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Decentralized Adaptive fuzzy sliding mode control of Robot Manipulator

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ABSTRACT

Robot manipulator has highly nonlinear dynamics. Therefore the control of multi-link robot arms is a challenging and difficult problem. In this paper a decentralized adaptive fuzzy sliding mode scheme is developed for control of robot manipulators. The proposed scheme does not require an accurate manipulator dynamic model, yet it guarantees asymptotic trajectory tracking despite gross robot parameter variations. Numerical simulation for decentralized control of a 3-axis PUMA arm will also be included.

Keywords : Fuzzy control, adaptive control, decentralized control, sliding mode control, robot control

1. Introduction

Many researchers have considered the problem of designing advanced control of robot manipulator in the last decade. One of the interesting schemes is decentralization of the system, indicating that this method is very useful for large-scale system control. Due to the physical configuration and high dimensionality of robot manipulator a centralized control may not be economically feasible. It is very hard to implement in real time for control of multi-link manipulator with a fuzzy controller. The number of fuzzy rules grows exponentially in case of increasing the input variables.

In order to overcome the problems, the decentralized control scheme is still adopted by the majority of modern robots in favor of its computational simplicity. Therefore decentralized control of manipulator has been attracted some attention (1-9).

Recently, several researchers have combined three concepts of fuzzy logic, sliding mode control, and adaptive control. In this combination, the universal approximating capability and learning ability of fuzzy logic system. The adaptation capability of adaptive control and the disturbance rejection of sliding mode control are collected in one control strategy, namely adaptive fuzzy sliding mode control.

The fuzzy logic has been shown to be a powerful technique in integrating human knowledge and intuition for control of complex systems. Wang (10) introduced the concept of fuzzy basis functions and used the mathematical framework for stability analysis of adaptive fuzzy controllers for nonlinear systems. Others to derive rigorous stability results for fuzzy systems later used this mathematical representation of fuzzy rule-sets. The logic systems are capable of uniformly approximating any nonlinear function over compact input space to any degree of accuracy. Jin (11) developed a decentralized adaptive fuzzy control scheme for robot manipulators via a combination of genetic algorithm and gradient method. Zhang and Feng(12) proposed a decentralized adaptive fuzzy control scheme based on the principle of sliding mode control and fuzzy set theory. The decentralized fuzzy systems are used to approximate adaptively the controlled process. Lo and Kuo(13) presented a decoupling method which provides a simple way to achieve asymptotic stability for a class of fourth-order nonlinear system with only five fuzzy control rules.

In this paper we have combined four concepts of decentralized scheme, fuzzy logic, sliding mode control, and adaptive control. Under normal applications of fuzzy sliding mode control, the presence of system disturbances may result in steady state error since the error vector is deviated from the sliding surface. This paper presents a new approach to decentralized adaptive fuzzy sliding mode control of a robot manipulator with more robustness to system disturbances. The proposed control scheme does not require an accurate mathematical model of the system. It incorporates an integral term in the sliding surface, which eliminates steady state error. The feedback-controlled loop is guaranteed to be stable. The feedback derivative term is added so that the differentiation of the Lyapunov function is assured negative definite. As a result, asymptotic stability is proven. The paper is organized as follows. In section 2, the basic configuration of fuzzy logic systems is described [10]. Section 3 illustrates the proposed decentralized scheme and derives adaptive fuzzy sliding mode control law as applied to control of a robot manipulator. Numerical simulation for a 3-axis PUMA arm will be included.

2. Fuzzy Logic Systems and Fuzzy Basis Function

A fuzzy logic knowledge base consists of a set of fuzzy IF-THEN rules which themselves consist of a set of linguistic variables associated with inputs and outputs and fuzzy operators such as AND and OR. Since a multi-output system can always be separated into a group of single output systems, without loss of generality, let's consider a Multi-Input Single-Output (MISO) rule structure such as below,

$$R^{(l)}: \text{IF } x_1 \text{ is } A_1^l \text{ and } \cdots \text{ and } x_n \text{ is } A_n^l, \text{ THEN } y \text{ is } B^l \quad (1)$$

where $x=(x_1,\cdots,x_n)^T \in V \subset R^n$ is compact and $y \in W \subset R$ represent the linguistic inputs and output of the fuzzy logic system respectively. A_i^l and B^l are labels of the fuzzy sets in V and W respectively. $i=1,2,\cdots,n$ corresponds to the input number where n is the number of inputs, and $l=1,2,\cdots,m$ corresponds to the rule number where m is the number of rules.

There are many alternatives to implementation of fuzzy rules. In this paper, the product form of t-norm fuzzy implication is used.

$$A_1^l \times A_2^l \times \cdots \times A_n^l \rightarrow B^l \qquad (2)$$

and

$$\mu_{A_1^l \times \cdots \times A_n^l \rightarrow B^l}(\underline{x}, y) = \mu_{A_1^l}(x_1) \star \cdots \star \mu_{A_n^l}(x_n) \star \mu_{B^l}(y) \qquad (3)$$

where $\star$ denotes the t-norm product operator and corresponds to the conjunction "and" in the linguistic rule-representation.

Let A_x be an arbitrary fuzzy set in V, then each fuzzy rule determines a fuzzy set, $A_x \circ R^{(l)}$, in R based on the following sup-star compositional rule of inference,

$$\mu_{A_x \circ R^{(l)}}(y) = \sup_{x \in U}[\mu_{A_x}(\underline{x}) \star \mu_{A_1^l \times \cdots \times A_n^l \rightarrow B^l}(\underline{x}, y)] \qquad (4)$$

All m fuzzy rules are then combined to determine a final fuzzy through the fuzzy disjunction:

$$\mu_{A_x \circ (R^{(1)},\cdots,R^{(m)})}(y) = \mu_{A_x \circ R^{(1)}}(y) \dot{+} \cdots \dot{+} \mu_{A_n \circ R^{(m)}}(y) \qquad (5)$$

where $\dot{+}$ denotes the t-conorm, which is commonly, defined as fuzzy union, algebraic sum, or bounded sum. In this paper, however, the center-average defuzzifier is used to aggregate rules. The center-average-defuzzifier is defined as

$$y^* = \frac{\sum_{l=1}^{m} \bar{y}^l (\mu_{A_x \circ R^{(l)}}(\bar{y}^l))}{\sum_{l=1}^{m} (\mu_{A_x \circ R^{(l)}}(\bar{y}^l))} \qquad (6)$$

where $\bar{y}^l$ is the point in the R at which $\mu_{B^l}(y)$ achieves its maximum value (assume that $\mu_{B^l}(\bar{y}^l)=1$). In [10], it is shown that using center-average-defuzzifier, product inference, and singleton defuzzifier, the above equation reduces to,

$$y^* = f(x) = \frac{\sum_{l=1}^{m} \bar{y}^l (\prod_{i=1}^{n} \mu_{A_i^l}(x_i))}{\sum_{l=1}^{m} (\prod_{i=1}^{n} \mu_{A_i^l}(x_i))} \qquad (7)$$

If we fix the $\mu_{A_i^l}(x_i)$'s and view the $\bar{y}^l$'s as adjustable parameters, then eq.(7) can be written as

$$f(x) = \varphi^T \xi(\underline{x}) \tag{8}$$

where $\varphi = (\bar{y}^1, \cdots, \bar{y}^m)^T$ is a parameter vector, and $\xi(\underline{x}) = (\xi^1(\underline{x}), \cdots, \xi^m(\underline{x}))^T$ is a regressive vector with the regressor $\xi^l(\underline{x})$ defined as

$$\xi^l(\underline{x}) = \frac{\prod_{i=1}^{n} \mu_{A_i^l}(x_i)}{\sum_{l=1}^{m}(\prod_{i=1}^{n} \mu_{A_i^l}(x_i))} \tag{9}$$

It has been proved [10,14] that fuzzy logic system in the form of eq.(7) is universal approximators. So the above fuzzy logic system is capable of uniformly approximating any nonlinear function over compact input space to any degree of accuracy.

3. Design of Adaptive Fuzzy Independent Joint Controller

In general, the Lagrange-Euler equations of motion for an n-degree of freedom manipulator can be expressed in matrix vector notation as [6]

$$M(\theta)\ddot{\theta} + N(\theta, \dot{\theta}) + G(\theta) + H(\dot{\theta}) = \tau \tag{10}$$

where $\theta(t)$ is the $n \times 1$ vector of joint angular position, $\tau(t)$ is the $n \times 1$ applied torque vector, $G(\theta)$ is the $n \times 1$ gravity force vector, $M(\theta)$ is the $n \times n$ symmetric positive-definite inertia matrix, $N(\theta, \dot{\theta})$ is the $n \times 1$ coriolis and centrifugal force vector, and $H(\dot{\theta})$ is the $n \times 1$ frictional force vector. The elements of $M(\theta)$, $N(\theta, \dot{\theta})$, $G(\theta)$, and $H(\dot{\theta})$ are highly coupled nonlinear functions of $\theta(t)$ and $\dot{\theta}(t)$.

The manipulator dynamic model (10) shows strong interactions between joint motions. The coriolis and centrifugal forces are particularly important when the manipulator is moving at high speed. The manipulator control problem is to improve a control method which generates the joint torque vector $\tau(t)$ such that the joint angle vector $\theta(t)$ tracks the $n \times 1$ desired trajectory vector $\theta_d(t)$ as closely as possible. Multi-Link robotic system can be viewed as a large-scale system consists of several subsystems where each subsystem is a joint interconnected to other subsystem by "coupling forces". These coupling forces account for the inertial coupling terms and the coriolis, centrifugal, friction, and gravity terms in (10). Therefore the manipulator dynamic model (10) can be described by a collection of n second-order nonlinear scalar differential equations

$$m_{ii}(\theta)\ddot{\theta}_i(t) + \sum_{\substack{j=1 \\ j\neq i}}^{n} m_{ij}(\theta)\ddot{\theta}_j(t) + n_i(\theta, \dot{\theta}) + g_i(\theta) + h_i(\dot{\theta}) = \tau_i$$

$$i = 1, 2, \cdots, n \tag{11}$$

Due to the positive-definiteness of inertia matrix $M(\theta)$, $m_{ii}(\theta)$ is always positive, and is the time varying effective inertia seen at the ith joint.

As a consequence, eq.(11) can be written as

$$m_{ii}(\theta)\ddot{\theta}_i(t) + d_i(\theta, \dot{\theta}, \ddot{\theta}) = \tau_i(t) \tag{12}$$

$$i = 1, 2, \cdots, n$$

where

$$d_i(\theta, \dot{\theta}, \ddot{\theta}) = \sum_{\substack{j=1 \\ j\neq i}}^{n} m_{ij}(\theta)\ddot{\theta}_j(t) + n_i(\theta, \dot{\theta}) + g_i(\theta) + h_i(\dot{\theta}) \tag{13}$$

Eq.(12) is the input-output dynamic model of the ith subsystem with the joint torque $\tau_i(t)$. The term d_i is considered as a "disturbance torque" containing the gravity, friction, coriolis, and centrifugal torques for the ith joint. From this point, the term d_i represents the coupling between the ith subsystem and the remaining subsystems. So the joint control laws are restricted to be decentralized. The decentralized manipulator control problem is to design a set of independent joint controllers in which the ith controller generates the joint torque $\tau_i(t)$.

From eq.(12), we can rewrite as follows,

$$\begin{aligned} \ddot{\theta}_i &= -\frac{1}{m_{ii}(\theta)} d_i(\theta, \dot{\theta}, \ddot{\theta}) + \frac{1}{m_{ii}(\theta)} \tau_i(t) \\ &= f_i + b_i \tau_i, \qquad i = 1, 2, \cdots, n \end{aligned} \tag{14}$$

The function f_i is not exactly known. The control gain b_i is also unknown, but it is lower bounded by a known b_{il}, that is $0 < b_{il} \le b_i$, $b_i = b_{il} + \Delta b_i$.

Now, let $e_i(t) = \theta_i(t) - \theta_{d_i}(t)$ where $\theta_{d_i}(t)$ is the desired trajectory. Then the sliding surface may be defined by,

$$s_i(t) = \dot{e}_i(t) + k_{i1} e_i(t) + k_{i2} \upsilon_i(t) \tag{15}$$

where

$$\upsilon_i(t) = \int_0^t e_i(\tau)d\tau$$

$\upsilon_i(t)$ allows including an integration term to reduce steady state error. By taking a derivative of both sides of eq.(15),

$$\begin{aligned}\dot{s}_i(t) &= \ddot{e}_i(t) + k_{i1}\dot{e}(t) + k_{i2}\upsilon_i(t) \\ &= \ddot{\theta}_i(t) - \ddot{\theta}_{d_i}(t) + k_{i1}\dot{e}_i(t) + k_{i2}e_i(t) \\ &= f_i + b_i\tau_i - \ddot{\theta}_{d_i}(t) + k_{i1}\dot{e}_i(t) + k_{i2}e_i(t) \qquad (16)\end{aligned}$$

If the effective inertia $m_{ii}(\theta)$ and the disturbance torque $d_i(\theta,\dot{\theta},\ddot{\theta})$ are known, we can easily obtain the optimal sliding mode controller [15]. Due to the poor knowledge of f_i and b_i we replace f_i by the fuzzy logic system $\hat{f}_i(\theta \mid \varphi_i)$, which is in the form of eq.(8) and consider the term $k_{i3}\cdot\text{sgn}(s_i)$ to reduce the unknown disturbances. The resulting adaptive fuzzy sliding mode independent joint controller dedicated to the ith joint is as follows.

$$\begin{aligned}\tau_i(t) &= \frac{1}{b_{il}}[-\hat{f}_i(\theta \mid \varphi_i) \\ &+ \ddot{\theta}_{d_i}(t) - k_{i1}\dot{e}_i(t) - k_{i2}e_i(t) - k_{i3}\cdot\text{sgn}(s_i) - k_{i4}s_i] \qquad (17)\end{aligned}$$

where the term $k_{i4}s_i$ is added so that $\dot{v}(t)$ is assured more negative. Figure 1 illustrates a realization of the proposed adaptive fuzzy sliding mode control scheme for manipulator joint i. The term $k_{i3}\cdot\text{sgn}(s_i)$ gives rapid switching on the sliding surface. It depends on the sampling frequency. Each joint motor cause large chattering at this sampling frequency. In order to reduce the chattering, we use the technique that makes the term $\text{sgn}(s_i)$ continuous as follows,

$$\text{sgn}(s_i) \rightarrow \frac{s_i}{|s_i| + \delta_i} \qquad (18)$$

where $\delta_i > 0$

Substituting eq.(17) into eq.(16) yields,

$$\begin{aligned}\dot{s}_i(t) &= f_i - \hat{f}_i(\theta \mid \varphi_i) \\ &- k_{i4}s_i + \frac{\Delta b_i}{b_{il}}F_i - \frac{b_i}{b_{il}}k_{i3}\cdot\frac{s_i}{|s_i| + \delta_i} \qquad (19)\end{aligned}$$

where

$$\begin{aligned}F_i &= -f_i(\theta \mid \varphi_i) \\ &+ \ddot{\theta}_{d_i}(t) - k_{i1}\dot{e}_i(t) - k_{i2}e_i(t) - k_{i4}s_i \qquad (20)\end{aligned}$$

Define the minimum approximation error ω_i,

$$\omega_i = f_i - \hat{f}_i(\theta \mid \varphi_i^*) \qquad (21)$$

where φ_i^* is the optimal parameter vector of fuzzy logic system. Then,

$$\begin{aligned}\dot{s}_i(t) &= \hat{f}_i(\theta \mid \varphi_i^*) - \hat{f}_i(\theta \mid \varphi_i) \\ &+ \omega_i + \frac{\Delta b_i}{b_{il}}F_i - \frac{b_i}{b_{il}}k_{i3}\cdot\frac{s_i}{|s_i| + \delta_i} - k_{i4}s_i \qquad (22)\end{aligned}$$

If we choose $\hat{f}_i$ to be the fuzzy logic systems in the form of eq.(8), then it can be rewritten as

$$\begin{aligned}\dot{s}_i &= \phi_i^T\xi_i(\theta) + \omega_i \\ &+ \frac{\Delta b_i}{b_{il}}F_i - \frac{b_i}{b_{il}}k_{i3}\cdot\frac{s_i}{|s_i| + \delta_i} - k_{i4}s_i \qquad (23)\end{aligned}$$

where $\phi_i = \varphi_i^* - \varphi_i$, and $\xi_i(\theta)$ is the fuzzy basis function eq(9).

Let us now define the scalar positive-definite Lyapunov function,

$$v_i = \frac{1}{2}s_i^2 + \frac{1}{2r_i}\phi_i^T\phi_i \qquad (24)$$

where s_i is given by eq.(15) and r_i is a positive constant. Differentiating v_i along the sliding surface, we have

$$\begin{aligned}\dot{v}_i &= s_i\dot{s}_i + \frac{1}{r_i}\phi_i^T\phi_i \\ &= s_i[\phi_i^T\xi_i(\theta) + \omega_i + \frac{\Delta b_i}{b_{il}}F_i - \frac{b_i}{b_{il}}k_{i3}\cdot\frac{s_i}{|s_i| + \delta_i} - k_{i4}s_i] + \frac{1}{r_i}\phi_i^T\phi_i \\ &= \frac{1}{r_i}\phi_i^T[r_is_i\xi_i(\theta) - \dot{\varphi}_i] - \frac{1}{b_{il}}(k_{i3}b_i\frac{s_i^2}{|s_i| + \delta_i} - \Delta b_i\cdot s_i\cdot F_i - b_{il}\cdot s_i\cdot\omega_i) - k_{i4}s_i^2 \\ &\le \frac{1}{r_i}\phi_i^T[r_is_i\xi_i(\theta) - \dot{\varphi}_i] - \frac{1}{b_{il}}(k_{i3}b_i\frac{s_i^2}{|s_i| + \delta_i} - b_i|s_i\cdot F_i| - b_i|s_i\cdot\omega_i|) - k_{i4}s_i^2\end{aligned} \qquad (25)$$

Choose $k_{i3}(gain)$ and δ_i so that it satisfies the inequality,

$$k_{i3} \frac{s_i^2}{|s_i| + \delta_i} \rangle |s_i| (|F_i| + |\omega_i|) \quad (26)$$

then eq.(25) becomes

$$\dot{v}_i \langle \frac{1}{r_i} \phi_i^T (r_i s_i \xi_i(\theta) - \dot{\varphi}_i) - k_{i4} s_i^2 \quad (27)$$

The term $s_i\omega_i$ is of the order of minimum approximation error. Because of the universal approximation theorem [10], we can expect that ω_i should be small. If we choose the adaptive law,

$$\dot{\varphi}_i = r_i s_i \xi_i(\theta) \quad (28)$$

then we can always find positive constants k_{i3} satisfying the following equation as

$$\dot{v}_i \langle 0 \quad (29)$$

Using Barbalat's lemma [16], one can show that s_i converges to zero. From eq.(15), the convergence of s_i to zero implies that of the position tracking error e_i. So the controller ensures asymptotic stability of the ith local subsystem. To show global asymptotic stability, we combine the ith subsystem dynamics eq.(14) for $i = 1, 2, \cdots, n$ to obtain composite system and sum up the local Lyapunov function v_i of the individual subsystems to form the global Lyapunov function v. Since $v \rangle 0$ and $\dot{v} \langle 0$, we conclude that the composite system is globally asymptotically stable using the local adaptive fuzzy controllers.

4. Simulation Results

For the decentralized adaptive fuzzy sliding mode control derived in previous section, we investigate the performance of the system under practical environmental conditions in order to show the effectiveness of the proposed controllers. We consider the first three-link-joints (i.e., base, shoulder and elbow) of the PUMA arm. All joints are revolute with torque applied by actuators at each of the joints.

The dynamic model of three-link PUMA arm is simulated using MATLAB's command "ode 45" with a sampling period of 1ms. The parameters used in simulation are the following:

- The desired trajectory
  $\theta_{d_1}(t) = 0.15(0.8\pi t - \sin(0.8\pi t))$
  $\theta_{d_2}(t) = 0.15(-0.8\pi t + \sin(0.8\pi t))$
  $\theta_{d_3}(t) = 0.3(0.8\pi t - \sin(0.8\pi t))$
- $m_1 = 2.27kg$, $m_2 = 15.91kg$, $m_3 = 11.36kg$
- $k_{11} = 8$, $k_{12} = 20$, $k_{13} = 0.9$, $k_{14} = 1$
- $k_{21} = 8$, $k_{22} = 20$, $k_{23} = 0.5$, $k_{24} = 1$
- $k_{31} = 12$, $k_{32} = 40$, $k_{33} = 0.2$, $k_{34} = 1$
- $b_{il} = 2.2$, $b_{2l} = 3.2$, $b_{3l} = 0.3$
- $\delta_1 = 0.01$, $\delta_2 = 0.01$, $\delta_3 = 0.01$
- $r_1 = 100000$, $r_2 = 1000000$, $r_3 = 10000$

The two initial position of the 3-axis PUMA are given by $\theta = (0,0,0)$ and $\theta = (0.2, -0.2, 0.3)$. The desired task is to drive the robot manipulator in order to follow the reference trajectory. The results of this simulation are shown in Fig. 2 and 3, which shows that the joint angles $\theta_1(t)$, $\theta_2(t)$, and $\theta_3(t)$ have followed to their desired trajectory and indicate that the proposed controller is performing satisfactory. Fig. 4 shows the errors of joint angles of the robot manipulator. In order to see the effectiveness, the mass of the link have suddenly changed at t = 1.5 sec. In spite of these sudden changes in mass, the proposed fuzzy controller continues to perform very well and also show that it does not require an accurate manipulator dynamic model.

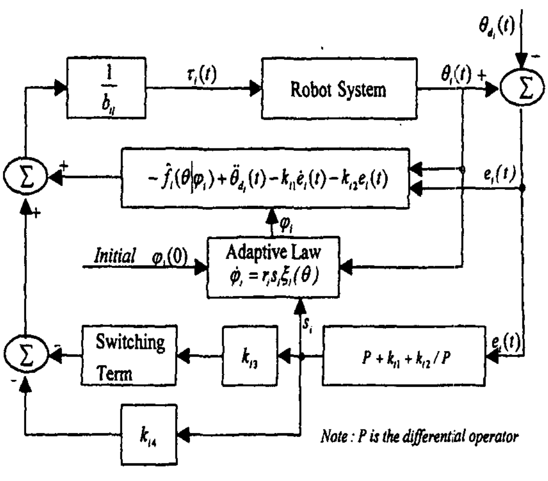

Fig. 1 Robot control system with decentralized adaptive fuzzy sliding mode controller.

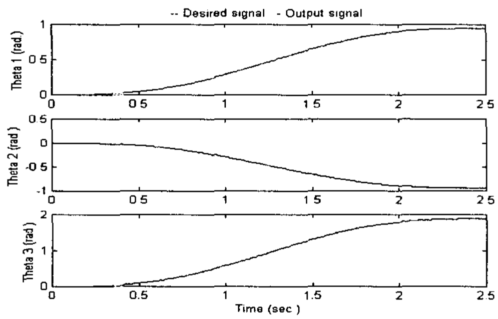

Fig. 2 Response of the joint angles with initial position (0, 0, 0)

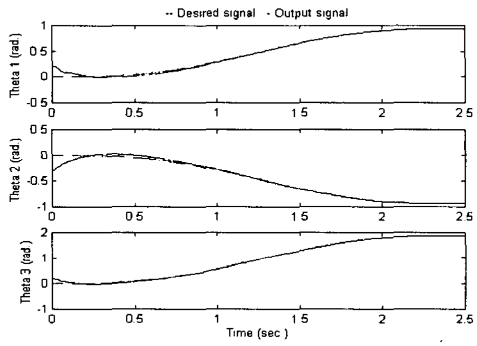

Fig. 3 Response of the joint angles with initial position (0.2 -0.3 0.2)

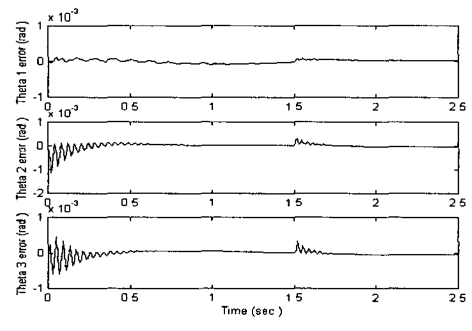

Fig. 4 Response the error of the joint angles with sudden load change at t=1.5 sec.

Conclusion

In this paper we considered the development of the independent joint controller for the robot manipulator. It was based on adaptive fuzzy sliding mode principle. The main point is that the independent joint control algorithm requires much less computation time than the single algorithm for the centralized control law. The reason is that the number of fuzzy rules grows exponentially in case of increasing the input variables for the centralized control law.

In addition, it incorporates an integral term in the sliding surface, which eliminates steady state error. The proposed control scheme does not require an accurate mathematical model of the system.

From the numerical simulation results, it is shown that the independent joint adaptive fuzzy sliding mode control result in a good performance moving the end effector of the robot manipulator along the desired trajectory.

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