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Positioning Control of an Antagonistic Pneumatic Muscle Actuated System using Feedforward Compensation with Cascaded Control Scheme

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Abstract: This paper presents a feedforward compensation with cascaded control scheme (FFC) for the positioning control of a vertical antagonistic based pneumatic muscle actuated (PMA) system. Owing to the inherent nonlinearities and time varying parameters exhibited by PMA, conventional fixed controllers unable to demonstrate high positioning performance. Hence, the feedforward compensation with cascaded control scheme is proposed whereby the scheme includes a PID controller coupled with nonlinear control elements. The proposed scheme has a simple control structure in addition to its straightforward design procedures. Though there are nonlinear control elements involved, these elements are derived from the open loop system responses that does not requires any accurate known parameters. Performance of the FFC scheme are then evaluated experimentally and compared to a PID controller with feedforward compensation (FF-PID) in point-to-point motion of different step heights. Overall, the experimental results show that the effectiveness of the proposed FFC scheme in reducing the steady state error to zero in comparison to FF-PID controller for all cases of step heights examined.

Keywords: Cascaded control, feedforward compensation, pneumatic muscle actuator

1. Introduction

Pneumatic muscle actuators (PMA) have been gaining much attraction in industrial applications due to the favorable advantages that PMA has to offers such as inherent compliant safety, compactness, dust-resistant and powerful. However, the highly non-linear phenomenon exhibited by PMA poses a challenge in accurate positioning control of the mechanism. Numerous controllers have been proposed to address this problem in which can be classified into four categories, namely conventional control, intelligent control, model-based control and hybrid control. Conventional controllers such as PID remains favorable where industrial applications are concerned due to its simple structure and practical design procedure (Caldwell et al., 1993) (Sakthivelu et al., 2016) (Chong et al., 2016).

However, performance of classical control deteriorates progressively when subjected to setpoint changes and nonlinear properties. This leads to the proposal of model-based control strategies such as adaptive control (Lilly, 2003), sliding mode control (Aschemann et al., 2008), switching model predictive control (Andrikopoulos et al, 2013) and others. Nonetheless, these controllers of such requires determination of accurate plant model parameters, which are onerous and time-consuming. Then, the emergence of intelligent control techniques such as neural network (Anh et al., 2011) and fuzzy logic control (Balasubramaniam et al., 2003) which are able to overcome the problem in the absence of accurate model through soft computing algorithms have been proposed. Still, lacking a tangible design procedure directs researchers to augment classical control or model-based control with intelligent control (Thanh et al., 2006) (Chang et al., 2011) (Shi et al.,2013) (Wang et al., 2016).

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Though these control methods have showed promising positioning performances, the design procedures of such controllers are often laborious and difficult while one may need high degree of control knowledge to realize them. In which, the control methods deemed impractical in real life applications. Hence, an improvement of the conventional PID controller with nonlinear control elements augmentation is proposed in this paper. The nonlinear control elements are modelled through experimental open-loop responses. The controller is named as feedforward compensation with cascaded control scheme. Similarly, the design procedures and structure retain its simplicity to that of a conventional PID.

The rest of this paper is organized as follows; First, the controller concept and design procedures will be explained. Next, a brief description on the experimental setup is discussed followed by the performance validation of controller.

2. Controller Concept and Design Procedures

Fig 1. shows the block diagram of the proposed FFC scheme. The proposed controller consists of four main elements: - PID controller, velocity feedforward element (V-FF), model-based feedforward element (P-FF and D-FF) and model-based compensator (PC element). The inclusion of the model-based elements aims at reducing the influence of PMA nonlinearities. Despite having model-based control elements, tedious and rigorous modelling efforts are omitted in this research. Instead, control elements are constructed from measured input output relationship from the experimental open-loop driving characteristics. Also, the controller is constructed in a cascaded manner with outer position feedback and inner pressure feedback. The cascaded form was undertaken to reduce the adverse effect of small changes in muscle pressure. Based on the controller concept introduced, the outline for the proposed controller may be summarised as follows: -

1. Design the feedback PID controller by using Ziegler-Nichols tuning method 2.
2. Realize the velocity feedforward and pressure feedback.
3. Construct the additional control elements.

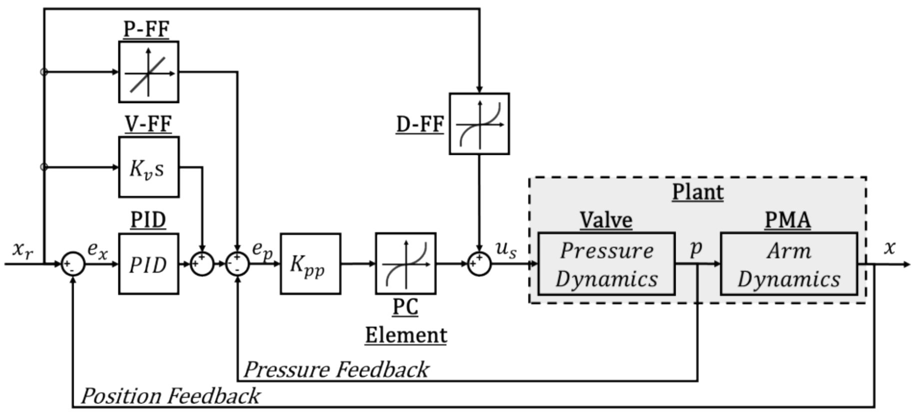

Fig. 1 - Block diagram of feedforward compensation with cascaded control scheme

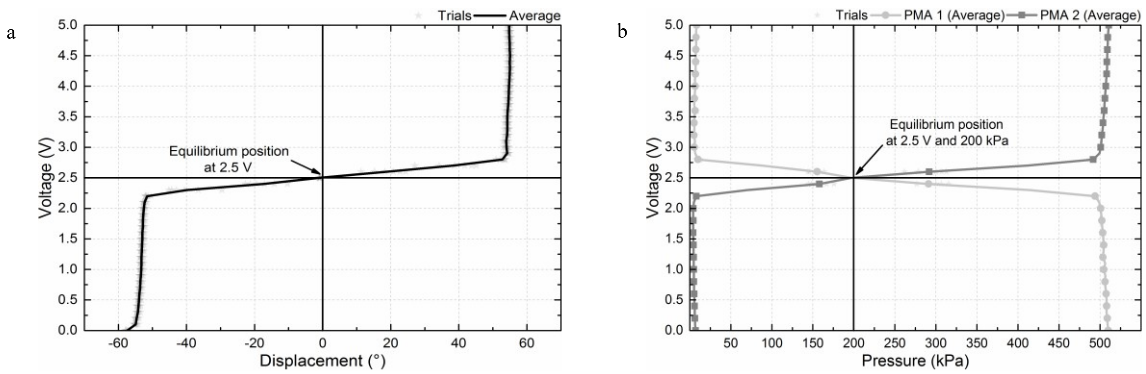

Fig. 2 - Static relationship of voltage against (a) displacement; (b) pressure

3. Experimental Setup

Fig. 3(a) and Fig. 3(b) show the operation of the PMA system in both positive and negative direction with the acting muscle in state inflation. Fig. 3(c) depicts the schematic diagram for the experimental testbed that are utilised for experimental validation of the proposed controller in this research. The testbed consists of a pair of muscle of identical nominal length and diameter arranged in vertical parallel antagonistic manner. The two PMAs (Model: DMSP-10-150N-RM-CM) generate pulling forces, resulting in an up and down motions with rotational motion about the shaft. The angle of rotation is measured by a rotary encoder (METRONIX H40-8-3600-ZO-1), with resolution of 3600 pulses per revolution (0.1° resolution). In addition, a 5-port 3-way proportional servo valve (FESTO MPYE-5-1/HF-710B) is used to enable pressure supply to the muscle. The muscle pressures are measured by using two pressure sensors (SMC PSE540A-01). Data is collected by a data acquisition unit at a sampling rate of 1 kHz. Also, all experiments were conducted at pressure of 5 bar.

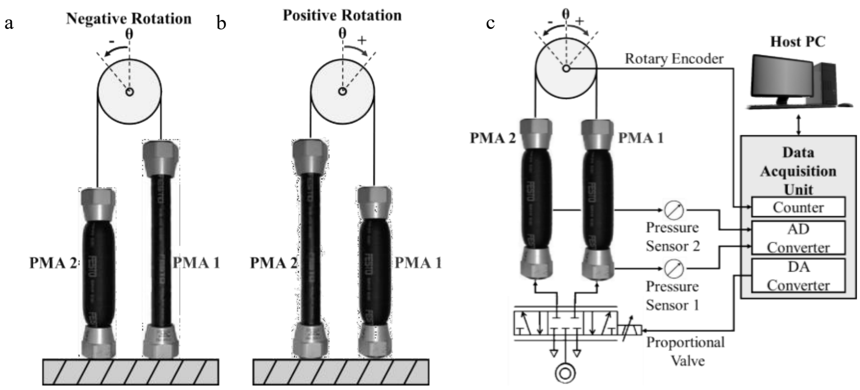

Fig. 3 - (a) Operation of system in negative direction; (b) Operation of system in positive direction; (c) Experimental setup for antagonistic based PMA system

4. Point to Point Positioning Performance

To illustrate the effectiveness of the proposed feedforward compensation with cascaded control approach, the control scheme is realized and verified through experimental works in terms of point to point motion. For comparative purpose, a PID with feedforward control is designed without the inclusion of pressure feedback and pressure related compensator. Both controllers are designed to achieve similar transient performance at 10° tuning height. The fine-tuned controller parameters for both schemes are as shown in Table 1.

Table 1 - Controller parameters for FFC control scheme and FF-PID controller

Controller	K_p (kPa / °)	K_i (kPa / ° s)	K_d (kPa / ° s^{-1})	K_v (kPa / ° s^{-1})	K_{pp}
FFC	4.8	68.57	0.084	2.4 $(K_p/2)$	4.8 (K_p)
FF-PID	4.8	68.57	0.084	0.096 $(K_p/5)$	

Fig. 4 (a) and (b) show the comparative experimental step response for FFC and FF-PID controls with a commanded step height of 1° for positive and negative direction respectively. It can be clearly seen that the FFC scheme (denoted by black solid line) demonstrates zero steady-state error as compared to the FF-PID controller (denoted by light grey solid line) of ± 0.1°. On the other hand, the transient performance of both FFC scheme and FF-PID controller remains almost indifferent. However, the FFC scheme manages to demonstrate a faster settling time than that of FF-PID controller.

Further investigation on the control performance were done by increasing the step heights from 1° to 5° and 10° as shown in Fig. 5 and Fig. 6 respectively. Despite the increment in step heights examined, the FFC scheme demonstrates a better accuracy whereby zero steady state errors were obtained compared to FF-PID controller that maintains the steady state error within ± 0.1°. The error sustained by the FF-PID during the steady state can be attributed to the variations of the muscle pressure as shown in Fig. 7. This poses an adverse effect to the positioning accuracy of the FF-PID although the amplitudes of the pressure variations are generally lower than 5 kPa. With the inclusion of pressure feedback, the FFC scheme does not suffer from this as the slight variations are compensated. (It is to be noted that the pressure signals are post filtered from the acquired data.)

The effectiveness of the proposed FFC scheme with respect to the change of step heights were verified successfully. From the experimental results presented, the FFC scheme has successfully demonstrated promising positioning accuracy while maintaining a simple control structure and practical design procedures. Also, it is also noteworthy that the FFC scheme is capable of demonstrating an ameliorated performance even at 1° while having a narrow band of control voltage as shown in Fig. 2.

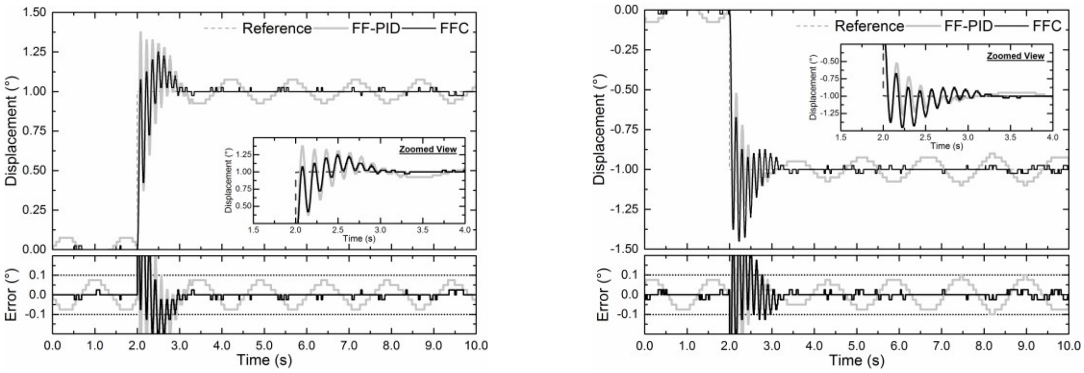

Fig. 4 - Comparative step response of FFC and FF-PID controller at (a) 1.0°; (b) -1.0°

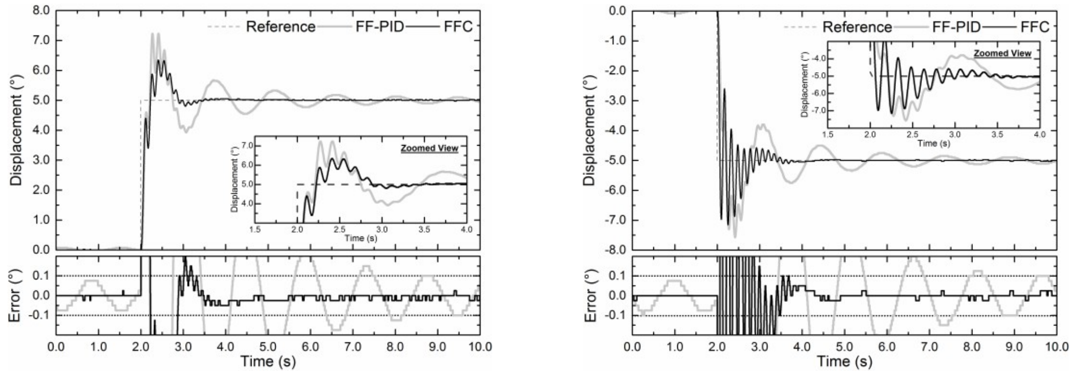

Fig. 5 - Comparative step response of FFC and FF-PID controller at (a) 5.0°; (b) -5.0°

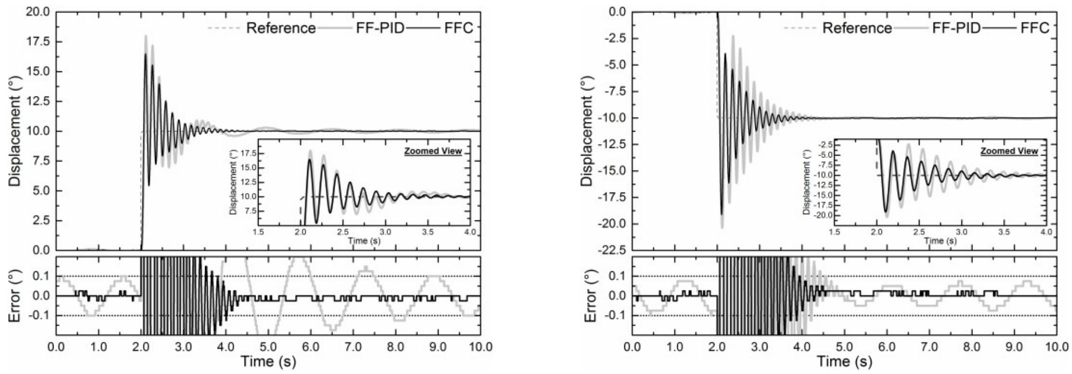

Fig. 6 - Comparative step response of FFC and FF-PID controller at (a) 10.0°; (b) -10.0°

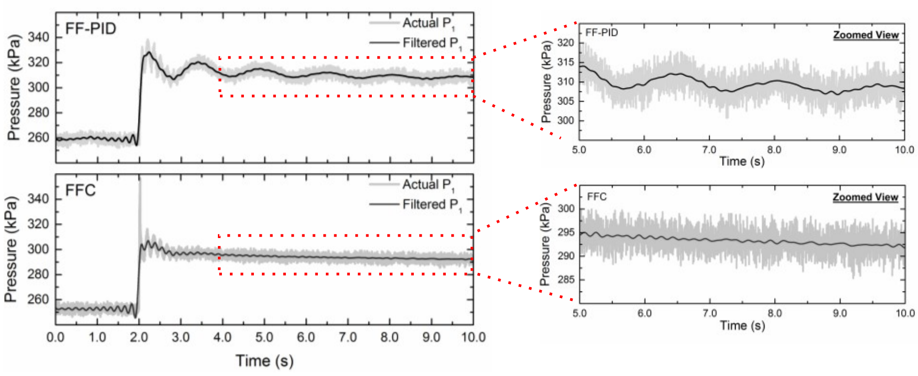

Fig. 7 - Comparative pressure response of FFC and FF-PID controller at 10.0°

5. Conclusion

A practical control strategy is introduced in this paper for the positioning control of a highly nonlinear pneumatic muscle actuated system. The controller consists of the PID controller, displacement feedforward term, pressure feedforward term and velocity feedforward element. The displacement and pressure feedforward term are model based compensator constructed using the driving characteristics of the system through open loop configuration. Hence, the scheme retains a simple structure and straightforward design procedures. Comparative experimental works shows the advantage of the FFC scheme in improving the steady state accuracy in comparison to the FF-PID control. Further work should be pursued in the direction of improving the performance of the system during the transient portion of the positioning effort as well as examining the tracking performance of the controller.

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References

[1] Caldwell, D. G., Medrano-Cerda, G. a., & Goodwin, M. J. (1993). Braided pneumatic actuator control of a multi-jointed manipulator. Proceedings of IEEE Systems Man and Cybernetics Conference - SMC, 423-428.
[2] Sakthivelu, V., Chong, S. H., Tan, M. H., & Ghazaly, M. M. (2016). Phenomenological modeling and classic control of a pneumatic muscle actuator system. International Journal of Control and Automation, 9(4), 301-312.
[3] Chong, S. H., Chan, C. Y., Sato, K., Sakthivelu, V., & Loh, S. L. (2016). Modified-PID control with feedforward improvement for 1-degree-of-freedom pneumatic muscle actuated system. Jurnal Teknologi. 79(5-2), 51-57.
[4] Lilly, J. H. (2003). Adaptive tracking for pneumatic muscle actuators in bicep and triceps configurations. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11(3), 333-339.
[5] Aschemann, H., & Schindele, D. (2008). Sliding-Mode Control of a High-Speed Linear Axis Driven by Pneumatic Muscle Actuators. IEEE Transactions on Industrial Electronics, 55(11), 3855-3864.
[6] Andrikopoulos, G., Nikolakopoulos, G., Arvanitakis, I., & Manesis, S. (2013). Switching model predictive control of a pneumatic artificial muscle. International Journal of Control, Automation and Systems, 11(6), 1223-1231.
[7] Anh, H. P. H., & Nam, N. T. (2011). Modeling and Adaptive Self-Tuning MVC Control of PAM Manipulator Using Online Observer Optimized with Modified Genetic Algorithm. Engineering, 03(02), 130-143.
[8] Balasubramanian, K., & Rattan, K. (2003). Fuzzy logic control of a pneumatic muscle system using a linearing control scheme. 22nd International Conference of the North American Fuzzy Information Processing Society, 432-436.
[9] Thanh, T. D. C., & Ahn, K. K. (2006). Nonlinear PID control to improve the control performance of 2 axes pneumatic artificial muscle manipulator using neural network. Mechatronics, 16(9), 577-587.
[10] Chang, M. K., Liou, J. J., & Chen, M. L. (2011). T-S fuzzy model-based tracking control of a one-dimensional manipulator actuated by pneumatic artificial muscles. Control Engineering Practice, 19(12), 1442-1449.
[11] Shi, G. L., & Shen, W. (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.
[12] Wang, S., & Sato, K. (2016). High-precision motion control of a stage with pneumatic artificial muscles. Precision Engineering, 43, 448-461.