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FUZZY DISTURBANCE REJECTION CONTROL OF TWO LINK ROBOT MANIPULATOR

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ABSTRACT

It is well known that robotic manipulators are nonlinear coupling dynamic systems. The control strategy is fuzzy logic technique to cope with the model parameter disturbances. The simulation is implemented to verify the effectiveness of the proposed fuzzy control policy. From the simulation results, strong robustness, fast response, good disturbance rejection capability and good tracking capability can be obtained. It is also illustrated from simulation results that the proposed control technique is valid for the two-link robot manipulator.

1. INTRODUCTION

In recent decades, the robot research has been paid great attention. Robotic is a vast and fast growing research field, mainly because of the many potential applications. The problem in robot control is to make manipulator to follow reference trajectory. Therefore, it must be controlled to track angle reference because there exist strong coupling and time-varied of the system parameters, and external disturbances. In order to achieve this target, many strategies which were proportional, integral and derivative (PID) control, optimal control, variable structures control (VSS), adaptive control, fuzzy control and so on, have been presented, Jinkun [1].

The modeling complexity of multi-link robots is well documented in the previous papers, [2-5]. Hence, even if an accurate robot model can be concluded, it is often too complex to use in controller development, especially for many control design methods that require definite plant assumptions (e.g., nonlinearities). It is for this reason that conventional robot control are extracted either (1) via simple straightforward plant models that descript the needful assumptions, or (2) via the cling tuning of linear/nonlinear control polices.

However, such control policies that use heuristics to tune the controller parameters have been succeeded. For a process such as two link robot, the success can be achieved to the use traditional control strategies with mathematical model. In this paper, a method for fuzzy control tuning will be introduced.

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2. LAGRANGIAN FORMULATION OF MANIPULATOR DYNAMICS

In Engineering, robots not only can improve productivity but also can perform at hazardous jobs, highly difficult and high-strength. Manipulators are the usual plants in robotics. Using the Lagrangian formulation, the dynamic equation of rigid manipulator can be presented as follows, Siciliano and Khatib [6].

$$g_{sl_1}(0) = \begin{bmatrix} I & \begin{pmatrix} 0 \\ 0 \\ r_o \end{pmatrix} \\ 0 & 1 \end{bmatrix} \text{ and } g_{sl_2}(0) = \begin{bmatrix} I & \begin{pmatrix} 0 \\ r_1 \\ l_o \end{pmatrix} \\ 0 & 1 \end{bmatrix} \quad (1)$$

To calculate the kinetic energy of robot manipulator with n joints we define a coordinate frame, L_i, attached to the center of mass of the i^{th} link

$$T_i(\theta,\dot{\theta}) = \frac{1}{2}(V_{sli}^b)^T M_i V_{sli}^b = \frac{1}{2}\dot{\theta}^T J_i^T(\theta) M_i J_i(\theta)\dot{\theta}, \quad (2)$$

Where M_i is the generalized inertia matrix for the i^{th} link. Now the total kinetic energy can be formulated as

$$T(\theta,\dot{\theta}) = \sum_{i=1}^{n} T_i(\theta,\dot{\theta}) = \frac{1}{2}\dot{\theta}^T M(\theta)\dot{\theta} \quad (3)$$

The matrix $M(\theta) \in \mathrm{R}^{nxn}$ is the manipulator inertia matrix which is defined as

$$M(\theta) = \sum_{i=1}^{n} J_i^T(\theta) M_i J_i(\theta) \quad (4)$$

With this choice of link frames, the inertia matrices will be presented in the next form.

$$M_i = \begin{bmatrix} m_i & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{xi} & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{yi} & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{zi} \end{bmatrix} \quad (5)$$

where I_{xi}, I_{yi}, and I_{zi} are the moments of inertia about axes of the i^{th} link frame and m_i is the mass of the object. Computation the link frame Jacobians.

$$J_1 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix} \text{ and } J_2 = \begin{bmatrix} -r_1 C\phi & 0 \\ 0 & 0 \\ 0 & -r_1 \\ 0 & -1 \\ -S\phi & 0 \\ C\phi & 0 \end{bmatrix} \quad (6)$$

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The inertia matrix for the system is given by

$$M(\theta) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = J_1^T M_1 J_1 + J_2^T M_2 J_2 \quad (7)$$

where $M_{11} = I_{y2} S^2\phi + I_{z1} + I_{z2} C^2\phi + m_2 r_1^2 C^2\phi$, $M_{12} = 0$, $M_{21} = 0$, $M_{22} = I_{x2} + m_2 r_1^2$

To complete the derivation of the lagrangian, we must calculate the potential energy of the manipulator. Let $h_i(\theta)$ be the center height of the ith link mass (height is the component of the position of the centre mass opposite the direction of gravity). The i^{th} link potential energy is:

$$V(\theta) = \sum_{i=1}^{n} V_i(\theta) = \sum_{i=1}^{n} m_i g h_i(\theta) \quad (8)$$

Where g is the gravitational constant and m_i is the mass of the ith link.
Gathering this with the kinetic energy:

$$L(\theta, \dot{\theta}) = \frac{1}{2} \dot{\theta}^T M(\theta) \dot{\theta} - V(\theta) \quad (9)$$

Substitute in lagrange's equations,

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}_i} - \frac{\partial L}{\partial \theta_i} = \tau_i \quad (10)$$

where τ_i is the actuator torque. Then,

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + N(\theta, \dot{\theta}) = \tau \quad (11)$$

Where N(θ, θ) includes gravity terms and others forces which act at the joints and τ is the vector of actuator torques. This is a 2nd order vector differential equation for the manipulator motion. The matrices C and M, which illustrate the manipulator inertial properties, have important properties.
The forces are presented as:

$$C_{ij}(\theta, \dot{\theta}) = \sum_{k=1}^{n} \Gamma_{ijk} \dot{\theta}_k = \frac{1}{2} \sum_{k=1}^{n} \left(\frac{\partial M_{ij}}{\partial \theta_k} + \frac{\partial M_{ik}}{\partial \theta_j} - \frac{\partial M_{kj}}{\partial \theta_i} \right) \dot{\theta}_k \quad (12)$$

A messy calculation clears that the non-zero values of Γ_{ijk} are given

$\Gamma_{11} = C\phi S\phi (I_{y2} - I_{z2} - m_2 r_1^2)$, $\Gamma_{12} = C\phi S\phi (I_{y2} - I_{z2} - m_2 r_1^2)$, $\Gamma_{21} = C\phi S\phi (I_{z2} - I_{y2} + m_2 r_1^2)$

Finally, the effect of gravitational forces on the manipulator are written as $N(\theta, \dot{\theta}) = \frac{\partial V}{\partial \theta}$,

where $V: \mathbb{R}^n \rightarrow \mathbb{R}$ is the manipulator potential energy.

$$V(\theta) = m_1 g h_1(\theta) + m_2 g h_2(\theta) \quad (13)$$

Where h_i is the center of mass height for the ith link. By using the forward kinematics map we can get,

$$g_{sl_i}(0) = e^{\hat{\zeta}_1 \theta_1} \ldots\ldots e^{\hat{\zeta}_i \theta_i} g_{sl_i}(0) \quad (14)$$

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which gives $h_1(\alpha) = r_o$, $h_2(\phi) = l_o - r_1 S\phi$

By taking the derivative gives

$$N(\theta,\dot{\theta}) = \frac{\partial V}{\partial \theta} = \begin{bmatrix} 0 \\ -m_2 g r_1 C\phi \end{bmatrix} \quad (15)$$

3. FUZZY CONTROLLER DESIGN

In this part, a primary objective here is to reduce the vibration at the end point as much as possible while still achieving adequate slew rates, it was decided to couple the controller for the elbow to the shoulder link. Note that in addition to the six normalizing gains g_{e1}, g_{e2}, g_{a1}, g_{a2}, g_{v1}, and g_{v2} a seventh gain is g_{a12} is added to the system. This gain can also be varied to tune the controller and need not be the same as g_{a1}.

Essentially, in coupling the controllers we are using our experience and intuition to redesign the fuzzy controller. Figure 1.a shows the proposed coupled fuzzy controller and the rule base and the membership functions for the shoulder are shown in Figure 1.b and Table 1, and the elbow link rule base is formulated to include the acceleration information from the shoulder link endpoint. The number of rules for the 2nd link with 7 fuzzy sets increased to *343 (7x7x7)*. Hence, the number of rules used for the coupled direct fuzzy controller is 121 for the shoulder controller, plus *343* for the elbow link controller, for a total of 464 rules.

The universe of discourse for the position error is chosen to be *[-250, 250]* degree. The universe of discourse for the endpoint acceleration of the shoulder link is *[-8, 8]g*. The output universe of discourse of *[-0.8, 0.8]* volts as in the uncoupled case. The universe of discourse for the acceleration of the shoulder link is *[-2, 2]g*. The output voltage universe of discourse is *[-4, 4]* volts.

Tables 3-9 depict 3D rule base table for the elbow link. Table 6 represents the case when the acceleration input from the shoulder link is zero, and is the center of the rule base (the body of the table denotes the indices *m* for V_2). Tables 3-5 are for the case when the shoulder endpoint acceleration is negative, and Tables 7-9 are for the case when the shoulder endpoint acceleration is positive. The central portion of the rule base where makes use of the entire output universe of discourse. This is part of the rule base where the acceleration input from the shoulder link endpoint is zero or small. As we move away from the center of the rule base (to the region where the shoulder link endpoint acceleration is large), only a small portion of the output universe of discourse is used to keep the output of the controller small.

Thus the speed of the elbow link is dependent on the acceleration input from the shoulder link endpoint. The speed of the elbow link is decreased if the acceleration is large and is increased as the acceleration input decreases.

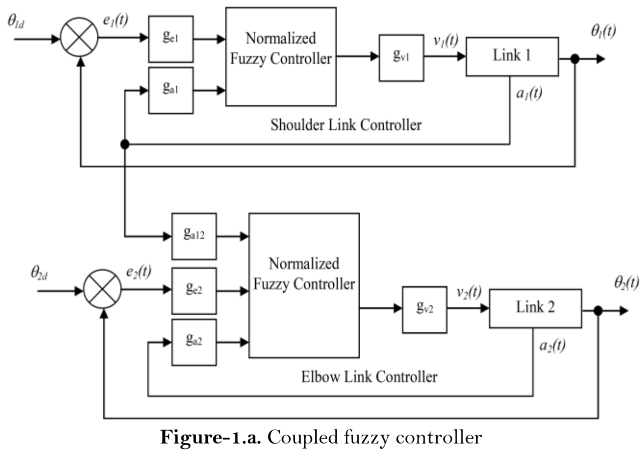

Figure-1.a. Coupled fuzzy controller

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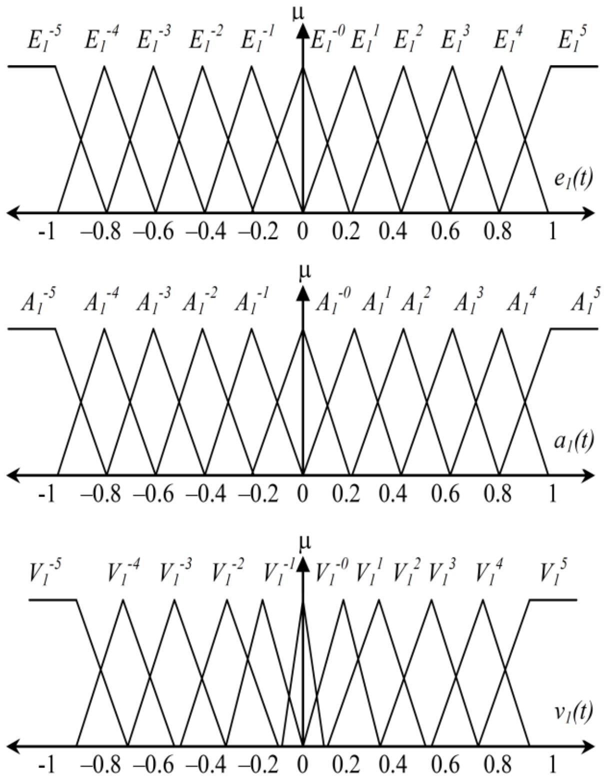

Figure-1.b. Membership functions for the shoulder controller

Table 1. Rule Base for Shoulder Link

V_1^m		A_1^k										
		-5	-4	-3	-2	-1	0	1	2	3	4	5
E_1^j	-5	-5	-5	-5	-4	-4	-3	-3	-2	-2	-1	0
	-4	-5	-5	-4	-4	-3	-3	-2	-2	-1	0	1
	-3	-5	-4	-4	-3	-3	-2	-2	-1	0	1	2
	-2	-4	-4	-3	-3	-2	-2	-1	0	1	2	2
	-1	-4	-3	-3	-2	-2	-1	0	1	2	2	3
	0	-4	-3	-2	-1	0	0	0	1	2	3	4
	1	-3	-2	-2	-1	0	1	2	2	3	3	4
	2	-2	-2	-1	0	1	2	2	3	3	4	4
	3	-2	-1	0	1	2	2	3	3	4	4	5
	4	-1	0	1	2	2	3	3	4	4	5	5
	5	0	1	2	2	3	3	4	4	5	5	5

Table-2. Rule Base for Base Link

V_2^m		A_2^k										
		-5	-4	-3	-2	-1	0	1	2	3	4	5
E_2^j	-5	-5	-5	-4	-4	-3	-3	-3	-2	-2	-1	0
	-4	-5	-4	-4	-3	-3	-3	-2	-2	-1	0	1
	-3	-4	-4	-3	-3	-3	-2	-2	-1	0	1	2
	-2	-4	-3	-3	-3	-2	-2	-1	0	1	2	2
	-1	-4	-3	-3	-2	-2	-1	0	1	2	2	3
	0	-4	-3	-2	-1	0	0	0	1	2	3	4
	1	-3	-2	-2	-1	0	1	2	2	3	3	4
	2	-2	-2	-1	0	1	2	2	3	3	3	4
	3	-2	-1	0	1	2	2	3	3	3	4	4
	4	-1	0	1	2	2	3	3	3	4	4	5
	5	0	1	2	2	3	3	3	4	4	5	5

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Also note that in Tables 5-7 there are three zeros in the middle rows to reduce the sensitivity of the controller to the noisy accelerometer signal. This noise is not a significant problem when the endpoint is oscillating, and so the rule base does not have the zero in the outer region. Taking the rule base as a three dimensional array, we get a central cubical core made up of zeros. Also notice that some parts of the rule base, especially toward the extremes of the third dimension, are not fully uniform. This has been done to slow down the elbow link when the acceleration input from the shoulder link is very large. Overall we, are incorporating our understanding of the physics of the plant into the rule base. We are shaping the nonlinearity of the fuzzy controller to try to improve performance.

The coupled proposed fuzzy controller seeks to vary the speed of the elbow link depending on the amplitude of oscillation in the shoulder link. If the shoulder link is oscillating too much, the speed of the elbow link is reduced so as to allow the oscillations in the shoulder link to be damped; and if there are no oscillations in the shoulder link, then the 2nd link speed is increased. We do this to eliminate the oscillation of the elbow link close to the set point, where the control voltage from the elbow link controller is small. This scheme works well as will be shown by the results, but the drawback is that it slow down the overall plant response as compared to the uncoupled case.

Table-3. Portion of Rule Base Array for the Elbow Link

A_1^{-3} V_2^m		A_2^k						
		-3	-3	-1	0	1	2	3
E_2^j	-3	-3	-3	-2	-2	-1	-1	0
	-2	-3	-2	-2	-1	-1	0	1
	-1	-2	-2	-1	-1	0	1	1
	0	-2	-1	-1	0	1	1	2
	1	-1	-1	0	1	1	2	2
	2	-1	0	1	1	1	2	2
	3	0	1	1	1	2	2	2

Table-4. Portion of Rule Base Array for The Elbow Link

A_1^{-2} V_2^m		A_2^k						
		-3	-3	-1	0	1	2	3
E_2^j	-3	-3	-3	-3	-2	-2	-1	0
	-2	-3	-3	-2	-1	-1	0	1
	-1	-3	-2	-2	-1	0	1	1
	0	-2	-2	-1	0	1	1	2
	1	-2	-1	0	1	1	2	2
	2	-1	0	1	1	2	2	2
	3	0	1	1	2	2	2	3

Table-5. Portion of Rule Base Array for The Elbow Link

A_1^{-1} V_2^m		A_2^k						
		-3	-3	-1	0	1	2	3
E_2^j	-3	-4	-4	-3	-3	-2	-1	0
	-2	-4	-3	-3	-2	-1	0	1
	-1	-3	-3	-2	-1	0	1	1
	0	-2	-2	0	0	0	1	2
	1	-2	-1	0	1	2	2	3
	2	-1	0	1	2	2	3	3
	3	0	1	2	2	3	3	3

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Table-6. Portion of Rule Base Array for The Elbow Link

A_1^{-0} V_2^m		A_2^k						
		-3	-3	-1	0	1	2	3
E_2^j	-3	-5	-4	-4	-3	-3	-2	0
	-2	-4	-4	-3	-2	-1	0	1
	-1	-4	-3	-2	-1	0	1	1
	0	-2	-1	0	0	0	1	2
	1	-2	-1	0	1	2	3	4
	2	-1	0	2	2	3	4	4
	3	0	1	2	3	4	4	5

Table-7. Portion of Rule Base Array for The Elbow Link

A_1^1 V_2^m		A_2^k						
		-3	-3	-1	0	1	2	3
E_2^j	-3	-4	-3	-3	-2	-2	-1	0
	-2	-3	-3	-2	-2	-1	0	1
	-1	-3	-2	-2	-1	0	1	2
	0	-2	-1	0	0	0	1	2
	1	-2	-1	0	1	2	3	3
	2	-1	0	1	2	3	3	4
	3	0	1	2	3	3	4	4

Table-8. Portion of Rule Base Array for The Elbow Link

A_1^2 V_2^m		A_2^k						
		-3	-3	-1	0	1	2	3
E_2^j	-3	-3	-2	-2	-1	-1	-1	0
	-2	-3	-2	-2	-1	-1	0	1
	-1	-2	-2	-1	-1	0	1	2
	0	-2	-1	-1	0	1	1	2
	1	-1	-1	0	1	1	2	3
	2	-1	0	1	1	2	3	3
	3	0	1	2	2	3	3	4

4. SIMULATION RESULTS

The simulation results to track reference based on the fuzzy control system by using MATLAB software is shown in Figure 2 and 3. The response arrived the steady state conditions with very small lag time. For the base axis and nearly the same for the shoulder axis. The error between the actual position output and the desired position output can converge to zero. Simultaneously, the controller signal changed according the reference inputs.

Figure 4-a shows the time responses of step disturbance reference input, the recovering had happened after 0.4 sec. for the base axis with zero steady state error. In Figure 5-a after 0.5 sec. for the shoulder axis with zero steady state error. The cross-ponding controller signal is shown in Figures 4-b and 5-b.

Table 9. Portion of Rule Base Array for The Elbow Link

A_1^3 V_2^m		A_2^k						
		-3	-3	-1	0	1	2	3
E_2^j	-3	-2	-2	-2	-1	-1	-1	0
	-2	-2	-2	-1	-1	-1	0	1
	-1	-2	-2	-1	-1	0	1	2
	0	-2	-1	-1	0	1	1	2
	1	-1	-1	0	1	1	2	2
	2	-1	0	1	1	2	2	3
	3	0	1	1	2	2	3	3

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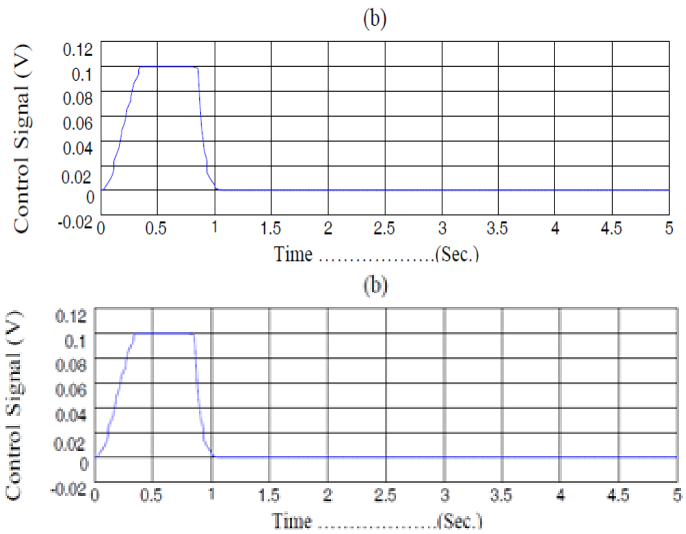

Figure-2. System motion curve response based on fuzzy controller (Base Axis)

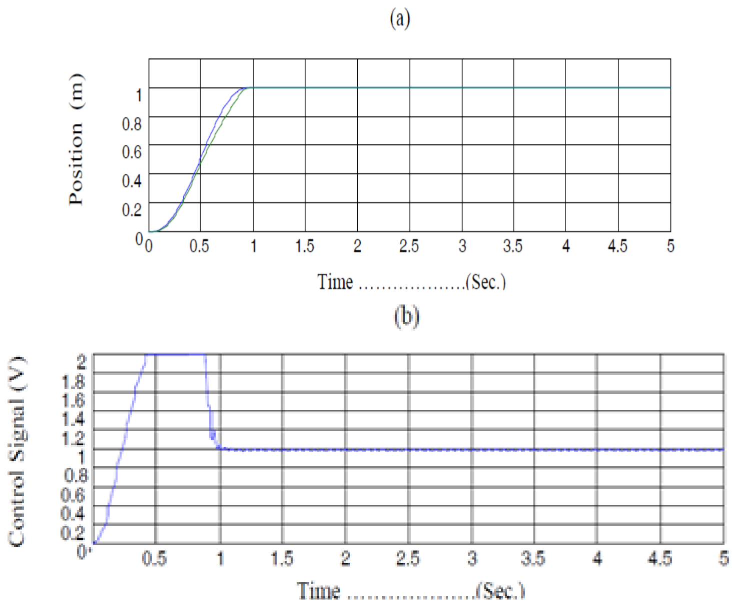

Figure-3. System motion curve response based on fuzzy controller (Shoulder Axis)

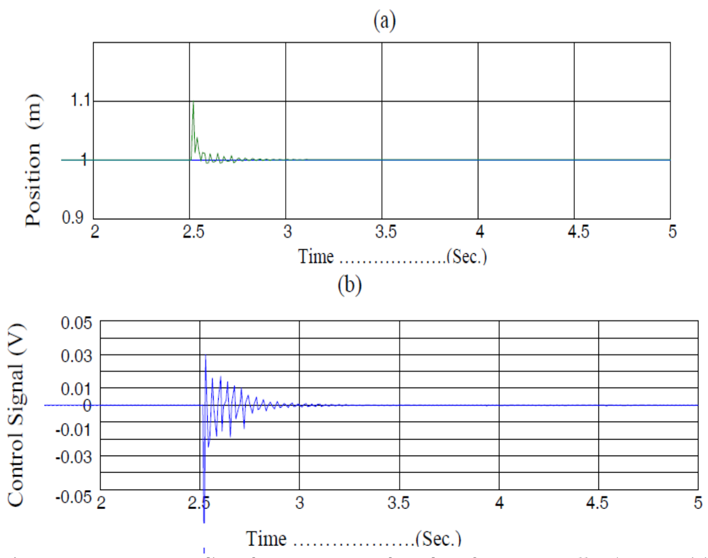

Figure-4. System step disturbance response based on fuzzy controller (Base Axis)

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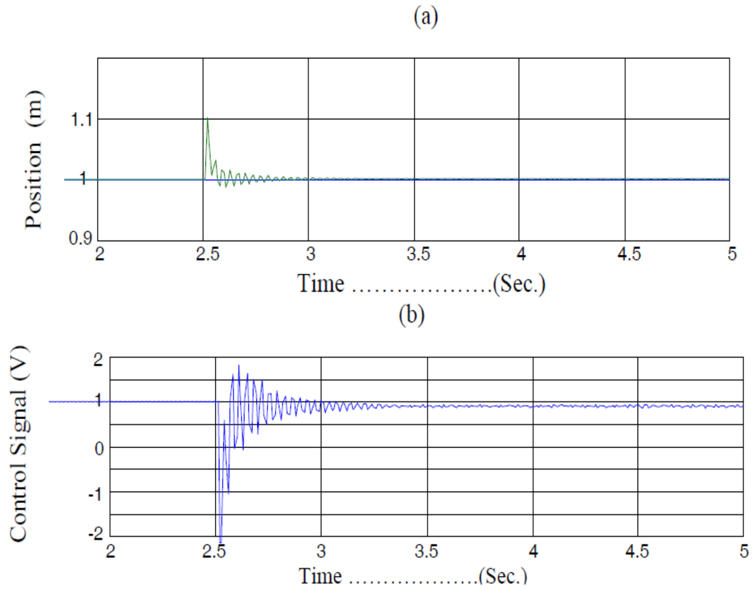

Figure-5. System step disturbance response based on fuzzy controller (Shoulder Axis)

5. CONCLUSIONS

One of the important challenges in the field of robotics is manipulators control with acceptable performance, because these systems are multi-input multi-output (MIMO), nonlinear and uncertainty. The control problem of a nonlinear system such as the coupled 2-DOF is investigated in this paper. A fuzzy control system has been implemented. The simulation results illustrate that the proposed controller can achieve desired performance and the algorithm is suitable for an inaccurate robot system. Simulation results also show the precise angle control, which is obtained in spite of disturbance in the system. These results also prove that the fuzzy control schemes are effective for the 2-link robot manipulator.

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