

Real-Time On Line Tuning Of Fuzzy Controller for Two Link Rigid-Flexible Robot Manipulators

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Abstract: - In this paper, a real time self-tuning MIMO fuzzy bang-bang controller (FBBC) is proposed to control two link rigid and flexible robot manipulators. Two link rigid and flexible robot manipulators are highly nonlinear plants. The fuzzy control is based on the Takagi-Sugeno's type architecture fuzzy model combined with online self-tuning so that both the desired transient and steady state responses can be achieved. The online self-tuning is based on the gradient steepest descent tuning method, which learns to tune the FBBC's inputs and outputs gains online. The controller operation is demonstrated by simulation of tracking ability and manipulator's positioning control with different payload. Based on the simulation results, the proposed controller shows good performance in tracking ability even with big payload.

Key-Words: - Rigid-flexible manipulators; Bang-Bang control; online self-tuning; Takagi-Sugeno; MIMO dynamic systems.

1 Introduction

Dynamics of a robot manipulator is highly nonlinear and contains uncertain elements such as friction. Efforts have been made in developing control schemes to achieve the precise control of robot manipulators [1, 2, 3, 4, 5, 6 and 7]. Among the available options, fuzzy control has the greatest potential since it is able to compensate for the un-models dynamics using capability of human control behavior. In control theory, a bang-bang on-off controller switches abruptly between two states. They are often used to control a plant that accepts a binary input, for example a furnace that is either completely on or completely off. Most common residential thermostats are bang-bang controllers. The Heaviside step function in its discrete form is an example of a bang-bang control signal. Due to the discontinuous control signal, systems that include bang-bang controllers are variable structure systems, and bang-bang controllers are thus variable structure controllers. Artificial intelligence technique such as fuzzy logic has provided the means to develop flexible fuzzy bang-bang controller. One of the earliest fuzzy bang-bang controllers (FBBC) was developed by Chiang and Jang [8]. It made debut in Cassini spacecraft's deep space exploration project.

Fuzzy bang-bang controller (FBBC) has been successfully applied in various areas for nearly two decades. Some of these are in spacecraft satellite attitude control systems [9], the servo systems VIA [10], control of water tank system [11], in the reduction of harmonic current pollution [12], crane hosting and lowering operation [13], the elevator control [14] and in process control valves operation [15]. FBBC has become a popular tool after these successful applications. Recently, many analysis results and design methodologies of fuzzy control have been reported. However, most of these reported research only focused on single-input-single-output (SISO) systems.

Tuning of fuzzy sets has many facets. Scaling factor (SF) tuning is done externally on the inputs and outputs gains of the fuzzy controller. They have critical effect on the response of the fuzzy controller and are easier to tune. Passino and Yurkovich [16] state that tuning of error input gain has effect of changing the loop-gain, resulting in overshoot, while tuning of input- change in error results in altering the derivative gain which effects the transient response of the system such as settling and rise time. The scaling factor of output MF's has effect of increasing the saturation of level of the output of the controller. It is not necessary that fuzzy controller can give satisfactory performance

by tuning the gains when subjected to disturbance and non-linearities. Maeda and Murakami [17] proposed a *self-tuning* algorithm of the fuzzy logic controller, which has two functions, in adjusting the scaling factors that are the parameters of the fuzzy logic controller and in improving the control rules (*self-organizing*) of the fuzzy logic controller by evaluating the control response at real time and the control results after operations. A more robust tuning method is to tune the MF shape and position or let the optimization process tuned both, the SF and MF at the same time for square error minimization. Demaya *et al.* [18] discussed in details the effects of tuning SF and MF. They argued that SF has more profound effect than MF tuning and SF should be used for course and MF for the fine-tuning of the response. Habbi and Zelmat [19] designed a PI-type Fuzzy controller using the approximate reasoning for modeling the optimization strategy with the help of IF-THEN fuzzy rules. The proposed fuzzy rule base is used for the computation of the gradient step which is adjusted continuously with respect to the amount of variation of the performance criterion and the direction of the gradient vector of the fuzzy controller parameters. M. Salehi *et al.* [20] proposed Sliding Mode Impedance Controller and online Particle Swarm Optimization (PSO) algorithm for gain tuning of impedance control at the contact moment of end effectors and unknown environments.

The controlling technique described in this paper is different from the previous works. Firstly, fuzzy structure is different. The fuzzy model base on Takagi-Sugeno's model uses tuned based on parameterized output function. However due to fixed b_i -level output of bang-bang action an output gain parameter is used. Secondly, technique of self tuning in this work, it is based on simple gradient descent method for MIMO fuzzy bang-bang controller. Thirdly, in this work, the controller design is based on compensation of steady state error and reduction of cross coupling effects as well as improvement of settling time when the FBBC is applied to control two links rigid and flexible type's robot manipulators. In most tuning applications isosceles triangular membership functions are used with TSK or Mamdani model. Commonly, center of area (COA) defuzzification for Mamdani model is used for tuning. In this paper a different defuzzification, largest of maxima (LOM) is used to arrange the output function in a certain way rend Bang-Bang output from the controller. A major practical advantage of bang-bang controls is that

they can be implemented with simple on-off action. The control output takes on either its minimum or maximum value yields minimum-time control of the system.

In this paper the proposed FBBC consists of sets of linguistic rules. The consequent part of the fuzzy rules has only three linguistic values, while the premise parts are freely chosen. It is structurally simple due to three membership functions in its fuzzy output set and rule matrix. An important feature of FBBC is its flexibility and its optimal time response, which is independent of initial conditions. The rest of the paper is organized as follows. In section 2, a two-link rigid and flexible manipulators robot system is studied to demonstrate the FBBC. In section 3, the self-tuning MIMO fuzzy bang-bang controller is reviewed and the membership functions for a complement type are defined. Section 4, shows the simulation results and its discussion. Finally, conclusions are presented in section 5.

2. Two Link Rigid and Flexible Type Robot Manipulators

This section presents two studies of the performance of the FBBC of a two-joint type rigid robot, and a two-joint type flexible robot.

2.1. Two-Link Type Rigid Robot Model

In this section, we illustrate the performance of the FBBC by simulation of a two-joint type rigid robot. For the following robot model the link masses are non-concentrated at the centers of masses. Hence, each link has different moments of inertia. All one, there are frictions in the joints. The mechanical model of a robot manipulator is shown in Fig.1. Table 1 shows the parameters of the two-link rigid type robot [1].

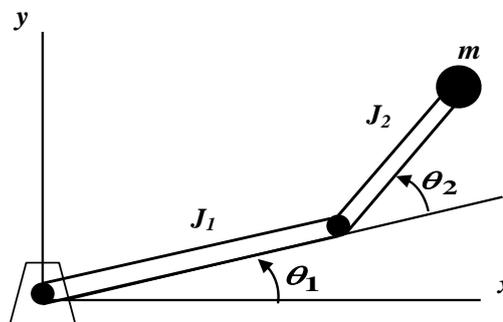


Fig.1. Two-link rigid type robot manipulator.

Table 1. Parameters of the two-link rigid type robot [1].

Parameters link 1	Parameters link 2
$m_1 = 13.86 \text{ oz}$	$m_2 = 3.33 \text{ oz}$
$J_1 = 42.39 \text{ oz in}^2$	$J_2 = 80.70 \text{ oz in}^2$
$l_1 = 8 \text{ in}$	$l_2 = 6 \text{ in}$
$r_1 = 4.12 \text{ in}$	$r_2 = 3.22 \text{ in}$
$b_1 = 20 \text{ oz in s}$	$b_2 = 50 \text{ oz in s}$
$m_L \in [10,20] \text{ oz}$	

The robot system is simulated with the goal of controlling the manipulator movement from any initial position to an upward or downward position with different payload. The dynamic equation of the SCARA robot manipulator as taken from reference [1] is defined below:

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} + \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} + \begin{bmatrix} W_1 \\ W_2 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (1)$$

where

q is the generalized coordinate vector

τ is the generalized force vector

$M(q)$ is the inertia matrix

$V(q, \dot{q})$ is the Coriolis/centripetal vector

$W(q)$ is the gravity vector

$U(q)$ is the friction vector

The elements in the above equation have been calculated as follows.

$$q = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix} = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}, \quad \tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$$

$$M_{11} = J_1 + J_2 + m_1 r_1^2 + m_2 l_1^2 + m_2 r_2^2 + 2m_2 l_1 r_2 \cos q_2 + m_L l_1^2 + m_L l_2^2 + 2m_L l_1 l_2 \cos q_2$$

$$M_{12} = J_2 + m_2 r_2^2 + 2m_2 l_1 r_2 \cos q_2 + m_L l_2^2 + m_L l_1 l_2 \cos q_2$$

$$M_{21} = J_2 + m_2 r_2^2 + m_2 l_1 r_2 \cos q_2 + m_L l_2^2 + m_L l_1 l_2 \cos q_2$$

$$M_{22} = J_2 + m_2 r_2^2 + m_L l_2^2$$

$$V_1 = (m_2 l_1 r_2 + m_L l_1 l_2)(2\dot{q}_1 - \dot{q}_2)\dot{q}_2 \sin q_2$$

$$V_2 = (m_2 l_1 r_2 + m_L l_1 l_2)\dot{q}_2 \sin q_2$$

$$U_1 = b_1 \dot{\theta}_1 = -b_1 \dot{q}_1$$

$$U_2 = b_2 \dot{\theta}_2 = b_2 \dot{q}_2$$

$$W_1 = (m_1 g r_1 + m_2 g l_1 + m_L g l_1) \sin q_1 + (m_2 g r_2 + m_L g l_2) \sin(q_1 + q_2)$$

$$W_2 = (m_2 g r_2 + m_L g l_2) \sin(q_1 + q_2)$$

The control is given by FSC, hence

$$\tau = M(q)u + N(q, \dot{q}) \quad (2)$$

Where:

$$N(q, \dot{q}) = \begin{bmatrix} V_1 + U_1 + W_1 \\ V_2 + U_2 + W_2 \end{bmatrix}$$

Under the FSC control; that is

$$\ddot{q} = M(q)^{-1}(\tau - N(q, \dot{q}))$$

2.2. Two-Link Type Flexible Robot Model

Here we illustrate the dynamic analysis of pneumatic flexible robot with two degrees of freedom. This model considers the force for each of the joints and the simplified structure, as shown in Fig 2. The robot system is simulated with the goal of tracking and controlling the manipulator movement from any initial position to an upward or downward position.

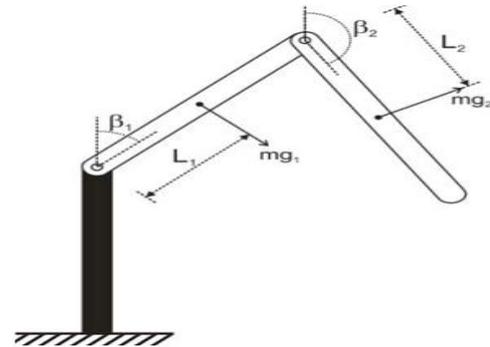


Fig. 2 Two-link flexible type robot manipulator

Table 2. Parameters of the two-link flexible type robot [7].

Parameters link 1	Parameters link 2
$m_1 = 1.1 \text{ Kg}$	$m_2 = 1.5 \text{ Kg}$
$J_1 = 0.015193 \text{ Kg m}^2$	$J_2 = 0.03192 \text{ Kg m}^2$
$L_1 = 0.5 \text{ m}$	$L_2 = 0.5 \text{ m}$
(Friction constant) $K=0.25$	
(Gravity force) $g = 9.81 \text{ m/s}^2$	

The dynamic equations of the pneumatic flexible robot manipulators are derived in reference [7]. To convert the dynamic equations into space states, equation (3) is used.

$$\begin{aligned} X_1 &= \dot{B}_1 & \dot{X}_1 &= \ddot{B}_1 \\ X_2 &= \dot{B}_1 & \dot{X}_2 &= \dot{B}_1 = X_1 \\ X_3 &= \dot{B}_2 & \dot{X}_3 &= \ddot{B}_2 \\ X_4 &= \dot{B}_2 & \dot{X}_4 &= \dot{B}_2 = X_3 \end{aligned}$$

The space state for dynamic equations is:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_3 \cos(X_4 - X_2) & 0 & 2C_1 \\ 0 & 0 & 1 & 0 \\ 0 & 2C_2 & 0 & C_3 \cos(X_4 - X_2) \end{bmatrix} \begin{bmatrix} \dot{X}_4 \\ \dot{X}_3 \\ \dot{X}_2 \\ \dot{X}_1 \end{bmatrix} = \begin{bmatrix} X_3 \\ C_4 \sin X_2 + C_3 \sin(X_4 - X_2)X_4^2 \\ X_1 \\ C_5 \sin X_4 - C_3 \sin(X_4 - X_2)X_1^2 \end{bmatrix}$$

(3)

Where:

$$C_1 = \frac{1}{2}m_1L_1^2 + 2m_2L_1^2 + \frac{1}{2}J_1$$

$$C_2 = \frac{1}{2}(m_2L_2^2 + J_2)$$

$$C_3 = 2m_2L_1L_2$$

$$C_4 = gL_1(\frac{1}{2}m_1 + m_2)$$

$$C_5 = \frac{1}{2}m_2gL_2$$

Equation (4) shows the friction force, on each of joint, with torque considerations.

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_3 \cos(X_4 - X_2) & 0 & 2C_1 \\ 0 & 0 & 1 & 0 \\ 0 & 2C_2 & 0 & C_3 \cos(X_4 - X_2) \end{bmatrix} \begin{bmatrix} \dot{X}_4 \\ \dot{X}_3 \\ \dot{X}_2 \\ \dot{X}_1 \end{bmatrix} = \begin{bmatrix} X_3 \\ C_4 \sin X_2 + C_3 \sin(X_4 - X_2)X_4^2 - K_2X_2 + \tau_2 \\ X_1 \\ C_5 \sin X_4 - C_3 \sin(X_4 - X_2)X_1^2 - K_1X_1 + \tau_1 \end{bmatrix} \quad (4)$$

Where K is the constant friction of each joint.

3- Structure Of Fuzzy Bang-Bang Controller For Mimo System

The FBBC is reviewed in this section. In addition, a special type of membership functions, the complement type, is defined. The ranges of state input and output variables are necessary for any fuzzy controller, which are considered to be a reasonable representation of situations that controller may face and yield to stability of the controller. Fig.3 shows the structure of FBBC with the self-tuning scheme.

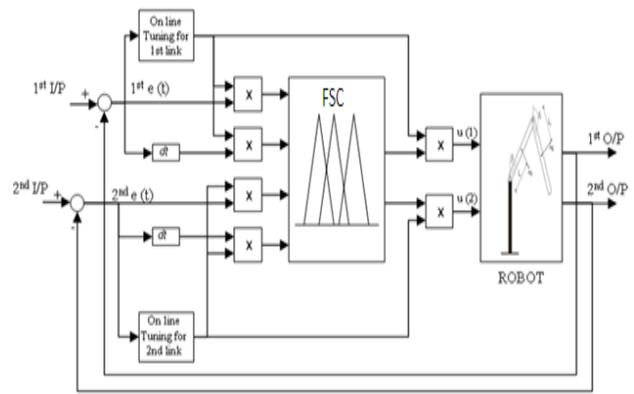


Fig.3 The structure of FBBC with the On line self-tuning scheme in Matlab/Simulink environment.

3.1. Linguistic Description

The input and output parameters, as well as the partitions and spread of the controller membership functions are initially selected to match the dynamic response of a robotics manipulator system. The inputs $x_i \in X_i$, where $i=1,2,3,4$ is the input index of the controller and X_i is the universe of discourse of the four inputs. For input variable, x_1 = "error angle for link 1", x_2 = "error angle for link 2", the universe of discourse, $X_{i=1,2} = [-20, 20]$ deg, which represents the range of perturbation angle about the zero reference. For input variable x_3 = "error angle rate for link 1", and x_4 = "error angle rate for link 2", the universe of discourse $x_3 = x_4 = [-10, 10]$ deg. The output universe of the Takagi-Sugeno's discourse $u_j = [-1, 1]$ represents the bang-bang output Where $j=1,2$ is the output index of the controller. The linguistic variable \tilde{A}_i^k is the membership function of antecedent part defined as $\tilde{A}_i^k = [\tilde{A}_i^1 = LN, \tilde{A}_i^2 = LP]$ (5)

where, Index k is assigned to tally the linguistic input membership functions and Index i is assigned to tally the input variables. Similar values are selected for inputs $x_{i=1,2,3,4}$ where the membership functions are assigned as $\tilde{A}_1^k \equiv \tilde{A}_2^k \equiv \tilde{A}_3^k \equiv \tilde{A}_4^k$. The set B^k which denotes the membership function values for outputs variable u_j are defined as

$$B_j^k = [B_1^1 \rightarrow Nbang_1, B_1^2 \rightarrow Pbang_1]$$

$$B_j^k = [B_2^1 \rightarrow Nbang_2, B_2^3 \rightarrow Pbang_2] \quad (6)$$

Where, Index k is assigned to tally the input membership functions. $j=1, 2$ is the output index of the controller for the robot manipulators link 1 and link 2, respectively. Fig.4 shows two levels Bang-Bang y^{crisp} output.

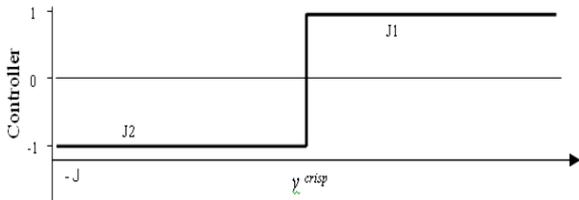
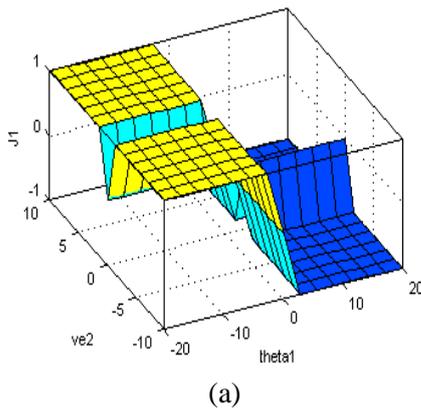


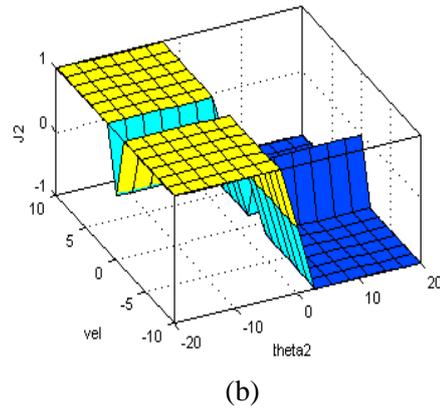
Fig.4. FBBC two levels Bang-Bang y^{crisp} output.

3.2. Fuzzy Rules

The Fuzzy bang-bang linguistic rules assembled in this work reset the robot manipulators to the desired position. These rules are based on four inputs variables, each with three linguistic values are defined as (LN, Z, and LP). Where LN = Large Negative, LP = Large Positive, thus there are at most ($N= 34$) possible rules. The tuning rules-partitions are heuristically chosen to reset the links smoothly over the universe of discourse. Fig.5 ((a) & (b)) respectively show the surface for the rules of the FBBC for MIMO. These rules can be illustrated as a representation of the matrix (34×3) (the number of membership function is depicted). The main diagonal entry in the rules given in Table 3 is not used. The tuning rules-partitions are heuristically chosen to reset the links smoothly over the universe of discourse.



(a)



(b)

Fig.5. Viewer Surface for the rules of the FBBC: (a) First Output (b) Second Output.

Table 3 Fuzzy Rules for FBBC

$E \delta$	LN	Z	LP
LN	+J	+J	
Z	+J		-J
LP		-J	-J

The symmetry of the rules matrix is expected as it arises from the symmetry of the system dynamics. Minimum decomposition of linguistic rules from the FBBC's inputs to the outputs is described in the following equation.

$$\mu_{B_i}(y_n) = \left[\mu_{A_{i,j}^k}(x_i) \wedge \mu_{A_{i+1,j}^k}(x_{i+1}) \right] \quad (7)$$

where $i=1,2,3,4$ is the input index of the controller and $j= 1, 2, 3, 4, \dots, N$, is the index of N matching rules, which are applicable from inferences of inputs. $n=1, 2$ is the output index of the system.

3.3 Fuzzy Set Membership Functions

The input variables and values assigned to fuzzy set membership functions are shown in Fig. 6. Triangular shape membership functions are used in this work. These membership functions are sensitive to small changes that occur in the vicinity of their centers. A small change across the central membership function A_i^2 , located at the origin, can produce abrupt switching of control command u_j between the +ve and -ve halves of the universe of discourse, resulting in chattering. The overlapping of the central membership function membership function A_i^2 with the neighboring membership functions A_i^1 and A_i^3 reduce the sensitivity of the bang-bang control action where, $i=1,2,3,4$ is the input index of the controller. Triangular

membership functions in Fig.6 are based on mathematical characteristics given in Table 4. In Table 4, the a_i and b_i are the parameters for range and central location of membership functions respectively, where $i=1, 2, 3, 4$ is the input index of the controller and shown in Fig.6. Smooth transition between the adjacent membership functions is achieved with higher percentage of overlap, which is commonly set to 50%.

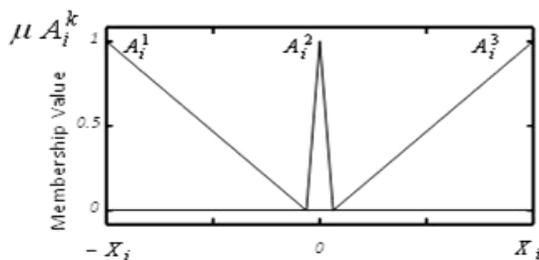


Fig.6. The input variables and values assigned to fuzzy set membership functions

Table 4 Mathematical Characterization of Triangular Membership Functions

Linguistic value	Triangular Membership functions
$A_i^{k=1}$	$\mu_i A_i^1(x_i) = \begin{cases} 1 & x = -b_i \\ 1 + \frac{2 x - a_i }{b_i} & -b_i < x_i \leq -a_i \end{cases}$
$A_i^{k=2}$	$\mu_i A_i^2(x_i) = \begin{cases} 1 - \frac{2 x_i - a_i }{b_i} & -a_i \leq x_i \leq 0 \\ 1 + \frac{2 x_i - a_i }{b_i} & 0 < x_i \leq a_i \end{cases}$
$A_i^{k=3}$	$\mu_i A_i^3(x_i) = \begin{cases} 1 - \frac{2 x_i - a_i }{b_i} & a_i \leq x_i \leq b_i \\ 1 & x_i = b_i \end{cases}$

3.4. Online Self-Tuning

Control performance of a system can be improved by tuning the controller gains. The proposed tuning method in this paper adjusts the heading reference command of the controller instead of directly adjusting the controller gains. The tuning method uses the gradient descent method to tune the fuzzy gains values. The originality on this proposed method is the use of the fuzzy bang-bang controller together with the online self-tuning to control heading direction of the robot's manipulators. The steady state error is eliminated online during the robot work. The cross coupling effect to the control axis is also reduced. It is a kind of an adaptive control, since when the robot dynamics changes, the control system will tune itself and adapt to the new

position movement condition. The main advantage of online tuning is that it makes the development simpler in practical. In this proposed method, the fuzzy parameters are adapted online and automatically based on the control performance. The method of steepest descent (also known as the gradient method) is the simplest example of a gradient based method for minimizing a function of several variables. Fig.7 illustrates one of the online self-tuning blocks.

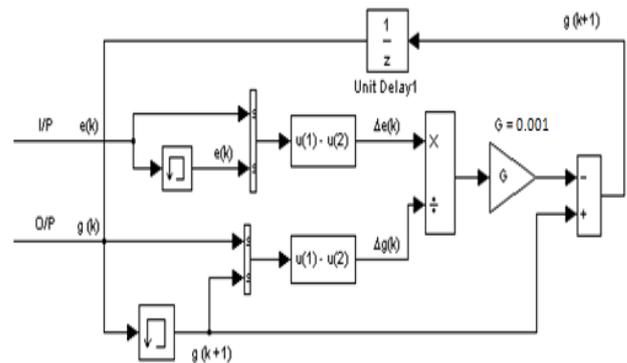


Fig.7 block diagram of the online self-tuning

The online self-tuning mechanism is shown in Fig.7, heading error, $e(k)$, and change of heading error, $e\Delta(k)$, are determined as follow.

$$e(k) = y_r(k) - y(k) \tag{8}$$

$$e\Delta(k) = e(k) - e(k-1) \tag{9}$$

Where $y_r(k)$ is the command reference and $y(k)$ is the actual output response. The self-tuning method of the FBBC applies double gradient descent block technique each one tune FBBC output. The FBBC is tuned by minimizing a cost function. The cost function is defined as the difference between the actual heading and the reference command as expressed in equation (10).

$$\Delta f = \frac{\Delta e(k)}{\Delta g(k)} \tag{10}$$

Substitute equation (10) in (9) yield

$$e(k+1) = e(k) - G \frac{\Delta e(k)}{\Delta g(k)} \tag{11}$$

The search starts at an arbitrary point e_0 and then slide down the gradient, until we are close enough to the suitable gains. Obviously, we need to move to the point where the function $f \rightarrow e$ takes on a minimum value, by using descent gradient method update of

$$g(k+1) = g(k) + G \frac{\partial E(k)}{\partial g(k)} \tag{12}$$

Where,

$e(k), e(k+1)$ = values of the error variables in the k and $k+1$ iteration.

$f(k)$ = The choice of direction function to be minimized.

Δf = gradients of the objective function, constituting the direction of travel.

G = the gradients step size.

$g(k)$ = is the gain of the output point of the gradient.

$\Delta g(k)$ = the deference of the output point gain's reference command

The method of Steepest Descent is simple, easy to apply and each iteration is fast. Is it also very stable; if the minimum points exist, the method is guaranteed to locate the suitable gains values after a few number of iterations [21].

4. Simulation Results and Discussion

In order to show the improvement due to the proposal controller, we demonstrate in two sections the proposed real time FBBC by the tracking control of a two-link rigid and flexible robotic manipulator with two degree of freedom rotationally.

Rigid robot manipulators described by angles q_1 and q_2 to evaluate the performance of the proposed controller thus obtained, we simulate the actual response of the system for different m_L . Fig (8, a) shows the robot's links precisely tracking the desired input under the FBBC with payload 20 oz and $q_1 = \frac{\pi}{2} \sin(\frac{\pi}{2})$ rad/sec, $q_2 = \frac{\pi}{2} \sin(\frac{\pi}{2})$ rad/sec desired angles and input frequency $\omega = 0.5$ rad/sec. Figs (8, b & c) show the speed of tuned FBBC action for link1 and link2 respectively even with big payload and friction. Fig (8, d & e) show respectively small error evaluation around 0.01 rad/sec for link 1 and 0.02 rad/sec for link 2.

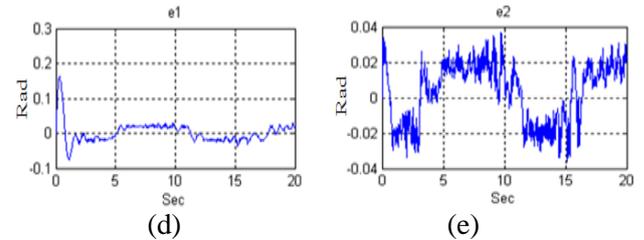


Fig.8. The rigid robot manipulators with $m_L=20$ oz under FBBC: (a) link1 position and link2 position, (b) FBBC input for link 1(c) FBBC input for link 2, (d) error of link 1 (e) error of link 2.

Figs.9 demonstrates the performance of the proposed controller in controlling the rigid manipulators' upward movement with 15 oz payload and $q_1 = \frac{\pi}{2}$ rad/sec, $q_2 = \frac{\pi}{2}$ rad/sec desired angles. Fig (9, a) shows fast convergence time just in 8 sec for link 1 and 5 sec for link 2. Less overshoot for link 1 and very small for link 2. Figs (9, b & c) show the tuned FBBC's action for link 1 and link 2 respectively. Fig (9, d & e) show respectively link 1 and link2 error's evaluation which are both approximately zero.

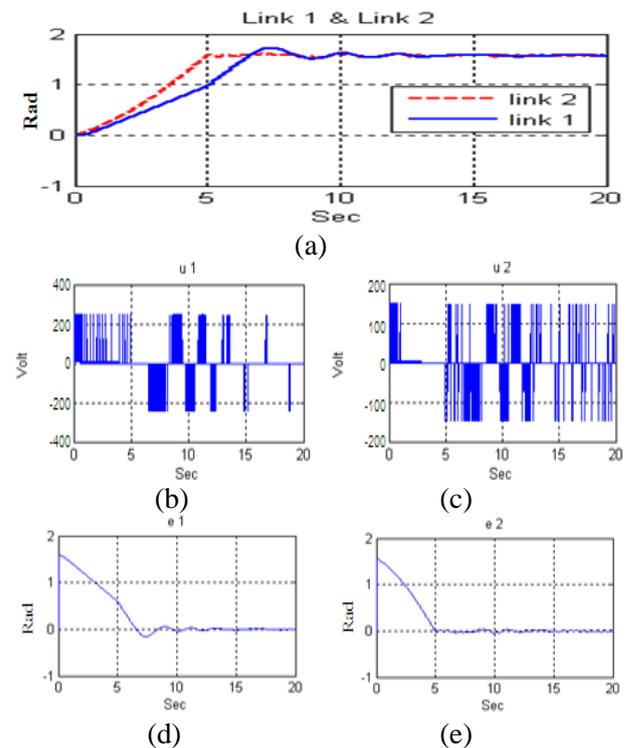
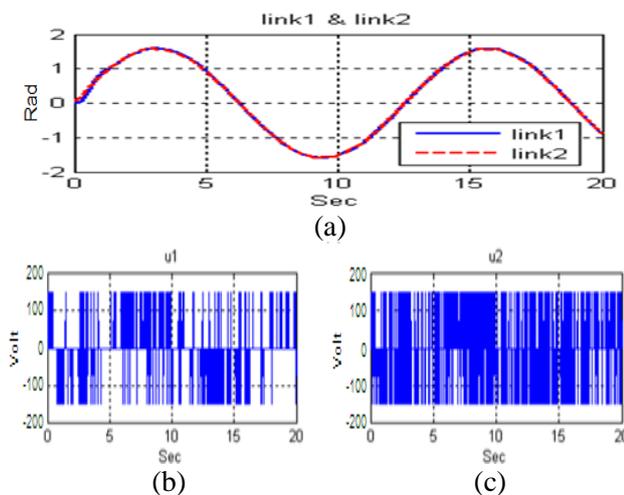


Fig.9. The rigid robot manipulators with $m_L=20$ oz under FBBC: (a) link 1 position and link 2 position, (b) FBBC input for link 1(c) FBBC input for link 2, (d) error of link 1 (e) error of link 2.

Figs.10 demonstrates the performance of the proposed controller in controlling the rigid

manipulator downward movement with 10 oz payload and $q_1 = -\frac{\pi}{2}$ rad/sec, $q_2 = -\frac{\pi}{2}$ rad/sec. Fig

(10, a) shows fast convergence time and overshoot approximately zero for link1 one and link 2. Figs (10, b & c) show the tuned FBBC's action for link 1 and link 2 respectively. Fig (10, d & e) show that both link 1 and link2 have very justify errors. indicating that of the proposed tuned controller is accurate.

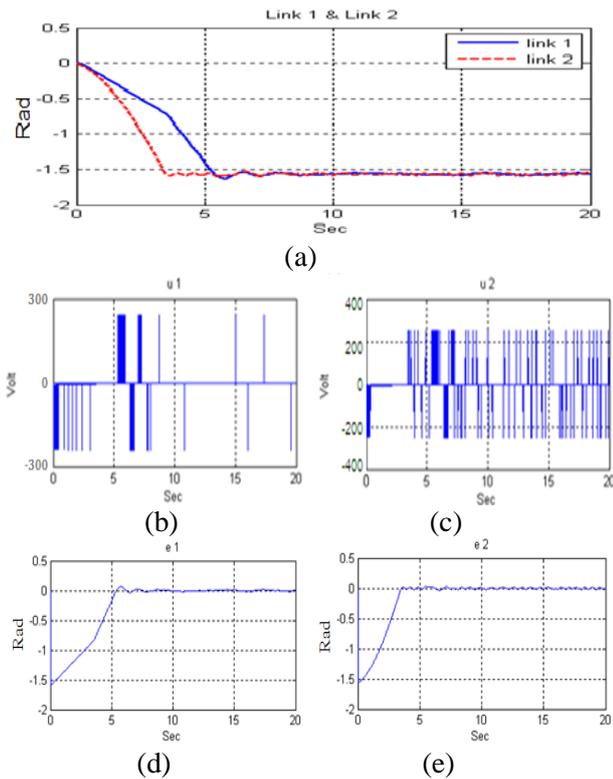


Fig.10. The rigid robot manipulators with $m_L=20$ oz under FBBC: (a) link 1 position and link 2 position, (b) FBBC input for link 1(c) FBBC input for link 2, (d) error of link 1 (e) error of link 2.

Flexible robot manipulators described by angles β_1 and β_2 to evaluate the performance of the proposed controller thus obtained, we simulate the actual response of the system. The tracking capabilities of the real time FBBC for the two link flexible robot's manipulator are shown in Fig11. Fig (11, a) shows the high nonlinear flexible robot's links precisely tracking the desired input under the FBBC and with $\beta_1 = -\frac{\pi}{2} \sin(\frac{\pi}{2})$ rad/sec, $\beta_2 = -\frac{\pi}{2} \sin(\frac{\pi}{2})$ rad/sec desired angles and input frequency $\omega = 0.5$ rad/sec. Figs (11, b & c) show the speed of tuned FBBC action for link1 and link2 respectively. Fig (11, d & e) show respectively

small error evaluation around 0.001 rad/sec for link 1 and 0.006 rad/sec for link 2.

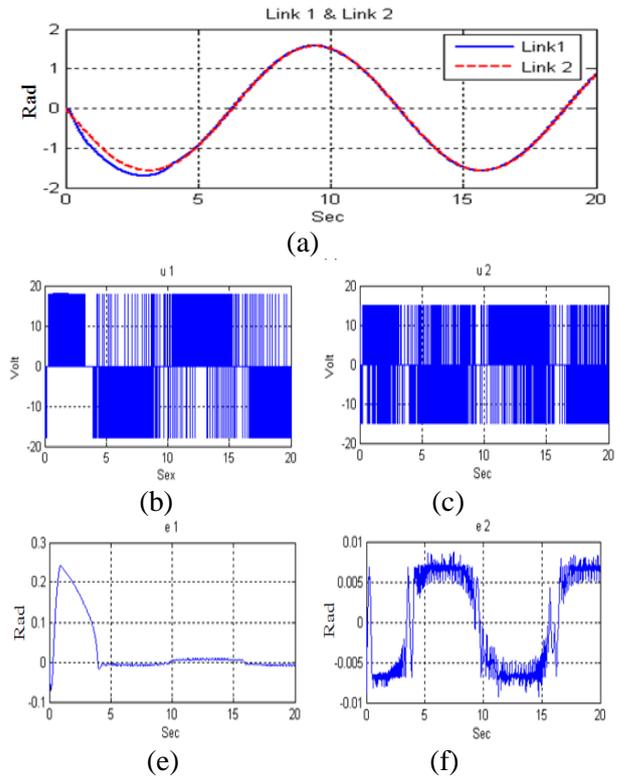


Fig.11. The flexible robot manipulators under FBBC: (a) link1 position and link2 position, (b) FBBC input for link 1(c) FBBC input for link 2, (d) error of link 1 (e) error of link 2.

In Fig.12 shows the performance of the proposed controller in controlling the two link flexible manipulators' upward movement by $\beta_1 = (\pi)$ rad, $\beta_2 = (\pi)$ rad. Fig (12, a) shows fast convergence time around 12 sec for link 1 and 8 sec for link 2 also, small overshoot for link 1 one and link 2 around 1.35 rad/sec . Figs (12, b & c) show the tuned FBBC's action for link1 and link2 respectively. The steady state error eliminated Fig (12, d & e) show that both link 1 and link 2 have errors close to zero. The effect of cross coupling was reduced. However, as shown in the results, there are some overshoots in the output responses. This was because of the fixed tuning rate. In order to achieve a better result, variation of the tuning rate is required.

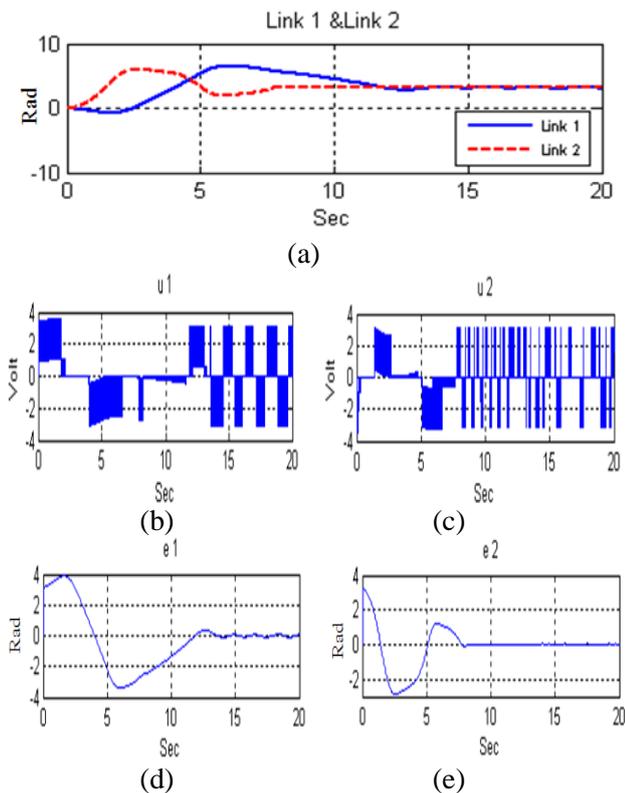


Fig.12. The flexible robot manipulators under FBBC: (a) link 1 position and link 2 position, (b) FBBC input for link 1(c) FBBC input for link 2, (d) error of link 1 (e) error of link 2.

In Fig.13 shows the performance of the proposed controller in controlling the two link flexible manipulator downward movement by $\beta_1 = (-\pi)$ rad, $\beta_2 = (-\pi)$ rad. Fig (13, a) shows fast convergence time around 10 sec link 1 and 7 sec for link 2 also, small overshoot for link 1 and link 2 which around 1.25 rad/sec . Figs (13, b & c) show the tuned FBBC's action for link 1 and link 2 respectively. Fig (13, d & e) show that link 1 and link 2 have small errors approximately zero.

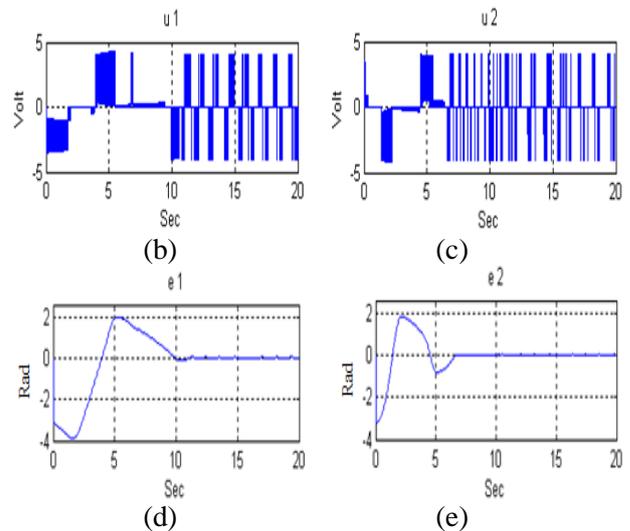
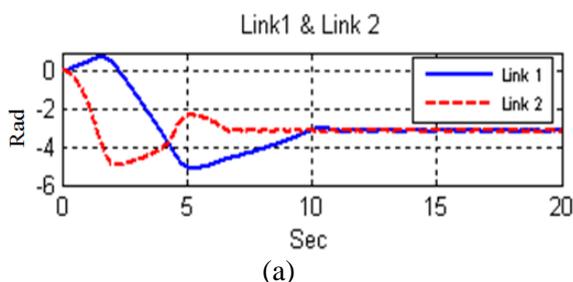


Fig.13. The flexible robot manipulators under FBBC: (a) link 1 position and link 2 position. (b) FBBC input for link 1(c) FBBC input for link 2, (d) error of link 1 (e) error of link 2.

5. Conclusion

A MIMO fuzzy bang-bang controller for rigid and flexible robot is proposed and the effectiveness is confirmed through simulations for both rigid and flexible manipulators. The simulation models representing rigid and flexible robots have non-concentrated link masses at the centers. Hence, each link has a moment of inertia. We also assume that there are frictions in the joints. Fuzzy controllers as known for absorbing the non-linearity of the systems and, as the results showed, it works well for real nonlinear MIMO systems. The bang-bang controller is inherently stable, and this property is an important feature of FBBC. The FBBC parameters are tuned automatically online. This real time tuning is simply done by adding the gradient method in front of the FBBC controller. The performance was evaluated by many simulations.

The results demonstrated good performance of online self-tuning. The steady state error was eliminated. The effect of cross coupling was reduced. The settling time is also decreased. However, as shown in the results, there are some overshoots in the output responses. This was because of the fixed learning rate. In order to achieve a better result, variation of the learning rate is required. The new controller is simple in configuration with two level output, similar to Bang-Bang relay controls and yet has a fuzzy decision making capability on its input side. The front-end inputs are similar to standard fuzzy controllers based upon Takagi-Sugeno's type fuzzy

model but have a largest of Maxima defuzzification output. The simulation results confirm the dynamic control capabilities of the FBBC combined with an online self-tuning.

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