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An Adaptive Robust Control for Trajectory Tracking Of a Robotic Manipulator System

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***Abstract*—The conventional adaptive control algorithm has a very high real-time requirement for six degrees-of-freedom (DOF) series robotic manipulator system. When the unknown parameters of the robotic manipulator are mutated, it is difficult to ensure the stability of the robotic manipulator system. Aiming at this phenomenon, an optimal algorithm based on adaptive robust control is proposed. When the algorithm is applied to the robotic manipulator system, the actual trajectory at the end of the manipulator is as close as possible to the desired trajectory in the simulation. The algorithm is based on the conventional algorithm, the design of the sliding mode surface to reduce the system position error, adding robust control algorithm to compensate for the instability of the system. The simulation results show that the actual trajectory can quickly track the desired trajectory, and the position error approaches zero.**

***Index Terms*— six-DOF, adaptive control algorithm, robust control algorithm.**

I. Introduction

The robotic manipulator is an inherently nonlinear, strongly coupled and time-varying system [1]. And the control design and stability analysis of robotic manipulator have received considerable attention. At the same time, there were many control strategies that have been proposed, such as the PID (proportional-integral-derivative) control, the sliding mode control, the adaptive control, the neural network control and so on. In fact, the robotic system is inherently nonlinear with partially known or unknown dynamics makes the use of conventional methods difficult [2]. There are numerous applications in industries like manufacturing, aerospace and medical in which they are used to pick up the appointed objects. Therefore, the accurate position tracking control is the core of the robotic system.

In [3], an improved adaptive robust control is proposed, which is based on the desired compensation adaptive robust control. This strategy uses the method of maximum likelihood parameter estimation to obtain the accurate results of parameter identification, and the integral parameter estimation is adjusted to the proportional integral parameter estimation. The simulation results prove that the control has significantly improved the stability and controllability of this system. In [4], based on the conventional PID control, it adds an algorithm for estimating the equivalent rotational inertia. It proposes an APID (Adaptive PID) control algorithm. The simulation results prove that this algorithm has the advantages of stable tracking performance, high control precision and strong robustness compared to the conventional PID control. In [5], an adaptive neural synovial control is proposed in which it adds an adaptive control system for neural network error based on the traditional neural synovial control. The simulation results prove that this algorithm realize the automatic tracking of modeling error and uncertain interference, and improve the stability of the system. In [6], it combines the PD control with the feed forward control and there is an experiment act on a 2-DOF humanoid manipulator. The simulation results prove that this method successfully reduces the average absolute error of the robotic manipulator.

In this paper, we studied and learned lots of differently solutions and used the existing 6-DOF series robotic manipulator for research objects. We firstly analyzed the structure of the robotic manipulator, and used D-H (Denavit-Hartenberg) method to construct the transformation matrix between each joint of the robotic manipulator, and deduced the positive kinematics model of the robotic manipulator. Then, we optimized the adaptive control algorithm and used it for simulation and experiment. The simulation results proved that this algorithm improved the tracking performance of the system.

II. Kinematics Model

The motion analysis of the series robotic manipulator is to solve the position and posture of the hand claw knowing the motion parameters of each joint. In order to describe the movement of the robotic manipulator of the link, we usually use D-H method to establish the coordinate system [7]-[9].

In Fig.1, we set up the coordinate system of links $\{i\}$ (i=1, 2... 6), let ${}^{i-1}_{i}T$ as the transformation of links of coordinate system $\{i\}$ relative to $\{i-1\}$. The transformation of links ${}^{i-1}_{i}T$ can be regarded as the coordinate system $\{i\}$ is obtained though the following four transformation:

1) Revolved angle (θ_i) around the axis (z_{i-1});
2) Moved length (d_i) along the axis (z_{i-1});
3) Moved length (a_i) along the axis (x_i);
4) Revolved angle (α_i) around the axis (x_i).

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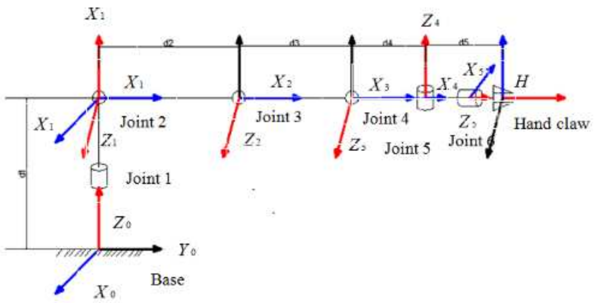

Fig.1. The coordinate system of links.

where θ represents the rotation angle around the z axis, d represents the distance between two adjacent common perpendicular lines on the z axis, a represents the length of links, α_i represents the angle between two adjacent z axis. Therefore,

$$ {}^{i-1}_{i}T = Rot(z,\theta_i)\cdot \mathrm{Trans}(0,0,d_i)\cdot \mathrm{Trans}(a_i,0,0)\cdot Rot(x,\alpha_i) \tag{1} $$

where

$$ Rot(z,\theta_i)=\begin{bmatrix} c\theta_i & -s\theta_i & 0 & 0 \\ s\theta_i & c\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

$$ \mathrm{Trans}(0,0,d_i)=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

$$ \mathrm{Trans}(a_i,0,0)=\begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

$$ Rot(x,\alpha_i)=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c\alpha_i & -s\alpha_i & 0 \\ 0 & s\alpha_i & c\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

Therefore,

$$ {}^{i-1}_{i}T=\begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6} $$

where s^* and c^* denotes $\sin^*$ and $\cos^*$.

According to the D-H method, the transformation of links of coordinate system {6} relative to {0}:

$$ {}^{0}_{6}T=\begin{bmatrix} m_{11} & n_{12} & l_{13} & p_x \\ m_{21} & n_{22} & l_{23} & p_y \\ m_{31} & n_{32} & l_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}=\begin{bmatrix} \vec{m} & \vec{n} & \vec{l} & \vec{p} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7} $$

where $\vec{m}=\begin{bmatrix} m_{11} & m_{21} & m_{31}\end{bmatrix}^T$, $\vec{n}=\begin{bmatrix} n_{12} & n_{22} & n_{32}\end{bmatrix}^T$, $\vec{l}=\begin{bmatrix} l_{13} & l_{23} & l_{33}\end{bmatrix}^T$, $\vec{p}=\begin{bmatrix} p_x & p_y & p_z\end{bmatrix}^T$.

Equation (7) is the forward kinematics model of this 6-DOF robotic manipulator, where the vectors ($\vec{m},\vec{n},\vec{l}$) represent the direction vectors of the three axes (x_6, y_6, z_6) of the coordinate system {6} in the coordinate system {0}. The vector $\vec{p}$ represents the position of the origin of coordinates (H) of the coordinate system {6} in the coordinate system {0}. We can figure out the position coordinates of the hand claw relative to the base when we substitute the parameters of links and joints into these equations.

III. DYNAMIC MODEL

Considering a robotic manipulator of n-joint, its dynamic performance can be described by a second order nonlinear differential equation [6]:

$$ D(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)+\omega=\tau \tag{8} $$

where $q\in R^n$ is the angular displacement of the joint, $D(q)\in R^{n\times n}$ is the positive definite inertia matrix, $C(q,\dot{q})\in R^n$ is the centrifugal force and Coriolis force, $G(q)\in R^n$ is gravity, $\tau\in R^n$ is control torque, $\omega\in R^n$ is the bounded external interference (if $d>0,\|\omega\|<d$).

The kinetic characteristics of the robot system are as follows:

Property 1 [10]-[11]: $D(q)-2C(q,\dot{q})$ is a skew symmetric matrix;

Property 2 [12]: is a symmetrical positive definite matrix, $\forall\, \mathrm{m}_1,\mathrm{m}_2>0$, and

$$ \mathrm{m}_1\|x\|^2\le x^T D(q)x\le \mathrm{m}_2\|x\|^2 \tag{9} $$

Property 3 [12]: There is a vector so that $D(q)$, $C(q,\dot{q})$ and $G(q)$ satisfy the following linear relationship:

$$ D(q)\vartheta+C(q,\dot{q})\rho+G(q)=\Phi(q,\dot{q},\rho,\vartheta)\theta \tag{10} $$

where $\Phi(q,\dot{q},\rho,\vartheta)\in R^{n\times n}$ is a regression matrix, $\theta\in R^n$ is a parameter vector.

Lemma 1 [13]: If there exists a continuous and positive definite Lyapunov function $V(t)$ satisfying the following conditions, and it is proved that this system is globally uniformly ultimately bounded (GUUB).

$$ V\le-\beta V(t)+C^* \tag{11} $$

where β and C^* are two positive constants.

The tracking error variables e is defined as follows:

$$e = q - q_d \quad (12)$$

where q_d is desired trajectory.

Let

$$x = \dot{e} + \lambda e \quad (13)$$

$$\dot{q}_r = \dot{q}_d - \lambda e \quad (14)$$

where λ is a positive constant. Therefore,

$$x = \dot{e} + \lambda e = \dot{q} - \dot{q}_d + \lambda e = \dot{q} - \dot{q}_r \quad (15)$$

According to Property 3, let $\vartheta = \ddot{q}_r, \rho = \dot{q}_r$, therefore,

$$D(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + G(q) = \Phi(q,\dot{q},\dot{q}_r,\ddot{q}_r)\theta \quad (16)$$

Substituting (8) into (16):

$$D(\ddot{q} - \dot{x}) + C(\dot{q} - x) + G = \Phi(q,\dot{q},\dot{q}_r,\ddot{q}_r)\theta \quad (17)$$

Substituting (15) into (17):

$$D\dot{x} = \tau - \Phi(q,\dot{q},\dot{q}_r,\ddot{q}_r)\theta - \omega - Cx \quad (18)$$

IV. Control Design

The control law τ is given as follows:

$$\tau = -K_p e - K_v \dot{e} + \Phi(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta} + u \quad (19)$$

where K_p and K_v are the control gains, and k_{pi}, k_{vi}, (i =1, 2… n) are positive constants. $\hat{\theta}$ is the estimated values of θ, u is the robust control law.

The robust control law u is given as follows:

$$u = \begin{cases} -\dfrac{xd}{\|x\|} & \|x\| d > \varepsilon \\ -\dfrac{xd^2}{\varepsilon} & \|x\| d \le \varepsilon \end{cases} \quad (20)$$

Designing the following Lyapunov function:

$$V(t) = \frac{1}{2}x^T Dx + \frac{1}{2}e^T K_p e + \frac{1}{2}\lambda e^T K_v e + \frac{1}{2}\tilde{\theta}^T \Gamma \tilde{\theta} \quad (21)$$

where $\tilde{\theta} = \theta - \hat{\theta}$, $\Gamma = diag(\gamma_1, \gamma_2, ...\gamma_n)$, $\gamma_i > 0$, (i =1, 2… n). Therefore,

$$\dot{V}(t) = x^T D\dot{x} + \frac{1}{2}x^T \dot{D}x + \dot{e}^T K_p e + \lambda e^T K_v \dot{e} + \tilde{\theta}^T \Gamma \dot{\tilde{\theta}} \quad (22)$$

According to (18):

$$x^T D\dot{x} = x^T(\tau - \Phi\theta - \omega - Cx) \quad (23)$$

Substituting (19) into (23):

$$\begin{aligned} x^T D\dot{x} &= x^T(-K_p e - K_v \dot{e} + \Phi\hat{\theta} + u - \Phi\theta - \omega - Cx) \\ &= x^T(-K_p e - K_v \dot{e}) + x^T \Phi\tilde{\theta} + x^T(u - \omega) \\ &\quad -x^T Cx \end{aligned} \quad (24)$$

Substituting (24) into (22):

$$\begin{aligned} \dot{V}(t) &= x^T(-K_p e - K_v \dot{e}) + x^T \Phi\tilde{\theta} + x^T(u - \omega) - \\ &\quad x^T Cx + \frac{1}{2}x^T \dot{D}x + \dot{e}^T K_p e + \lambda e^T K_v \dot{e} + \tilde{\theta}^T \Gamma \dot{\tilde{\theta}} \end{aligned} \quad (25)$$

According to Property 1:

$$-x^T Cx + \frac{1}{2}x^T \dot{D}x = \frac{1}{2}x^T(\dot{D} - 2C)x = 0 \quad (26)$$

and $x^T = \dot{e}^T + \lambda e^T$, therefore,

$$\begin{aligned} x^T(-K_p e - K_v \dot{e}) &= -\dot{e}^T K_p e - \dot{e}^T K_v \dot{e} - \lambda e^T K_p e \\ &\quad -\lambda e^T K_v \dot{e} \end{aligned} \quad (27)$$

Substituting (26) and (27) into (25):

$$\begin{aligned} \dot{V}(t) &= -\lambda e^T K_p e - \dot{e}^T K_v \dot{e} + x^T(u - \omega) \\ &\quad + x^T \Phi\tilde{\theta} + \tilde{\theta}^T \Gamma \dot{\tilde{\theta}} \end{aligned} \quad (28)$$

The adaptive control law is designed as follows:

$$\dot{\hat{\theta}} = -\Gamma^{-1}\Phi^T(q,\dot{q},\dot{q}_r,\ddot{q}_r)x \quad (29)$$

Substituting (29) into (28):

$$\dot{V}(t) = -\lambda e^T K_p e - \dot{e}^T K_v \dot{e} + x^T(u - \omega) \quad (30)$$

where $x^T \Phi\tilde{\theta} = \tilde{\theta}^T \Phi^T x$, $\dot{\hat{\theta}} = \dot{\tilde{\theta}}$.

According to Property 2:

$$\begin{aligned} \lambda e^T K_p e &\ge \lambda m_{p1}\|e\|^2 \\ \dot{e}^T K_v \dot{e} &\ge m_{v1}\|\dot{e}\|^2 \end{aligned} \quad (31)$$

where $m_{p1} = \min\{k_{pi}\}, m_{v1} = \min\{k_{vi}\}$. Therefore,

$$\lambda e^T K_p e + \dot{e}^T K_v \dot{e} \ge \lambda m_{p1}\|e\|^2 + m_{v1}\|\dot{e}\|^2 \ge m_1\|x\|^2 \quad (32)$$

where $m_1 = \min\{m_{p1}, m_{v1}\}$.

Substituting (32) into (30):

$$\dot{V}(t) \le -m_1\|x\|^2 + x^T u - x^T \omega \quad (33)$$

and $-x^T\omega \le \|x^T\| \cdot \|\omega\| \le \|x\| \cdot d$. Therefore,

$$\dot{V}(t) \le -m_1\|x\|^2 + x^T u + \|x\| \cdot d \quad (34)$$

When $\|x\| d > \varepsilon$, and

$$\dot{V}(t) \le -m_1\|x\|^2 \le 0 \quad (35)$$

When $\|x\| d \le \varepsilon$, and

$$\dot{V}(t) \le -m_1\|x\|^2 - \frac{\|x\|^2 d^2}{\varepsilon} + \|x\| d \quad (36)$$

and when $\|x\| d = \varepsilon / 2$,

$$\left\{-\frac{\|x\|^2 d^2}{\varepsilon} + \|x\| d\right\}_{\max} = \frac{\varepsilon}{4}$$

Therefore,

$$\dot{V}(t) \le -m_1\|x\|^2 + \frac{\varepsilon}{4} \quad (37)$$

Integrating (35) and (37):

$$\dot{V}(t) \le -m_1\|x\|^2 + \frac{\varepsilon}{4} \quad (38)$$

According to (21) and Property 2:

$$\frac{1}{2}m_1^*\|x\|^2 + C_1^* \le V \le \frac{1}{2}m_2^*\|x\|^2 + C_2^* \quad (39)$$

where

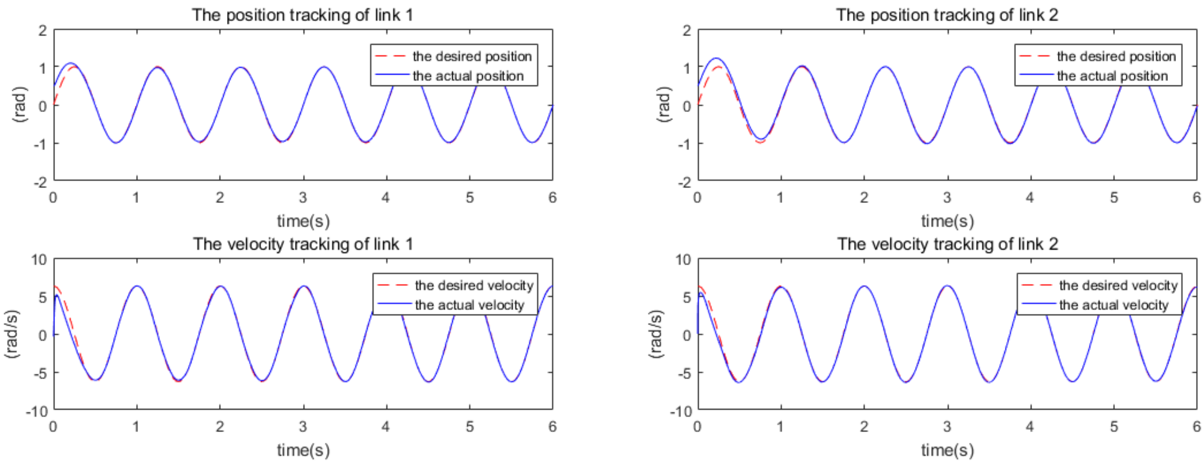

Fig.2. The position tracking and velocity tracking of links.

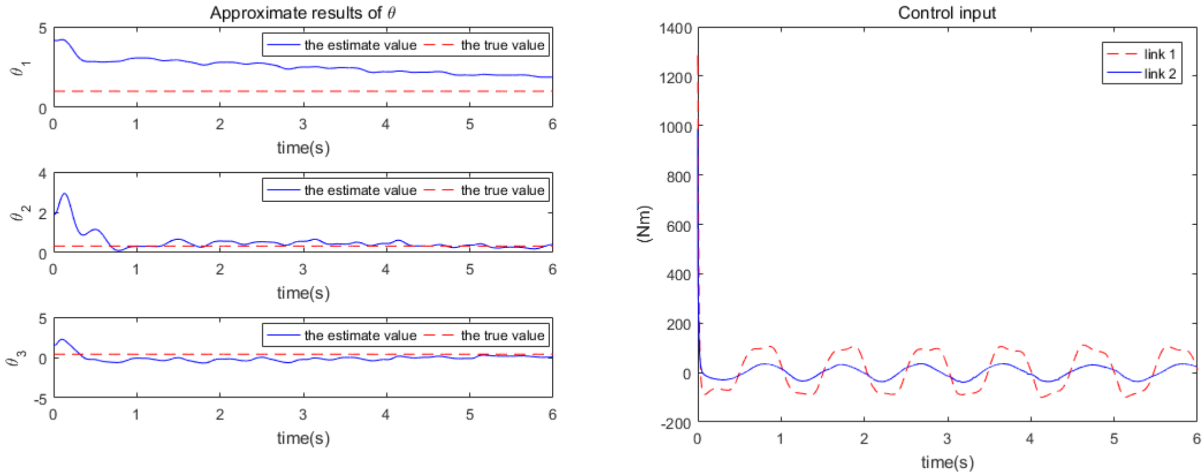

Fig.3. Approximate results of θ and control input.

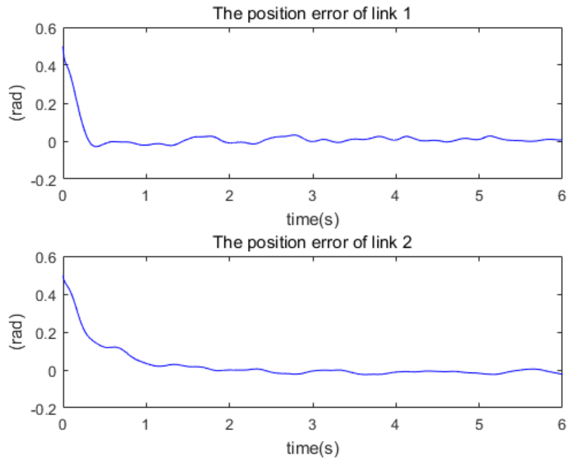

Fig.4. The position tracking error of links.

$$C_1^* = \frac{1}{2} m_{p1} \|e\|^2 + \frac{1}{2} m_{v1} \|\dot{e}\|^2 + \frac{1}{2} \gamma_{\min} \|\tilde{\theta}\|^2$$

$$C_2^* = \frac{1}{2} M_{p1} \|e\|^2 + \frac{1}{2} M_{v1} \|\dot{e}\|^2 + \frac{1}{2} \gamma_{\max} \|\tilde{\theta}\|^2$$

where

$$M_{p1} = \max\{k_{pi}\},\ M_{v1} = \max\{k_{vi}\},$$

$$\gamma_{\min} = \min\{\gamma_i\},\ \gamma_{\max} = \max\{\gamma_i\}.$$

According to (39):

$$-\|x\|^2 \le -\frac{2}{m_2^*} V + \frac{2}{m_2^*} C_2^* \tag{40}$$

Substituting (40) into (38):

$$\dot{V}(t) \le -\frac{2m_1}{m_2^*} V + \frac{2m_1}{m_2^*} C_2^* + \frac{\varepsilon}{4} \tag{41}$$

According to Lemma 1, the control law (19), (20) and (29) can guarantee that the entire robotic manipulator closed loop system is globally uniformly ultimately bounded.

V. Simulation

In this section, we will verify the effectiveness of the proposed adaptive robust control law for the 2-DOF robotic manipulator. The parameterized model of the 2-DOF robotic manipulator is [10], [14]:

$$D(q) = \begin{bmatrix} \theta_1 + \theta_2 + 2\theta_3 \cos q_2 & \theta_2 + \theta_3 \cos q_2 \\ \theta_2 + \theta_3 \cos q_2 & \theta_2 \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} -\theta_3 \dot{q}_2 \sin q_2 & -\theta_3(\dot{q}_1 + \dot{q}_2) \sin q_2 \\ \theta_3 \dot{q}_1 \sin q_2 & 0 \end{bmatrix} \tag{42}$$

$$G(q) = \begin{bmatrix} \theta_1 \gamma \cos q_2 + \theta_3 \gamma (q_1 + q_2) \\ \theta_3 \gamma (q_1 + q_2) \end{bmatrix}$$

where $\theta = \begin{bmatrix} \theta_1 & \theta_2 & \theta_3 \end{bmatrix}^T$ is unknown parameters vector, $\gamma = g / r_1$, g is the gravity acceleration, $g = 9.8 m / s^2$. r_1, r_2 are the length of links. m_1, m_2 are the mass of links.

The desired position trajectories are as follows:

$$q_{d1} = q_{d2} = \sin(2\pi t)$$

The initial states of the system are as follows:

$$q_1(0) = 0.5, \dot{q}_1(0) = 0, q_2(0) = 0.5, \dot{q}_2(0) = 0$$

The external disturbances are as follows:

$$\omega_1 = 3\dot{q}_1 \sin t, \omega_2 = 3\dot{q}_2 \cos t$$

The parameters of the robotic manipulators are as follows:

$$r_1 = 1.0m, r_2 = 0.8m, m_1 = 0.5kg, m_2 = 0.5kg$$

The true value of unknown parameters are as follows:

$$\theta = \begin{bmatrix} 1 & 0.32 & 0.4 \end{bmatrix}^T$$

The control parameters are respectively:

$$K_p = \begin{bmatrix} 150 & 0 \\ 0 & 150 \end{bmatrix}, K_v = \begin{bmatrix} 150 & 0 \\ 0 & 150 \end{bmatrix}$$

$$\lambda = \begin{bmatrix} 5 & 0 \\ 0 & 5 \end{bmatrix}, \Gamma = \begin{bmatrix} 5 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 5 \end{bmatrix}$$

$$d = 3, \varepsilon = 0.01$$

Fig.2 shows the position tracking and the velocity tracking of the robotic manipulator respectively, Fig.3 and Fig.4 show the approximate results of the unknown parameters, control input and the position tracking error respectively. From the figures, it can be seen that the link 1 can track the desired position around 0.5s, that is, the position error of link 1 converges to zero. The link 2 can also obtain the same tracking effect around 1s. Because velocity is the derivative of the displacement, the proposed controller ensures that the robotic manipulators track the desired velocity. There is a better effect that the estimate value of θ_2 and θ_3 converge to the true value compared to θ_1.

VI. Conclusion

In this paper, we use D-H method to construct the transformation matrix between each joint of the robotic manipulator, and deduced the positive kinematics model of the robotic manipulator. For the trajectory tracking of robotic manipulators with uncertain external disturbances, an adaptive robust control strategy is proposed. The stability of the closed loop system has been proved by Lyapunov function. Simulation results have been proved that this method is able to guarantee the robotic manipulators track the desired trajectory successfully, where the system error is converging to zero.

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