Backstepping Adaptive Fuzzy Control for two-link robot manipulator

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Abstract

In this paper, based on Lyapunov method, a backstepping adaptive fuzzy control scheme is presented for the two-link robot manipulator system. The control strategy consists of the traditional backstepping control and adaptive fuzzy control to cope with the model unknown and parameter disturbances.The simulation is presented to verify the effectiveness of the proposed control scheme. From the simulation results, fast response, strong robustness, good disturbance rejection capability and good angle tracking capability can be obtained. The output tracking error between the actual position output and the desired position output can asymptotically converge to zero. It is also revealed from simulation results that the proposed control strategy is valid for the two-link robot manipulator.

Keywords: *Backstepping control, Adaptive Fuzzy control, Two-link robot manipulator,MATLAB simulation.*

1. Introduction

In recent decades, the robot research has been paid great attention. Robotic is a vast research field, mainly because of the many potential applications. The basic problem in controlling robot is to make manipulator to perform preplanned trajectory. Therefore, it must be controlled properly to track some trajectory because there exist the uncertainties, nonlinear, strong coupling and time-varied of the robot system, and external disturbances. In order to achieve this goal, many schemes which were PID control, optimal control, sliding mode control(SMC), adaptive control, fuzzy control and so on, have been presented[1].

In this paper, based on Lyapunov method, an adaptive fuzzy control scheme combining backstepping is presented for the two-link robot manipulator system which has two rotational joints on a horizontal plane and one translational joint on the vertical axis. It is proved that the closed-loop system is globally stable in the Lyapunov sense. If all the signals are bounded, the system output can track the desired reference output asymptotically with uncertainties and disturbances[2-3].

2、Model of two-link manipulator

2.1 Model Description

In Engineering, robots not only can improve productivity but also can achieve high-strength, highly difficult and hazardous jobs. Manipulators are the usual plants in robotics. Using the lagrangian formulation, the dynamic equation of a planner n degrees of freedom rigid manipulator can be expressed as follows.

$$M\left(q_k(t)\right)\ddot{q}_k(t) + C\left(q_k(t),\dot{q}_k(t)\right)\dot{q}_k(t) + G\left(q_k(t)\right) = \tau_K(t) + d_k(t) \quad (1)$$

Where $M\left(q_k(t)\right) \in R^{n\times n}$ is the inertia matrix. $q_k(t) \in R^n$ is the angle vector, $\dot{q}_k(t) \in R^n$ is the velocity vector, also the $\ddot{q}_k(t) \in R^n$ is acceleration vector. t denotes the time and is the nonnegative integer. $k \in Z_+$ denotes the operation or iteration times. $C\left(q_k(t),\dot{q}_k(t)\right) \in R^n$ is a vector resulting from the centrifugal and coriolis forces. $G\left(q_k(t)\right)$ is the gravity. $\tau_K(t) \in R^n$ is the control moment applied to the joints,and $d_k(t) \in R^n$ is the vector containing the unmodeled dynamics and other unknown external disturbances.

The characteristics of the kinetic model of a robot manipulator[4]:

(1) Kinetic mode contains more number of items: The number of items included in the equation increases with the increase in the number of robot joint.
(2) Highly nonlinearity: Each item of the equations contains non-linear factors such as sine and consine, et al.
(3) High degree of coupling.
(4) Model uncertainty and time-variant: Because the objects are not similar, the load will vary when the robot moves the objects. Also the joint friction torque will also change over time.

Suppose that the parameters of the system are unknown, and the following properties are written as:

Property 1

$M\left(q_k\left(t\right)\right) \in R^{n\times n}$ is a positive-definite symmetric, and bounded matrix. There exists positive constant,

$\sigma_0 > 0, \sigma_0 \in R, 0 < M\left(q_k\left(t\right)\right) \le \sigma_0 I$

Property 2

$C\left(q_k\left(t\right), \dot{q}_k\left(t\right)\right)$ is bounded. there exists known $c_b\left(q\right)$ such that

$\left|C\left(q_k\left(t\right), \dot{q}_k\left(t\right)\right)\right| \le c_b\left(q\right)\left\|\dot{q}_k\left(t\right)\right\|$

Property 3

Matrix $\dot{M}\left(q_k\left(t\right)\right) - 2C\left(q_k\left(t\right), \dot{q}_k\left(t\right)\right)$ is a symmetric matrix, and

$$X^T\left(\dot{M}\left(q_k\left(t\right)\right) - 2C\left(q_k\left(t\right), \dot{q}_k\left(t\right)\right)\right)X = 0 \qquad (2)$$

where X is a vector.

Property 4

The known disturbance is satisfied with $\left\|d_k\right\| \le d_m$, where d_m is a known positive constant.

2.2 Mathematical model

The two-link robot manipulator generally has two revolute joints and prismatic joint. The schematic diagram of the two-link manipulator is shown in Fig.1. The robots transport a load horizontally by actuating the two revolute joints. The robots transport a load vertically by actuating the prismatic joint[5].

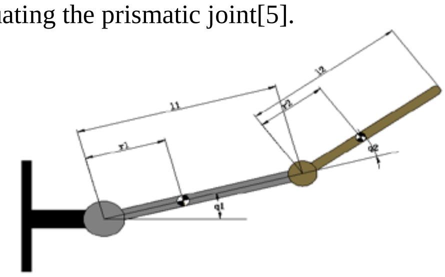

Fig.1 The schematic diagram of the two-link manipulator

The dynamic equation of the model for two-link robot manipulator can be expressed as follows:

$$M\left(q_k\left(t\right)\right)\ddot{q}_k\left(t\right) + C\left(q_k\left(t\right), \dot{q}_k\left(t\right)\right)\dot{q}_k\left(t\right) + d_k\left(t\right) = \tau_K\left(t\right)$$

$$y = q_k\left(t\right) \qquad (3)$$

According to Lagrangian method, the inertia matrix $M\left(q_k\left(t\right)\right)$ can be written as:

$$M\left(q_k\left(t\right)\right) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \qquad (4)$$

Where

$$M_{11} = J_1 + J_2 + 2m_2 r_2 l_1 \cos\theta_2,$$
$$M_{12} = J_2 + m_2 r_2 l_1 \cos\theta_2,$$
$$M_{21} = J_2 + m_2 r_2 l_1 \cos\theta_2,$$
$$M_{22} = J_2,$$
$$J_1 = \frac{4}{3}m_1 r^2{}_1 + m_2 l^2{}_1,$$
$$J_2 = \frac{4}{3}m_2 r^2{}_2$$

Also the $C\left(q_k\left(t\right), \dot{q}_k\left(t\right)\right)$ is given by:

$$C\left(q_k\left(t\right), \dot{q}_k\left(t\right)\right) = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \qquad (5)$$

Where

$$C_{11} = -2m_2 r_2 l_1 \dot{\theta}_2 \sin\theta_2,$$
$$C_{12} = -m_2 r_2 l_1 \dot{\theta}_2 \sin\theta_2,$$
$$C_{21} = m_2 r_2 l_1 \dot{\theta}_2 \sin\theta_2,$$
$$C_{22} = 0,$$
$$q = \left[\theta_1 \quad \theta_2\right]^T, \tau = \left[\tau_1 \quad \tau_2\right]^T$$

Where m_1 is the mass of the 1th link, m_2 is the mass of the 2th link, l_1 and l_2 are the length of each link. r_1 and r_2 are distances between the gravity center position and rotational position of the each links. θ_1 and θ_2 are the angle of each links. J_1 and J_2 are the inertia matrix of two links. In addition, $G\left(q_k\left(t\right)\right)$ terms are ignored in this paper because the absence of the $G\left(q_k\left(t\right)\right)$ terms in the equation of motion could be interpreted as assuming the robot is statically balanced. On the other hand, the absence of gravity is interpreted by simply assuming that the robot is working in outer space.

2.3 Design of Controller and Analysis of the Stability

In order to apply Backstepping method, define

$$x_1 = q_k(t), x_2 = \dot{q}_k(t).$$

Using (1),we can obtain :

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = M^{-1}(x_1)\tau - M^{-1}(x_1)C(x_1, x_2)x_2 - M^{-1}(x_1)d \qquad (6)$$
$$y = x_1$$

STEP 1:

Assuming y_d is the expected angle and has second order derivative. Define $z_1 = y - y_d$. α_1 is the estimation of the x_2.Define $z_2 = x_2 - \alpha_1$. According to selecting the appropriate α_1, making $z_2 \to 0$, we can obtain $\dot{z}_1$ following as:

$$\dot{z}_1 = \dot{x}_1 - \dot{y}_d = z_2 + \alpha_1 - \dot{y}_d \quad (7)$$

Select the virtual control item as:

$$\alpha_1 = -\lambda_1 z_1 + \dot{y}_d \left(\lambda_1 > 0\right) \quad (8)$$

Select the Lyapunov function for the first subsystem as :

$$V_1 = \frac{1}{2} z_1^T z_1 \quad (9)$$

There

$$\begin{aligned} \dot{V}_1 &= z_1^T \dot{z}_1 = z^T_1(\dot{y} - \dot{y}_d) \\ &= z^T_1(z_2 + \alpha_1 - \dot{y}_d) \\ &= -\lambda_1 z^T_1 z_1 + z^T_1 z_2 \end{aligned} \quad (10)$$

If z_2 is zero, the first subsystem is stable.

STEP 2:

Using (3) (5), we can obtain :

$$\dot{z}_2 = \dot{x}_2 - \dot{\alpha}_1 = -M^{-1}Cx_2 - M^{-1}d + M^{-1}\tau - \dot{\alpha}_1 \quad (11)$$

Select the control rule as following:

$$\tau = -\lambda_2 z_2 - z_1 - \phi \quad (12)$$

Select the Lyapunov function for the second subsystem:

$$V_2 = V_1 + \frac{1}{2} z^T_2 M z_2 \quad (13)$$

Therefore

$$\begin{aligned} \dot{V}_2 &= \dot{V}_1 + \frac{1}{2}\dot{z}^T_2 M z_2 + \frac{1}{2} z^T_2 \dot{M} z_2 + \frac{1}{2} z^T_2 M \dot{z}_2 \\ &= -\lambda_1 z^T_1 z_1 + z^T_1 z_2 + z^T_2 M(\dot{x}_2 - \dot{\alpha}_1) + \frac{1}{2} z^T_2 \dot{M} z_2 \\ &= -\lambda_1 z^T_1 z_1 + z^T_1 z_2 + z^T_2 M(-M^{-1}Cx_2 - M^{-1}d + M^{-1}\tau - \dot{\alpha}_1) + z^T_2 C z_2 \\ &= -\lambda_1 z^T_1 z_1 + z^T_1 z_2 + z^T_2(f - \lambda_2 z_2 - z_1 - \phi) - z^T_2 d \\ &= -\lambda_1 z^T_1 z + -\lambda_2 z^T_2 z_2 + z^T_2(f - \phi) \end{aligned}$$

(14)

Where $f = -C\alpha_1 - M\dot{\alpha}_1$

From the expression of the f, we can obtain the modeling information of robotics system. In order to realize the control without model information, we make fuzzy system approximate the f .If ϕ is used to approximate the fuzzy system of the nonlinear function f, the single value fuzzification, the product inference engine and the center average defuzzifier are adopted [3,6,7,8].

If fuzzy system is consisted of N fuzzy rules, the ith fuzzy rule is expressed as:

R^i :IF x_1 is $\mu^k{}_1$ and...and x_n is $\mu^k{}_n$, then y is B^k (k=1,2, …N) ,Where $\mu^k{}_i$ is the membership function of the x_i (i =1,2, …n).

The output of fuzzy system is written as:

$$y = \frac{\sum_{k=1}^{N} \theta_K \prod_{i=1}^{n} \mu^k{}_i\left(x_i\right)}{\sum_{k=1}^{N} \prod_{i=1}^{n} \mu^k{}_i\left(x_i\right)} = \xi^T\theta \quad (15)$$

Where $\xi = \left[\xi_1(x), \xi_2(x), \xi_3(x), \ldots, \xi_N(x)\right]$,

$$\xi_K(x) = \frac{\prod_{i=1}^{n} \mu^k{}_i\left(x_i\right)}{\sum_{k=1}^{N} \prod_{i=1}^{n} \mu^k{}_i\left(x_i\right)},$$

$$\theta = \left[\theta_1, \theta_2, \theta_3, \ldots, \theta_N\right]^T. \quad (16)$$

Based on the fuzzy approximation of the f, the fuzzy system for $f(1)$ and $f(2)$ is designed as:

$$\begin{aligned} \phi_1(x) &= \frac{\sum_{k=1}^{N} \theta_{1K} \prod_{i=1}^{n} \mu^k{}_i\left(x_i\right)}{\sum_{k=1}^{N}\left[\prod_{i=1}^{n} \mu^k{}_i\left(x_i\right)\right]} = \xi_1^T\theta_1 \\ \phi_1(x) &= \frac{\sum_{k=1}^{N} \theta_{2K} \prod_{i=1}^{n} \mu^k{}_i\left(x_i\right)}{\sum_{k=1}^{N}\left[\prod_{i=1}^{n} \mu^k{}_i\left(x_i\right)\right]} = \xi_2{}^T\theta_2 \end{aligned} \quad (17)$$

Define

$$\Phi = \left[\phi_1, \phi_2\right]^T = \begin{bmatrix} \xi_1^T & 0 \\ 0 & \xi_2{}^T \end{bmatrix}\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \xi^T\theta \quad (18)$$

θ^* is defined the optimal approximative constant. The following inequality is established for a given any small constant $\varepsilon(\varepsilon > 0)$ [9].

$\left\| f - \Phi^* \right\| \le \varepsilon$ 。令 $\tilde{\theta} = \theta^* - \theta$.

The self-adaptive control law is designed as:

$$\dot{\theta} = \gamma(z_2{}^T\xi^T(x))^T - 2k\theta \quad (19)$$

STEP 3:

The Lyapunov function is selected for the whole system:

$$V = \frac{1}{2} z_1^T z_1 + \frac{1}{2} z_2{}^T M z_2 + \frac{1}{2\gamma}\tilde{\theta}^T\tilde{\theta}(\gamma > 0) \quad (20)$$

Therefore

$$\dot{V} = -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T (f - \xi(x)\theta) - z_2^T - \frac{1}{\gamma}\tilde{\theta}^T \dot{\theta} \quad (21)$$
$$= -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T (f - \xi(x)\theta^*) + z_2^T (\xi(x)\theta^* - \xi(x)\theta) - z_2^T d - \frac{1}{\gamma}\tilde{\theta}^T \dot{\theta}$$

Then

$$\dot{V} \le -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + \left\| z_2^T \right\| \bullet \left\| (f - \xi(x)\theta^*) \right\| + z_2^T (\xi(x)\tilde{\theta}) + \left\| z_2^T \right\| \bullet \left\| d \right\| - \frac{1}{\gamma}\tilde{\theta}^T \dot{\theta}$$
$$\le -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + \frac{1}{2}\left\| z_2^T \right\|^2 + \frac{1}{2}\varepsilon^2 + \frac{1}{2}\left\| z_2^T \right\|^2 + \frac{1}{2}\left\| d \right\|^2 + \tilde{\theta}^T \left[(z_2^T \xi(x))^T - \frac{1}{\gamma}\dot{\theta} \right] \quad (22)$$

Because of $\dot{\theta} = \gamma (z_2^T \xi^T(x))^T - 2k\theta$, we can obtain:

$$\dot{V} \le -\lambda_1 z_1^T z_1 - (\lambda_2 - 1) z_1^T z_2 + \frac{k}{\gamma}(2\theta^{*T}\theta - 2\theta^T\theta) + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \quad (23)$$

Using (22)and $\left(\theta - \theta^*\right)^T \left(\theta - \theta^*\right) \ge 0$,
we can obtain:

$$\dot{V} \le -\lambda_1 z_1^T z_1 - (\lambda_2 - 1) z_2^T z_2 + \frac{k}{\gamma}(-\theta^{*T}\theta^* - \theta^T\theta) + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \quad (24)$$

Due to $\left(\theta + \theta^*\right)^T \left(\theta + \theta^*\right) \ge 0$

Then

$$\tilde{\theta}^T\tilde{\theta} = (\theta^{*T} - \theta^T)(\theta^* - \theta) \le 2\theta^{*T}\theta^* + 2\theta^T\theta - \theta^T\theta - \theta^{*T}\theta^* \le -\frac{1}{2}\tilde{\theta}^T\tilde{\theta} \quad (25)$$

Namely

$$\dot{V} \le -\lambda_1 z_1^T z_1 - (\lambda_2 - 1) z_2^T M^{-1} M z_2 - \frac{k}{2\gamma}\tilde{\theta}^T\tilde{\theta} + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \quad (26)$$

The optimal parameter is defined as: $\lambda_2 > 1$,

$$M \le \sigma_0 I, \ -M^{-1} \le -\frac{1}{\sigma_0} I \quad (27)$$

We can obtain:

$$\dot{V} \le -\lambda_1 z_1^T z_1 - (\lambda_2 - 1)\frac{1}{\sigma_0} z_2^T M z_2 - \frac{k}{2\gamma}\tilde{\theta}^T\tilde{\theta} + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \quad (28)$$

Define

$$\frac{c_0}{2} = \min\left\{\lambda_1, (\lambda_2 - 1)\frac{1}{\sigma_0}, \frac{k}{2}\right\} \quad (29)$$

Then

$$\dot{V} \le -c_0\left(\frac{1}{2} z_1^T z_1 + \frac{1}{2} z_2^T M z_2 + \frac{1}{2\gamma}\tilde{\theta}^T\tilde{\theta}\right) + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d$$
$$\le -c_0 V + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{1}{2}d^T d \quad (30)$$

Because the interference $d \in R^n$ is bounded, then there exists the $D > 0$ and meets the $d^T d \le D$.
Then

$$\dot{V} \le -c_0 V + \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{D}{2} = -c_0 V + c_{V\max} \quad (31)$$

Where $c_{V\max} = \frac{2k}{\gamma}\theta^{*T}\theta^* + \frac{\varepsilon^2}{2} + \frac{D}{2}$

By solving the inequality(30), we can obtain:

$$V(t) \le V(0)\exp(-c_0 t) + \frac{c_{V\max}}{c_0}\left[1 - \exp(-c_0 t)\right] \le V(0) + \frac{c_{V\max}}{c_0}, (t \ge 0) \quad (32)$$

Where $V(0)$ is the initial value of the V. Defining the compact set, $\Omega_0 = \left\{ X V(X) \le V(0) + \frac{c_{V\max}}{c_0} \right\}$, then $\left\{z_1, z_2, \tilde{\theta}\right\} \in \Omega_0$, we can obtain the conclusion that V is bounded, and all the signals of closed-loop system are bounded.

3、Simulation

In order to verify the effectiveness of the Backstepping Adaptive Fuzzy controller, MATLAB is used to make simulation for the two-link robot manipulator. The parameters for simulation are shown in table 1.

Table 1. parameters

Description	parameter
m_1	0.1kg
m_2	0.1kg
l_1	0.25m
l_2	0.25m
r_1	0.15
r_2	0.15

The initial state value of system is as:

$$x(0) = \begin{bmatrix} 1 & 1 & 0 & 0 \end{bmatrix}^T$$

The external disturbance is selected as:

$$d = \begin{bmatrix} 0.5\sin t & 0.5\cos t \end{bmatrix}$$

Design parameter are selected as:

$$\lambda_1 = 10, \lambda_2 = 15, k = 1.5, \gamma = 2,$$

$$\lambda_1 = 2, \lambda_2 = 2.5, k = 1.5, \gamma = 2,$$

Desired trajectory is as: $y_d = \sin(2\pi t)$.

The membership function is seclected as:

$$\mu_{F_i}^{1} = \exp[-0.5((x_i + 1.25)/0.6)^2];$$

$$\mu_{F_i}^{2} = \exp[-0.5((x_i)/0.6)^2];$$

$$\mu_{F_i}^{3} = \exp[-0.5((x_i - 1.25)/0.6)^2];$$

Simulation results are shown from Fig.2 to Fig.6.

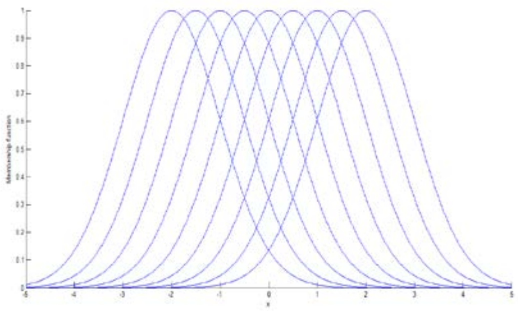

Fig.2 The member function of x_i

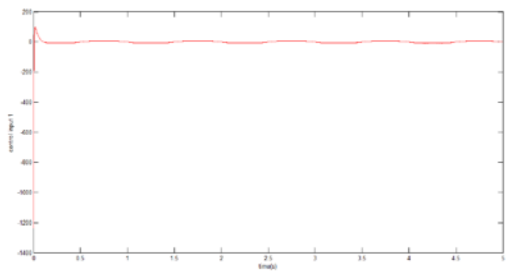

Fig.3 Control input of 1th link

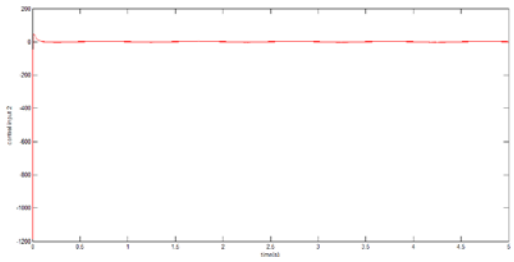

Fig.4 Control input of 2th link

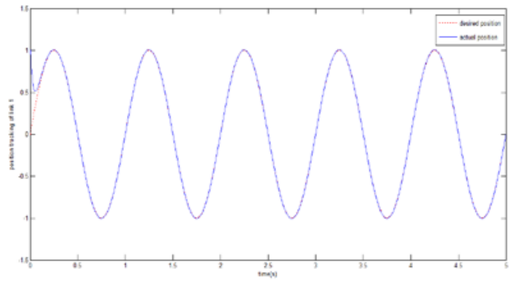

Fig.5 Response of the angle q_1

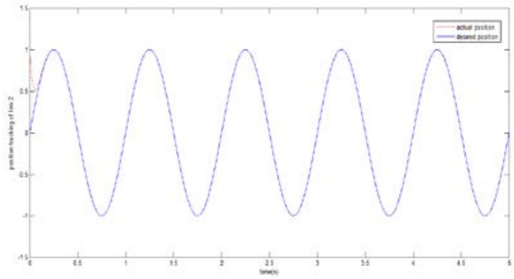

Fig.6 Response of the angle q_2

4、Conclusions

In this paper, an adaptive fuzzy control algorithm combining backstepping control algorithm is proposed for the two-link robot manipulator. Based on the above control algorithm, the robust tracking performance of the two-link robot manipulator can be guaranteed without needing an accurate robot model. The simulation results show that the adaptive controller can achieve desired performance and the algorithm is suitable for an inaccurate robot system. Simulation results also show the precise angle control, which is obtained in spite of disturbance and uncertainties in the system. These results also prove that the proposed control schemes are effective for the two-link robot manipulator.

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