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

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**ABSTRACT**: This paper shows implementation of indirect 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 Robot manipulator with the inclusion of DC motor dynamics and magnetic ball suspension system. Simulation is performed on nonlinear systems using MATLAB.

**Keywords**: Fuzzy System, Lyapunov Function, Adaptive Control, Robot Manipulator, DC motor dynamics, Magnetic Ball Suspension 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

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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 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. Section 5 presents 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.

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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 $y_m(t)$,

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

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.

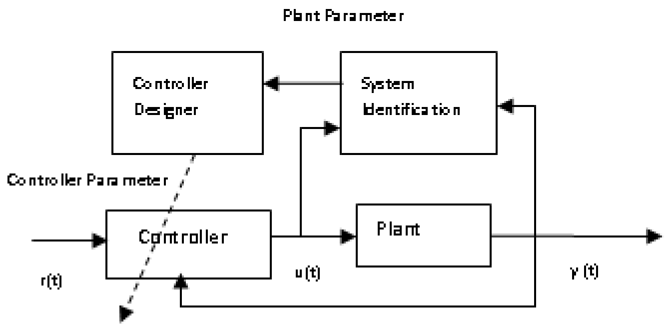


Fig.1 Indirect Adaptive Control using Takagi-Sugeno Fuzzy System

### B. *Online Approximator*

Consider the plant

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

$$y(k+d) = \alpha\big(x(k)\big) + \beta\big(x(k)\big)u(k) \tag{7}$$

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

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 $\theta_\alpha$ and $\theta_\beta$.

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

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

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

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

The parameter errors are

$$\widetilde{\theta_\alpha}(t) = \theta_\alpha(t) - \theta_\alpha^* \tag{11}$$

$$\widetilde{\theta_\beta}(t) = \theta_\beta(t) - \theta_\beta^* \tag{12}$$

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 control term*

The tracking error be

$$e(t) = y_m(t) - y(t) \tag{14}$$

$K = [k_0, k_1, k_2, \ldots k_{d-2}, 1]^T$ 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

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

$\gamma > 0$ is a design parameter.

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*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 $\xi_\alpha$ and $\xi_\beta$ 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 $\xi_\beta$ are adaptation gains.

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

$$\dot{L_\iota} = -\gamma e_s^2 - \left(f_\alpha(x) + f_\beta(x)u_{eq}\right)e_s - \left(\beta_k(t) + \beta(x)\right)u_{sm}e_s \quad (20)$$

*E. Sliding mode control term*

Assume

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

So $\dot{L_\iota} \le -\gamma e_s^2$

Since $\gamma e_s^2 \ge 0$ 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. 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

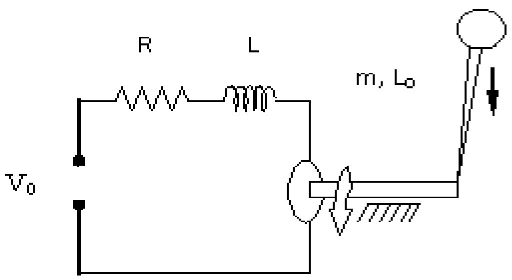


Fig.2 Robot Manipulator with Permanent Magnet Brush DC Motor

$$M\ddot{q} + B\dot{q} + N\sin(q) = I \quad (22)$$

$$M = \frac{J}{K_\tau} + \frac{mL_0^2}{3K_\tau} + \frac{M_0L_0^2}{K_\tau} + \frac{2M_0R_0^2}{5K_\tau} \quad (23)$$

$$N = \frac{mL_0G}{2K_\tau} + \frac{M_0L_0G}{K_\tau}, \; B = \frac{B_0}{K_\tau} \quad (24)$$

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

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electromechanical conversion of armature current to torque. The electrical subsystem dynamics for the permanent magnet brush dc motor assumed to be

$$L\dot{I} = V_e - RI - K_B\dot{q} \tag{25}$$

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

$$\frac{dx_1(t)}{dt} = x_2(t) \tag{26}$$

$$\frac{dx_2(t)}{dt} = g - \frac{x_3^2(t)}{Mx_1(t)} \tag{27}$$

$$\frac{dx_3(t)}{dt} = -\frac{R}{L}x_3(t) + \frac{1}{L}\text{v(t)} \tag{28}$$

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. Indirect adaptive control of Robotic Manipulator*

Universe of discourse for membership function has been taken from -0.3 to 0.3 and total nine rules have been used.

***1)*** *For desired position [1.9 0.02 0.0]*

The nonlinear unknown components which affects the dynamics of the robotic manipulator are identified using Takagi-Sugeno Fuzzy System. The indirect adaptive control technique has been used to identify nonlinear components $\theta_\alpha$ and $\theta_\beta$ . The simulation of robotic manipulator for system conditions described in Table 1 has been performed in MATLAB.

Table 1 Tuned Design Parameters for Robot Manipulator

| Desired position | Initial Position | K0 | K1 | γ | $\xi_\alpha$ | $\xi_\beta$ |
|---|---|---|---|---|---|---|
| [1.9 0.02 0.0] | [0.6 0.01 0.0] | 100 | 20 | 2 | 4 | 4 |
| [0.9 -0.02 0.0] | [0.4 -0.01 0.0] | 98 | 19.9 | 4 | 2 | 2 |

The response of robotic manipulator with indirect adaptive control and identified nonlinear components is demonstrated for initial position [0.6 0.01 0.0] and desired position [1.9 0.02 0.0] in figures 3. 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 0.4 sec The system is able to reduce the tracking error in steady state.

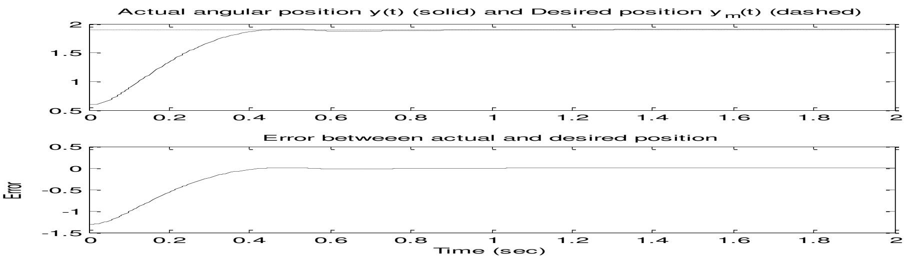


Fig.3 Variation of desired, actual angular position and their error magnitude for robotic manipulator.

*2) For desired position [0.9 -0.02 0.0]*

The developed adaptive control algorithm is also tested for different initial and desired angular position of manipulator and it is found that algorithm effectively controls the dynamics of the system under variation in initial condition and other system parameters. The dynamical behaviour of response of robotic manipulator during its transition from initial position [0.4 -0.01 0.0] and desired position [0.9 -0.02 0.0] is also shown in the figures 4.

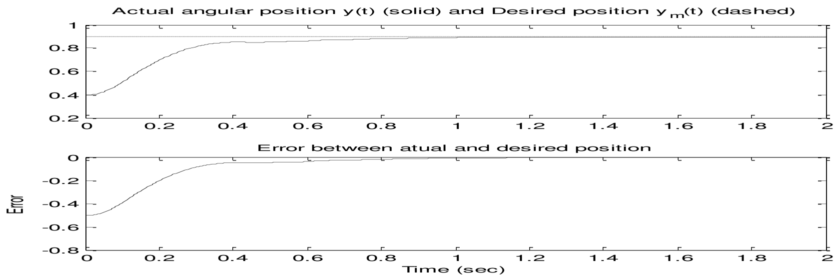


Fig .4 Variation of desired, actual angular position and their error magnitude for robotic manipulator.

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

The nonlinear unknown components which affects the dynamics of the magnetic ball suspension system are identified using Takagi-Sugeno Fuzzy System. The simulation of magnetic ball suspension system for system conditions described in Table 2 has been performed in MATLAB.

Table 2 Tuned Design Parameters for Magnetic Ball Suspension System

| Desired position | Initial Position | K0 | K1 | $\gamma$ | $\xi_\alpha$ | $\xi_\beta$ |
|---|---|---|---|---|---|---|
| [1.9 0.02 0.0] | [0.6 0.01 0.0] | 13 | 7.2 | 4 | 4 | 4 |
| [0.9 0.02 0.0] | [0.4 0.01 0.0] | 18 | 9 | 4 | 4 | 4 |

*1) For desired position [0.6 0.01 0.0]*

The response of magnetic ball suspension system with indirect adaptive control and identified nonlinear components is demonstrated for initial position [1.9 0.02 0.0] and desired position [0.6 0.01 0.0] in figures 5 . 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 in steady state.

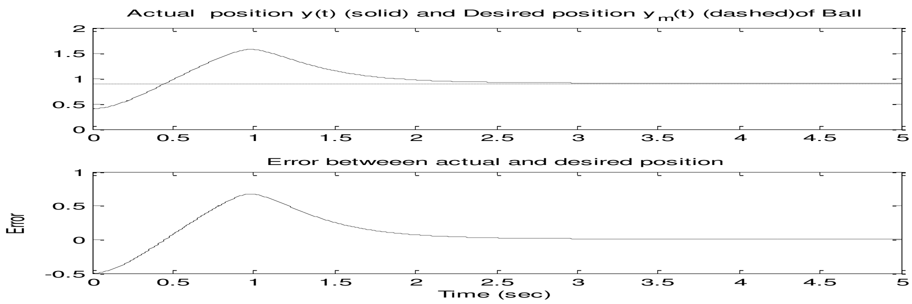


Fig .5 Variation of desired, actual angular position and their error magnitude for magnetic ball suspension system.

*2) For desired position [0.4 0.01 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 dynamical behavior of 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 also shown in the figures 6.

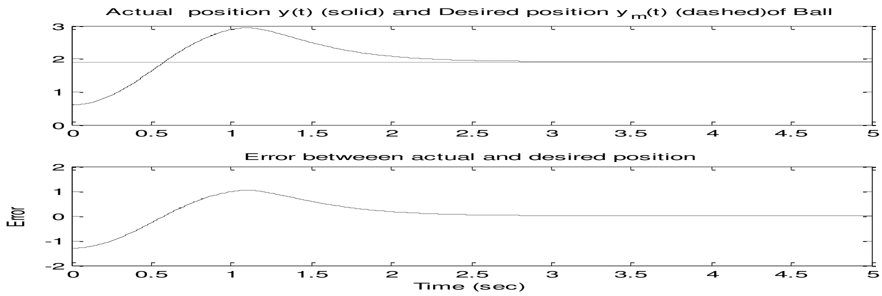


Fig .6 Variations of desired, actual angular position and their error magnitude for magnetic ball suspension system

## VI. CONCLUSIONS

An indirect adaptive control law is developed 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. Nonlinear components of the systems which affect the performance of controller are identified and used to improve the system performance. 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 different 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. Error between actual and desired positions is presented under different operating conditions. This confirms the stability of proposed indirect adaptive control law.

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