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FUZZY SLIDING MODE CONTROL SCHEME FOR UNCERTAIN TWO-DEGREE OF FREEDOM POLAR ROBOT

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Abstract. *This paper proposes a new fuzzy sliding mode control scheme for uncertain two-degree of freedom polar robot system. Based on the proposed sliding mode control scheme, the stability of the closed-loop system is established. The designed controller can drive the polar robot system to the desired state. The corresponding numerical simulations are demonstrated to verify the effectiveness of the proposed method.*
Keywords: Freedom polar robot, Sliding mode control, Stability, Fuzzy control

1. Introduction.

Recently, many researchers are interested in the stabilization problem for robot manipulators systems. However, the control of these systems, which have the characteristics of parameter inaccuracy, unknown external disturbances, as well as time varying has been a serious challenge to the control community. In recent years, there are many robust control techniques to tackle this problem, such as backstepping control [1], sliding mode control [2-7], adaptive control [8,9], fractional-order control [10] and fuzzy control [11].

Recently, Faieghi et al. [4] proposed an adaptive control scheme for robotic manipulators with unknown uncertainties and disturbances. Meanwhile, they found appropriate values for the controller parameters by using particle swarm optimization (PSO). In [5], Yang et al. proposed a high-order sliding mode control scheme for two-degree of freedom polar robot with unknown disturbance. It is emphasized two main advantages of the sliding mode control method: (1) the dynamic behavior of the system may be tailored by the particular choice of switching functions and (2) the closed-loop response becomes totally insensitive to a particular class of uncertainty. In addition, the ability to specify performance directly makes sliding mode control attractive from the design perspective. Fuzzy logic control has undergone rapid development. It has been proven that fuzzy logic can approximate any nonlinear function to any desired accuracy because of the universal approximation theorem. Fuzzy control schemes have been found to be particularly useful to model unknown functions in nonlinear systems rather than only unknown parameters. There have been significant research efforts on adaptive fuzzy control for nonlinear systems. Compared with related works, there are three main contributions that are worth to be emphasized:

(1) Compared with the results in [5], the uncertain two-degree of freedom polar robot system with unknown control gains is considered.

(2) Avoid the calculate of the inverse operation for unknown control gains in the control design.

(3) An adaptation law is proposed to update the fuzzy parameters.

The multiple advantages of this approach include its large set of globally and asymptotically stabilizing control laws and its capability to improve robustness and solve adaptive problems.

Thus, the research on higher-order sliding mode control scheme for two-degree of freedom polar robot is an interesting and challenging problem. The major contribution of this paper is that a high-order sliding mode control scheme incorporating backstepping technique is proposed to stabilize two-degree of freedom polar robot with unknown external disturbance.

The organization of this paper is described as follows. In the next section, system model is derived, and the problem statement is also given. By using Lyapunov stability theory, we design an adaptive fuzzy sliding mode controller in Section 3. The main results are analyzed in Section 4. The simulation results are presented to demonstrate the effectiveness of the proposed control scheme in Section 5. Conclusion is presented in Section 6.

2. **Problem Formulation and Preliminaries.** As shown in Figure 1, a two-degree of freedom polar robot manipulator has one rotational and sliding joint in the (x, y) plane. Neglecting the gravity force and normalizing the mass and length of the arm, a mathematical model of two-degree of freedom polar robot can be expressed as follows

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = \dfrac{[\mu x_1 + M(x_1 + a)]x_4^2 + u_1 + d_1(t, x)}{\mu + M}, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = \dfrac{-2[M(x_1 + a) + \mu x_1]x_2 x_4 + u_2 + d_2(t, x)}{J_1 + J_2 + \mu x_1^2 + M(x_1 + a)^2}, \end{cases} \tag{1}$$

where $x = [x_1, x_2, x_3, x_4]^T$ is the state vector, where x_1 is the position of the center arm, x_2 is center arm speed, x_3 is angular position of the arm, x_4 is angular velocity of the arm, μ is the mass of motional link, M is the payload, and J_1 and J_2 are moments of inertia of the motional link with respect to the vertical axis through c and o, respectively. $d_i(t, x)$ is an unknown external disturbance.

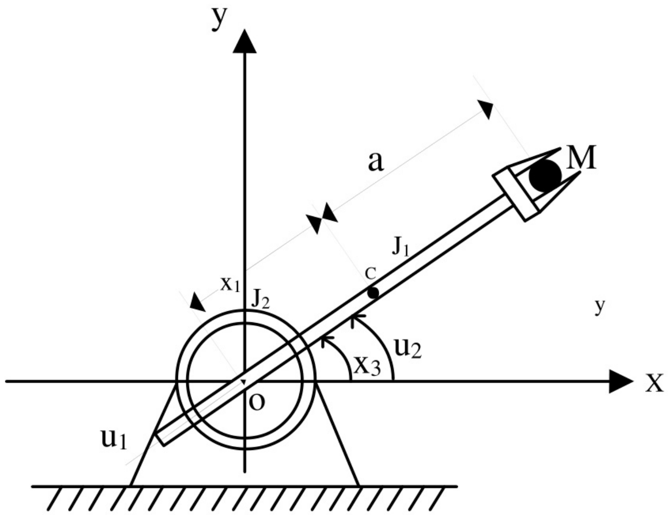

FIGURE 1. A two-degree of freedom polar robot manipulator

Assumption 2.1. *The disturbance $d_i(t, x)$ is bounded, $i = 1, 2$.*

We rewrite the system (1) as

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = f_1(t, x) + g_1(t, x)u_1, \\ \dot{x}_3 = x_4, \\ \dot{x}_4 = f_2(t, x) + g_2(t, x)u_2, \end{cases} \tag{2}$$

where $f_1(t,x) = \frac{[\mu x_1+M(x_1+a)]x_4^2+d_1}{\mu+M}$, $g_1(t,x) = \frac{1}{\mu+M}$, $f_2(t,x) = \frac{-2(M(x_1+a)+\mu x_1)x_2+x_4+d_2}{J_1+J_2+\mu x_1^2+M(x_1+a)^2}$, $g_2(t,x) = \frac{1}{J_1+J_2+\mu x_1^2+M(x_1+a)^2}$. *Obviously,* $g_i(t,x) > 0$, $i = 1, 2$.

Assumption 2.2. *Nonlinear function* $f_i(t,x)$ *and* $g_i(t,x)$ *are unknown but bounded.*

Duo to the fact that $f_i(t,x)$ *and* $g_i(t,x)$ *are unknown in (2), we use fuzzy logic system to approximate the unknown functions.*

3. **Fuzzy Logic Systems.** The basic configuration of a fuzzy logic system consists of a fuzzifier, some fuzzy IF-THEN rules, a fuzzy inference engine and a defuzzifier. The fuzzy inference engine uses the fuzzy IF-THEN rules to perform a mapping from an input vector $x = [x_1, x_2, \cdots, x_n]^T \in R^n$ to an output $\alpha(x) \in R$. The ith fuzzy rule is written as

Rule i: if x_1 is F_1^i and $\cdots$ and x_n is F_n^i then $\alpha(x)$ is α_i.

where $F_1^i, F_2^i, \cdots$ and F_n^i are fuzzy sets and α_i is the fuzzy singleton for the output in the ith rule. By using the singleton fuzzifier, product inference, and the center-average defuzzifier, the output of the fuzzy system can be expressed as follows:

$$\alpha(x) = \frac{\sum_{j=1}^N \alpha_j \prod_{i=1}^n \mu_{F_i^j}(x_i)}{\sum_{j=1}^N \left[\prod_{i=1}^n \mu_{F_i^j}(x_i)\right]} = \theta^T \psi(x),$$

where $\mu_{F_i^j}(x_i)$ is the degree of membership of x_i to F_i^j, N is the number of fuzzy rules, $\theta = [\alpha_1, \cdots, \alpha_N]^T$ is the adjustable parameter vector, and $\psi(x) = [p_1(x), p_2(x), \cdots, p_N(x)]^T$, where

$$p_j(x) = \frac{\prod_{i=1}^n \mu_{F_i^j}(x_i)}{\sum_{j=1}^N \left[\prod_{i=1}^n \mu_{F_i^j}(x_i)\right]}$$

is the fuzzy basis function. It is assumed that fuzzy basis functions are selected so that there is always at least one active rule.

4. **Main Results.** In this paper, the control objective is to make the states x_1 and x_3 of the system (1) to track the desired command x_{d1} and x_{d3}, respectively. The tracking error is defined as follows:

$$e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} x_1 - x_{d1} \\ x_3 - x_{d3} \end{bmatrix}. \quad (3)$$

The tracking error dynamics is driven directly by substituting (1) in (2):

$$\begin{cases} \dot{e}_1 = e_3, \\ \dot{e}_3 = f_1(t,x) + g_1(t,x)u_1 - \ddot{x}_{d1}, \\ \dot{e}_2 = e_4, \\ \dot{e}_4 = f_2(t,x) + g_2(t,x)u_2 - \ddot{x}_{d2}, \end{cases} \quad (4)$$

where $e_3 = x_2 - \dot{x}_{d1}$, $e_4 = x_4 - \dot{x}_{d2}$.

Define the sliding surface s as

$$s = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} e_3 + \lambda_1 e_1 \\ e_4 + \lambda_2 e_2 \end{bmatrix}, \quad (5)$$

where λ_1, λ_2 are positive constants.

By applying the introduced fuzzy systems, approximation of function $f_i(t,x)$ and $g_i(t,x)$ $(i = 1, 2)$ can be expressed as follows:

$$\hat{f}_i(x, \theta_{f_i}) = \theta_{f_i}^T \psi_{f_i}(x), \quad \hat{g}_i(x, \theta_{g_i}) = \theta_{g_i}^T \psi_{g_i}(x), \quad i = 1, 2. \quad (6)$$

Optimal parameters $\theta_{f_i}^*$ and $\theta_{g_i}^*$ can be defined such that

$$\theta_{f_i}^* = \arg\min_{\theta_i} \left[\sup \left|f_i(t,x) - \hat{f}_i(t,x)\right|\right], \quad \theta_{g_i}^* = \arg\min_{\theta_i} \left[\sup \left|g_i(t,x) - \hat{g}_i(t,x)\right|\right], \quad (7)$$

$i = 1, 2$. Defining the parameter estimation errors and the fuzzy approximation errors as follows:

$$\tilde{\theta}_{f_i} = \theta_{f_i} - \theta^*_{f_i}, \quad \tilde{\theta}_{g_i} = \theta_{g_i} - \theta^*_{g_i}, \tag{8}$$

and

$$\varepsilon_{f_i}(x) = f_i(t,x) - f_i(x, \theta^*_{f_i}), \quad \varepsilon_{g_i}(x) = g_i(t,x) - g_i(x, \theta^*_{g_i}). \tag{9}$$

For fuzzy approximation errors $\varepsilon_{f_i}(x)$ and $\varepsilon_{g_i}(x)$, there exist unknown constants ε_{1i} and ε_{2i} such that $|\varepsilon_{f_i}| \leq \varepsilon_{1i}$, $|\varepsilon_{g_i}| \leq \varepsilon_{2i}$, $i = 1, 2$.

The controller can be constructed as follows.

Theorem 4.1. *Consider the system (4). If the sliding mode surface s is selected as (5), u_1, u_2 are designed as follows:*

$$\begin{cases} u_1 = s_1 \bar{u}_1 = s_1 \dfrac{s_1 \hat{f}_1(x, \theta_{f_1}) + \lambda_1 s_1 e_3 + k_1 s_1^2 + \bar{\bar{u}}_1 - s_1 \ddot{x}_{d1}}{-s_1^2 \hat{g}_1(x, \theta_{g_1}) + \mu_1 s_1^2 + \bar{\bar{u}}_1^2}, \\ u_2 = s_2 \bar{u}_2 = s_2 \dfrac{s_2 \hat{f}_2(x, \theta_{f_2}) + \lambda_2 s_2 e_4 + k_2 s_2^2 + \bar{\bar{u}}_2 - s_2 \ddot{x}_{d2}}{-s_2^2 \hat{g}_2(x, \theta_{g_2}) + \mu_2 s_2^2 + \bar{\bar{u}}_2^2}, \end{cases} \tag{10}$$

where $k_1, k_2 > 0$, $\mu_i = \nu + |\hat{g}_i(x, \theta_{g_i})|$, ν is a small given positive constant, $i = 1, 2$. And $\bar{\bar{u}}_1$ and $\bar{\bar{u}}_2$ are designed as

$$\begin{cases} \dot{\bar{\bar{u}}}_1 = 1 - \bar{u}_1 \bar{\bar{u}}_1 - \dfrac{\bar{\bar{u}}_1 \left(|s_1| \hat{\varepsilon}_{11} + s_1^2 \left(\hat{\varepsilon}_{21} + \mu_1 \right) |\bar{u}_1| \right)}{\bar{\bar{u}}_1^2 + \alpha_1^2}, \\ \dot{\bar{\bar{u}}}_2 = 1 - \bar{u}_2 \bar{\bar{u}}_2 - \dfrac{\bar{\bar{u}}_2 \left(|s_2| \hat{\varepsilon}_{12} + s_2^2 \left(\hat{\varepsilon}_{22} + \mu_2 \right) |\bar{u}_2| \right)}{\bar{\bar{u}}_2^2 + \alpha_2^2}, \end{cases} \tag{11}$$

with

$$\begin{cases} \dot{\alpha}_1 = - \dfrac{\alpha_1 \left(|s_1| \hat{\varepsilon}_{11} + s_1^2 \left(\hat{\varepsilon}_{21} + \mu_1 \right) |\bar{u}_1| \right)}{\bar{\bar{u}}_1^2 + \alpha_1^2}, \\ \dot{\alpha}_2 = - \dfrac{\alpha_2 \left(|s_2| \hat{\varepsilon}_{12} + s_2^2 \left(\hat{\varepsilon}_{22} + \mu_2 \right) |\bar{u}_2| \right)}{\bar{\bar{u}}_2^2 + \alpha_2^2}, \end{cases} \tag{12}$$

where $\bar{\bar{u}}_1(0)$, $\bar{\bar{u}}_2(0) \neq 0$, and $\hat{\varepsilon}_{1i}$ and $\hat{\varepsilon}_{2i}$ are the estimates of ε_{1i} and ε_{2i}, respectively. And we choose adaptive laws:

$$\begin{cases} \dot{\theta}_{f_i} = \gamma_{f_i} s_i \psi_{f_i}, \\ \dot{\theta}_{g_i} = \gamma_{g_i} s_i^2 \psi_{f_i} \bar{u}_i \\ \dot{\hat{\varepsilon}}_{1i} = |s_i|, \\ \dot{\hat{\varepsilon}}_{2i} = s_i^2 |\bar{u}_i|, \quad i = 1, 2, \end{cases} \tag{13}$$

where $\gamma_{f_i}, \gamma_{g_i} > 0$, $i = 1, 2$. Then, all signals in the closed-loop system are bounded and that the tracking errors converge asymptotically to zero.

Proof: Let $\tilde{\theta}_{f_i} = \theta^*_{f_i} - \theta_{f_i}$, $\tilde{\theta}_{g_i} = \theta^*_{g_i} - \theta_{g_i}$, $\tilde{\varepsilon}_{1i} = \hat{\varepsilon}_{1i} - \varepsilon_{1i}$, $\tilde{\varepsilon}_{2i} = \hat{\varepsilon}_{2i} - \varepsilon_{2i}$, $i = 1, 2$. Consider the Lyapunov function as $V_1 = V_1 + V_2$, where

$$V_1 = \frac{1}{2} \left[s^T s + \sum_{i=1}^{2} \frac{1}{\gamma_{f_i}} \tilde{\theta}_{f_i}^T \tilde{\theta}_{f_i} + \sum_{i=1}^{2} \frac{1}{\gamma_{g_i}} \tilde{\theta}_{g_i}^T \tilde{\theta}_{g_i} \right], \tag{14}$$

$$V_2 = \frac{1}{2} \left[\sum_{i=1}^{2} \tilde{\varepsilon}_{1i}^2 + \sum_{i=1}^{2} \tilde{\varepsilon}_{2i}^2 + \sum_{i=1}^{2} \bar{\bar{u}}_i^2 + \sum_{i=1}^{2} \alpha_i^2 \right]. \tag{15}$$

The time derivative of V_1 is

$$\begin{aligned}\dot{V}_1 &= \sum_{i=1}^{2}\left[s_i\dot{s}_i - \tilde{\theta}_{f_i}^T\dot{\theta}_{f_i} - \tilde{\theta}_{g_i}^T\dot{\theta}_{g_i}\right] \\ &= \sum_{i=1}^{2}\Big[-k_is_i^2 + s_i(f_i(t,x) - \hat{f}_i(x,\theta_{f_i})) + s_i^2(g_i(t,x) - \hat{g}_i(x,\theta_{g_i}))\bar{u}_i \\ &\quad + \mu_is_i^2\bar{u}_i - \bar{\bar{u}}_i + \bar{u}_i\bar{\bar{u}}_i^2 - \tilde{\theta}_{f_i}^T\dot{\theta}_{f_i} - \tilde{\theta}_{g_i}^T\dot{\theta}_{g_i}\Big] \\ &= \sum_{i=1}^{2}\Big[-k_is_i^2 + s_i\tilde{\theta}_{f_i}^T\psi_{f_i} + s_i^2\tilde{\theta}_{g_i}^T\psi_{g_i}\bar{u}_i + \mu_is_i^2\bar{u}_i - \bar{\bar{u}}_i + \varepsilon_{f_i}s_i + s_i^2\varepsilon_{g_i}\bar{u}_i \\ &\quad + \bar{u}_i\bar{\bar{u}}_i^2 - \tilde{\theta}_{f_i}^T\dot{\theta}_{f_i} - \tilde{\theta}_{g_i}^T\dot{\theta}_{g_i}\Big].\end{aligned} \tag{16}$$

Substituting the adaptive laws (13) into (16), one gets

$$\begin{aligned}\dot{V}_1 &= \sum_{i=1}^{2}\Big[-k_is_i^2 + \mu_is_i^2\bar{u}_i - \bar{\bar{u}}_i + \varepsilon_{f_i}s_i + s_i^2\varepsilon_{g_i}\bar{u}_i + \bar{u}_i\bar{\bar{u}}_i^2\Big] \\ &\le \sum_{i=1}^{2}\Big[-k_is_i^2 + \mu_is_i^2\bar{u}_i - \bar{\bar{u}}_i + \varepsilon_{1i}|s_i| + s_i^2\varepsilon_{2i}|\bar{u}_i| + \bar{u}_i\bar{\bar{u}}_i^2\Big].\end{aligned} \tag{17}$$

The time derivative of V_2 is

$$\begin{aligned}\dot{V}_2 &= \sum_{i=1}^{2}\left[\tilde{\varepsilon}_{1i}\dot{\hat{\varepsilon}}_{1i} + \tilde{\varepsilon}_{2i}\dot{\hat{\varepsilon}}_{2i} + \bar{\bar{u}}_i\dot{\bar{\bar{u}}}_i + \alpha_i\dot{\alpha}_i\right] \\ &= \sum_{i=1}^{2}\left[|s_i|\tilde{\varepsilon}_{1i} + s_i^2|\bar{u}_i|\tilde{\varepsilon}_{2i} + \bar{\bar{u}}_i\left[1 - \bar{u}_i\bar{\bar{u}}_i - \frac{\bar{\bar{u}}_i\left(|s_i|\hat{\varepsilon}_{1i} + s_i^2\left(\hat{\varepsilon}_{2i} + \mu_i\right)|\bar{u}_i|\right)}{\bar{\bar{u}}_i^2 + \alpha_i^2}\right]\right. \\ &\quad \left. + \alpha_i\left[-\frac{\alpha_i\left(|s_i|\hat{\varepsilon}_{1i} + s_i^2\left(\hat{\varepsilon}_{2i} + \mu_i\right)|\bar{u}_i|\right)}{\bar{\bar{u}}_i^2 + \alpha_i^2}\right]\right] \\ &= \sum_{i=1}^{2}\Big[-|s_i|\varepsilon_{1i} - s_i^2|\bar{u}_i|\varepsilon_{2i} + \bar{\bar{u}}_i - \bar{u}_i\bar{\bar{u}}_i^2 - \mu_is_i^2|u_i|\Big].\end{aligned} \tag{18}$$

Using (17) and (18), one obtains

$$\dot{V} = \dot{V}_1 + \dot{V}_2 \le -\sum_{i=1}^{2}k_is_i^2. \tag{19}$$

From (19), it is concluded that the signals s_i, θ_{f_i}, θ_{g_i}, $\hat{\varepsilon}_{1i}$, $\hat{\varepsilon}_{2i}$ are bounded. Integrating both sides of (19), one gets

$$\int_0^t\sum_{i=1}^{2}k_is_i^2\mathrm{d}\tau \le V(0) - V(t).$$

This implies $s_i \in L_2$ and $\dot{s}_i \in L_\infty$, by using Babalat's Lemma [11], it is concluded that $\lim_{t\to\infty} s_i(t) = 0$ which implies that the tracking errors converge asymptotically to zero. This completes the proof.

5. **Simulation Studies.** This section describes the numerical simulations performed to validate the above control law design. We define seven Gaussian membership functions uniformly distributed on the interval $[-10, 10]$. We choose the initial values of parameters of the fuzzy systems as $\theta_{f_i} = \theta_{g_i} = 0$, $i = 1, 2$. The other parameters are chosen as $\gamma_{f_1} = \gamma_{g_i} = k_i = 2$, $\nu = 0.1$, $i = 1, 2$, $\lambda_1 = \lambda_2 = 3$, $d_1 = 0.5\sin(x_1)$, $d_2(t) = 0.5\cos(x_3)$,

$M = 1.5$kg, $\mu = 1$kg, $J_1 = J_2 = 1$kg·m^2 and $a = 1$m. Initial conditions are set as follows: $[x_1(0), x_2(0), x_3(0), x_4(0)]^T = [-0.2, -0.25, 3.6, 0.98]^T$, $\bar{\bar{u}}_1(0) = \bar{\bar{u}}_2(0) = 0.5$. Desired trajectories are:

$$x_{d1} = 0.5\cos\left(\frac{\pi t}{7}\right) m, \quad x_{d3} = \pi\cos\left(\frac{\pi t}{7}\right) rad.$$

The states of system (4) under the proposed control scheme (10)-(13) are shown in Figures 2 and 3. One can see the states x_1 and x_3 are fast driven to x_{d1} and x_{d3}, respectively. Obviously, the numerical simulations verify the theoretical analysis.

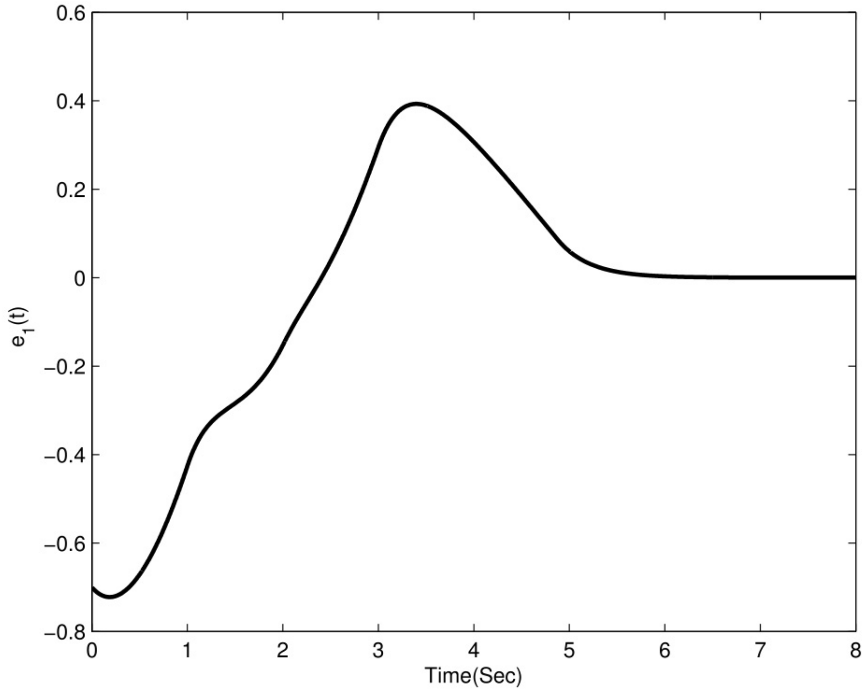

FIGURE 2. Response of e_1 under the proposed control scheme (10)-(13)

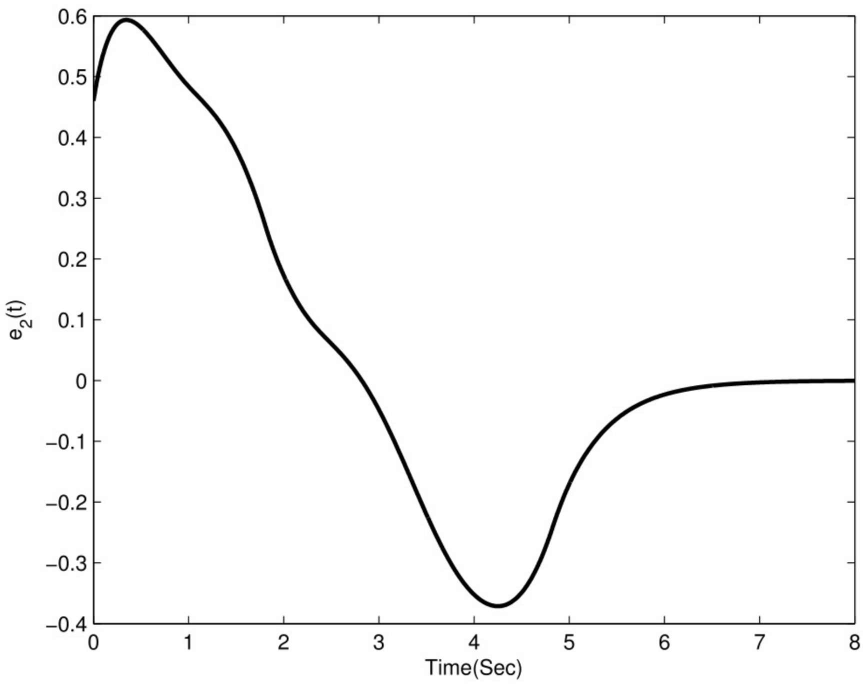

FIGURE 3. Response of e_2 under the proposed control scheme (10)-(13)

6. **Conclusion.** In this paper, we address the problem of adaptive fuzzy feedback control problem for uncertain two-degree of freedom polar robot system. In control design, the fuzzy logic systems are used to identify the unknown nonlinear functions. By using the sliding mode control technique, the present control approach has been developed and the stability of the closed-loop system has been proved. Simulation results have shown the effectiveness of the proposed scheme. Fuzzy adaptive prescribed performance control for uncertain two-degree of freedom polar robot is our next research direction.

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