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Indirect Adaptive Control of Nonlinear Systems

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Abstract— This paper proposes a novel adaptive control law for nonlinear systems using Takagi-Sugeno fuzzy system. Takagi-Sugeno fuzzy system is used to identify nonlinear system components theta alpha and theta beta. Stable Indirect Adaptive control law is such that it has two control components one is certainty equivalence control and other is sliding mode control. Sliding mode controller is used to ensure the stability of Lyapunov Function. Stability of adaptive control law is tested on two nonlinear systems cart pole system and ball beam system. Simulation is performed on nonlinear systems using MATLAB.

Keywords— Fuzzy System, Lyapunov Function, Indirect Adaptive Control, Cart Pole System, Ball Beam System

I. INTRODUCTION

There is extensive literature available on fuzzy logic application on nonlinear system. A mathematical way is building a fuzzy model for any nonlinear system. The fuzzy implications of the system model and the least square identification method [1] have been used to describe the nonlinear systems. Simulation can be performed using tuned fuzzy logic controllers. The fuzzy logic controller [2] displayed good stability and performance robustness characteristics for a wide range of operation. Self tuning features [3] for both the data base and the rule base can be designed using fuzzy controller. A PD controller, [4] a linear quadratic controller, a nonlinear controller 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 employs fuzzy systems, [5] which are expressed as a series expansion of basis functions, to adaptively compensate for the plant nonlinearities. The controller output [6] will be 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 some adaptive algorithm for the purpose of controlling the system state to hit a user-defined sliding surface and then slide along it. The fuzzy sliding mode controller [8] can well control most of the complex systems without known their mathematical model. The dynamics 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 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 system function of nonlinear system. A fuzzy logic controller [13] which produces desirable transient performance for nonlinear systems guarantee closed loop stability. An adaptive fuzzy control scheme [14] employs a fuzzy controller and a compensation controller for a class of nonlinear continuous systems. Stable fuzzy controllers [15] can be synthesized in terms of Mamdani model to stabilize nonlinear systems. Fuzzy logic controller [16] can control a cart balancing a 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] for each rule governing the control of the plants cannot be guaranteed when all of these rules are put together into a rule base for the fuzzy logic controller. Design of fuzzy logic controllers [19] for nonlinear systems with guaranteed 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 system function of nonlinear systems. A hybrid [21] fuzzy logic 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] fuzzy logic controller can be used for tracking for a class of nonlinear dynamic systems. A nonlinear system [23] can be represented by Takagi-Sugeno fuzzy model and a fuzzy logic controller can be constructed by blending all local state feedback controllers with a sliding mode controller. A robust adaptive fuzzy controller [24] can be used for a class of nonlinear systems in the presence of dominant uncertain nonlinearities. 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. Adaptive control schemes [27] using fuzzy logic control can be used for robot manipulator which has the parametric uncertainties'. A model based fuzzy controller [28] can be used for a class of uncertain nonlinear systems to

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achieve a common observability Gramian. [29] Exact fuzzy modeling and optimal control can be used for inverted pendulum on cart. The nonlinear fuzzy PID [30] controller can be applied successfully in control systems with various nonlinearities. The uncertain nonlinear system [31] can be represented by uncertain Takagi-Sugeno fuzzy model structure. Most of real word systems [32] have dynamic features, i.e. the actual output depends on the previous values, and these are called autoregressive dynamic fuzzy system. A fuzzy variable structure controller [33] based on the principle of sliding mode variable structure control can be used both for the dynamic as well as for static control properties of the system. Adaptive fuzzy sliding mode control scheme [34] which incorporates the fuzzy logic into sliding mode control is used to approximate the equivalent control and the upper bound of uncertainty which involved the disturbance and approximation error. The control algorithm [35] of robust controller for a nonlinear system is based on sliding mode control that incorporates a fuzzy tuning technique, and it superposes equivalent control, switching control and fuzzy control. Based [36] on the Lyapunov approach, 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. This paper comprises of following sections. Section 2, the fuzzy logic control system concerned in this paper will be discussed. The proposed stability design approach using Lyapunov Function will be presented in Section 3. Section 4 presents dynamics of nonlinear systems and section 5 simulation results and discussion. 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

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

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

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

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

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

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

III. STABLE 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 $y_m(t)$,

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

For $r(t) = 0, t \geq 0,\ y(t) \to 0$ as $t \to \infty$.

Hence choose $y_m(t) = \dot{y}_m(t) = \cdots = y_m^{(d)}(t) = 0$. (5)

Figure 1 shows the block diagram for indirect adaptive control.

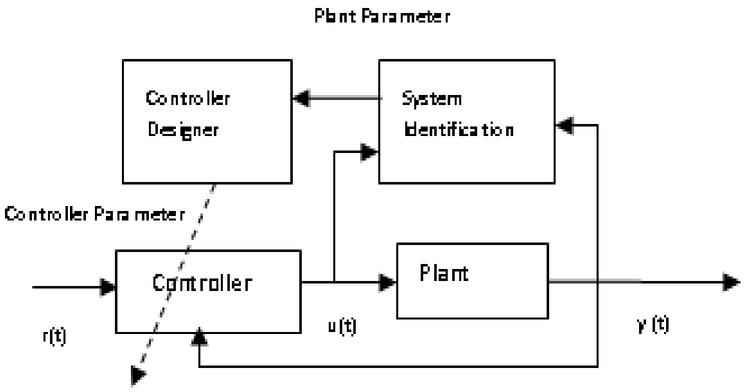

Fig.1 Indirect Adaptive Control using Takagi-Sugeno Fuzzy System

B. Online Approximator

Consider the plant

$$\dot{x} = f(x) + g(x)u \quad (6)$$

$$y(k + d) = \alpha\big(x(k)\big) + \beta\big(x(k)\big)u(k) \quad (7)$$

$$y^{(d)} = \big(\alpha_k(t) + \alpha(x)\big) + \big(\beta_k(t) + \beta(x)\big)u \quad (8)$$

Here d 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 nonlinear 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 θ_α and θ_β.

The approximations of $\alpha(x)$ and $\beta(x)$ of the actual system are

$$\hat{\alpha}(x) = \theta_\alpha{}^T(t)\phi_\alpha(x) \quad (9)$$

$$\hat{\beta}(x) = \theta_\beta{}^T(t)\phi_\beta(x) \quad (10)$$

where the vectors $\theta_\alpha(t)$ and θ_β are updated online.

The parameter errors are

$$\tilde{\theta}_\alpha(t) = \theta_\alpha(t) - \theta_\alpha^* \quad (11)$$

$$\tilde{\theta}_\beta(t) = \theta_\beta(t) - \theta_\beta^* \quad (12)$$

The adaptive control law $u = u_{eq} + u_{sm}$ (13)

where u_{eq} is the certainty equivalence control term and u_{sm} is the sliding mode term.

C. Certainty Equivalence Term

The tracking error be

$$e(t) = y_m(t) - y(t) \quad (14)$$

$K = [k_0, k_1, k_2, \ldots k_{d-2}, 1]^T$ be a vector of design parameters.

The shape of the error dynamics is controlled by the choice of k_0. The equivalence control term can be defined as

$$u_{eq} = \frac{1}{\beta_k(t)+\hat{\beta}(x)}\left(-\big(\alpha_k(t) + \hat{\alpha}(x)\big) + z(t)\right) \quad (15)$$

$\gamma > 0$ is a design parameter.

D. Parameter Update Laws

Consider following Lyapunov function:

$$L_i = \frac{1}{2}e_s^2 + \frac{1}{2\xi_\alpha}\tilde{\theta}_\alpha^T\tilde{\theta}_\alpha + \frac{1}{2\xi_\beta}\tilde{\theta}_\beta^T\tilde{\theta}_\beta \quad (16)$$

Where ξ_α and ξ_β are design parameters.

$$\dot{L}_i = e_s\dot{e}_s + \frac{1}{\xi_\alpha}\tilde{\theta}_\alpha^T\dot{\tilde{\theta}}_\alpha + \frac{1}{\xi_\beta}\tilde{\theta}_\beta^T\dot{\tilde{\theta}}_\beta \quad (17)$$

$$\dot{\theta}_\alpha(t) = -\xi_\alpha\phi_\alpha(x)e_s \quad (18)$$

$$\dot{\theta}_\beta(t) = -\xi_\beta\phi_\beta(x)e_s u_{eq} \quad (19)$$

$\xi_\alpha > 0$ and ξ_β are adaptation gains.

Assume ideal parameters are constant. $\dot{\tilde{\theta}}_\alpha = \dot{\theta}_\alpha$ and $\dot{\tilde{\theta}}_\beta = \dot{\theta}_\beta$.

$$\dot{L}_i = -\gamma e_s^2 - \big(f_\alpha(x) + f_\beta(x)u_{eq}\big)e_s - \big(\beta_k(t) + \beta(x)\big)u_{sm}e_s \quad (20)$$

E. Sliding mode control term

Assume

$$u_{sm} = \frac{(F_\alpha(x)+F_\beta(x)|u_{eq}|)}{\beta_0}sgn(e_s) \quad (21)$$

So $\dot{L}_i \leq -\gamma e_s^2$

Since $\gamma e_s^2 \geq 0$ this shows that L_i, which is a measure of the tracking error and parameter estimation error, is a non-increasing function of time.

IV. Dynamics of Nonlinear Systems

A. Dynamics of Cart Pole System

single-input multi-output inverted pendulum shown in figure 2 can be represented by a fourth order non-linear equation.

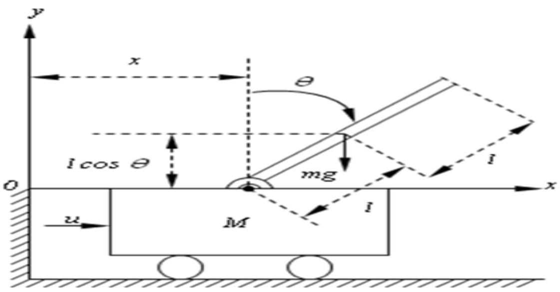

Fig.2 Inverted Pendulum Mounted on Cart

Let d be the distance of the cart from centre and α be the angle of the pendulum.

Defining the state vector x as $x = \lfloor d \; \dot{d} \; \alpha \; \dot{\alpha} \rfloor$,

The system equations can be written as follows:

$$x'_1 = x_2$$

$$x'_2 = \frac{lx^3 \sin x_3 - g \sin x_3 \cos x_3 + \frac{1}{m} u}{\frac{M}{m} + (\sin x_3)^2}$$

$$x'_3 = x_4$$

$$x'_4 = \frac{\frac{M+m}{m} g \sin x_3 - l x_3^2 \sin x_3 \cos x_3 - \frac{\cos x_3}{m} u}{l \left(\frac{M}{m} + (\sin x_3)^2 \right)}$$

Where
Mass of the cart, M = 0.455 kg
Mass of pendulum, m = 0.210 kg
Half length of pendulum rod, l = 0.305 m
Acceleration due to gravity, g = 9.81m/s^2
u= input force applied to the cart, N

B. Ball Beam System

Consider a 4th order nonlinear system, ball and beam system, for the simulation shown in figure 3. The beam is made to rotate in a vertical plane by applying the torque at the centre of rotation and the ball is free to roll along the beam. The ball remains in contact with the beam. Let $x = [x_1 \;\; x_2 \;\; x_3 \;\; x_4] := \left[r \;\; \frac{dr}{dt} \;\; \theta \;\; \frac{d\theta}{dt} \right]$ be the state of the system, $y = x_1$ be the output of the system and u be the input to the system.

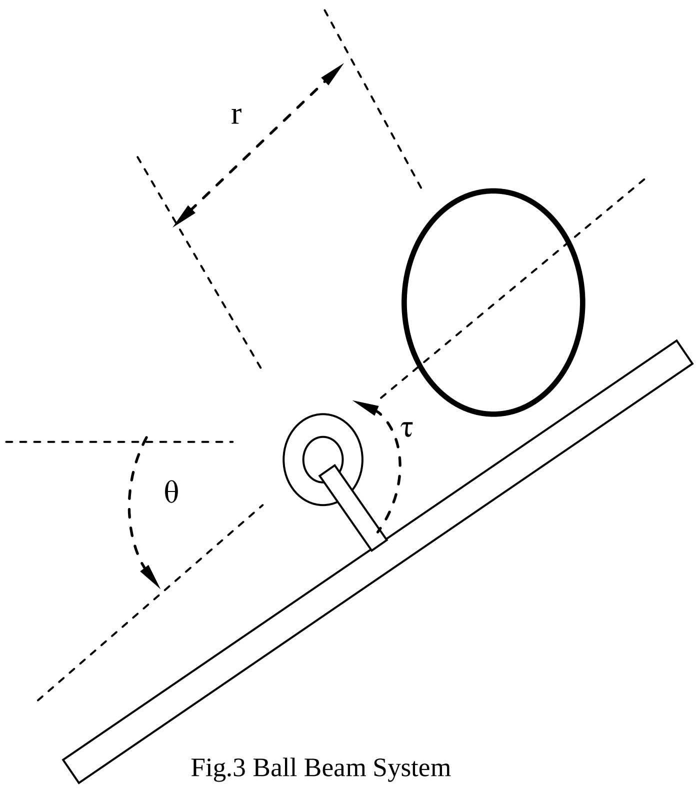

Fig.3 Ball Beam System

Then system can be represented by the state-space model

$$\begin{bmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \\ \frac{dx_3}{dt} \\ \frac{dx_4}{dt} \end{bmatrix} = \begin{bmatrix} x_2 \\ B(x_1 x_4^2 - G \sin x_3) \\ x_4 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u$$

where u is the input to the system, and B,G are the system parameters.

V. SIMULATION RESULTS AND DISCUSSION

A. Indirect Adaptive Control of Cart Pole System

Universe of discourse for membership function for error and change in error of Cart Pole System is -0.3 TO 0.3.

Table 1 Tuned Design Parameters for Inverted Pendulum System

Initial position	K0	K1	K2	γ	ξ_α	ξ_β
[0.4 -1.2 0.2 -0.2]	2600	620	110	4	2	2

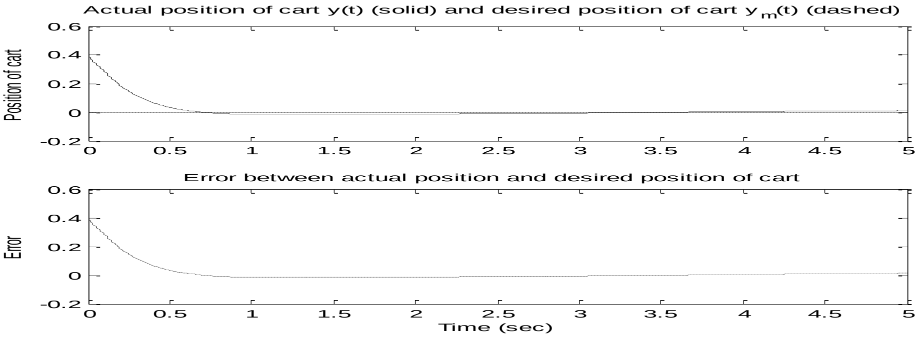

Fig. 4 (a) Actual Cart Position and Desired Cart Position, (b) Error between Actual Cart Position and Desired Cart Position

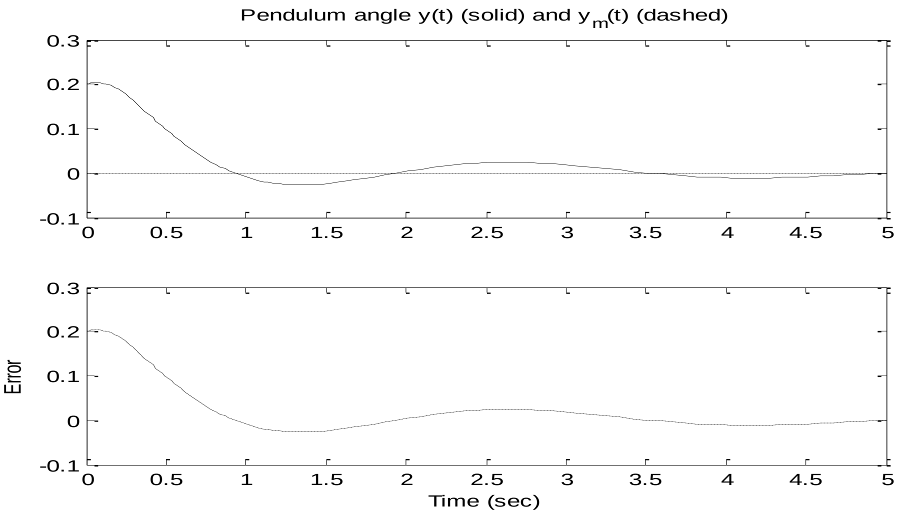

Fig. 5 (a) Actual Pendulum Angle and Desired Pendulum Angle,(b) Error between Actual and Desired Pendulum Angle.

Figure 4 and 5 shows that Cart position converges to origin and Pendulum angle also converges at origin which is also the requirement for a balance of Inverted Pendulum on Cart. Also error reduces to zero for both Cart position as well as Pendulum angle.

B. Indirect Adaptive Control of Ball Beam System

Universe of discourse for triangular membership function is -0.3 to 0.3. Total Sixteen rules have been used.

Table 2 Tuned Design Parameters for Ball Beam System

Initial position	K0	K1	K2	γ	ξ_α	ξ_β
[0.4 0.0 0.9 0.0]	2.71	1	1.521	5	4	4

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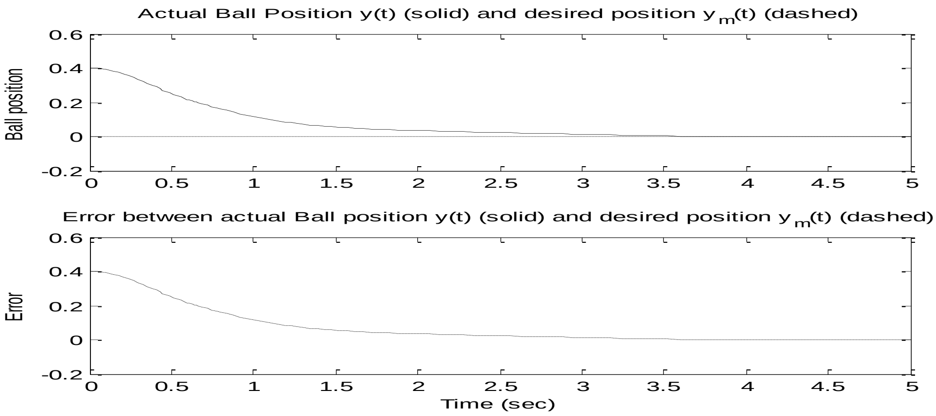

Fig.6 (a) Actual Ball Position and Desired Ball Position, (b) Error between Actual and Desired Ball Position

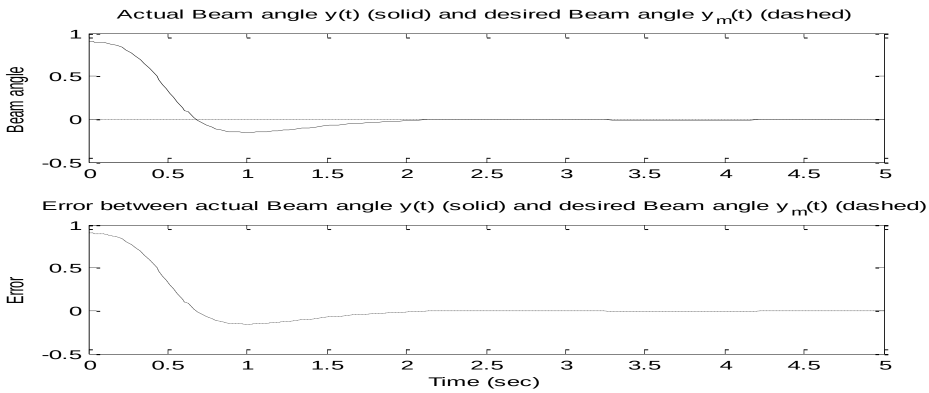

Fig.7 (a) Actual Beam Angle and Desired Beam Angle, (b) Error between Actual and Desired Beam Angle

Figure 6 and 7 shows that Ball position reaches to origin and Beam angle converges at origin for a balance of Ball on Beam. Also error reduces to zero for both Ball position as well as Beam angle.

VI. CONCLUSION

A Stable adaptive control using Lyapunov function has been proposed for nonlinear systems. Takagi fuzzy system is used for identification and control of nonlinear systems. The proposed stable adaptive control law is tested on Ball Beam System and Inverted Pendulum mounted on a Cart. Universe of discourse for membership function have been taken from -0.3 to 0.3. Total sixteen rules have been used. Design parameters k_0, k_1, k_2 , γ, ξ_α and ξ_β are tuned in order to get desired results. It has been observed that Ball Position converges to origin and Beam angle converges to zero such that at balance Ball position and Beam angle are at origin. Also on second nonlinear system Inverted pendulum on a Cart, it has been observed that Inverted pendulum angle reaches to zero while Cart Position converges at origin which is the requirement for a balance between Inverted Pendulum and Position of Cart. Above nonlinear systems have been tested for given initial positions. This confirms the stability of proposed adaptive control law.

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