Jurnal
Teknologi

Full Paper

Modified-PID Control with Feedforward Improvement for 1-Degree-of-freedom Pneumatic Muscle Actuated System

Article history
Received
30 August 2016
Received in revised form
13 November 2016
Accepted
13 March 2017

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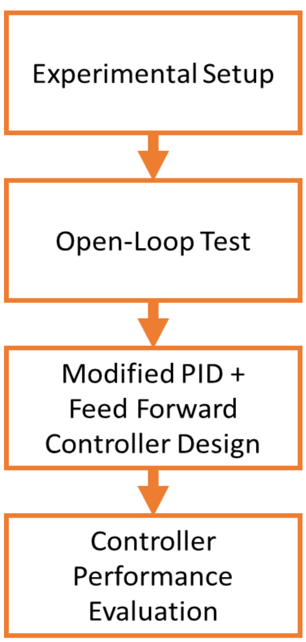
Graphical abstract



Abstract

Over the past decade, pneumatic muscle actuators (PMA) has been receiving much attention due to the favorable advantages that PMA has to offer such as inherent compliant safety, compactness, dust-resistant and powerful, especially for rehabilitation application. However, the highly non-linear phenomenon exhibited by PMA poses a challenge in positioning control of the mechanism. Due to the highly nonlinear properties of the PMA system, it is difficult and challengeable to model the system accurately. Many advanced controls have been proposed, however, majority of them requires accurate model parameters for the design and/ or deep understanding of control theory. Therefore, this research aims to highlight a practical and simple control framework capable of providing ameliorated compensation towards the non-linearities in a PMA positioning system. The proposed controller is a combination of a modified PID control incorporated with a model-based feed-forward element. The modified PID control is cascaded with a modeled-nonlinear function and a linearizer that works to compensate the influence of the nonlinearities. The design procedure of the proposed control remains simple and none of the known parameter is required. The proposed controller is verified experimentally using the constructed testbed – 1DOF PMA system; in point-to-point motion that driving in several step heights (5 mm, 10 mm, 20 mm, and 30 mm). At the step height of 30 mm, the proposed control has demonstrated three times smaller of overshoot and the reduction of 39% of settling time as compared with the conventional PID control. Overall, the experimental results show that the proposed controller is capable of demonstrating a satisfactory transient, with better overshoot reduction characteristic and faster settling time; and robust performance under default and in the presence of the change of load, in comparison with the conventional PID control.

Keywords: Pneumatic muscle actuator, linearizer, modified-PID control, feedforward, point-to-point

1.0 INTRODUCTION

Pneumatic muscle actuators (PMA) are instances of technology inspired from mechanical features existing in any biological organisms that utilizes appendages to locomotion [1]. PMA working principle is similar to that of an inverse bellow whereby contraction or pulling force is generated upon inflation of the pneumatic bladder [2]. When operate, this fluid-driven actuator is adept of striking a close resemblance to that of human skeletal musculature properties explicitly the compactness and the capability to produce high power to weight ratio [3]. Besides, PMAs offer a lower level of safety breach in the event of human interactions permitted by its inherent compliant behavior (Coined as "soft actuator") in which it is considered safer than electric or hydraulic drives producing the same force level [4]. Apart from that, the cost effectiveness from implementation to maintenance pushes the deployment of the actuation scheme in various applications. Figure 1 shows few of commercially available PMA manufactured by Festo.

Figure 1 Festo Fluidic Muscle

Though the extensive applications currently, there are a few long-standing detriments that deter the development of PMA. The detriments is mainly accorded to the non-linear force-displacement relationship as well as hysteresis induced from the friction acting inside the braided mesh [5-6]. Apart from that, PMA also suffers from creep phenomenon [7]. Consequently, these disadvantages lead to the absence of an accurate mathematical model that can be used to describe the dynamics characteristics of PMA. Thus, motion and positioning control are deemed as challenging efforts.

However, the complexity of the control architecture can be simplified via the utilization of model-free controller namely advance controllers such as adaptive control [8], neuro-fuzzy network [9], fuzzy back-stepping [10], fuzzy linearizing control scheme [11], intelligent switching using neural network [12], sliding mode control [13],[14], adaptive robust control [15], nonlinear model predictive control [16], T-S fuzzy model-based [17], fuzzy adaptive control [18], and hybrid of advanced controls [19],[20],[21]. Despite the capability to yield a satisfactory point-to-point (PTP) positioning results, there is still a need for sufficient knowledge in control theory and determination of exact model parameters leading to tedious and time-consuming design procedures. On the other hand, there are group of researchers have devoted to improve the conventional PID control by modification or hybrid it with other advanced controls, such as nonlinear PID control [22],[23].

Therefore, in this research, the conventional Proportional-Integral-Derivative (PID) controller is utilized primarily due to its easy design procedure and high adaptability nature. The PID control is cascaded with a nonlinear function and a linearizer scheme. In order to achieve a fast and precise positioning system, a feed-forward term is added into the control architecture. Henceforth, in this research, emphasis is put on the easy to design procedure and the robustness in point-to-point (PTP) positioning performance.

This paper presents the practical control framework that emphasizes simple design procedure for the positioning control of PMA. The rest of the paper is organized as follows: Section 2 briefly describes the dynamic modelling of PMA, and provides explanation on the 1-DOF PMA setup which is utilized as testbed to clarify the usefulness of the proposed controller experimentally. Besides, the control framework and design are explained in section 2, too. The experimental performance of the controller is highlighted in section 3. Lastly, conclusions are drawn in section 4.

2.0 METHODOLOGY

2.1 Modeling of PMA

Currently, there are several models being employed to explain the PMA system characteristics as well as serving the purpose of relating the length and pressure of PMA along the axis of force exertion [24]. However, the three element phenomenological model approach is used in this research to model the basic dynamic characteristic of the PMA system because it uses an engineering approach to muscle modeling [25].

The phenomenological model is employed to explain the fundamental knowledge with respect to the dynamics of the system. Figure 2 depicts the phenomenological model free body diagram. If the displacement or contraction of PMA is represented by x, the governing equation of motion for the biomimetic model can be represented as:

$$M\ddot{x} + B\dot{x} + Kx = F_{ce} - F_L \qquad (1)$$

where M is the mass at one end of the PMA, K is the spring coefficient, B is the damping coefficient, Fce is the contractile force generated when pressure is supplied to the system and F_L is the external load acting on the system.

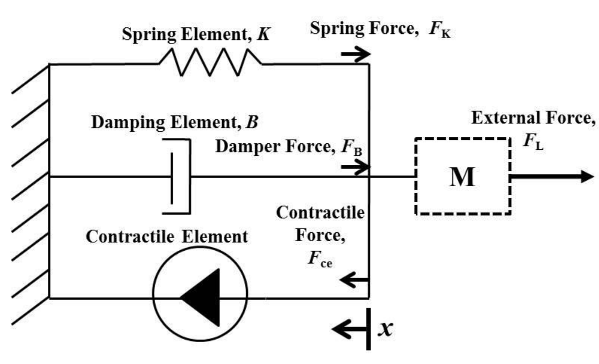


Figure 2 Three element phenomenological model of PMA

In the cases where $F_{ce} = F_L$, there is no resultant motion at which the initial displacement and velocity to be zero $[x(0) = \dot{x}(0) = 0]$. In the cases where $F_{ce} > F_L$, the right hand side of equation 1 provides the driving force of the system. In the cases where $F_{ce} < F_L$, the PMA is in an overstretched state [26].

The static and dynamic characterization experiments have been carried out in a horizontal experimental setup. One end of the muscle is fixed with a load cell while the other end is attached with a mover table in the horizontal layout. As one end of the muscle is fixed, it is practical to assume that half of the PMA mass is supported. Therefore, only half of the PMA mass is taken into consideration. However, a maximum deviation of less than 1% of the total contraction displacement subdues the need of including the inertial effects in the model. Hence, PMA is considered a low mass system, in which the M element can be neglected. With the assumption of M element = 0, the simplified equation is shown in equation 2.

$$B\dot{x} + Kx = F_{ce} - F_L \qquad (2)$$

2.2 Experimental Setup

An experimental setup for motion control of the pneumatic muscle actuator has been developed solely for this research [27]. Figure 3 depicts the experimental setup used in this research. The experimental setup consists of three main components: - incitement element, driving mechanism and sensing modules. The incitement element is provided by a Proportional Pressure Regulator (PPR) (Model: MPPE-3-1/8-6-010B) manufactured by Festo which is used to regulate the pressurization of the pneumatic muscle. The main focal point of this research, the driving mechanism comprises of a Festo Fluidic Muscle Actuator (Model: MAS-20-250N-AA-MC-K). The utilized PMA has a nominal length of 250 mm, inner diameter of 20 mm and a maximum working range of 4% of its nominal length. The axial contractile force is measured by using a Futek load cell (Model: LCF451) mounted at the fixed end of the PMA. The change in contraction length is measured with a LVDT (SR Series VR 100.0 SBLS) by Solatron Metrology. A Festo pressure transducer (Model: SDE1-D10-G2-W18-L-PU-M8) is affixed near to the outlet of PPR in order to measure as well as monitor the pressurization of the PMA. The air supply to the system is provided by a Kinki mini air compressor (Model: KAC-14 6L 1/4HP 100Psi). Sampling rate for the real-time control system is measured at 1000 Hz. Meanwhile, the range of the operating pressure is from 0 kPa to 550 kPa and the operating temperature is kept at ambient temperature of approximately 25 degrees Centigrade.

2.3 Control System Design

Apart from the above-mentioned advantages, the significant nonlinear effects exhibited by PMA causing modelling effort are often challenging and difficult. Generally, modelling of PMA mechanism manages to capture the macroscopic characteristic of the system but not the microscopic characteristic such as fine vibratory motion. The impracticability to employ a complex model in controller design has suggested that the design procedure without a plant model is much desired.

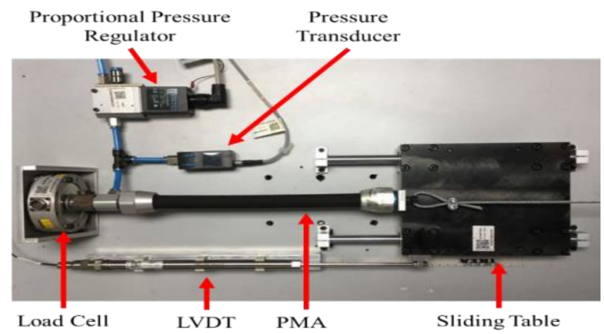


Figure 3 1-DOF horizontal PMA experimental setup

Henceforth, instead of an accurate plant model, the driving characteristics of the PMA system are employed in the controller design. The novelty of the proposed control framework lies on its easy to design procedure. This section provides a clear elucidation on the controller design outline and evaluation of point-to-point positioning performance.

The proposed controller architecture is as depicted in Figure 4. The controller consists of a feedback and feed forward path. The feed forward path is governed by the driving element. While, the feedback path is governed by a PID controller incorporated with a pressure-displacement nonlinear function block and a linearizer unit.

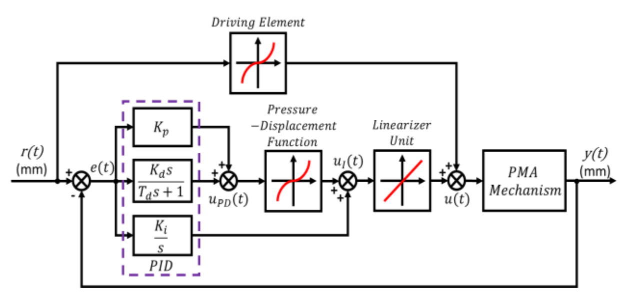


Figure 4 Proposed controller block diagram

In the feed forward path, the driving element functions by providing a suitable voltage to drive the mover to the target position. Referring to Figure 4, it can be seen that the structure of PID controller is slightly different from the conventional PID controller. The PD controller is cascaded with a pressure-displacement nonlinear function block. The function block encompasses the stick-slip effect of the PMA. Hence, further tuning of the PD gains is set to reduce the residual vibration and overshoot issue of the system in which the non-linearity effect is compensated with the use of function block. The 'I' element is fed into the pressure node as the steady state error is directly influenced by the internal bladder pressure. The output $u_1(t)$ is directly connected to a linearizer unit that holds the linearized value of the non-linear correlation between the pressure and input voltage supplied to the system.

Based on the controller concept introduced above, the outline for the controller design is as follows:-

1) A feedback PID controller is designed by employing Ziegler-Nichols tuning method 2.
2) A pressure-displacement nonlinear function block (see Figure 5) and a linearizer unit (see Figure 6) are constructed based on the actual response of the PMA in order to compensate the non-linear relationship of the displacement, pressure and control voltage.
3) The PID gains are then fine-tuned to yield a satisfactory positioning performance within the allowable margin of error and residual vibration.
4) The feedforward element is constructed by using the PMA system open loop driving characteristic.

Figure 5 illustrates the pressure-displacement function block that constructed based on the open-loop experimental responses in which define the PMA pressure versus the mover position characteristics. Since the function block is constructed based on the system actual response, the non-linear effect such as coulomb friction, stick slip effect and pressure-displacement relation are considered has been included in the function. Figure 6 presents the linearizer unit that constructed using actual open-loop responses of the PMA system that performing linearization of the relationship between the input voltage and pressure.

Figure 7 shows the feedforward path driving element as part of the element in the proposed control structure. The driving element functions in such a way to supply a suitable voltage to allow PMA contraction towards the target position. Since the target position is known, the input voltage being supplied to proportional pressure regulator can be determined as well. Hence, the driving element is designed and constructed based on the actual response of the plant. The data used in constructing the driving element comprises of the average value from 10 sets of repeatability tests. The repeatability test provides a validity test to the accuracy of data collections.

As most of the components in the proposed control framework are obtained from the actual response of the system, it can be safely presumed that the non-linearities effects are already accounted for in the controller. The design procedure is free of known model parameters and deep understanding of control theory too.

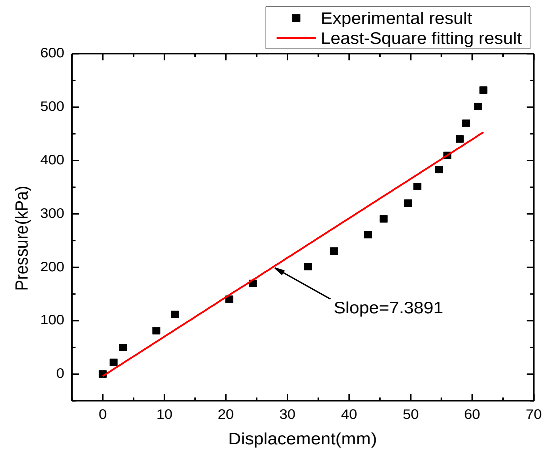


Figure 5 Pressure – Displacement nonlinear function

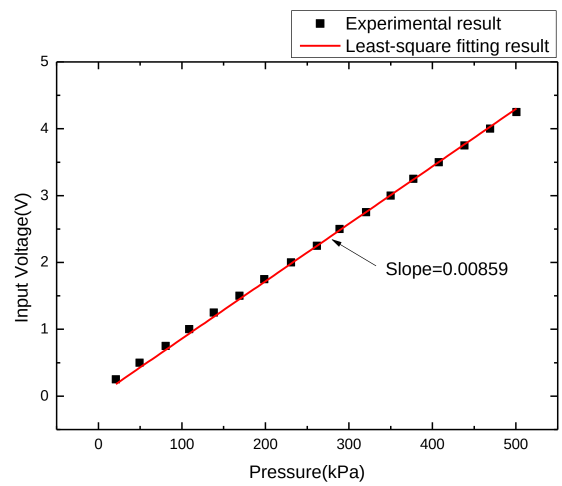


Figure 6 Linearizer – relationship between the pressure and input voltage

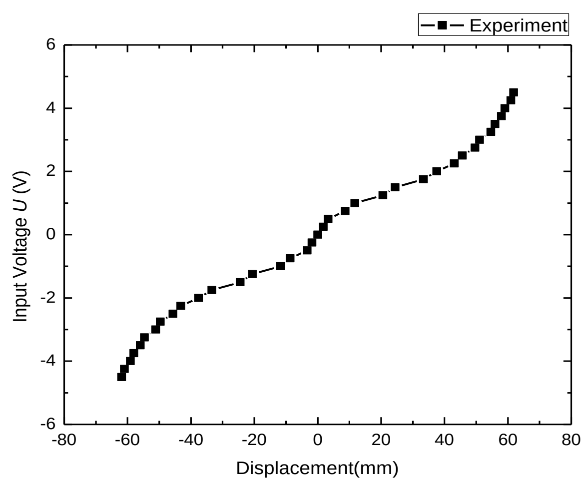


Figure 7 Feedforward element – relationship between the displacement and input voltage

3.0 RESULTS AND DISCUSSION

The usefulness of the proposed controller is experimentally evaluated using the constructed 1-DOF PMA system. As above-mentioned, the proposed controller is to reduce the residual vibration influence (stick-slip effect) of the PMA system and to improve the steady-state error that less than 50 μm.

Figure 8 shows the comparative experimental positioning responses of the proposed feed forward + modified PID with conventional PID. The conventional PID control is fine-tuned experimentally. Table 1 shows the controller parameters of the PID gains. The positioning experiment is set to drive the PMA system to different target positions ranging from 5 mm to 30 mm with default mass.

Table 1 Controller parameters

Controller	K_p	K_i	K_d
Proposed controller	0.301	11.54	0.0001
Conventional PID control	0.921	11.23	0.019

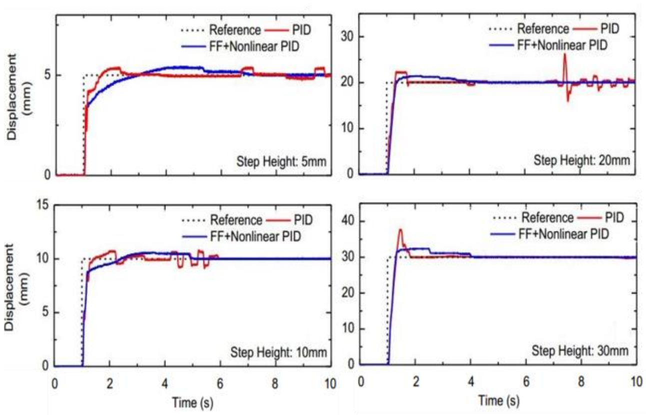


Figure 8 Experimental positioning responses to different step heights with default mass

From the results in Figure 8, it can be observed that the PID controller suffers from vibration in the transient response, and the phenomenon becomes severe at step height larger than 10 mm. at the step height 5 mm, the responses of PID control exhibit stick-slip phenomena in the steady-state response. On the other hand, the proposed control has demonstrated better transient performance in terms of overshoot reduction and settling time. Although the proposed control shows slightly overshoot, but it is still smaller than the conventional PID control. The proposed control is capable to reach positioning accuracy smaller than 50 μm faster than the conventional PID control. Table 2 presents the average and standard deviation of maximum steady state error (e_{max}) of the proposed controller. The findings tell that the proposed controller manages to suppress the residual vibration during the steady state phase. The suppression can be associated with the inclusion of the compensator for the non-linearity of the plant in the controller design.

Table 2 Average and standard deviation of maximum steady-state errors for 10 experiments

Step Height	e_{max} of FF + Nonlinear PID	
	Average(μm)	Std. Dev. (μm)
5 mm	3.97 x 10^{1}	1.816 x 10^{1}
10 mm	3.62 x 10^{1}	2.34 x 10^{1}
20 mm	3.95 x 10^{1}	4.25 x 10^{1}
30 mm	4.56 x 10^{1}	3.91 x 10^{1}

Table 3 summarizes the quantitative PTP transient performance of 10 experiments for both controllers. The proposed controller demonstrates a reduction of 65.9% overshoot over the PID control at step height of 30 mm. The smaller overshoot percentage is recorded by the proposed controller as compared with the PID control. Besides, the proposed controller performs two times faster settling time than the PID control when the mechanism is driven to 10 mm, 20 mm and 30 mm destinations. Overall, the results show that the proposed controller is able to yield a noteworthy positioning performance and better motion accuracy with the rejection of the nonlinear effect of the system as compared to the conventional PID control.

Table 3 Average (avg) and standard deviation (std) of of 10 experiments for PTP positioning performance

			Proposed controller	PID control
5 mm	t_r (s)	avg	8.71 x 10^{-1}	2.81 x 10^{-1}
		std	1.323 x 10^{-1}	3.73 x 10^{-2}
	OS (%)	avg	8.54	7.28
		std	9.68 x 10^{-1}	8.99 x 10^{-1}
	t_s (s)	avg	6.68	8.19
		std	6.90 x 10^{-1}	2.14
10 mm	t_r (s)	avg	3.96 x 10^{-1}	1.538 x 10^{-1}
		std	1.005 x 10^{-1}	5.67 x 10^{-2}
	OS (%)	avg	5.48	6.54
		std	6.31 x 10^{-1}	1.163
	t_s (s)	avg	4.68	9.89
		std	6.05 x 10^{-1}	6.76 x 10^{-2}
20 mm	t_r (s)	avg	1.802 x 10^{-1}	1.486 x 10^{-1}
		std	1.75 x 10^{-2}	3.17 x 10^{-2}
	OS (%)	avg	6.31	7.96
		std	3.11 x 10^{-1}	6.60
	t_s (s)	avg	4.29	9.61
		std	3.93 x 10^{-1}	6.32 x 10^{-1}
30 mm	t_r (s)	avg	1.996 x 10^{-1}	2.19 x 10^{-1}
		std	1.59 x 10^{-2}	1.130 x 10^{-2}
	OS (%)	avg	7.85	2.3 x 10^{1}
		std	4.86 x 10^{-1}	2.27
	t_s (s)	avg	3.87	6.34
		std	1.701 x 10^{-1}	3.54

Figure 9 shows the comparative experimental positioning responses of the proposed feed forward + nonlinear PID with conventional PID of different target positions ranging from 5 mm to 30 mm with added mass. With the added mass, the proposed controller is still capable of yielding a satisfactory positioning performance of no residual vibration as compared to the conventional PID controller. Apart from that, the proposed controller is more robust towards the rejection of uncertainties in the loading variations. The vibration still can be observed at the transient part of the PID control responses. There is slight overshoot is evidenced at the responses of the proposed control, too. Hence, the future works will focus more on improving the overshoot performance to allow better overshoot reduction characteristic and higher motion accuracy controller for the motion control of PMA positioning system.

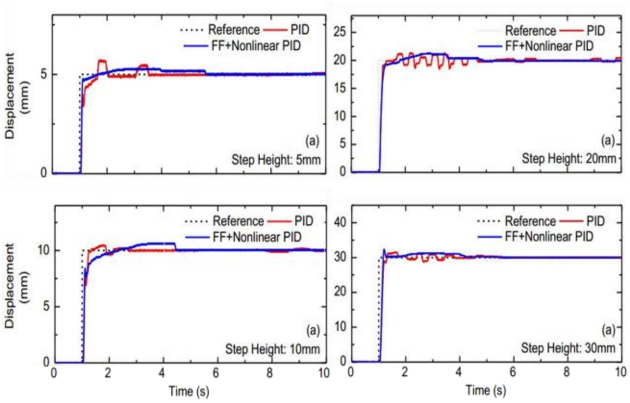


Figure 9 Experimental positioning responses to different step heights in the presence of mass change

4.0 CONCLUSION

Studies have shown that pneumatic muscle actuator renders prominent prospect in robotic and industrial applications. However, due to its inherent dynamic characteristics, the effort to control its motion is reckoned challenging. In addition, it is challenging to obtain accurate model parameters for a PMA system too. For that reason, a simple and direct control framework that do not acquire known model parameters in the design procedure is proposed. The proposed controller involving a modified PID incorporated with a model-based feedforward element. The control framework was then validated experimentally with respect to the point to point positioning performance. The practicality of the control framework is indicated in the experimental result whereby it is adept of a better transient response, higher motion accuracy and robust performance. This research has contributed towards a practical and easy control design procedure that is capable of reducing the effect of PMA nonlinearities towards the controller design. Though, overshoot can still be observed in the proposed controller performance, this research serves as a benchmark for the practical and easy methodology in designing a robust controller for a highly nonlinear system.

Acknowledgement

Authors would like to extend their gratitude towards Motion Control Research Laboratory, Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka for the equipment and laboratory supports throughout this research. This work is financially supported by Ministry of Higher Education through the Fundamental Research Grant Scheme (FRGS/2/2014/TK03/FKE/02/F00240).

References

[1] Redlarski, G., Blecharz, K., Dąbkowski, M., Palkowski, A. and Tojza, P.M. 2012. Comparative Analysis of Exoskeletal Actuators. *Pomiary Autom. Robot*. 16(12): 133-138.

[2] Repperger, D. W., Phillips, C. A., Neidhard-doll, A., Reynolds, D. B., and Berlin, J. 2006. Actuator Design Using Biomimicry Methods and A Pneumatic Muscle System. *Control Eng. Pract.* 14: 999-1009.

[3] Repperger, D. W., Phillips, C. A., Neidhard-Doll, A., Reynolds, D. B., and Berlin, J. 2005. Power/Energy Metrics for Controller Evaluation of Actuators Similar to Biological Systems. *Mechatronics*. 15(4): 459-469.

[4] Tsagarakis, N., and Caldwell, D. G. 2003. Development and Control of a 'Soft-Actuated' Exoskeleton for Use in Physiotherapy and Training. *Auton. Robots*. 15(1): 21-33.

[5] Yeh, T., Wu, M., Lu, T., Wu, F., and Huang, C. 2010. Control of McKibben Pneumatic Muscles for a Power-Assist, Lower-Limb Orthosis. *Mechatronics*. 20(6): 686-697.

[6] Balasubramanian, S., Ward, J., Sugar, T., and He, J. 2007. Characterization of The Dynamic Properties of Pneumatic Muscle Actuators. *IEEE 10th Int. Conf. Rehabil. Robotics (ICORR)*. Nertherlands. 13-15 June 2007. 764-770.

[7] T. V. Minh, B. Kamers, H. Ramon, and H. Van Brussel. 2012. Mechatronics Modeling and Control of A Pneumatic Artificial Muscle Manipulator Joint – Part I : Modeling of A Pneumatic Artificial Muscle Manipulator Joint with Accounting for Creep Effect. *Mechatronics*. 22(7): 923-933.

[8] D. G. Caldwell, G. a. Medrano-Cerda, and M. Goodwin. 1995. Control of Pneumatic Muscle Actuators. *IEEE Control Systems Magazine*. 15(1): 40-48.

[9] M. Iskarous and K. Kawamura. 1995. Intelligent Control Using a Neuro-Fuzzy Network. *Intelligent Robots and Systems 95.'Human Robot Interaction and Cooperative Robots', IEEE/RSJ International Conference*. Pennsylvania, USA. 5-9 August 1995. 350-355.

[10] P. Carbonell, Z. P. Jiang, and D. W. Repperger. 2001. A Fuzzy Backstepping Controller for A Pneumatic Muscle Actuator System. *The IEEE International Symposium on Intelligent Control (ISIC '01)*. Mexico. 5-7 September 2001. 353-358.

[11] K. Balasubramanian and K. Rattan. 2003. Fuzzy Logic Control of A Pneumatic Muscle System Using a Linearing Control Scheme. *The 22nd International Conference of the North American Fuzzy Information Processing Society (NAFIPS)*, Chicago, USA. 24-26 July 2003. 432-436.

[12] K. Ahn and T. Thanh. 2004. Improvement of The Control Performance of Pneumatic Artificial Muscle Manipulators Using an Intelligent Switching Control Method. *KSME Int. J.* 18(8): 1388-1400.

[13] Lilly, J. and Yang. L. 2005. Sliding Mode Tracking for Pneumatic Muscle Actuators in Opposing Pair Configuration. *Control System Technology.* 13(4): 550-558.

[14] J. Sárosi, S. Csikós, I. Asztalos, J. Gyeviki, and A. Véha. 2011. Accurate Positioning of Spring Returned Pneumatic Artificial Muscle Using Sliding-mode Control. *1st REgional Conference-Mechatronics in Practice and Education (MECH-CONF)*. Subotica, Serbia. 8 December 2011. 350-356.

[15] X. Zhu, G. Tao, B. Yao, and J. Cao. 2008. Adaptive Robust Posture Control of Parallel Manipulator Driven by Pneumatic

Muscles With Redundancy. *IEEE/ASME Trans. Mechatronics.* 13(4): 441-450.

[16] D. Schindele and H. Aschemann. 2008. Nonlinear Model Predictive Control of a High-Speed Linear Axis Driven by Pneumatic Muscles. *American Control Conference (ACC), 2008.* Seatle, Washington, USA. 11-13 June 2008. 3017-3022.

[17] M. K. Chang, J. J. Liou, and M. L. Chen. 2011. T-S Fuzzy Model-Based Tracking Control of A One-Dimensional Manipulator Actuated by Pneumatic Artificial Muscles. *Control Eng. Pract.* 19(12): 1442-1449.

[18] A. Hosovsky, J. Novak-Marcincin, J. Pitel, J. Borzikova, and K. Zidek. 2012. Model-Based Evolution of A Fast Hybrid Fuzzy Adaptive Controller for a Pneumatic Muscle Actuator. *International Journal of Advanced Robotic System.* 9(40): 1-11.

[19] G. L. Shi and W. Shen. 2013. Hybrid Control of A Parallel Platform Based on Pneumatic Artificial Muscles Combining Sliding Mode Controller and Adaptive Fuzzy CMAC. *Control Engineering Practice.* 21(1): 76-86.

[20] A. Hošovský, P. Michal, M. Tóthová, and O. Biroš. 2014. Fuzzy Adaptive Control for Pneumatic Muscle Actuator with Simulated Annealing Tuning. *IEEE 12th Symposium on Applied Machine Intelligence and Informatics (SAMI)*. Herl'any, Slovakia. 23-25 January 2014. 205-209.

[21] H. Pham, H. Anh, and K. K. Ahn. 2011. Hybrid Control of A Pneumatic Artificial Muscle (PAM) Robot Arm Using an Inverse NARX Fuzzy Model. *Engineering Application of Artificial* Intelligence. 24(4): 697-716.

[22] T. D. C. Thanh and K. K. Ahn. 2006. Nonlinear PID Control to Improve The Control Performance of 2 Axes Pneumatic Artificial Muscle Manipulator using Neural Network. *Mechatronics*. 16(9): 577-587.

[23] H. Anh and N. Nam. 2011. A New Approach of the Online Tuning Gain Scheduling Nonlinear PID Controller Using Neural Network. *PID Control, Implementation and Tuning*. InTech.

[24] E. Kelasidi, G. Andrikopoulos, G. Nikolakopoulos, and S. Manesis. 2011. A Survey on Pneumatic Muscle Actuators Modeling. *The 20th IEEE Int. Symp. Industrial Electronics (ISIE).* Gdansk, Poland. 27-30 June 2011. 1263-1269.

[25] D. B. Reynolds, D. W. Repperger, C. A. Phillips, and G. Bandry. 2003. Modeling The Dynamic Dharacteristics of Pneumatic Muscle. *Ann. Biomed. Eng.* 31(3): 310-317.

[26] J. L. Serres, D. B. Reynolds, C. a Phillips, M. J. Gerschutz, and D. W. Repperger. 2009. Characterisation of A Phenomenological Model for Commercial Pneumatic Muscle Actuators. *Computer Methods Biomech. Biomed. Engineering.* 12(4): 423-30.

[27] V. Sakthivelu, S. Chong, M. H. Tan, and M. Ghazaly. 2016. Phenomenological Modeling and Classic Control of A Pneumatic Muscle Actuator System. *International Journal of Control Automation.* 9(4): 301-312.