theta}_f + 6\dot{\theta}_0)t_f - (\ddot{\theta}_0 - \ddot{\theta}_f)t_f^2}{2t_f^5} \end{cases} \quad (3)$$

2.2. Improved five spline interpolation algorithm

The sliding average filtering algorithm has a strong adaptive capability and excellent suppression of anomalous data. It can obtain the arithmetic average of a set of windowed data, namely the filtered data set, by sliding the window back and forth along the time series.

Set the width of the sliding window to N, if $N = 2k + 1$, then

$$y(n) = \frac{1}{2k+1} \sum_{i=-k}^{i=k} x(n+i) \quad (4)$$

where $x(n)$ 、 $y(n)$ represent the input and output respectively.

Although the angular acceleration calculated by the five-spline interpolation algorithm is a smooth curve with no abrupt changes, it still contains the problems of over-sharp values in some regions, absence in homogeneous section, and inability to perform homogeneous planning based on desired angular velocity. In addition, the five-spline interpolation algorithm is one of the polynomial

interpolation algorithms, with the feature of decelerating the angular acceleration process as the order of the polynomial increases. Therefore, the angles, angular velocities and angular accelerations output from the five-spline interpolation algorithm are used as the data set in the sliding average filter algorithm to obtain smoother data curves by utilizing the advantages of the sliding average filtering algorithm in high smoothness and interference suppression.

3 Improved robot arm trajectory control algorithm

3.1. Joint space motion

The six-degree-of-freedom robot arm is used as an objective, and a motion model for a fixed robot arm is established in the coordinate system $X_c Y_c Z_c$. Set the space vector as $\varphi \in R^n$, the end joint node vector as $r_b \in R^n$, and the two vectors satisfy:

$$f(\varphi) = r_b \quad (5)$$

where $f(\varphi)$ denotes a differentiable non-linear function.

By transforming the three-dimensional coordinates into two-dimensional coordinates, the

$$r_b^T = f^T(\varphi) = \begin{bmatrix} l_{65}(c_5 s_{32} c_1 - s_5 c_4 c_{32} c_1 + s_5 s_4 s_1) + l_{43} s_{32} c_1 + l_2 s_2 c_1 \\ l_{65}(c_5 s_{32} s_1 - s_5 c_4 c_{32} s_1 - s_5 s_4 s_1) + l_{43} s_{32} s_1 + l_2 s_2 s_1 \\ l_{65}(s_5 c_4 s_{32} + c_5 c_{32}) + l_{43} c_{32} + l_2 c_2 + l_1 + l_0 \end{bmatrix}^T \quad (7)$$

Where l_i means the i -th linkage length, l_{65} means $l_6 + l_5$, l_{43} means $l_4 + l_3$, c_i means $\cos \varphi_i (i=1, 2, \dots, 6)$, s_i means $\sin \varphi_i (i=1, 2, \dots, 6)$, s_{32} means $\sin(\varphi_3 + \varphi_2)$, and c_{32} means $\cos(\varphi_3 + \varphi_2)$.

3.2. Improvement of joint space motion of robotic arm

The joint axes are biased during the motion of the robot arm and the angles, angular velocity and angular acceleration [14] datasets are generated. Then, the datasets of angle, angular velocity and angular acceleration are cleaned using the sliding average filtering algorithm described above.

Assuming the angle and angular velocity of the robotic arm joints is $(\theta, \dot{\theta})$. The joint moment τ

position of the end-effector is assumed to be (X_e, Y_e) , the joint space is assumed to be (θ_1, θ_2) , and the length of each section of the linkage is assumed to be 1, the position mapping relationship from the joint space to the operation space can be obtained, which is shown in equation (6).

$$\begin{cases} X_e = \cos(\theta_1 + \theta_2) + \cos \theta_1 \\ Y_e = \sin(\theta_1 + \theta_2) + \sin \theta_1 \end{cases} \quad (6)$$

The structure and parameters of the fixed robotic arm are known, and the D-H parameters of the six degree of freedom robotic arm are shown in Table 1.

Table 1: Table of D-H parameters of the six-degree-of-freedom robot arm

#	φ_i / rad	l_i / m	a_i / rad	α_i / m
1	φ_1	0	0	0
2	φ_2	0	3.20	1.57
3	φ_3	0	9.75	0
4	φ_4	8.87	2	1.57
5	φ_5	0	0	-1.57
6	φ_6	0	0	1.57

In the table, $\varphi_i, l_i, a_i, \alpha_i$ represent the joint angle, linkage deflection, linkage length, linkage rotation angle respectively, and the kinematic equation [13] is expressed as equation (7).

is calculated from the joint acceleration $\ddot{\theta}$, which can also be used to address the joint acceleration for the next stage of motion by forward dynamics [15-17]. The algorithm for calculating the forward dynamics of the system consists of three processes: forward recursion, reverse recursion, and again forward recursion. These processes traverse all connecting rods in turn according to the principle of depth-first, reverse depth-first, and the depth-first [18]. Equations (8), (9) and (10) are the formulas for the calculation of Forward Kinematics.

$$\begin{cases} T_{\lambda(i),i} = f(\theta) \\ V_i = Ad_{T_{\lambda(i),i}^{-1}} V_{\lambda(i)} + S_i \dot{\theta}_i \\ \eta_i = ad_{V_i} S_i \dot{\theta}_i + \dot{S}_i \dot{\theta}_i \end{cases} \quad (8)$$

$$\left\{ \begin{array}{l} \hat{I}_i = I_i + \sum_{k \in \mu(i)} \text{Ad}_{T_{i,k}}^* \Pi_k \text{Ad}_{T_{i,k}}^{-1} \\ \hat{B}_i = -\text{ad}_{V_i}^* I_i V_i - F_i^{\text{ext}} + \sum_{k \in \mu(i)} \text{Ad}_{T_{i,k}}^* \beta_k \\ \Psi_i = (S_i^T \hat{I}_i S_i)^{-1} \\ \Pi_i = \hat{I}_i - \hat{I}_i S_i \Psi_i S_i^T \hat{I}_i \\ \beta_i = \hat{B}_i + \hat{I}_i \{ \eta_i + S_i \Psi_i [\tau_i - S_i^T (\hat{I}_i \eta_i + \hat{B}_i)] \} \\ \ddot{\theta}_i = \Psi_i [\tau_i - S_i^T \hat{I}_i (\text{Ad}_{T_{k(i),i}}^{-1} \dot{V}_{\lambda(i)} + \eta_i) - S_i^T \hat{B}_i] \\ \dot{V}_i = \text{Ad}_{T_{k(i),i}}^{-1} \dot{V}_{\lambda(i)} + S_i \ddot{\theta}_i + \eta_i \\ F_i = \hat{I}_i \dot{V}_i + \hat{B}_i \end{array} \right. \quad (9)$$

Where $\hat{I}_i$ denotes the i -th joint inertia, $\hat{B}_i$ denotes the i -th joint parent bias force, $\hat{I}_i$ denotes the i -th shutdown sub-joint inertia, $\text{Ad}_{T_{i,k}}$ denotes the coordinate transformation matrix, Π_k denotes the generalized inertia of the k -th joint, $\text{ad}_{V_i}^*$ denotes the generalized inertia of the i -th joint and at each end body, Ψ_i denotes the generalized velocity of the i -th joint in the solid joint coordinate system, τ_i denotes the induced partial force, β_k denotes the k -th joint generalized force, η_i denoted as the correlation case at the i -th joint, $\ddot{\theta}_i$ denoted as the disturbance moment vector, $\dot{V}_i$ denoted as the deviation of the real dynamics model of the robot arm from the nominal dynamics model, $\text{Ad}_{T_{k(i),i}}^{-1}$ denoted as the dyadic operator, $\dot{V}_{\lambda(i)}$ denoted as the $n \times n$ antisymmetric matrix of the i -th joint, S_i denoted as the bias force of the i -th joint, F_i denoted as the known part of the generalized force.

4 Experimental simulation and result analysis

4.1.Sliding average filtering amplitude and frequency response simulation and analysis

Assuming that the input signal is a continuous function,

$$y(t) = \frac{1}{T_0} \int_{t-T_0}^t f(x) dx \quad (11)$$

Where $f(x)$ and $y(t)$ is the input and output respectively, and T_0 is the length of sliding filter.

For the sliding average filter amplitude-frequency response, assuming the filter period is T_0 , and the input signal is

$$f(x) = \cos\left(\frac{2\pi}{T} x\right) \quad (12)$$

$$T_0 = kT + R, (k = 0, 1, 2, \dots; 0 \leq R < T) \quad (13)$$

Taking equations (12) and (13) into equation (11) and calculating the amplitude of the input signal as

$$A = \frac{2}{T_0} \int_0^{R/2} \cos\left(\frac{2\pi}{T} x\right) dx \quad (14)$$

$$A = \frac{T}{nT_0} \sin\left(\frac{\pi T_0}{T} - k\pi\right) \quad (15)$$

The response of the sliding average filtered amplitude and frequency is shown in Figure 1. It can be seen that the continuous functions are smoothed and filtered. And the non-smooth data are averaged locally in some way and considered as close to smooth on a suitable small interval to reduce the random ups and downs caused by errors.

Figure 1:Sliding average filtering amplitude and frequency response

4.2.Simulation results and analysis of five times spline interpolation algorithm before and after improvement

The five spline interpolation algorithm and the five spline interpolation algorithm combined with the sliding average filtering algorithm are simulated by MATLAB and the simulation results are shown in Figure 2.

(a) Simulation comparison

(b) Location comparison

(c) Speed comparison

(d) Acceleration comparison

Figure 2: Comparison of five spline interpolation algorithm before and after improvement

Where the yellow curve indicates the five spline interpolation algorithm simulation curve; red, blue and green indicate the five spline interpolation algorithm combined with the sliding average filtering algorithm to compare position, velocity and acceleration respectively. Figure 2(a) is a general view of the five spline interpolation algorithm and the five spline interpolation algorithm combined with the sliding average filtering algorithm comparing position (Fig. 2(b)), velocity (Fig. 2(c)) and acceleration (Fig. 2(d)). As can be seen from the enlarged diagram, the five spline interpolation algorithm combined with the sliding average filtering algorithm effectively improves the smoothness of the curve, especially in the case of acceleration. Therefore, the problem of generating anomalous values in the five spline interpolation algorithm is effectively solved by combining the sliding average filter algorithm with the five spline interpolation algorithm.

4.3. Simulation results and analysis of joint space motion of robot arm before and after improvement

According to the simulation and analysis of the five times spline interpolation algorithm before and after the above improvement, it can be seen that the advantages of the five times spline interpolation algorithm combined with the sliding average filtering algorithm to clean the data are now applied to the joint space motion of the robot arm, and the simulation

results of the joint space motion before and after the improvement are shown in Figure 3.

(a) Angular comparison

(b) Angular velocity comparison

(c) Comparison of angular acceleration

Figure 3: Comparison of joint space motion of the arm before and after improvement

Among them, the red line is the joint space motion simulation result of the robotic arm, and the blue line is the joint space motion simulation result of the robotic arm after the improvement. From Fig.3(a), it can be seen that the end joint actuator motion angles before and after the improvement overlap, which indicates that the robotic arm trajectory control algorithm combined with the sliding average filter algorithm and the original trajectory control algorithm of the robotic arm are calculated for the same robotic arm trajectory motion; from Fig.3(b), it can be seen that 67% of the maximum velocity of the joint axis in the motion of the improved robotic arm is significantly reduced and the curve is smooth; from Fig.3(c), it can be seen that The angular acceleration of the improved robotic arm is significantly reduced, which indicates that the robotic arm trajectory control algorithm combined with the sliding average filtering algorithm effectively solves the problems of the robotic arm motion that is not smooth and the acceleration is abruptly changed.

Table 2: Comparison of angular velocity before and after improvement

#	Ω_1		Ω_2		Ω_3		Ω_4		Ω_5		Ω_6	
	Tra	Im	Tra	Im	Tra	Im	Tra	Im	Tra	Im	Tra	Im
Min.												
value	0	0	0	-0.02	-0.78	-0.71	-0.39	-0.35	-0.58	-0.53	0	-0.016
Maximum	0.392	0.356	0.196	0.178	0	-0.04	0	-0.05	0	-0.03	0.19	0.1783
value	7	6	3	3	0	53	0	819	0	14	63	

Table 3: Comparison table of angular acceleration before and after improvement

#	α_1		α_2		α_3		α_4		α_5		α_6	
	Tra	Im	Tra	Im	Tra	Im	Tra	Im	Tra	Im	Tra	Im

Min.	-0.24	-0.24	-0.12	-0.11	-0.48	-0.05	-0.24	-0.001	-0.36	-2.07	-0.12	-0.120
value	15	15	08	65	3	823	15	179	23	9e-16	08	8
Maximum	0.241	0.241	0.12	1.507	0.483	-4.01	0.241	0.020	0.362	0.058	0.120	0.120
value	5	5	08	e-16		2e-17	5	14	3	23	8	8

Note: Tra means Traditional, Im means Improvements.

Table 2 and Table 3 are the comparison data table of angular velocity before and after the improvement and the comparison data table of angular acceleration before and after the improvement, involving the minimum and maximum values of angular velocity and angular acceleration of six joints. According to the data in Table 2, it can be seen that the minimum value of angular velocity slightly increases and the maximum value generally decreases, for example, the minimum value remains unchanged and the maximum value decreases by 0.0361, overall, the minimum value of angular velocity under the improved algorithm is 5.32% higher than that under the traditional algorithm, and the maximum value of angular velocity under the improved algorithm is 6.84% lower than that under the traditional algorithm. According to the data in Table 3, it can be seen that the angular acceleration also has a slight increase in the minimum value and a general decrease in the maximum value, with an increase of 48.5% in the minimum value and a decrease of 62.4% in the maximum value.

5 Conclusion

A robotic arm trajectory control algorithm that uses a six degree of freedom robotic arm and combines a sliding average filtering algorithm is proposed to effectively reduce the maximum velocity and maximum acceleration of the end joint motion.

The results show that the five times spline interpolation algorithm is effective in improving the position, velocity and acceleration curves, however, the inflection points of some curves are still sharp. While the five-spline interpolation algorithm combined with the sliding average filtering algorithm could optimize the anomalous inflection points in the curve without changing the original position, velocity and acceleration curves, and obtain a smoother curve.

The comparison of the robot arm joint spatial motion before and after the improvement illustrate that robotic arm trajectory control algorithm combined with sliding average filtering algorithm achieves the requirement of spatial trajectory motion of robotic arm joints. There were 67% of joints with

significantly reduced maximum velocities, lower angular accelerations and smooth curves during the movement.

The results show that the arm trajectory control algorithm combined with the sliding average filtering algorithm provides a smoother trajectory motion with less error than the original arm trajectory control algorithm, and the maximum velocity and maximum acceleration of the joint are significantly reduced, which protects the arm control system to a certain extent.

Availability of data and materials

The code is referenced and modified on <https://blog.csdn.net/jldemanman/article/details/79303021>, https://blog.csdn.net/weixin_44947987/article/details/103843155

Competing Interest

No potential conflict of interest was reported by the authors.

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Authors' contributions

Corresponding author Xiao-Tong Chen ensured that all listed authors had approved the manuscript,

including the authors' names and order, and that all authors had received the submission and all substantive correspondence with the editor, as well as complete comments verifying that all data, graphics, and code met the field's and journal's standards for transparency and reproducibility. Each author is expected to have made substantial contributions to the conception OR design of the work; OR the acquisition, analysis, OR interpretation of data; OR the creation of new software used in the work.

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