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# Direct Adaptive Control of Robot Manipulator and Magnetic Ball Suspension System

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**ABSTRACT**: This paper presents an implementation of stable direct adaptive control on nonlinear systems using lyapunov function with fuzzy approach. Stable direct adaptive control law consists of an ideal control, and a sliding mode control. Sliding mode controller is used to ensure the stability of Lyapunov function. Stability of direct adaptive control law is tested on two nonlinear systems. Non linear systems analyzed are robot manipulator and magnetic ball suspension system. A computer simulation is performed on nonlinear systems by using MATLAB

**Keywords**: Fuzzy System, Lyapunov Function, Adaptive Control, Robot Manipulator, Magnetic Ball Suspension System**.**

## I. INTRODUCTION

A Fuzzy based mathematical model of a controller was described and designed with incorporation of Fuzzy Logic Controller (FLC) [1]. To test the performance of controller, a nonlinear system considered which was described by the least square identification method [2] and simulation studies were performed. It was observed that the performance of controller was robust for a wide range of operation and improved the system stability. Self tuning features [3] for both the data and the rule base can be designed by using FLC. The design of proportional derivative [4], linear quadratic and nonlinear controllers are based on differential geometric notions. Adaptive tracking control architecture for a class of continuous time nonlinear systems is performed for an explicit linear parameterization of the uncertainty in the dynamics is either unknown or impossible. The architecture of fuzzy systems, [5] expressed as a series expansion of basis functions. The controller output [6] has provided the result of applying fuzzy logic theory to manipulate the given set of control laws for nonlinear systems. The parameters of the membership functions in the fuzzy rule base [7] are changed according to adaptive algorithm for the purpose of controlling the system state in a user-defined sliding surface. The fuzzy sliding mode controller [8] efficiently controls most of the complex systems even though their mathematical models are unknown. The dynamic behavior of the controlled system can be approximately dominated by a fuzzified sliding surface. Fuzzy logic control and sliding mode control techniques have been integrated to develop a fuzzy sliding mode controller. A decentralized fuzzy logic controller [9] has been designed for large-scale nonlinear systems. An approximate method [10] is formulated for analyzing the performance of a broad class of linear and nonlinear systems controlled by using fuzzy logic. Decision rules can be automatically [11] generated for FLC to provide a stable closed loop system using Lyapunov function. Fuzzy logic system [12] that uses adaptive sliding mode control can approximate the unknown function of nonlinear systems. The FLC[13] which produces desirable transient performance for nonlinear systems which promises closed loop stability. An adaptive fuzzy control scheme [14] employs a fuzzy controller and a compensation controller for a class of nonlinear continuous systems. A stable fuzzy controller [15] has been synthesized in terms of Mamdani model to stabilize nonlinear systems. FLC [16] can control a cart balancing flexible pole under its first mode of vibration. Adaptive fuzzy logic controller [17] uses the uniform ultimate boundedness of the closed-loop signals for a class of discrete-time nonlinear systems. The overall system stability [18] governing the control of the plants has been put together into a rule base for the FLC. Design of FLC [19] for nonlinear systems with assured closed loop stability and its application on combining controller is based on heuristic fuzzy rules. Adaptive sliding mode schemes [20] along with fuzzy approximators are used to approximate the unknown function of nonlinear systems. The hybrid FLC [21] which is proportional plus conventional integral derivative controller is more effective in comparison with the conventional PID controller, when the controlled object operates under uncertainty or in the presence of a disturbance. A direct adaptive [22] FLC has been used for tracking a class of nonlinear dynamic systems. A nonlinear system [23] can be represented by Takagi-Sugeno FLC and it can be constructed by blending all local state feedback controllers with a sliding mode controller. A robust adaptive fuzzy

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controller [24] has been used for a class of nonlinear systems in the presence of dominant uncertainties. Fuzzy logic system can be used to compensate [25] the parametric uncertainties that has the capability to approximate any nonlinear function with the compact input space. Limit cycle of a system [26] can be controlled by a fuzzy logic controller via some of the classical control techniques used to analyze nonlinear systems in the frequency domain. An adaptive control scheme [27] with fuzzy logic control has been used for robot manipulator with parametric uncertainties. A model based fuzzy controller [28] can be used for a class of uncertain nonlinear systems to achieve a common observability. Exact fuzzy modeling and optimal control [29] has been used on inverted pendulum. The nonlinear fuzzy PID [30] controller has been applied successfully in control systems with various nonlinearities. The uncertain nonlinear system [31] has been represented by uncertain Takagi-Sugeno fuzzy model structure. Most of real word systems [32] have dynamic features, and these are also known as autoregressive dynamic fuzzy systems. A fuzzy variable structure controller [33] based on the principle of sliding mode variable control can be used both for the dynamic as well as static control properties of the system. Adaptive fuzzy sliding mode control scheme [34] incorporates the fuzzy logic into sliding mode control. The control algorithm [35] of robust controller for a nonlinear system is based on sliding mode incorporates a fuzzy tuning technique. Based on the Lyapunov approach [36], the adaptive laws and stability analysis can be used for a class of nonlinear uncertain systems. A neuro-fuzzy learning algorithm [37] has been applied to design a Takagi-Sugeno type FLC for a biped robot walking problem. In this paper we discussed the fuzzy logic control system in Section 2, the proposed stability design approach using Lyapunov Function in Section 3, dynamics of nonlinear systems in section 4 and simulation results in Section 5 are presented. Conclusion is given in Section 6 followed by References.

## II. TAKAGI-SUGENO FUZZY SYSTEMS

For the functional fuzzy system singleton fuzzification is used and the premise is defined the same as it is for the rule for the standard fuzzy system .The consequents of the rules are different, however instead of a linguistic term with an associated membership function, in the consequent a function $b_i = g_i(.)$ have been used that does not have an associated membership function. The argument of $g_i$ contains the fuzzy system inputs which are used in the premise of the rule.

R denote the number of rules .For the functional fuzzy system an appropriate operation for representing the premise and defuzzification is obtained as

$$y = \frac{\sum_{i=1}^{R} b_i \mu_i(z)}{\sum_{i=1}^{R} \mu_i(z)} \tag{1}$$

Where $\mu_i(z)$is the premise membership function.

$$b_i = g_i(.) = a_{i,0} + a_{i,1}u_1 + \cdots + a_{i,n}u_n \tag{2}$$

where $a_{i,j}$ is fixed real number .The functional fuzzy system is referred to as a"Takagi-Sugeno fuzzy system"..

A Takagi-Sugeno fuzzy system is given by

$$y = F_{ts}(x,\theta) = \frac{\sum_{i=1}^{R} g_i(x)\mu_i(x)}{\sum_{i=1}^{R} \mu_i(x)} \tag{3}$$

Where $a_{i,j}$ are constants,

## III. STABLE DIRECT ADAPTIVE CONTROL USING LYAPUNOV STABILITY APPROACH

### *A. Adaptive control*

For adaptive control aim is that reference model, trajectory to be tracked be $y_m(t)$ and its derivatives are $\dot{y}_m(t),\ldots,y_m^{(d)}(t)$ such that output $y(t)$ and its derivatives $\dot{y}(t),\ldots,y^{(d)}(t)$ follow the reference trajectory. Assume that $y_m(t)$ and its derivatives $\dot{y}_m(t),\ldots,y_m^{(d)}(t)$ are bounded. For a reference input $r(t)$ and reference trajectory $y_m(t)$

$$\frac{Y_m(s)}{R(s)} = \frac{q(s)}{p(s)} = \frac{q_0}{s^d + p_{d-1}s^{d-1} + \cdots + p_0} \tag{4}$$

$$\text{For } r(t) = 0,\ t \geq 0,\ y(t) \to 0 \text{ as } t \to \infty. \tag{5}$$

Hence choose

$$y_m(t) = \dot{y}_m(t) = \cdots = y_m^{(d)}(t) = 0. \tag{6}$$

For $R(s) = 0$,

$$p(s)Y_m(s) = 0 \tag{7}$$

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Or

$(s^d + p_{d-1}s^{d-1} + \cdots + p_0)Y_m(s) = 0$ (8)
Or
${y_m}^{(d)}(t) + p_{d-1}{y_m}^{d-1}(t) + \cdots + p_0 y_m(t) = 0$ (9)
Parameters $p_{d-1},\ldots, p_0$ specify the dynamics of how $y_m(t)$ evolves over time and how $y(t)$ and its derivatives evolve over time. Figure 1 shows the block diagram for adaptive control using fuzzy logic system.

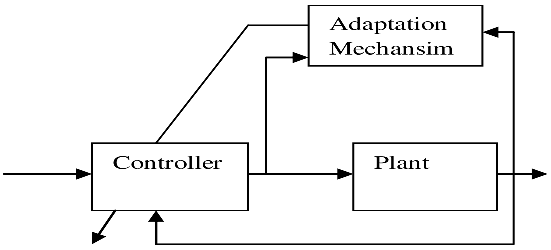


Fig.1 Adaptive Control using Takagi-Sugeno Fuzzy System

*B. Online Approximator*

Consider the plant
$\dot{x} = f(x) + g(x)u$ (10)
$y(k+d) = \alpha\big(x(k)\big) + \beta\big(x(k)\big)u(k)$ (11)

$y^{(d)} = \big(\alpha_k(t) + \alpha(x)\big) + (\beta_k(t) + \beta(x))u$

(12)

Here $d = n$ is the order of the plant. $y^{(d)}$ denotes the $d$- th derivative of $y$. $\alpha_k(t)$ and $\beta_k(t)$ are the known components of the plant dynamics, $\alpha(x)$ and $\beta(x)$ represent the non-linear dynamics of the plant that are unknown. $\alpha(x)$ and $\beta(x)$ are approximated with ${\theta_\alpha}^T\phi_\alpha(x)$ and ${\theta_\beta}^T\phi_\beta(x)$ by adjusting the $\theta_\alpha$ and $\theta_\beta$. The parameters $\theta_\alpha$ and $\theta_\beta$ are defined within the compact parameter sets $\Omega_\alpha$ and $\Omega_\beta$ respectively. $S_x \subseteq R^n$ be defined within the space through which the trajectory will travel under closed loop control.
$\alpha(x) = {\theta_\alpha^*}^T\phi_\alpha(x) + f_\alpha(x)$ (13)
$\beta(x) = {\theta_\beta^*}^T\phi_\beta(x) + f_\beta(x)$ (14)
$\theta_\alpha^* = \arg\min_{\theta_\alpha\epsilon\Omega_\alpha}(sup_{x\epsilon S_x}\left|{\theta_\alpha}^T\phi_\alpha(x) - \alpha(x)\right|)$ (15)
$\theta_\beta^* = \arg\min_{\theta_\beta\epsilon\Omega_\beta}(sup_{x\epsilon S_x}\left|{\theta_\beta}^T\phi_\beta(x) - \beta(x)\right|)$ (16)
so that $f_\alpha(x)$ and $f_\beta(x)$ are approximation errors, which arise when $\alpha(x)$ and $\beta(x)$ are represented by finite size approximators. The approximations of $\alpha(x)$ and $\beta(x)$ of the actual system are
$\hat{\alpha}(x) = {\theta_\alpha}^T(t)\phi_\alpha(x)$ (17)
$\hat{\beta}(x) = {\theta_\beta}^T(t)\phi_\beta(x)$ (18)
where the vectors $\theta_\alpha(t)$ and $\theta_\beta$ are updated online. The parameter errors are
$\widetilde{\theta_\alpha}(t) = \theta_\alpha(t) - \theta_\alpha^*$ (19)
$\widetilde{\theta_\beta}(t) = \theta_\beta(t) - \theta_\beta^*$ (20)
In addition to the assumptions made in the indirect adaptive control case, also required is
$\beta_k(t) = \alpha_k(t) = 0$ (21)
for all $t \geq 0$, and that there exist positive constants $\beta_0$ *and* $\beta_1$ such that
$0 < \beta_0 \leq \beta(x) \leq \beta_1$ (22)
Also it is assumed here a function $B(x) \geq 0$ such that
$\dot{\beta}(x) = \left|\left(\frac{\partial\beta}{\partial x}\right)^T \dot{x}\right| \leq B(x)$ (23)

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for all $x\epsilon S_x$. This requirement is often met in practice since $\dot{\beta}(x)$ is considered as the rate of change of the "gain" on the input term, it is often the case that this will be bounded . For example, notice that if $\beta(x)$ is constant that we know lies in a fixed interval, then all these coefficients are satisfied with $B(x) = 0$, for all $x$.

### C. *Controller Approximators*

There exists some ideal controller

$$u^* = \frac{1}{\beta(x)}\left(-\alpha(x) + v(t)\right) \tag{24}$$

where $v(t)$ is defined the same as in indirect adaptive control case. Let

$$u^* = \theta_u^{*T}\phi_u(x,v) + u_k(t) + w_u(x,v) \tag{25}$$

Where $u_k$ is a known part of the controller and

$$\theta_u^* = \arg\min_{\theta_u\epsilon\Omega_u}\left( sup_{x\epsilon S_x, v\epsilon S_m} \quad |\theta_u^T\phi_u(x,v) - (u^* - u_k)|\right) \tag{26}$$

So that $w_u(x,v)$ is the approximation error. It is assumed that $W_u(x,v) \geq |w_u(x,v)|$, where $W_u(x,v)$is a known bound on the error in representing the ideal controller .The approximation is

$$\hat{u} = \theta_u^T(t)\phi_u(x,v) + u_k \tag{27}$$

Where the matrix $\theta_u(t)$is the updated online .The parameter error is

$$\tilde{\theta}_u(t) = \theta_u(t) - \theta_u^* \tag{28}$$

Consider the control law

$$u = \hat{u} + u_{sd} \tag{29}$$

which is the sum of an approximation to an ideal control law, and a sliding mode control term. With this, the $d^{th}$ derivative of the tracking error becomes

$$e^{(d)} = y_m^{(d)} - \alpha(x) - \beta(x)(\hat{u} + u_{sd}) \tag{30}$$

Adding and subtracting $\beta(x)u^*$ and then using definition of $u^*$, we get

$$e^{(d)} = y_m^{(d)} - \alpha(x) - \beta(x)u^* - \beta(x)(\hat{u} - u^*) - \beta(x)u_{sd} \tag{31}$$

$$e^{(d)} = -\gamma e_s - \bar{e}_s - \beta(x)(\hat{u} - u^*) - \beta(x)u_{sd} \tag{32}$$

Or

in manner analogous to the indirect case,

$$\dot{e}_s + \gamma e_s = -\beta(x)(\hat{u} - u^*) - \beta(x)u_{sd} \tag{33}$$

### D. *Controller Parameter Updates*

Consider the following Lyapunov function candidate

$$V_d = \frac{1}{2\beta(x)}e_s^2 + \frac{1}{2\eta_u}\tilde{\theta}_u^T\tilde{\theta} \tag{34}$$

where $\eta_u > 0$.Since $0 < \beta_0 \leq \beta(x) \leq \beta_1$, $V_d$ is radially unbounded. The Lyapunov candidate $V_d$ is used to measure both the error in tracking and the error between the desired controller and the current controller.Taking the time derivative of equation (34) yields

$$\dot{V}_d = \frac{e_s}{\beta(x)}\dot{e}_s - \frac{\dot{\beta}(x)e_s^2}{2\beta^2(x)} + \frac{1}{\eta_u}\tilde{\theta}_u^T\dot{\tilde{\theta}} \tag{35}$$

Substituting $\dot{e}_s$ ,as defined in equation (33) ,we find

$$\dot{V}_d = \frac{e_s}{\beta(x)}\left(-\gamma e_s - \beta(x)\right)(\hat{u} - u^*) - \beta(x)u_{sd} - \frac{\dot{\beta}(x)e_s^2}{2\beta^2(x)} + \frac{1}{\eta_u}\tilde{\theta}_u^T\dot{\tilde{\theta}} \tag{36}$$

Use the update law

$$\dot{\theta_u}(t) = \eta_u\phi_u(x,v)e_s(t) \tag{37}$$

So $\eta_u > 0$ is an adaption gain. Since $\dot{\tilde{\theta_u}} = \theta_u$ ,

$$\dot{V}_d = \frac{-\gamma}{\beta(x)}\, e_s^2 - \left(\tilde{\theta}_u^T\phi_u(x,v) - \omega_u(x,v) + u_{sd}\right)e_s - \frac{\dot{\beta}(x)e_s^2}{2\beta^2(x)} + \tilde{\theta}_u^T\phi_u(x,v)e_s \tag{38}$$

and so

$$\dot{V}_d \leq \frac{-\gamma}{\beta(x)}\, e_s^2 - \left(\frac{\dot{\beta}(x)e_s^2}{2\beta^2(x)} - \omega_u(x,v)\right) e_s - e_s u_{sd} \tag{39}$$

We use a projection method to ensure that $\phi_u\epsilon\Omega_u$so in an analogous manner to the indirect case,

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Vol. 2, Issue 11, November 2013

$$\dot{V}_d \le \frac{-\gamma}{\beta(x)} e_s^2 - \left(\frac{\dot{\beta}(x) e_s^2}{2\beta^2(x)} - \omega_u(x,v)\right) e_s - e_s u_{sd} \quad (40)$$

*E. Sliding mode controller and stability properties term*

Once again a sliding mode control term is used to compensate for the approximation error in modeling $u^*$ by a finite size approximator. In

$$\dot{V}_d \le \frac{-\gamma}{\beta_1} e_s^2 + \left(\frac{|\dot{\beta}(x)||e_s|}{2\beta^2(x)} + |\omega_u(x,v)|\right) |e_s| - e_s u_{sd} \quad (41)$$

Now defining the sliding mode control term for the direct adaptive controller as

$$u_{sd} = \left(\frac{B(x)|e_s|}{2\beta_0^2} + W_u(x,v)\right) sgn(e_s) \quad (42)$$

which ensures that

$$\dot{V}_d \le -\frac{\gamma e_s^2}{\beta_1} \quad (43)$$

so that $V_d$ is a non-increasing function of time.

All signals are bounded and $e(t) \to 0 \; as \; t \to \infty$ so we get asymptotic tracking .There are practical application where $u_k$ can be designed so that the resulting transient performance can be improved. In an analogous manner to the indirect case, it is possible to define a smoothed version of the sliding mode control term that will only result in $e_s$ reducing to a neighborhood of zero.

## IV. DYNAMICS OF NONLINEAR SYSTEMS

*A. Robot Manipulator Dynamics*

Schematic diagram of robot manipulator with permanent magnet brush DC motor is shown in figure 2. The mechanical system dynamics for a single-link direct-drive manipulator actuated by a permanent magnet dc motor are assumed to be of the form

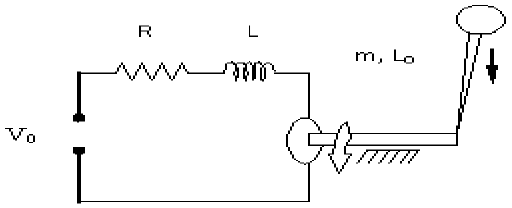


Fig.2 Robot Manipulator with Permanent Magnet DC Motor

$$M\ddot{q} + B\dot{q} + N\sin(q) = I \quad (44)$$

$$M = \frac{J}{K_\tau} + \frac{mL_0^2}{3K_\tau} + \frac{M_0 L_0^2}{K_\tau} + \frac{2M_0 R_0^2}{5K_\tau} \quad (45)$$

$$N = \frac{mL_0 G}{2K_\tau} + \frac{M_0 L_0 G}{K_\tau}, \; B = \frac{B_0}{K_\tau} \quad (46)$$

where $J$ is rotor inertia ,m is the link mass , $M_0$is the load mass , $L_0$is the link length , $R_0$ is the radius of the load, $G$ is the gravity coefficient , $B_0$ is the coefficient of viscous of friction at the joint , $q(t)$is the angular motor position (and hence the position of load ) , $I(t)$is the motor armature current and $K_\tau$is the coefficient which characterizes the electromechanical conversion of armature current to torque. The electrical subsystem dynamics for the permanent magnet brush dc motor assumed to be

$$L\dot{I} = V_e - RI - K_B\dot{q} \quad (47)$$

Where L is the armature inductance, $R$ is the armature resistance, $K_B$ is the back –emf coefficient and $V_e$ is the input control voltage.

*B. Magnetic Ball Suspension System*

The magnetic ball suspension system is given by

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$$\frac{dx_1(t)}{dt} = x_2(t) \quad (48)$$

$$\frac{dx_2(t)}{dt} = g - \frac{x_3^2(t)}{Mx_1(t)} \quad (49)$$

$$\frac{dx_3(t)}{dt} = -\frac{R}{L}x_3(t) + \frac{1}{L}v(t) \quad (50)$$

Where M=0.1Kg is the mass of the ball, g=9.81 m/s$^2$ is the gravitational acceleration, R=50 Ω is the resistance of winding, L=0.5 H is the winding inductance, v(t) is the input voltage and i(t) is the winding current.

## V. RESULTS AND DISCUSSION

### A. *Direct adaptive control of Robotic Manipulator*

Universe of discourse used for triangular membership function is -0.3 to 0.3, shown in figures 3 and 4.

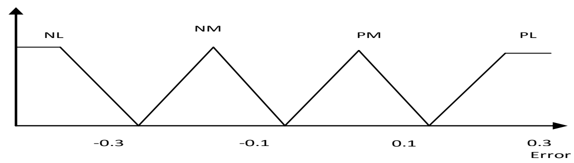


Fig.3 Membership Functions for input Error

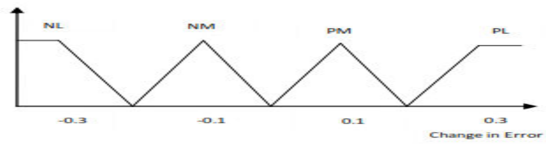


Fig. 4 Membership Functions for input change in error

The response of robotic manipulator with direct adaptive control is demonstrated for initial position [0.4 0.0 0.0] and desired position [1.3 0.0 0.0] in figures 5. Figure 6 shows the error between actual and desired angular position of robot manipulator. It is observed that with identified nonlinear dynamics based on Takgi Sugeno based adaptive control the system tracks the desired angular position accurately with rise time of 1.4 sec. The system is able to reduce the tracking error to zero in steady state. The simulation of robotic manipulator for design system parameters for operating conditions described in Table 1 has been performed in MATLAB.

1) For desired position [1.3 0.0 0.0]

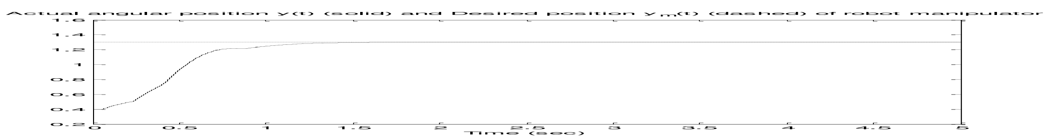

Fig.5 Actual angular position and Desired Position

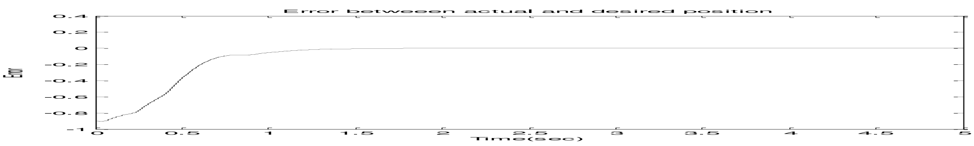

Fig. 6 Error between actual and desired angular position

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Table 1 Design Parameters for Robot Manipulator

| Initial position | Desired Position | K0 | K1 | γ | $\xi_u$ |
|---|---|---|---|---|---|
| [0.4 0.0 0.0] | [1.3 0.0 0.0] | 85 | 22 | 2 | 2 |
| [0.2 0.0 0.0] | [0.9 0.0 0.0] | 101 | 21 | 2 | 2 |

2) For desired position [0.9 0.0 0.0]

The response of robotic manipulator with direct adaptive control is demonstrated for initial position [0.2 0.0 0.0] and desired position [0.9 0.0 0.0] in figures 7. Figure 8 shows the error between actual and desired angular position of robot manipulator. Figure It is observed that with identified nonlinear dynamics based on Takgi Sugeno based direct adaptive control the system tracks the desired angular position accurately with rise time of 1.25 sec. The system is able to reduce the tracking error to zero in steady state.

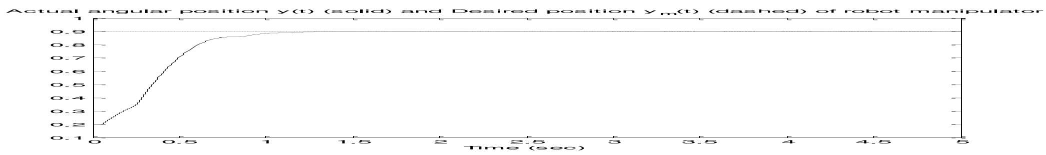

Fig.7 Actual angular position and Desired Position

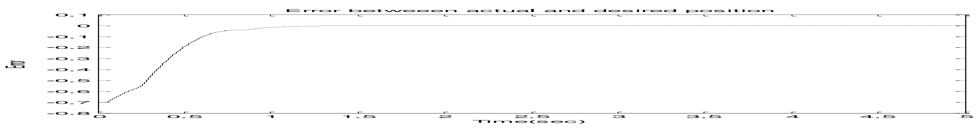

Fig. 8 Error between Actual angular position and Desired Position

*B. Direct adaptive control of Magnetic Ball Suspension System*

The The simulation of magnetic ball suspension system for system conditions described in Table 2 has been performed in MATLAB. The necessary of rule base has been developed which describes behavior of the nonlinear systems. The response of magnetic ball suspension system with indirect adaptive control and identified nonlinear components is demonstrated for initial position [0.9 0.0 0.0] and desired position [0.2 0.0 0.0] in figures 9 . Figure 10 shows the error between actual and desired position of ball. It is observed that with identified nonlinear dynamics based on Takgi Sugeno based adaptive control the system tracks the desired angular position accurately. The system is able to reduce the tracking error to zero in steady state.

Table 2 Design Parameters for Magnetic Ball Suspension System

| Initial Position | Desired Position | K0 | K1 | γ | $\xi_u$ |
|---|---|---|---|---|---|
| [0.9 0.0 0.0] | [0.2 0.0 0.0] | 40 | 15 | 2 | 4 |
| [0.4 0.0 0.0] | [0.1 0.0 0.0] | 36 | 18 | 2 | 4 |

**1)** For desired position [0.2 0.0 0.0]

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**Vol. 2, Issue 11, November 2013**

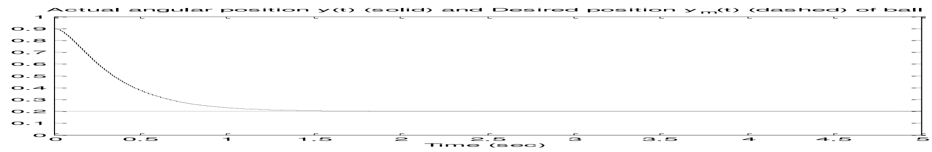


Fig.9 Actual angular position and Desired Position of Ball

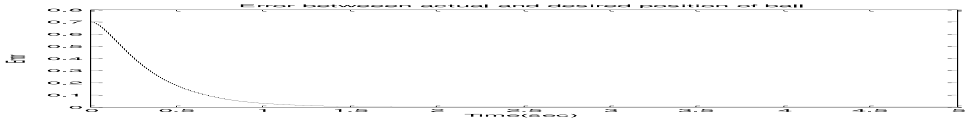


Fig.10 Error between Actual angular position and Desired Position

2) For desired position (0.1 0.0 0.0)

The developed adaptive control algorithm is also tested for different initial and desired position of ball and it is found that algorithm effectively controls the dynamics of the system under variation in initial condition and other system parameters. The response of magnetic ball suspension system during its transition from initial position [0.9 0.02 0.0] and desired position [0.4 0.01 0.0] is shown in figure 11 and figure 12 shows the error between actual position and desired position of ball. It is observed that with identified nonlinear dynamics based on Takgi Sugeno based adaptive control the system tracks the desired angular position accurately. The system is able to reduce the tracking error to zero in steady state.

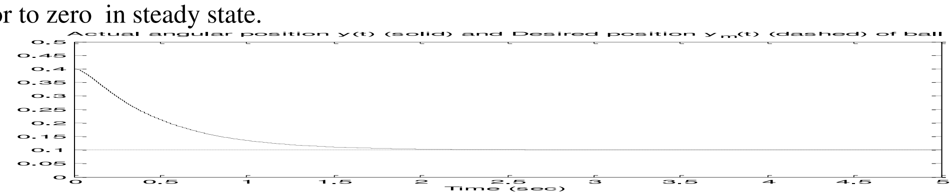


Fig.11 Actual angular position and Desired Position

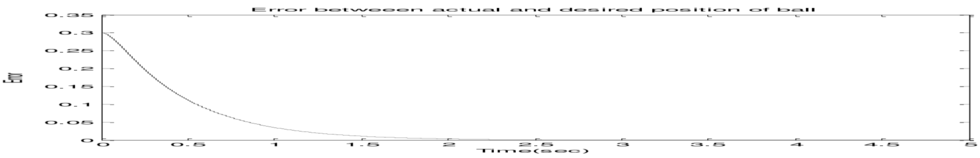


Fig. 12 Error between Actual position and Desired Position of ball

## VI. CONCLUSIONS

A stable direct adaptive control law is applied using Takagi-Sugeno Fuzzy System and stability of the system is investigated using Lyapunov Stability Criterion. The necessary adaptive gains and controller parameters are determined for desired operation of system under test. Two different classes of nonlinear systems are considered for implementation of developed adaptive control law and effectiveness of the controller under different operating conditions of the system are demonstrated. The nonlinear systems considered in the present study are Robot Manipulator with DC motor dynamics and Magnetic Ball Suspension System. Identification and Control of the systems under study were performed using Takagi-Sugeno Fuzzy system with nine rules. It has been observed that Robot manipulator and Magnetic Ball Suspension System tracks the desired position with good accuracy in the entire range of its operation. This confirms the stability of direct adaptive control law.

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