International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-9 Issue-1, October, 2019

Modeling and Controller Design for Pneumatic Artificial Muscle for Ankle-Foot Orthotic Device

Avinash Kumar, Ravi Prakash Tewari

Abstract: ***In the present era Electric motors are most commonly used actuators for various robotic and bio-robotic applications. However, the functioning of electric motor is not similar to human skeletal muscles. Also, the electric motors are prone to harm human beings in case of failure. Hence, the present work has focused on exploring a bio-inspired actuator, which functions similar to human skeletal muscles and is safe for human beings. The literature review has revealed that such an actuator is pneumatic artificial muscle (PAM). In the present work the researchers have focused on developing an efficient model and control strategy for PAM in order to use it for bio-robotic applications. An experimental setup has been prepared to analyze the behavior of PAM for different speeds of operation and different loading conditions during inflation/ deflation. Based on the experimental datasets an experimental model of PAM and Proportional Pressure Regulator (PPR) has been developed using polynomial curve fitting tool of MATLAB.***

Then a switched mode feedback PID control strategy has been developed for PAM which takes care for the hysteresis behavior of PAM. The control strategy has been simulated to achieve the trajectory angle tracking of ankle joint during the complete gait cycle. The simulation of the proposed control strategy with the developed model has shown that the proposed approach works fairly well and the error in the ankle joint movement could be limited in the range of -0.8° to 0.6° for the complete gait cycle. The result obtained in the present study is similar to the results as reported in the literature. However, this could be achieved with less system complexity using simpler modeling technique and "switched mode feedback PID controller", which has not been reported by any researcher till date.

Keyword (s): McKibben Actuator; Pneumatic Artificial Muscle (PAM); Orthosis; Bio-Robotic Applications; Bio-inspired; Modeling; Controller.

I. INTRODUCTION

Bio-inspired Robotics focuses on learning concepts from nature and developing new systems by acquiring knowledge from biological systems. Usually, the biological systems tend to be more efficient since the nature has been developing them through millions and billions of years of evolution. In present era, the electric motors are universally used as actuators for robotic and bio-robotic applications. However, their actuation mechanism is not similar to human skeletal muscles, which act in agonist-antagonist pair. Also, the electric motors are rigid actuators with low compliance and they are prone to harm human beings in case of failure.

Revised Manuscript Received on October 30, 2019.
* Correspondence Author
Avinash Kumar*, Assistant Professor at AIACTR Delhi, Government of NCT of Delhi since 2011.
Ravi Prakash Tewari, Professor of Applied mechanics department of MNNIT Allahabad, Prayagraj, U.P. India.

This fact has encouraged the authors to explore various non-conventional actuators in order to find a soft actuator which has an actuation mechanism similar to human skeletal muscles. The Pneumatic artificial muscle (PAM) has been found most similar to human skeletal muscles. PAM was invented by Joseph L. Mckibben in 1950 with a purpose to utilize it as an actuator for orthotic appliance for the assistance of polio patients.

The behavior of PAM is much similar to human skeletal muscle owing to its conformity to Hill muscle model [1]. Hence, it is also known as bio-inspired actuator as described by Nickel et al. [2], Chou and Hannaford [3], etc. Daerden and Lefeber [4] have suggested that the PAM is a soft actuator and it has great potential to be used in robotic applications in human environment owing to its light weight, high power to weight ratio, hazard free, robust and maintenance free operation. Xie and Jamwal [5] have designed and developed an ankle-foot orthosis powered by antagonistically paired PAM actuators.

PAM is actuated by the application of pressurized air as shown in figure 1. When pressurized air is pumped inside the PAM it inflates in its diameter and contracts in its length producing actuation force. The contraction of the PAM depends on the applied pressure and the external force on it. However, it has a non-linear relationship between these three variables i.e. Contraction length, developed force and the applied pressure. Also, it shows hysteresis behavior, i.e. the length of PAM is not same during inflation and deflation conditions for the same amount of applied pressure and force. Due to the non-linear behavior and inherent hysteresis the modeling of PAM and developing suitable control strategy for it has been a challenging task. The present study has focused on developing suitable model and control strategy for PAM with an aim to use it as an actuator for rehabilitation devices.

Various researchers have used three different types of modeling techniques for PAM viz. (i) Theoretical or Analytical or Mathematical modeling, (ii) Experimental or Empirical modeling and (iii) Phenomenological modeling.

Figure 1: Inflation and Deflation conditions of PAM

The initial work of PAM modeling using mathematical modeling technique has been carried out by Nickel et al. [2]. Later on Chou and Hannaford [3] have developed a mathematical model of PAM.

The work of Chou and Hannaford has been based on "Virtual work" argument and treated as milestone and reference point by the subsequent researchers to develop their own models of PAM. The experimental modeling of PAM has been carried out by Ganguly et al. [6] and many other researchers. On the other hand the phenomenological model of PAM has been developed by many researchers such as Fan et al. [7] etc.

Various researchers have developed a number of control strategies for PAM, which can be broadly categorized as follows: PID control; Nonlinear PID control; Neural network control; Fuzzy logic control; Neuro - Fuzzy control; Adaptive control; Impedance control; Hybrid control; Sliding mode control; Cascaded Control; Control strategies for safe human interaction and Different modern control strategies. The PID control strategy has been utilized by Ganguly et al. [6] etc. The non-linear PID control strategy has been explored by Andrikopoulos et al. [8] etc. The Neural Network control has been utilized by Hesselroth et al. [9] etc. The fuzzy logic control has been explored by Xie and Jamwal [5] etc. The Neuro-Fuzzy control has been used by Anh, Son and Nam [10] etc. The adaptive control strategy has been applied by Ahn and Anh [11] etc. The impedance control was utilized by Tsagarakis and Caldwell [12] etc. The hybrid control has been explored by Anh and Ahn [13] etc. The sliding mode control was adopted by Yang and Lilly [14] etc. The cascaded control strategy was explored by Fan et al. [7] etc. The Control strategies for safe human interaction have been formulated by Choi et al. [15] etc.

II. EXPERIMENTAL WORK AND METHODOLOGY

An experimental setup has been prepared for PAM (procured from FESTO) using PPR (manufactured by FESTO), ultrasonic sensor (HCSR04) and pressure sensor (using PPR), Arduino Uno microcontroller board, Arduino software and MATLAB / SIMULINK as shown in figure 2. The PPR has been used to apply the desired pressure (0-6 Bar) to PAM by regulating its voltage control signal (0-10 V DC). The control signal voltage of 0-5 V DC is originally generated by varying the PWM (0-255) through Arduino Uno microcontroller board. This 0-5 V DC voltage is doubled using an amplifier circuit (Motor driver board L293D) and used as control signal to PPR.

The ultrasonic sensor (HCSR04) with a sensitivity of 3 mm has been used to measure the length of PAM for various operating conditions through Arduino Uno microcontroller board. The PPR has an additional functionality to work as pressure sensor as well. It gives 0-10 V output signal corresponding to 0-6 bar pressure. This pressure sensor output is attenuated to half i.e. 0-5 V which is supplied to Arduino Uno microcontroller board in order to get the actual pressure data for different operating conditions. A load pan has been hanged vertically with the PAM in order to apply a desired load (kg) to PAM.

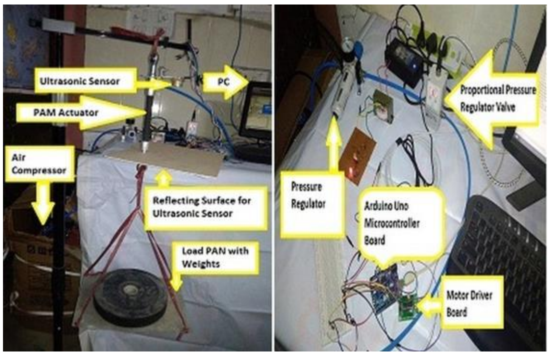

Figure 2: Actual snapshot of experimental setup

Thus, the experimental setup is able to apply a desired pressure to PAM (by varying PWM value through code of microcontroller) and find out its length at different operating conditions. The rate of pressure change is regulated by providing suitable delay in changing PWM value through code. Hence, a delay of 100 milliseconds indicates very fast operation (suitable for bio-robotic applications) and a delay of 2.5 second means sluggish operation (suitable for industrial applications). The load pan has been loaded with 1 kg load in order to find the behavior of PAM for ankle rehabilitation device as the total weight of foot segment along with orthotic structure is in the range of 1 kg. The experimental result for 1 kg load and 100 milliseconds delay has been shown in figure 3 below, which clearly indicates the hysteresis behavior during inflation and deflation.

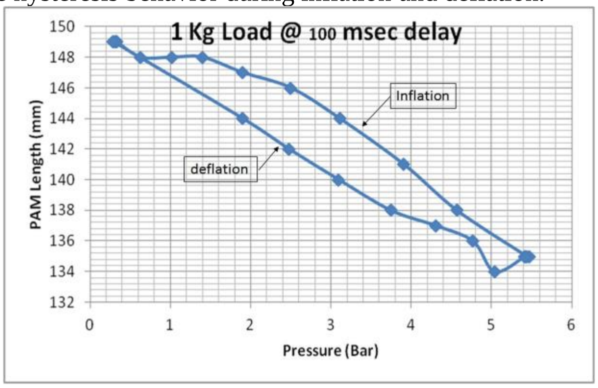

Figure 3: Experimental results for 1 kg load at fast speed operation (100 milliseconds delay)

The PAM behavior during inflation and deflation has been modeled using two different third order polynomials of the form $y = p_1x^3+p_2x^2+p_3x+p_4$ between y (PAM length in cm) and x (Pressure in bar) obtained from practical datasets as mentioned above. The values of the polynomial co-efficients for inflation condition have been evaluated using curve fitting toolbox of MATLAB, which comes out to be

p1 = 0.00362; p2 = -0.05605; p3 = -0.01697; p4 = 14.97;

Similarly, for deflation condition the four co-efficients come out to be

p1 = 0.01013; p2 = -0.09723; p3 = -0.005723; p4 = 14.99;

Another similar third order polynomials of the form $y = p_1x^3+p_2x^2+p_3x+p_4$ have been used to fit the relationship between experimental datasets of y (Pressure in bar) and x (PWM) for PPR during inflation and deflation.

The values of the polynomial co-efficients for inflation condition have been evaluated using curve fitting toolbox of MATLAB, which comes out to be

p_1 = -2.485e-07; p_2 = 0.0001772;
p_3 = -0.003781; p_4 = 0.2733;

Similarly, for deflation condition the four co-efficients come out to be

p1 = -2.329e-07; p2 = -2.823e-05;
p3 = 0.04341; p4 = -0.1836;

An ankle-foot orthotic device should be able to produce Dorsiflexion and Plantarflexion movements of ankle as shown in figure 4 below.

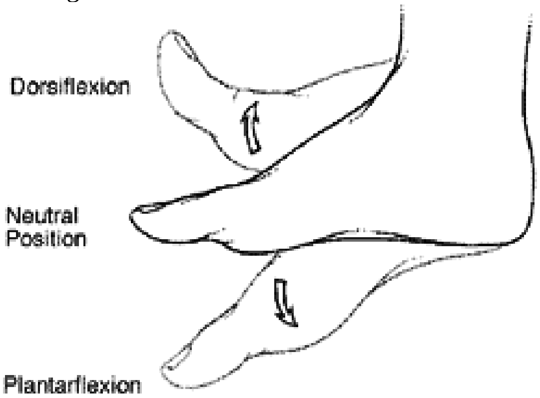

Figure 4: Dorsiflexion and Plantarflexion movement of the ankle joint

In order to develop an ankle-foot orthotic device using PAM, two PAMs of length L1 and L2 are required to be connected in agonist-antagonist fashion (similar to human skeletal muscles) as shown in figure 5 below. When PAM L1 contracts in length, L2 has to extend in length. Hence, for an ankle angle θ, the PAM length L2 can be calculated from trigonometry as

$L2 = SQRT(Y^2 + X_2^2 - 2YX_2Cos\theta)$; where X_2 and Y are the distances on shank and foot segments respectively where the PAM has been connected. Hence, the desired PAM length can be calculated for a particular ankle angle during the whole gait cycle. Now, the task is to design suitable control strategy so that the desired pressure can be applied to PAM resulting in desired PAM length and desired ankle angle is obtained.

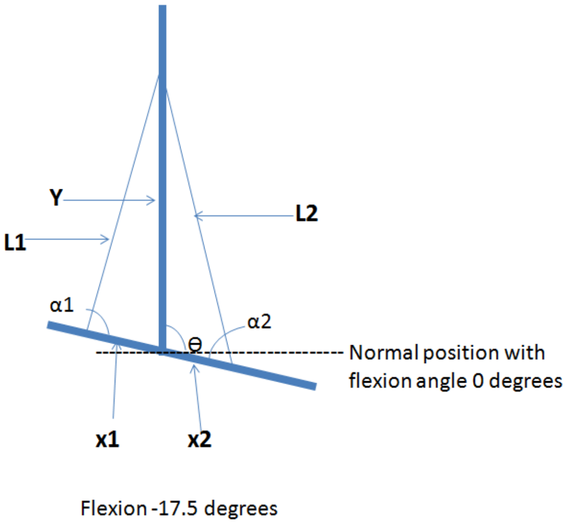

Figure 5: Agonist-antagonist PAM attachment at the ankle joint

The experimental data of desired flexion angle of ankle joint during the complete gait cycle is shown in figure 6 below, where complete gait cycle has been considered to be of 1000 milliseconds. It is evident from the curve that the PAM needs to contract and expand repeatedly in order to track the desired ankle flexion angle movement. But, due to the inherent hysteresis of PAM the PWM value needs to be different for same PAM length during inflation and deflation conditions. Hence, a switched mode feedback PID controller has been designed which switches the desired PWM value from inflation to deflation subsystem in order to take care of the hysteresis.

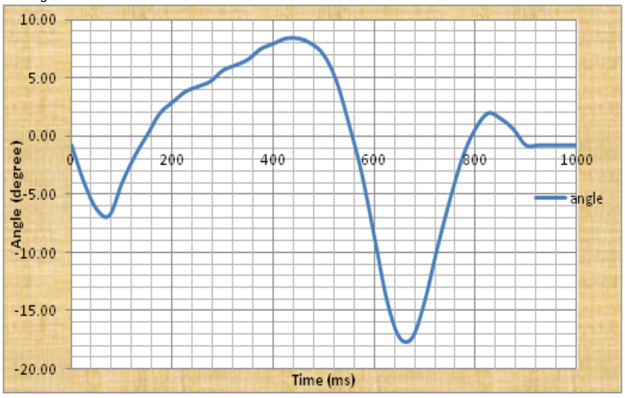

Figure 6: Plot of experimental data of Ankle flexion angle with time (ms) during gait cycle

In switched mode feedback PID control strategy two different PID controllers are tuned separately for inflation and deflation conditions respectively.

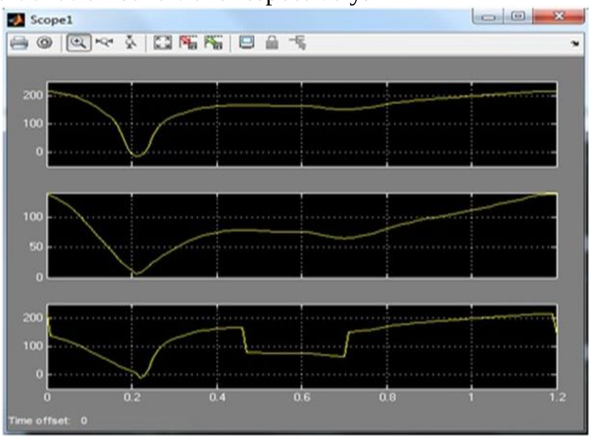

Figure 7: PWM output of PID considering full inflation; full deflation; switched mode PID

The output from the two PID controllers is switched from one to another depending on whether the PAM needs to be inflated or deflated in order to achieve the real time movement of ankle joint. The output of PID controller considering inflation condition, deflation condition and switched mode feedback PID controller considering actual condition of inflation/deflation according to the reference flexion angle of ankle joint has been shown by the three curves of figure 7 respectively.

III. RESULTS AND DISCUSSION

A switched mode feedback PID control strategy has been developed and applied with the polynomial curve fitted model of PAM and PPR. The aim has been to find out the PWM values at different instants of gait cycle so that the ankle joint can track the reference flexion angle during the complete gait cycle.

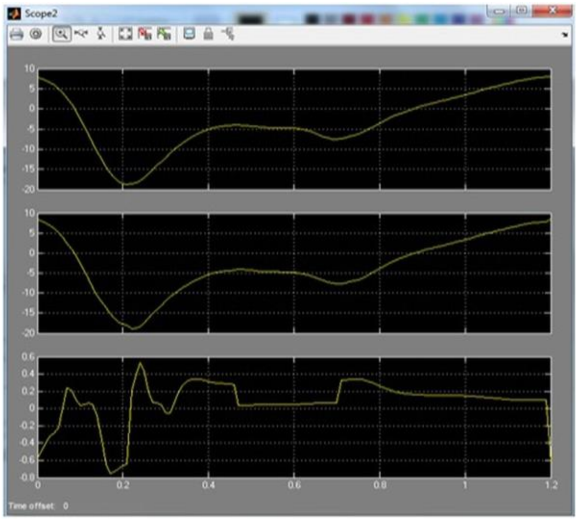

Figure 8: Desired ankle angle, actual ankle angle, error in ankle angle

The Arduino generates DC voltage in range of 0-5 volts corresponding to the PWM value produced at the output of the controller.

This voltage is amplified and used with PPR to give required pressure so that PAM can attain a desired length during the gait cycle period and ankle can track the reference flexion angle.

The present study has shown that the Pneumatic Artificial muscle actuator is giving satisfactory performance to be used as an actuator for making orthotic and assistive rehabilitation devices to be used by human subjects suffering from muscle related disorders etc. This control strategy worked fairly well and the error in the ankle flexion angle tracking could be limited in the range of -0.8° to 0.6° as shown in figure 8, which is the similar result as reported in the literature. However, in present case this result was obtained using less system complexity with simpler modeling technique and simple PID controller. The "switched mode feedback PID controller" has not been developed by any researcher till date. This control strategy has been able to compensate for the hysteresis behavior of PAM quite efficiently and resulted in excellent overall performance of the system.

IV. CONCLUSION

The present research work has been successful in developing a simple yet powerful experimental model of PAM actuator and PPR using experimental datasets. Also, the researchers have been able to design a novel "switched mode feedback PID controller" which has taken care for the hysteresis behavior of PAM during inflation and deflation conditions. The ankle foot orthotic device using PAM actuator has been able to limit the error at ankle joint in the range of -0.8° to 0.6° for the complete gait cycle. These results are quite encouraging in order to make the use of PAM possible for bio-robotic applications as a safe bio-inspired actuator replacing the conventional electric motors. In the present study the practical implementation could not be made due to paucity of time. In future practical implementation can be attempted and the error in ankle flexion angle can be further minimized by designing more sophisticated and modern control strategies.

REFERENCES

1. B. Tondu, S. D. Zagal "McKibben artificial muscle can be adapted to be in accordance with the Hill skeletal muscle model", *Proceeding of 1st IEEE/RAS-EMBS international conference on biomedical robotics and bio-mechatronics* 2006, 714–720
2. V. Nickel, I. Perry, and A. Garrett "Development of useful function in the severely paralyzed hand", *Journal of Bone and Joint Surgery* 1963, 45-A(5): 933-952.
3. C. P. Chou and B. Hannaford "Static and Dynamic Characteristics of McKibben Pneumatic Artificial Muscles", *Proceedings of IEEE International Conference on Robotics and Automation*, 1994, 281-286
4. F. Daerden and D. Lefeber "Pneumatic Artificial Muscles: actuators for robotics and automation", *European Journal of Mechanical and Environmental Engineering* 2002, 47: 10-21
5. S. Q. Xie and P. K. Jamwal "An iterative fuzzy controller for pneumatic muscle driven rehabilitation robot", *Expert Systems with Applications* 2011, 38: 8128–8137
6. S. Ganguly, A. Garg, A. Pasricha and S. K. Dwivedy "Control of pneumatic artificial muscle system through experimental modeling," *Journal of Mechatronics* 2012, 22(8): 1135-1147
7. J. Fan, J. Zhong, J. Zhou and Y. Zhu "BP neural network tuned PID controller for position tracking of a pneumatic artificial muscle", *Technology and Healthcare* 2015, 23: 231-238.
8. G. Andrikopoulos, G. Nikolakopoulos and S. Manesis "Advanced nonlinear PID-based antagonistic control for pneumatic muscle actuators", IEEE Transactions on Industrial Electronics 2014, 61(12): 6926-6937
9. T. Hesselroth, K. Sarkar, P. VanderSmagt, and K. Schulten "Neural network control of a pneumatic Robot arm", IEEE Transactions on System and Cybernetics 1994, 24(1): 28–38
10. H. P. H. Anh, N. N. Son and N. T. Nam "Adaptive Evolutionary Neural Control of Perturbed Nonlinear Serial PAM Robot", *Neurocomputing* 2017, 267: 525-544
11. K. K. Ahn and H. P. H. Anh "Design and implementation of an adaptive recurrent neural networks (ARNN) controller of the pneumatic artificial muscle (PAM) manipulator", *Mechatronics* 2009, 19: 816–828
12. N. G. Tsagarakis and D. G. Caldwell "Development and Control of a 'Soft-Actuated' Exoskeleton for Use in Physiotherapy and Training", *Autonomous Robots* 2003, 15: 21–33
13. H. P. H. Anh and K. K. Ahn "Hybrid control of a pneumatic artificial muscle (PAM) robot arm using an inverse NARX fuzzy model", *Engineering Applications of Artificial Intelligence* 2011, 24: 697–716
14. L. Yang and J. H. Lilly "Sliding Mode Tracking for Pneumatic Muscle Actuators in Bicep/Tricep Pair Configuration", *Proceedings of the American Control Conference, Denver* 2003, 4669-4674
15. T. Y. Choi, B. S. Choi and K. H. Seo "Position and compliance control of a pneumatic muscle actuated manipulator for enhanced safety", *IEEE transactions on Control Systems Technology* 2011, 19(4): 832–842

AUTHORS PROFILE

Avinash Kumar is a Ph.D. scholar (part time) of Applied mechanics department of MNNIT Allahabad, Prayagraj, U.P. India. He has received his B.Sc (Engg.) in Electrical Engineering from M.I.T. Muzaffarpur, Bihar in 2004 and M. Tech in Process Control Engineering from NSIT Delhi in 2006. He has scored 97.8%le in GATE 2004. His research interests include Robotics, Control systems and Biomedical Engineering. He is working as Assistant Professor at AIACTR Delhi, Government of NCT of Delhi since 2011. He has guided two M. Tech students for their thesis work. He has total 11 years of experience in teaching and industry.

Ravi Prakash Tewari is Professor of Applied mechanics department of MNNIT Allahabad, Prayagraj, U.P. India. He has received his B. E. in Mechanical Engineering from M. M. M. Engineering college, Gorakhpur, U. P. in 1990 and M. Tech in Biomedical Engineering from I.T. B.H.U. in 1993 and Ph.D. from I.T. B.H.U. in 1999. His research interests include Computational & Experimental Mechanics, Computational studies on flow in human respiratory system and centrifugal pumps, Synthesis & characterization of Ferrite for electronic application. He has more than 20 years of teaching and research experience and guided many Ph.D. and M. Tech students.