Dynamics and Control of a Pneumatically Actuated Robotic Manipulator

B. Sandeep Reddy and S.K. Dwivedy,
Department of Mechanical Engineering, Indian Institute of Technology, Guwahati, 781039, India

* Corresponding author (email: dwivedy@iitg.ernet.in)

Abstract

This paper deals with the dynamics and control of a two degree of freedom robot arm actuated by pneumatic artificial muscles (PAMs). The high power-weight ratio of PAMs justifies their use as actuators in robotics. To achieve trajectory tracking performance, controllers are constructed based on a dynamic model of the robot arm. Due to the high non-linear dynamics of the robotic system, fuzzy control is used for trajectory tracking tasks. The results in simulation are shown to achieve sufficiently good tracking performance.

Keywords: Dynamics, Control, PAM, Pneumatic,

Robot

1 Introduction

Modern day robotics shows a shift in trend from stiff industrial robots to robots designed to work in a domestic environment. The main research areas of focus in robotics today are [1]; autonomous behavior which refers to the robots performing single or multiple tasks without human supervision, human functionality which refers to the robot adopting human features, and compliant actuation, in which the robot has less rigid structures, low moving masses and light actuators enabling the robot to work in a domestic environment hence providing useful services to humans. This paper deals with the dynamics and control a robotic system having compliant actuators. There are several kind of pneumatic actuators [2]- cylinders, pneumatic engines, etc. But a less common type of actuator is the Pneumatic artifical muscle (PAM). Pneumatic artificial muscles (PAMs) are chosen as the actuators in the robot, as they are best suited for application in a domestic environment [3].

The advantages that a pneumatic actuator has over actuators like the commonly used DC motor is it's high-power-weight ratio [4] and compliance, where delicate operations like handling fragile objects (as in the case of manipulator arms) can be done with ease.

The pneumatic artificial muscle shown in Fig. 1 is very similar to the biological muscle. A PAM consists of a rubber tube surrounded by a braided nylon sheath with helical winding. When the rubber tube expands due to the increasing pressure, the diameter of the tube changes in the radial direction and length of the muscle changes in the axial direction. Thus a tensile force is exerted on the environment in the axial direction. This force is used for actuation in robotics.

The shape of the pneumatic muscle changes continuously as long as compressed air is supplied. Hence, there is a need to study the dynamic behavior of the entire system and accordingly develop an appropriate control strategy for trajectory tracking purposes.

The aim of this paper is to propose a mathematical model of the robot arm explaining the dynamics of the system and to develop a control strategy to implement end-effector tracking performance of a two DOF robot arm. However, the high non-linear and time varying characteristics of the muscle make it difficult to achieve good tracking performance. Many control studies have been performed on artificial muscle actuators. Chang and Wu [5] demonstrated trajectory tracking of a 2 DOF robot arm actuated by pneumatic muscle actuators using Adaptive fuzzy sliding mode control. Manuel and Carlos [6] developed a fuzzy controller for a one DOF flexible robot arm using pneumatic actuators. Several other studies have been made in the control of pneumatic actuation systems [7-11]. In general, Fuzzy control is used to control pneumatic actuators.

It is necessary to stress on the importance of fuzzy control. When considering the commonly used control techniques like PID control, etc, these do not show a high degree of accuracy in the control of pneumatic actuators. The pneumatic actuator (PAM) continuously changes shape during it's actuation. Hence, an accurate dynamic model may not be developed given such highly non-linear characteristics of the muscle. Fuzzy control has shown accuracy in dealing with poorly defined dynamic processes and it involves the incorporation of human knowledge directly into the system.

In this paper, fuzzy control is used to control the end-effector of the robot arm in trajectory tracking tasks. In the next section, the robotic system is described.

2 The Robotic System

In Figure 1, a schematic diagram of the robotic system under consideration for this paper is shown.

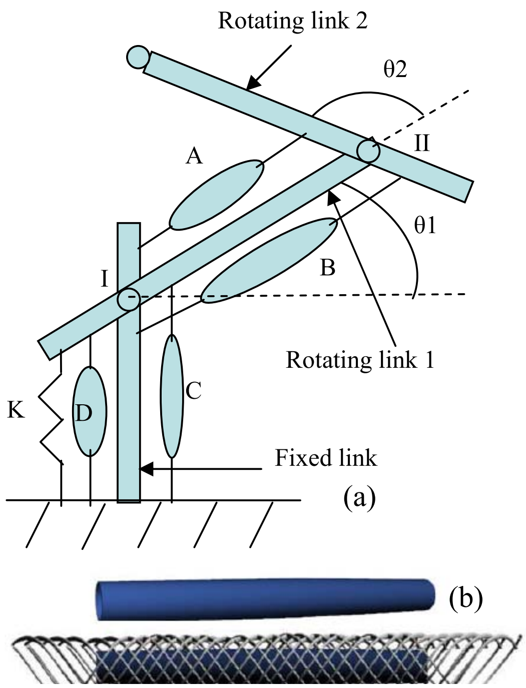

Fig. 1: (a) Schematic diagram of the robotic system, (b) Pneumatically actuated artificial muscle

The robot arm consists of two revolute joints, both of which are driven by two pneumatic muscles in an agonist-antagonist set-up. Link 1 rotates about the first joint I, driven by muscles C and D. Link 2 is mounted at the end of link 1, where the second joint II is located. Link 2 is driven by muscles A and B. The spring K is used to stabilize the first link of the robot arm.

The muscles generate a pull force. The set-up of the muscles considered in the work, with two muscles working on either side of the hinge, is called an agonist and antagonist setting, much like the human's biceps and triceps. The resulting torque exerting on the joint determines the system dynamics. The resulting torque is constituted by the forces of both muscles and the force of gravity working on the arm. The pull force of a muscle is controlled by controlling the pressure in the muscle. The device that enables the control of pressure by allowing the flow of air into and out of the muscle is called a valve. The valve is actuated by a valve signal v. In this paper, the valves are considered to be binary, i.e. when $v=1$ the valve is fully open, and when $v=0$ the valve is fully closed.

Each muscle is driven by two valves, only controlling the flow of air into the muscle and the other controlling the flow of air out of the muscle. Similar to biological muscles, pneumatic muscles act close to the rotation point. Although this makes it difficult to generate large momentum, small elongations of the muscle are sufficient to generate large rotations of the joints. The model of the robot arm is as given in Fig. 2.

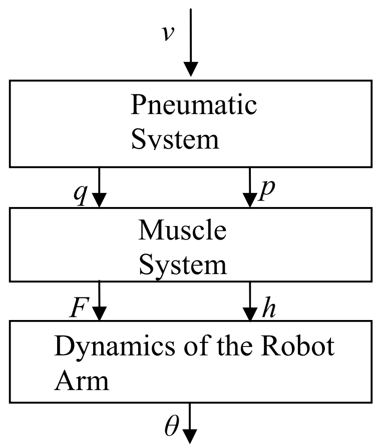

Fig. 2: The model of the robot arm

When the binary valve signal v is given as input to the pneumatic system, it calculates the flow rate through the muscles q. The muscle system then calculates the pressure in the muscles p, and hence the force exerted by the muscle F. Using the force, the dynamics of the robot arm can be used to find the angle by which the robot arm rotates θ, and also the actual length of the robot arm h. This is also used as input to the muscle system to calculate the pressure and hence the flow rate. Hence, this is a recursive process.

3 Dynamics of the Robot Arm

The dynamic model is derived from the multi-body approach. Fig. 3 shows the forces exerted by the muscles on the system.

Here COO is a fixed reference frame. CO1 and C12 are the points where links 1 and 2 respectively are hinged. CM1 and CM2 are the center of mass of link 1 and link 2. The forces acting on the system are calculated from pressure acting on the artificial muscle. The rate of change of pressure in the muscle is given by following differential equation

$$\dot{p} = \frac{(R_S T_{abs}(q_{in} - q_{out}) - p\frac{dV}{dt})}{V} \tag{1}$$

Where p is the pressure in the muscle, V is the volume of the muscle, q_{in}, q_{out} are the flow rates of air in and out of the muscle respectively, R_S is the specific gas constant and T_{abs} is the absolute temperature in the muscle. In this work, T_{abs} is assumed to be constant at 293K.The flow of air through the system can be modeled as flow through a throttle valve. This flow of air depends on the pressure difference between the two sides of the valve. With initial length of the artificial muscle as h_0 , one may obtain the change in length ($h-h_0$) of the artificial muscle using Eq (1).

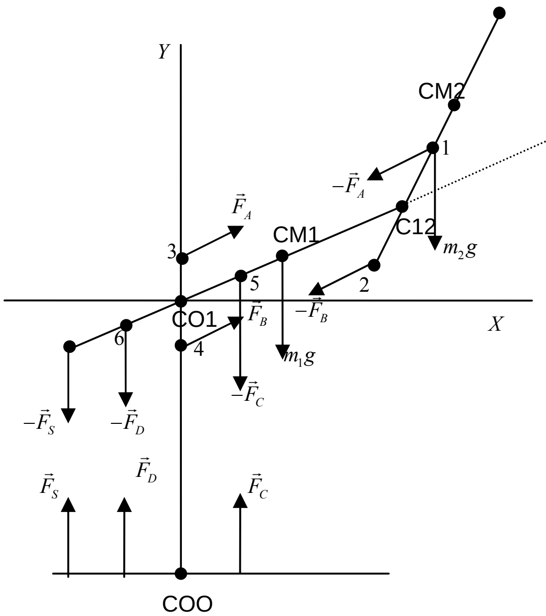

Fig. 3: Forces acting on the system due to the artificial muscles

It is important to note that the actual length of the muscles h can be calculated by position vectors of the end points of the muscle at all times. Hence, the force acting by the i^{th} artificial muscle can be given by

$$F_i = k\left(h_i - h_0\right) + c\dot{h}_i \tag{2}$$

Where k is the stiffness and c is the damping constant of the artificial muscle which can be determined experimentally.

Using forces acting at different points due to the artificial muscles as shown in Fig. 3 one may calculate the torque acting at the joints. The forces exerted by the muscles are shown in Fig. 3 at points 1-6. Now the dynamic equation of motion of the robot arm can be given by the Lagrange-Euler formulation as [2]:

$$\frac{d}{dt}(T_{,\dot{q}}) - T_{,q} + P_{,q} = Q_i \tag{3}$$

Where, T is Kinetic energy of the system, P is the potential energy of the system and Q is the generalized muscle force acting on the system.

The generalized force is calculated as:

$$Q_k = \sum_{i=1}^{n} \vec{F}_i \cdot \left(\frac{\partial \vec{r}_i}{\partial \theta_k} \right); \quad k = 1,2 \tag{4}$$

Where $\vec{r}_i$ is the position vector from the center of mass of the links to the points where the forces act, and $\vec{F}_i$ is the force exerted by the muscles. An example of a position vector is shown in Fig. 4. The vector from CM1 to point 3 is given by $\vec{r}_3$. Similarly, all the other position vectors can be calculated. Since the system has two degrees of freedom, Eq. (3) can be written as:

$$\left[\frac{d}{dt}(T_{,\dot{q}})\right]_{2\times1} - \left[T_{,q}\right]_{2\times1} + \left[P_{,q}\right]_{2\times1} = \left[Q_i\right]_{2\times1} \tag{5}$$

The detailed derivation can be found in the work of Reddy [12].

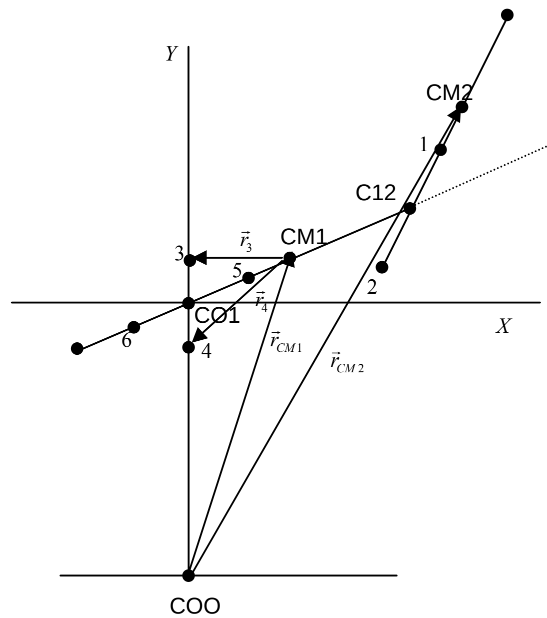

Fig. 4: An example of a position vector from the fixed frame to the center of mass of the link and to the points where the muscle forces act.

4 Control System Design

Fuzzy control is used for end-effector tracking performance as described in section 1. To control the position of the end-effector of the robot arm, it is necessary to control the joint angles, i.e. the rotation of the links of the robot arm. To control the rotation of the links, the pressure in the muscles has to be controlled. There are two ways to do that; by controlling the area of the valve allowing flow of compressed air into and out of the muscle, or by assuming pressure proportional valves [3] and directly calculating the pressure in the muscles. Thus, the parameters to be controlled are the valve signals or the pressure in the muscles. Both control strategies are investigated in this paper. The inputs to the controller are the error between the desired and actual trajectory and the derivative of error. The outputs are the parameters to be controlled. The control system is as shown in Fig. 5.

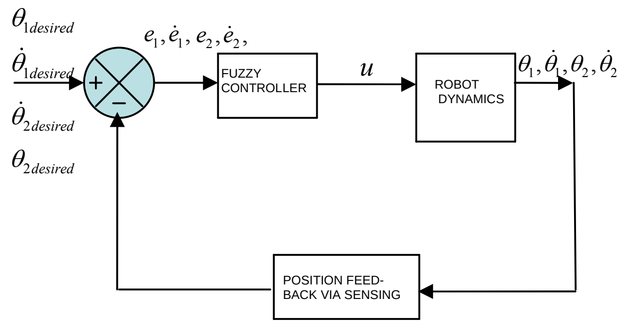

Fig. 5: Control System design

The control input to the system $\boldsymbol{u}$ can be either the valve signal or the pressure in the muscles. Since the valves are assumed to be binary, the valve signals shall be referred to as binary valve signals. Considering binary valve signal, the control input $\boldsymbol{u}$ is given by:

$$u = \begin{bmatrix} v_{in,A} & v_{out,A} & v_{in,D} & v_{out,D} \end{bmatrix} \tag{6}$$

Where, $v_{in,A}, v_{out,A}, v_{in,D}, v_{out,D}$ are the binary valve signals allowing flow of compressed air into and out of the muscle. Fig. 2 explains how the input u (in this case, the binary valve signals) allows us to calculate the joint angles. In this case, no flow of compressed air is allowed into muscles B, C. Hence, the pressure in muscles B, C remains constant.

For the input error and derivative of error, the fuzzy membership functions are given in Fig. 6 and Fig. 7 respectively. The corresponding inference rules are presented in Table 1.

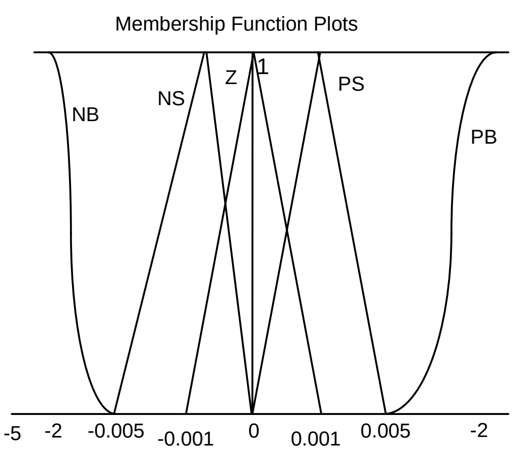

Fig. 6: Fuzzy membership function for input variable **e** (error)

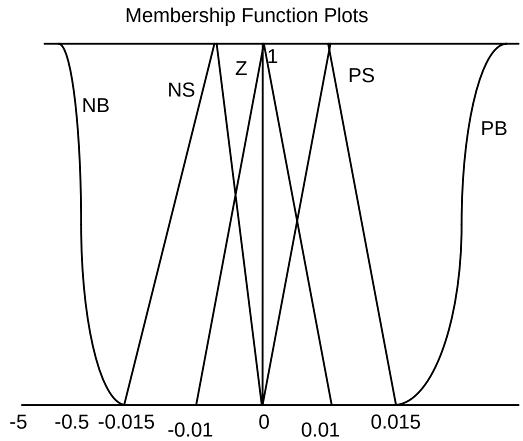

Figure 7: Fuzzy membership function for input variable **e_dot** (derivative of error)

Table 1: Fuzzy inference rules for muscles A, D

e_dot / e	NB	NS	Z	PS	PB
NB	0,1,1,0	0,1,1,0	0,0,0,0	1,0,0,1	1,0,0,1
NS	0,1,0,0	1,0,0,0	1,0,0,1	1,0,0,1	1,0,0,1
Z	1,0,0,0	1,0,0,0	0,0,0,0	1,0,0,1	1,0,0,1
PS	1,0,0,1	1,0,0,1	1,0,0,1	1,0,0,1	1,0,0,1
PB	1,0,0,1	1,0,0,1	1,0,0,1	1,0,0,1	1,0,0,1

It is important to note that the fuzzy membership functions chosen are triangular membership functions. These are the most commonly used membership functions owing to their simplicity in representation. However, if the membership plots are observed carefully, it can be noticed that the outer membership functions, NB and PB are sigmoid. The fuzzy inference rules given in Table 1 are devised by practice, where they are tried and revised constantly until they give high accuracy of the control system. Now considering pressure difference as input signal, the control input $\boldsymbol{u}$ is given by:

$$u = \begin{bmatrix} \Delta p_1 & \Delta p_2 \end{bmatrix} \tag{7}$$

Here $\Delta p_1, \Delta p_2$ are the pressure differences between the muscles. It is important to note that only a pressure difference between the muscles causes the robot arm to rotate. Hence, the pressure in the muscles is calculated as:

$$\begin{aligned} p_A &= p_A + \Delta p_2, \quad p_B = p_B - \Delta p_2, \\ p_C &= p_C - \Delta p_1, \quad p_D = p_D + \Delta p_1. \end{aligned} \tag{8}$$

where $p_{A,} p_B, p_C, p_D$ are the pressures in the muscles, and $\Delta p_1, \Delta p_2$ are changes in pressure as an arbitrary function of time. Figure 2 explains how the control input u (in this case, the pressure in the muscles) allows one to calculate the joint angles. In this case, considering Fig. 2, initial calculation of the flow rates and the pressure in the muscle is not required as it directly given by Eq. (8).

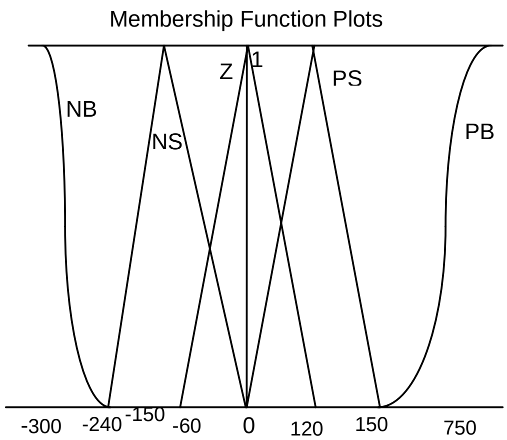

Fig. 8: Membership function for output variable Δp_1

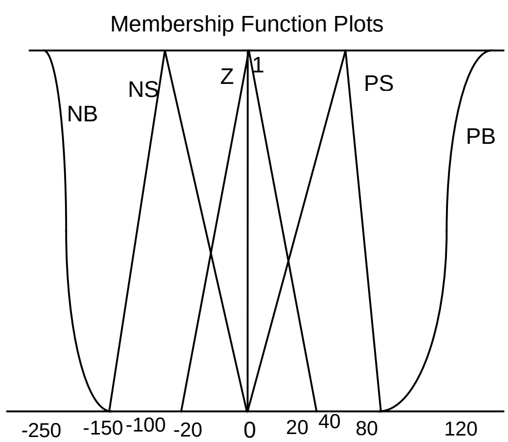

Fig. 9: Membership function for output variable Δp_2

Table 2: Fuzzy inference rules for $\Delta p_1, \Delta p_2$

e_dot / e	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PB	PB	PB

Muscles A, B rotate the elbow joint while C, D rotate the shoulder joint. Thus the control system is a four input-one output control system, with $e_1, \dot{e}_1, e_2, \dot{e}_2$ as input and θ as the output. For the output variables $\Delta p_1, \Delta p_2$, the fuzzy membership functions are given in Figs. 8, 9 and the inference rules are presented in Table 2. The membership functions for the input variables, i.e. the error and derivative of error remain the same as in the case when the binary valve signals.

5 Numerical Simulation and Discussion

In this section, the end-effector of the pneumatically actuated two link manipulator shown in Fig. 1 has been used to trace a straight line. The physical parameters for the considered muscle are shown in Fig. 10 and Table 3. Figure 10(b) is a representation of what the braid would look like if it was spread out on a 2-D plane, and n denotes the number of windings of the braid.

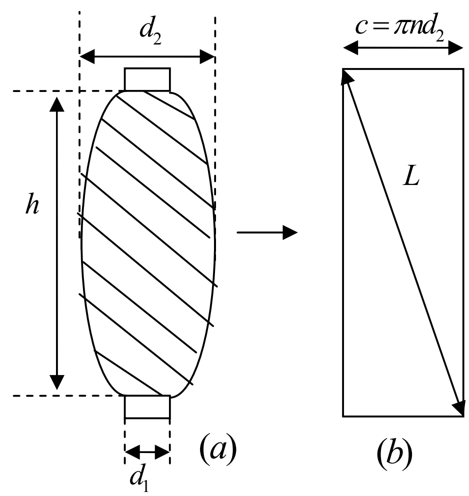

Fig. 10: Dimension of the Pneumatic muscle

Table 3: Characteristics of the Pneumatic muscle

Physical Characteristic	
Inner Diameter d_1	0.025 m
Maximum Length of the muscle h_{max}	0.235 m
Pressure at which the muscle is able to deliver force	0.3 bar
Maximum working pressure of the muscle	3.5 bar

From table 3, it is evident that if the length of the muscle goes beyond the maximum length, then it will be unable to exert any force on the robotic manipulator as given by Eq. 2 and thus will be incapable of actuation. Also, when the pressure in the muscle is gradually increased, only at 0.3 bar will the muscle be able to deliver force. Beyond 3.5 bar, the properties of the muscle may change, and it may not conform to the model given in this paper. So, the working pressure is kept below 3.5 bar.

The diameter d_2 of the muscle can be calculated from Figure 10 as:

$$d_2 = \frac{\sqrt{4L^2 - h^2}}{\pi n} \quad (9)$$

Also, assuming the muscle is barrel shaped, the volume of the muscle is given by:

$$V = \frac{\pi h}{60}(3d_1^{\ 2} + 4d_1 d_2 + 8d_2^{\ 2}) \quad (10)$$

Then the pressure in the muscle and the force exerted by the muscle can be calculated using Eqs. (1-2).

In this numerical simulation, the end-effector of the robot arm has to trace a straight line from point (0.52, 0.352) to (0.32, 0.352) in one second. The desired trajectory for the x co-ordinate can be assumed as a cubic trajectory which is obtained as

$$x_d = 0.52 - 0.6t^2 + 0.4t^3$$
$$y_d = 0.352 \quad (11)$$

The desired trajectories of the joint angles are calculated by using inverse kinematics. Now, the joint angles are calculated as:

$$\theta_{2d} = \cos^{-1}\left(\frac{x_d^{\ 2} + y_d^{\ 2} - l_1^2 - l_2^{\ 2}}{2l_1 l_2}\right)$$
$$\theta_{1d} = \tan^{-1}\left(\frac{y_d}{x_d}\right) - \tan^{-1}\left(\frac{l_2 \sin(\theta_2)}{l_1 + l_2 \cos(\theta_2)}\right) \quad (12)$$

Here length of link 1 l_1=0.52 m, length of link 2 is l_2=0.352 m. Joint constraint on θ_1=-45^0 to 50^0, and same constraint for link 2 i.e., θ_2= 40^0 to 140^0 . Now, the results in simulation of the control of a two DOF robot arm are presented. Even for a two DOF robot arm, there are two ways to approach the problem, i.e. by considering the pressure in the muscles as the controlled parameter or by considering the binary valve signals as the control parameter.

CASE 1: With binary valve signals as the controlled parameters.

Fig. 11 shows the desired and the actual trajectory traced by the joint1 of the robot arms using fuzzy control. Fig. 12 shows the error between the desired and actual joint angle trajectories which is found to be of the order of 10^{-4}. Similarly Fig. 13 shows the desired and the actual trajectory traced by the second joint of the robot arms using fuzzy control. Fig. 14 shows the corresponding error between the desired and actual joint angle trajectories which is found to be of the order of 10^{-4}.
The end-effector tracking responses are as shown in Fig. 11-14. The maximum tracking errors of the end-effector of the robot arm when the binary valve signal are the controlled parameter is -8×10^{-4} degrees for joint angle 1 and -4.5×10^{-3} degrees for joint angle 2.

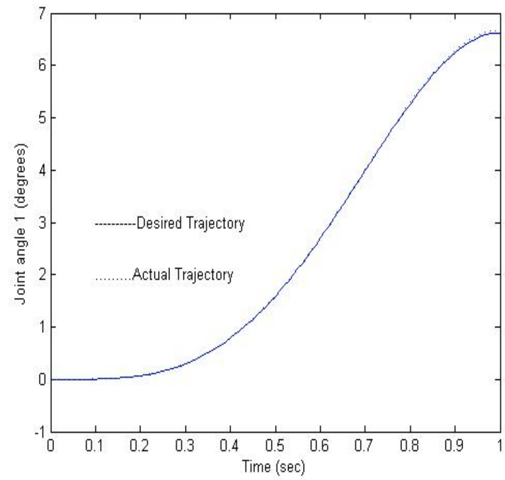

Fig. 11: Desired and Actual Joint Trajectories of joint Angle 1.

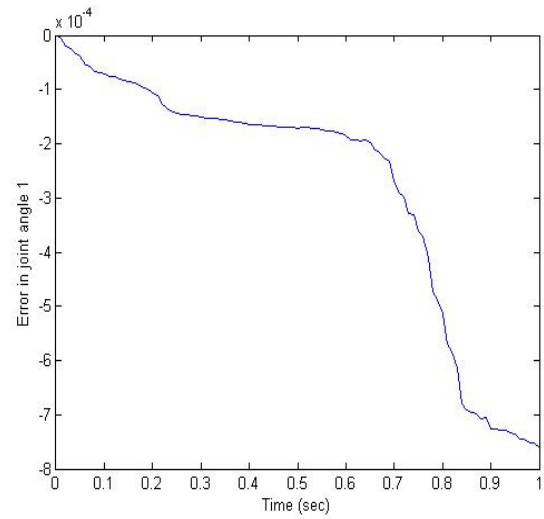

Fig. 12: Error Profile of joint Angle 1

CASE 2: With pressure in the muscles as the controlled parameters.

Similarly, the maximum tracking errors for the end-effector of the robot arm when the pressure difference□ p is the controlled parameter is 8×10^{-4} degrees for joint angle 1 and 2.5×10^{-4} degrees for joint angle 2. To trace the desired curve, it can be observed from Fig. 11, 13, 15, 17, that link 1 has rotated by approximately 6^0 and link 2 has rotated by approximately 27^0 in the time span of one second. For such a fast motion, the fuzzy controller shows accurate tracking responses with both binary valve signals and pressure difference in the muscles as the controlled parameters.

It can be observed from Fig. 12, 14, 16, and 18 that the error in the joint angle trajectories increases with time. This shows the robot arm is not able to maintain its positional accuracy with time. This is because the fuzzy controller implemented has fixed fuzzy rules. Hence, it cannot overcome the non-linearity of the pneumatic muscle over a period of time. The fuzzy rules should be modified to improve tracking performance.

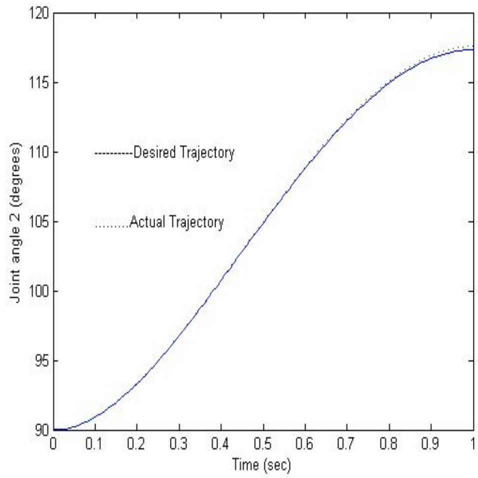

Fig. 13: Desired and Actual Joint Trajectories of joint Angle 2.

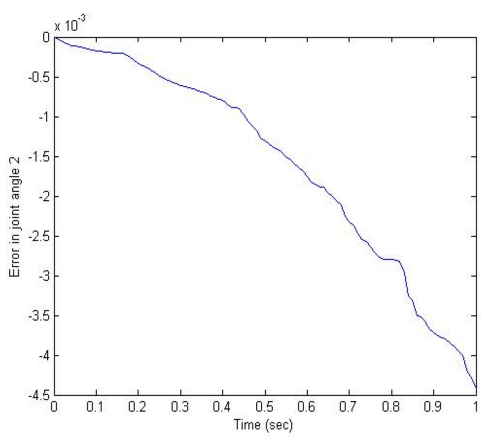

Fig. 14: Error Profile of joint Angle 2

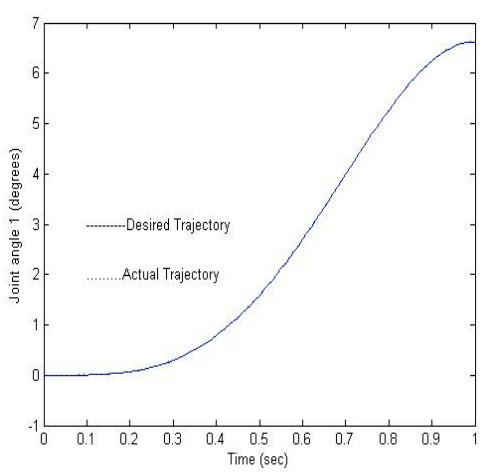

Fig. 15: Desired and Actual Joint Trajectories of joint Angle 1

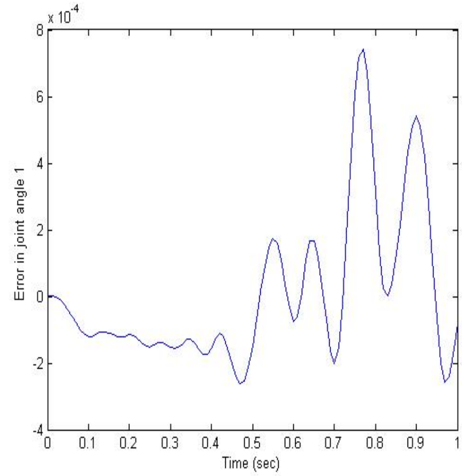

Fig. 16: Error Profile of joint Angle 1

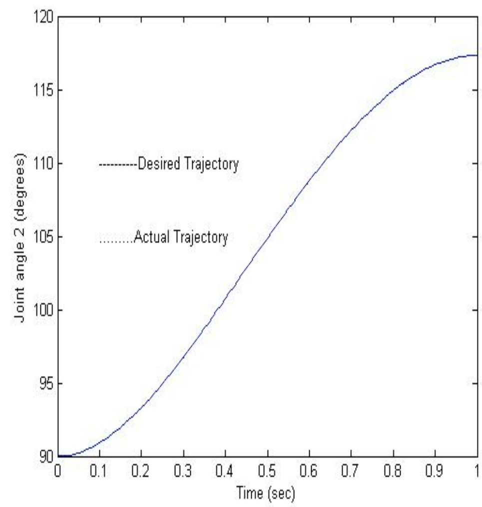

Fig. 17: Desired and Actual Joint Trajectories of joint Angle 2.

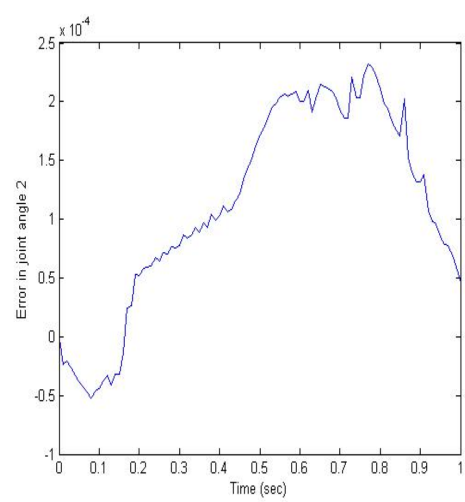

Fig. 18: Error Profile of joint Angle 2

6 Conclusion

The motion control of a two DOF robot arm in trajectory tracking tasks was studied. A fuzzy controller was used to control the end-effector of the two DOF robot arm actuated by highly non-linear pneumatic muscle actuators. To get a better system response, PID algorithm must be used in combination with fuzzy logic. Also, the fuzzy rules can be modified to reduce the tracking errors. It may also be suggested for future work, that other control techniques like neural networks and adaptive control or a combination of these can be used to control the end-effector of the robot arm in trajectory tracking tasks.

References

[1] M. Hackel, *"Humanoid Robots: Human like Machines*", Advanced Robotics Systems International, I-Tech Education and Publishing, Vienna, Austria, 2007.

[2] F. Daerden, D. Lefeber, "*Pneumatic Artificial Muscles: Actuators for Robotics and Automation*", Department of Mechanical Engineering, Vrije Universitat, Brussels, 2006.

[3] S.N.V.D. Brink, "*Modeling and control of a robotic arm actuated by non-linear artificial muscles"*, Master of Science Thesis, Dynamics and control group, Technical University of Eindhoven, 2007.

[4] Artificial Muscle Research Institute Website, www.unm.edu/~amri/

[5] M.K. Chang, J.C. Wu, *"Tracking Control of a 2-DOF Arm Actuated by Pneumatic Muscle Actuators Using Adaptive Fuzzy Sliding Mode Control", Journal of System Design and Dynamics*, Vol. 1, 2007.

[6] J.Manuel, J. Carlos, "*Pneumatic Fuzzy Controller Simulation vs Practical Results for a Flexible Manipulator"*, Universidad Technologica de San Juan del Rio, Mexico, 2007.

[7] D. Jutras, P. Bigras, "*Control of an actuator made of two antagonistic McKibben muscles via LMI optimisation"*, IEEE ISIE, July 9-12, Montreal, Quebec, Canada, 2006.

[8] M. Tai, K. Xu, "*Modelling of a Pneumatic actuator system for high performance non-linear controller design"*, ASME Int. Mech. Eng. Congress and Exposition, Anaheim, USA, November, pp-13-20, 2004.

[9] R.T. Pack, M. Iskarous and K. Kawamura . "Comparison of fuzzy and nonlinear control techniques for a flexible rubbertuator-based robot joint". *International Fuzzy Systems and Intelligent Control Conference*, pp 361–370, 1994.

[10] T. Diep, K.Kwan, "*Control of a Pneumatic Artificial Muscle Manipulator with non-linear PID Controller using Neural Network"*, Mechatronics Department, University of Ulsan, Korea, 2004.

[11] P. B. Petrovi´c . "*Modeling and control of an artificial muscle, part one: Model building"*. Buletinul ¸stiin¸tific al universit˘a¸tii "politehnica" din Timi¸soara, Transactions on Mechanics, 47(61). X-th Conference on Mechanical Vibrations, 2002.

[12] B. R.S. Reddy, "*Dynamics and Control of a Pneumatically actuated Robotic Arm",* M. Tech. Thesis, Department of Mechanical Engineering, Indian Institute of Technology Guwahati, 2009.