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# Nonlinear Control of Robotic Manipulators Driven by Pneumatic Artificial Muscles Using Optimal Control

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**ABSTRACT**: Robotic manipulators are increasingly being utilized in applications that require interaction with human. In order to enable safe physical human robot interaction, light weight and compliant manipulation are desirable. These requirements are problematic for many conventional actuation systems, which are often heavy and typically use high stiffness to achieve high performance, leading to large impact forces upon collision. Pneumatic Artificial Muscles (PAMs) exhibit these characteristics and are capable of higher specific work than comparably sized hydraulic actuators and electric motors. However control PAM- actuated systems are proven difficult due to the highly nonlinear nature of the actuators and pneumatic systems driving their actuation. In this project, PID control strategy containing a distinct level of priory model knowledge, and Linear Quadratic Regulator (LQR) was designed to enable motion tracking of the single degree of freedom PAM actuated manipulator.

**KEYWORDS:** Pneumatic Artificial Muscles, Compliant Manipulation, Sliding Mode Control

## I. INTRODUCTION

Pneumatic Artificial Muscles are extensional and contractile devices operated by pressurized air, filling a pneumatic bladder. In a vague approximation of human muscles, PAMs are usually grouped in pairs: one agonist and one antagonist. PAMs are light weight, soft actuators that employ pressurized air to generate axial force. It is a tube like actuator, when pressurized reduces the actual length. PAMs have nonlinear, hysteresis and time varying characteristics, which makes it difficult to model and design the controllers.

The “pneumatic artificial muscles” comprises a range of designs[1-6]. An elastomeric/bladder material and an inextensible fiber material are the main components of these actuators. The fiber can be embedded inside the elastomer or can surround and move freely on the bladder surface. The pressurization of a soft bladder causes the stiff braid fibers to reorient and generate stroke in one direction. Typically, Mckibben type PAMs are contractile, while expanding radially. The latter is traditionally known as a Mckibben actuator, named after Joseph Mckibbenwho popularized these devices as orthotics for polio patients in 1950s. the invention of the Mckibben type pneumatic muscles are generally attributed to R.H.Gaylord, who patented “Fluid actuated motor system and stroking device” in 1958. A similar “Elastic diaphragm” patended by A.H.Morin, awarded in 1953, is cited in the Gaylord patent.

PAMs have several appealing features for use in robotic systems. They are capable of excellent power-to-weight ratios and high specific work when pressurized. Additionally, they are easily scaled to different sizes; in fact, many researchers have focused on miniature” PAMs, roughly denoting muscles with diameters less than 0.25-in. These compliant actuators are damage tolerant and have been endurance tested for as many as 125 million cycles with minimal wear and little change in force characteristics.

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In some applications, PAMs are employed in antagonistic pairs. This arrangement is widely observed in biological systems. A commonly cited agonist-antagonist pair is the biceps-triceps pair of muscles on the human arm. As the agonist contracts, the antagonist extends, preserving the stiffness of the joint.

## II.PAM ACTUATED ROBOTIC MANIPULATOR

Fig.1 shows a PAM actuated manipulator. For the torque generation over a full range of motion, the features like parallel arrangement, unidirectional actuation and nonlinear geometry of the joint was optimized. The equation of motion relating PAM pressure[7-10] to joint torque is much complex as it has nonlinear force behavior and nonlinear joint geometry.

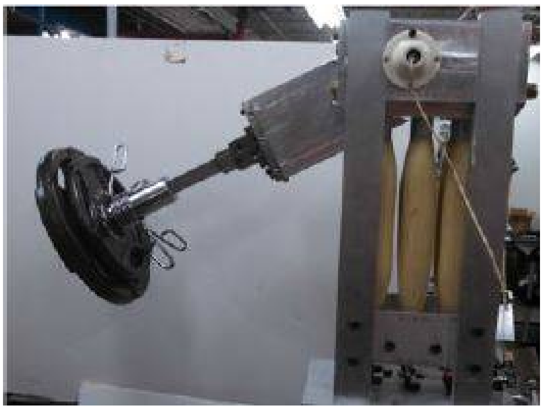

Fig.1.PAM-actuated manipulator

The quasi-static manipulator torque is given by

$$\tau(P,\theta) = C_1(\theta)P + C_2(\theta) \quad (1)$$

where $C_1(\theta)$ and $C_2(\theta)$ are third order polynomial functions of angle. Due to the PAM hysteresis, the torque during the compression and expansion are different. Within a range of angles, the model is accurate. It was sufficient to have this range of motion as it was intended for heavy lifting applications like patient placement and casualty extraction. Torque at all range of pressure outside the nominal range of motion i.e. at $150°$ is equal to zero. This results in the zero moment arm. Due to the air compressibility, it exhibit damping. Fig.2 shows the joint mechanism. The mechanism is in such a way that the sliding plate is pulled downward by the PAM force. Through a tendon link, the plate's motion is transferred to the arm link, causing it to rotate about a pinned joint attached to a rigid frame.

The fig 2 represents the joint mechanism for the PAM actuated robotic manipulator. When PAM force is applied to the system, then the sliding plate move downward with the help of the roller bearings and then the tendon link moves downward and lifting motion occurs through the pinned joint.

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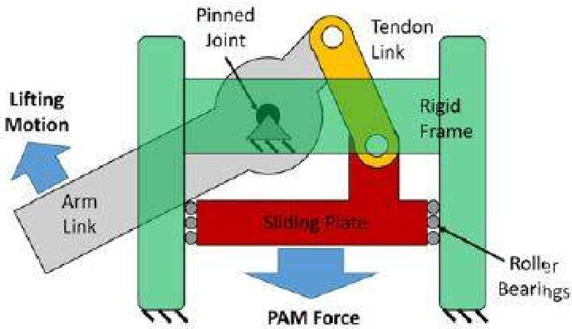

Fig.2. diagram of joint mechanism

For the single degree of freedom, equation of motion is given by

$$\tau(\theta) = I\ddot{\theta} + b\dot{\theta} + mgr\sin\theta \tag{2}$$

where *I* is the inertia of rotating arm link, *b* is the viscous damping, *m* is the mass of the link, *g* is the gravitational constant and *r* is the distance between the joint and the link centre of mass. State space form of the transfer function is obtained as

$$A = \begin{bmatrix} 0 & 1 \\ -8.75 & -0.25 \end{bmatrix},\ B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \end{bmatrix},\ D = 0,$$

where $m = 1kg$, $r = 1.75cm$, $g = 10m/s^2$, $b = 0.5$ and $I = 2kg - m^2$.

## III. CONTROL STRATEGIES

This section describes the design of two controllers- PID and Linear Quadratic Regulator Control.

### *A. PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROL*

PID control is a feedback strategy widely used in industrial applications. The controller input, voltage to the PAM is given by

$$u(t) = k_p e(t) + k_I \int e(t)dt + k_D \dot{e}(t) \tag{3}$$

The control signal constitutes three user-defined gains: the proportional, integral and derivative gain $k_p, k_I$, and $k_D$ respectively.

### *B. LINEAR QUADRATIC REGULATOR (LQR) CONTROL*

Optimal controllers, i.e., controllers that are the best possible, according to some figure of merit, turn out to generate only stabilizing controllers for MIMO plants. In this sense, optimal control solutions provide an automated design procedure – we have only to decide what figure of merit to use. The linear quadratic regulator (LQR) is a well-known design technique that provides practical feedback gains.

For the derivation of the linear quadratic regulator, assume the plant to be written in state-space form $\dot{x} = Ax + Bu$ and that all of the n states x are available for the controller. The feedback gain matrix K is implemented as $u = K(x - x_{desired})$. The system dynamics are then written as:

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$$\dot{x} = (A - BK)x + BKx_{desired} \quad (4)$$

$x_{desired}$ represents the vector of desired states, and serves as the external input to the closed-loop system. The "*A*-matrix" of the closed loop system is $A-BK$, and the "*B*-matrix" of the closed-loop system is $BK$. The closed-loop system has exactly as many outputs as inputs: n. The column dimension of $B$ equals the number of channels available in u, and must match the row dimension of $K$. Pole-placement is the process of placing the poles of $A-BK$ in stable, suitably-damped locations in the complex plane. The fig 3 shows the block diagram of LQR controller.

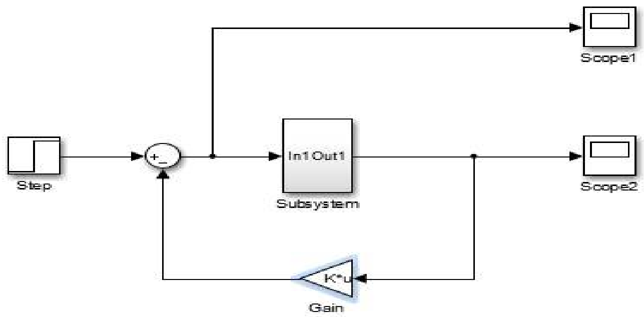


Fig 3.Block diagram of LQR controller

## IV. SIMULATION RESULTS

### A. *PID Control*

Tracking response of the PID controller is given in the fig 4. Even though it tracks the path it undergoes overshoot and the settling time is high. So to reduce these factors, optimal control is used.

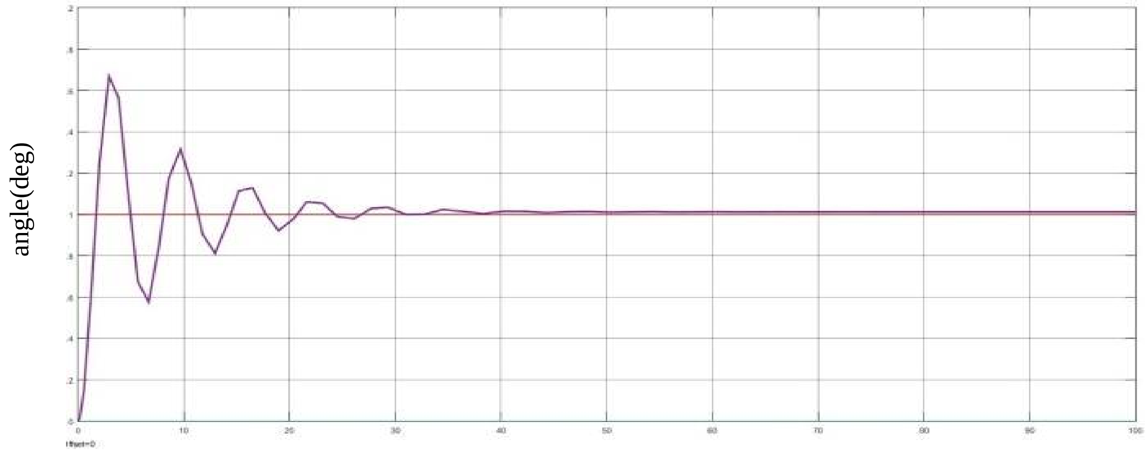


Fig 4. Angle versus time curve using PID

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### *B. LQR Control*

LQR control shows a better response with better overshoot and the settling time is very much less as compared to PID controller.

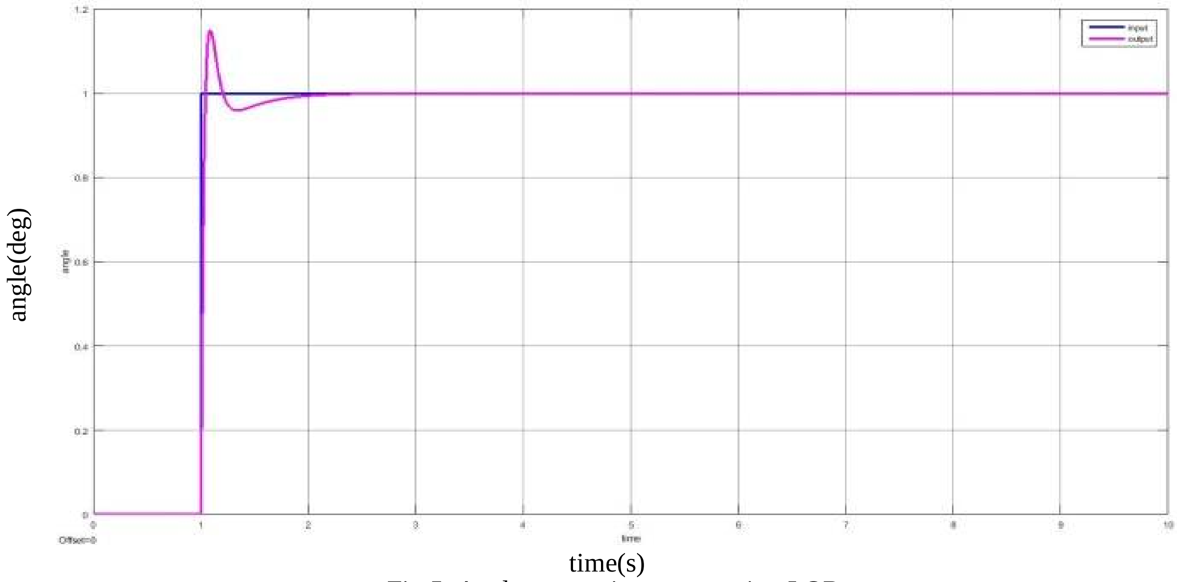


Fig 5. Angle versus time curve using LQR

## V. CONCLUSIONS

PID and LQR are the two control strategies has been proposed and implemented under robotic manipulators driven by pneumatic artificial muscles. PID undergoes tracking but the settling time is very high. By using LQR controller it has been able to reduce the settling time and hence got a better response with less overshoot.

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