A Research on Adaptive Control Method of Robot Manipulator Based on Fuzzy Compensation

Mingcheng Wang, Shanshan Huang, Chuanhong Sun, Zhongyong Zhou,

Weichen Fu, Xiuyuan Yi, Xiaohang Wu

School of Mechatronic Engineering, Southwest Petroleum University, Chengdu 610500, China

Abstract

In the process of manipulator control, the system has the characteristics of non-linearity, uncertainty, variability and strong coupling. Especially in the course of its motion, there will be some uncertain non-linear terms, such as friction.In order to eliminate the influence of friction and improve the control performance of the system, many scholars put forward some ways of compensation. But the friction model of manipulator in actual motion is often complex and unknown.In this article, by using the approximate characteristics of the fuzzy system, an adaptive control scheme for the manipulator with fuzzy compensation for uncertainties such as friction and disturbance is designed, which can offset the influence of these uncertainties on the motion of the manipulator and improve the trajectory tracking control accuracy of the manipulator. The simulation results show that the manipulator adaptive fuzzy control method based on LuGre model can compensate the unknown complex friction in the manipulator system well, and realize the high precision trajectory tracking control of the manipulator system.

Keywords

Robot manipulator; Trajectory tracking; Compensation control; Adaptive fuzzy control; LuGre model.

1. Introduction

With the rapid development of science and technology in today's world, the application fields of manipulator are becoming wider and wider.At present, in industrial production, cosmological survey and exploration, deep-sea area development, danger detection of military activities and other areas,robotic manipulators have more and more applications.Therefore, the algorithm research on trajectory tracking control and path planning control of manipulator is of milestone significance.The manipulator control system is the core part of the whole manipulator system, which directly determines the overall performance and advanced degree of the manipulator system, therefore, the research of manipulator control system has been the focus of control theory and control engineering for a long time[1].

And in the field of manipulator control research, friction [2] has always been one of the problems troubling many scholars in the field of mechanical and control.Because of the existence of friction, the performance of the system is reduced, especially for some systems, such as manipulators, CNC machine tools and so on, which is an important factor causing the deterioration of the system performance.The influence of friction force on the static performance of the system is that the output response has large error or steady limit cycle oscillation. The influence on the dynamic performance of the system is manifested as crawling or jitter phenomenon at low speed and waveform distortion phenomenon when the speed passes zero [3-4].The existence of friction is a serious factor that hardly affects the low-speed performance and tracking accuracy of the system in the control process.Therefore, in order to eliminate the influence of friction and improve the performance of the system, experts and scholars have developed some friction compensation methods.Friction compensation methods can be divided into two broad categories: model-based compensation and non-model-based compensation [5-9].Model-based friction compensation method: Based on the known friction model, a control action is designed to counteract the friction force in the system, which can eliminate the influence of friction on the performance of the whole system and reduce the tracking error of the system.But the types of friction are complex, especially the static friction, which is a complex physical phenomenon that has not yet been analyzed clearly. If we want to establish a mathematical model of friction in the actual situation accurately and compensate the friction by the mathematical model, this scheme is impossible to achieve.In the case of unclear friction model, the friction compensation methods without model include PID compensation [10], iterative learning compensation, high frequency chatter compensation, neural network compensation and fuzzy control compensation.If the relevant parameters in the friction model are adjusted off-line, it is called fixed compensation. On the contrary, if relevant parameters are obtained through online identification, it is called adaptive friction compensation [11]. For nonlinear unknown systems, at present, the main control methods are Backstepping control, synovial control, adaptive control, robust control and so on.

In order to solve the problem that the above friction links will lead to deterioration or even instability of the control performance of the manipulator system, an adaptive control algorithm for fuzzy compensation of uncertainties such as friction in the system is designed based on the model of two-joint manipulator and the approximation characteristics of the fuzzy system.

2. Manipulator dynamics model and LuGre friction model

2.1 Manipulator dynamics model

Considering an n-joint robot, its dynamic performance can be expressed by second-order nonlinear differential equation:

$$\tau = D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(q,\dot{q},\ddot{q}) \tag{1}$$

In the formula, $q = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}, \dot{q} = \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}, \ddot{q} = \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix}, \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix},$

$D(q)$—Moment of inertia；

$C(q,\dot{q})$ —Centrifugal force and coriolis moment；

$G(q)$ —Gravity item；

$F(q,\dot{q},\ddot{q})$ —friction torque F_r 。

2.2 LuGre friction model description

LuGre model is an extension of Dahl model and adopts the idea of bristle model at the same time.That is, at the micro level, the contact surface can be seen as a large number of elastic bristles with random behavior. The difference is that LuGre's model is based on the average deformation of bristles.

The average deformation of bristles is

$$\frac{dz}{dt} = v - \frac{|v|}{g(v)} z \tag{2}$$

$$g(v) = \frac{1}{\sigma_0}[f_c + (f_s - f_c)e^{-(v/v_s)^2}] \tag{3}$$

friction caused by bristle deflection can be expressed as

$$f = \sigma_0 z + \sigma_1 \frac{dz}{dt} + \sigma_2 v \tag{4}$$

and σ_0 - Stiffness of bristles; σ_1 - Microscopic Damping Coefficient; v - Relative velocity between two surfaces.

$g(v)$ expresses Stribeck effect, f_c is Coulomb friction， f_s is corresponding maximum static friction， v_s is Stribeck speed. When $g(v)=f_c$， $\sigma_0=\sigma_1$,LuGre model can be simplified to Dahl model. And when the average bristle deformation is assumed to be in steady state motion, $\dot{z}=0$, we can get Stribeck model

$$f=\sigma_0 z=g(v)\operatorname{sgn}(v) \tag{5}$$

LuGre model describes coulomb friction, presliding, variable static friction force, Stribeck model and friction hysteresis by first order differential equation, which is a continuous model. Different friction phenomena can transit smoothly, so there can be many applications.But parameter identification in the model is also a difficult problem, especially dynamic parameters σ_0、 σ_1.

LuGre friction model is the most famous model in control research, which is widely used in high-precision mechanical control system.The application of the numerical model is shown in the table below. The parameters play different roles under different conditions, so the model is a comprehensive model, which can describe various system states. Therefore, LuGre friction model is selected as the friction model in the manipulator joint in this article, which is the controlled object of the control system.

3. Fuzzy system and its approximation properties

It can be concluded from reference [12] that a fuzzy system is a universal approximator, that is, a fuzzy system can approximate any function on a compact set with any accuracy. Traditional adaptive fuzzy systems generally adopt product reasoning, single-valued fuzzification and central average ambiguity resolution, so the output of the fuzzy system is obtained as follows:

$$f(x)=\sum_{l=1}^{M}\theta_l\xi_l(x)=\boldsymbol{\theta}^T\xi(x) \tag{6}$$

In the formula: $\boldsymbol{\theta}$ is an adjustable parameter, $\boldsymbol{\theta}=(\theta_1,...,\theta_M)^T$; $\xi(x)$ is a fuzzy basis function vector, $\xi(x)=(\xi_1(x),...,\xi_M(x))^T$, its definition is:

$$\xi_l(x)=\frac{\prod_{i=1}^{n}\mu_{F_i^l}(x_i)}{\sum_{l=1}^{M}\prod_{i=1}^{n}\mu_{F_i^l}(x_i)} \tag{7}$$

In the formula: $l=1,2...M$; $\mu_{F_i^l}$ is a Gauss, triangle or other types of membership function.

As the proof formula(8), the fuzzy system shown in reference [13] can approximate any function on a compact set with any precision. According to the Universal Approximation Theorem: Assuming that the input universe U is a compact set on R^n ,and for any real continous function $g(x)$ and any $\varepsilon>0$ on U ,there must be a fuzzy system just like formula (1) to make the formula true, that is

$$\sup|f(x)-g(x)|<\varepsilon \tag{8}$$

So the fuzzy systems with product inference, singleton fuzzifier and central average defuzzifier are universal approximators.

4. Fuzzy compensation control based on friction, disturbance and load variation

When the friction, interference and load change of the manipulator are all considered as uncertain parts at the same time, since the load change is related to the acceleration of the manipulator， so $\hat{F}(q,\dot{q},\ddot{q}\mid\theta)$ can be used to represent the fuzzy system approaching the external disturbances. The uncertain term $F(q,\dot{q},\ddot{q}\mid\theta)$ can be decomposed to reduce the number of fuzzy rules, and then the control law is designed according to the traditional fuzzy compensation controller design method.

The dynamic formula of the manipulator is

$$D(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)+e(q,\dot{q},\ddot{q},t)+F_r(\dot{q})+\tau_d=\tau \tag{9}$$

In this formula

$$D(q)=D(m_n,q),C(q,\dot{q})=C(m_n,q,\dot{q}),G(q)=G(m_n,q)$$

$$e(q,\dot{q},\ddot{q},t)=e_D[D(q)\ddot{q}]+e_C[C(q,\dot{q})\dot{q}]+e_G[G(q)]$$

$$e_D=D(m_{nc},q,\dot{q})\dot{q}-C(m_n,q,\dot{q})\dot{q}$$

$$e_C=C(m_{nc},q,\dot{q})\dot{q}-C(m_n,q,\dot{q})\dot{q}$$

$$e_G=G(m_{nc},q)-C(m_n,q)\dot{q}$$

m_n is a konwn nominal value, m_{nc} is a actual value.

And the uncertain part can be expressed as

$$F(q,\dot{q},\ddot{q})=e(q,\dot{q},\ddot{q},t)+F(\dot{q})+\tau_d \tag{10}$$

The above formula can be decomposed into

$$F(q,\dot{q},\ddot{q})=F^1(q,\dot{q})+F^2(q,\ddot{q}) \tag{11}$$

In the above formula

$$F^1(q,\dot{q})=e_C[C(q,\dot{q})\dot{q}]+e_G[G(q)]+F_r(\dot{q})+\tau_d \tag{12}$$

$$F^2(q,\ddot{q})=e_D[D(q)\ddot{q}] \tag{13}$$

The adaptive fuzzy control law is designed as

$$\tau=D(q)\ddot{q}_r+C(q,\dot{q})\dot{q}_r+G(q)+\hat{F}^1(q,\dot{q}\mid\Theta^1)+\hat{F}^2(q,\dot{q}\mid\Theta^2)-K_Ds \tag{14}$$

The adaptive law is designed as

$$\dot{\Theta}_i^1=-\Gamma_{1i}^{-1}s_i\xi^1(q,\dot{q}),\quad i=1,2,...,n \tag{15}$$

$$\dot{\Theta}_i^2=-\Gamma_{2i}^{-1}s_i\xi^2(q,\dot{q}),\quad i=1,2,...,n \tag{16}$$

The Lyapunov function is defined as

$$V(t)=\tfrac{1}{2}\left(s^tDs+\sum_{i=1}^{n}\tilde{\Theta}_i^{1T}\Gamma_{1i}\tilde{\Theta}_i^1+\sum_{i=1}^{n}\tilde{\Theta}_i^{2T}\Gamma_{2i}\tilde{\Theta}_i^2\right) \tag{17}$$

$$\dot{V}(t)=-s^T(D\ddot{q}_r+C\dot{q}_r+G+F-\tau)+\sum_{i=1}^{n}\tilde{\Theta}_i^{1T}\Gamma_{1i}\tilde{\Theta}_i^1+\sum_{i=1}^{n}\tilde{\Theta}_i^{2T}\Gamma_{2i}\tilde{\Theta}_i^2 \tag{18}$$

The fuzzy approximation errors respectively are

$$w^1=F^1(q,\dot{q})-\hat{F}^1(q,\dot{q}\mid\Theta^{1*}) \tag{19}$$

$$w^2=F^2(q,\dot{q})-\hat{F}^2(q,\dot{q}\mid\Theta^{2*}) \tag{20}$$

than

$$\begin{aligned}\dot{V}(t)=-s^TK_Ds-s^T(w^1+w^2)+\sum_{i=1}^{n}(\tilde{\Theta}_i^{1T}\Gamma_{1i}\dot{\tilde{\Theta}}_i^1-s_i\tilde{\Theta}_i^{1T}\xi^1(q,\dot{q}))+\\ \sum_{i=1}^{n}(\tilde{\Theta}_i^{2T}\Gamma_{2i}\dot{\tilde{\Theta}}_i^2-s_i\tilde{\Theta}_i^{2T}\xi^2(q,\dot{q}))=-s^TK_Ds-s^T(w^1+w^2)\end{aligned} \tag{21}$$

In order to eliminate the influence of approximation error, the robust adaptive control law is designed as follows

$$\tau = D(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) + \hat{F}^1(q,\dot{q}\,|\,\Theta^1) + \hat{F}^2(q,\dot{q}\,|\,\Theta^2) - K_D s - W\,\mathrm{sgn}(s) \quad (22)$$

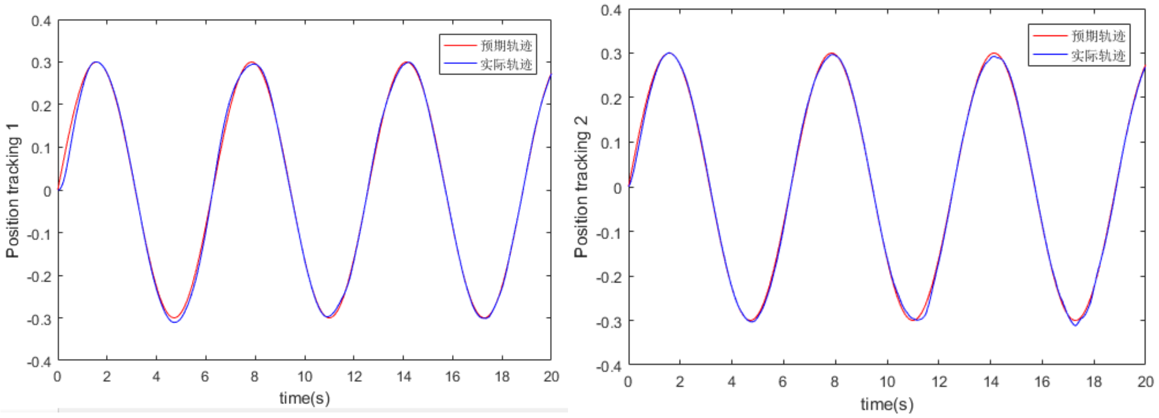
in the above formula, $W = diag[w_{M_1},\dots,w_{M_n}],\ w_{M_i} \geq |w_i|,\ i = 1,2,\dots,n$.

The fuzzy system is designed as

$$\hat{F}(q,\dot{q},\ddot{q}\,|\,\Theta) = \begin{bmatrix} \hat{F}_1^1(q,\dot{q}\,|\,\Theta_1^1) + \hat{F}_1^2(q,\dot{q}\,|\,\Theta_1^2) \\ \hat{F}_2^1(q,\dot{q}\,|\,\Theta_2^1) + \hat{F}_2^2(q,\dot{q}\,|\,\Theta_2^2) \\ \vdots \\ \hat{F}_n^1(q,\dot{q}\,|\,\Theta_n^1) + \hat{F}_n^2(q,\dot{q}\,|\,\Theta_n^2) \end{bmatrix} \quad (23)$$

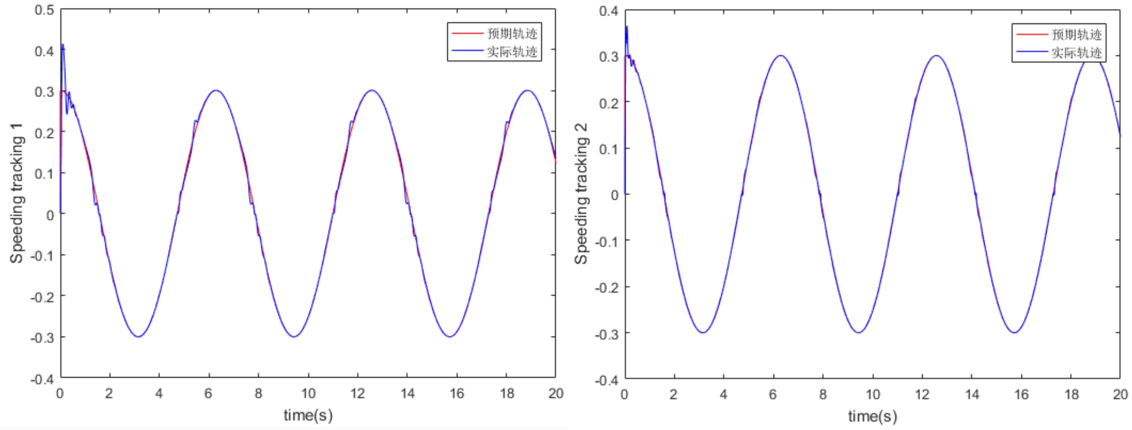
5. Simulation analysis

For the manipulator control with fuzzy compensation for friction, interference and load change, friction term $F(q,\dot{q}) = \begin{bmatrix} \sigma_0\dot{\theta}_1 + \sigma_1\dot{\theta}_1 + \sigma_2\theta_1 \\ \sigma_0\dot{\theta}_2 + \sigma_1\dot{\theta}_2 + \sigma_2\theta_2 \end{bmatrix}$ and external interference term $\tau_d = \begin{bmatrix} 0.05\sin(20t) \\ 0.1\sin(20t) \end{bmatrix}$ are controlled by the manipulator based on fuzzy compensation. The simulation results are shown in the following figure.



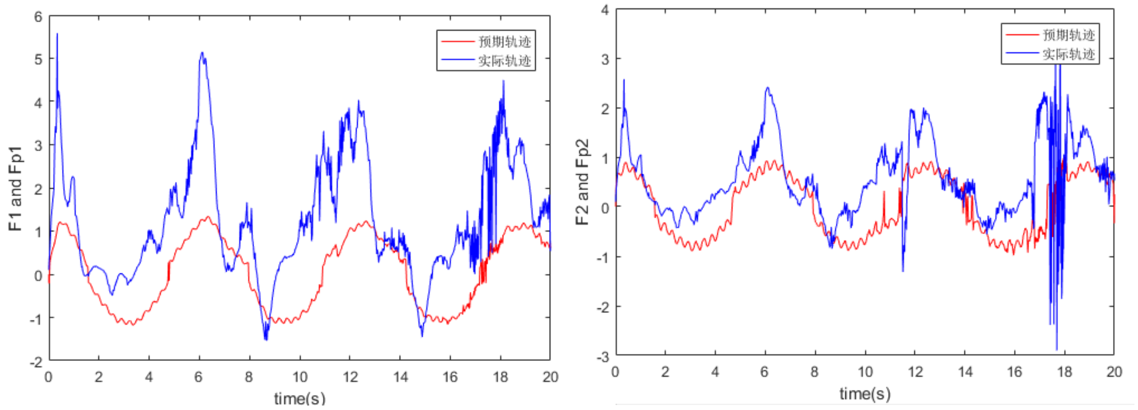
(Joint 1) (Joint 2)

Figure 1. Joint 1 and Joint 2 Position Tracking Curves



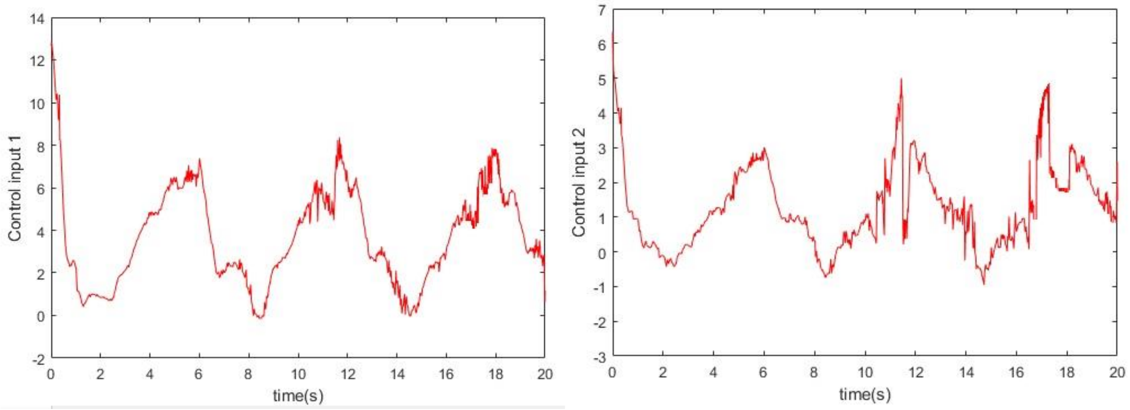
(Joint 1) (Joint 2)

Figure 2. Joint 1 and Joint 2 Velocity Tracking Curves



(Joint 1) (Joint 2)

Figure 3. Joint 1 and Joint 2 Friction and Compensation Curves



(Joint 1) (Joint 2)

Figure 4. Joint 1 and Joint 2 Input Curves

From the simulation curves, it can be seen that when friction, external disturbance and load change are considered as uncertain parts, the position and velocity signals of the manipulator joint can achieve tracking control effect with high precision by using an adaptive fuzzy controller based on fuzzy compensation. The compensation signal and the input signal have a certain amount of vibration. Finally, it can be concluded that the designed fuzzy compensation controller will not affect the position and speed control of the manipulator joint because of the existence of uncertainties or the number of uncertainties in the system, and can maintain its approximation characteristics.

6. Conclusion

In this paper, an adaptive fuzzy compensation method for uncertain model friction is designed to counteract the influence of friction in the process of manipulator control. The adaptive fuzzy control method with fuzzy compensation is used to design the adaptive law of controller parameters through the stability algorithm of Lyapunov equation. Then, a robust controller is added to obtain an adaptive robust tracking control algorithm, which can be used to eliminate the errors caused by fuzzy approximation system in the control process and the influence of external environment disturbance. Finally, the simulation experiment of the two-joint manipulator proves that the adaptive fuzzy control method based on LuGre model can compensate the unknown complex friction in the manipulator system well, and realize the high-precision trajectory tracking control of the manipulator system.

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