Faculty of Electrical Engineering

FEEDFORWARD COMPENSATION AND CASCADED CONTROL SCHEME FOR TRAJECTORY TRACKING OF PNEUMATIC MUSCLE ACTUATED SYSTEM

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FEEDFORWARD COMPENSATION AND CASCADED CONTROL SCHEME FOR TRAJECTORY TRACKING OF PNEUMATIC MUSCLE ACTUATED SYSTEM

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DECLARATION

I declare that this thesis entitled "Feedforward Compensation and Cascaded Control Scheme for Trajectory Tracking of Pneumatic Muscle Actuated System" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :
Name : Chan Chun Yuan
Date : 10 / 12 / 2018

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechatronics Engineering.

Signature :
Supervisor Name : Assoc. Prof. Dr. Chong Shin Horng
Date : 10 / 12 / 2018

DEDICATION

To my parents

ABSTRACT

Over the past decade, pneumatic muscle actuators (PMA) has been steadily receiving much attention not only in the areas of industrial applications as well in promising research areas such as robotics and biomedical engineering. The popularity can be much associated with the attractive advantages PMA has to offer such as inherent compliant safety, high power to weight ratio and compact form factor. Despite the attractive advantages it has to offer, PMA exhibits significant nonlinear characteristics such as hysteretic behavior and creep phenomenon. Subsequently, these dynamic and time varying behaviors often makes modelling and real time motion control a challenging effort. Although many control methods have been developed, these controller design procedures frequently require exact model of mechanism and deep understanding in modern control theory which leads to their impracticability. Henceforth, in this research, a practical control strategy namely the Feedforward Compensation with Cascaded Control (FFC) scheme is proposed for the trajectory control of the PMA mechanism. The practical control scheme employed heavily considers on simple structure and straightforward design framework. Hence, the proposed FFC controller includes control elements that are derived from the measured open loop responses. The tracking performance is examined and compared to a Proportional Integral Derivative (PID) controller through experimental works. Experimental results show that the proposed controller can produce zero steady state error in step positioning. Similarly, the feedforward compensation with cascaded control scheme performs better in tracking when compared to PID controller with a higher tracking accuracy with an average improvement of 45 % and 64 % for maximal tracking error and root mean square error respectively. Likewise, when evaluated for robustness towards load variations, the proposed control strategy provides an ameliorated performance over the PID controller with an error improvement of 58 % in terms of maximal tracking error and 44 % in terms of root mean square error.

ABSTRAK

Menelusuri dekad yang lalu, penggerak otot pneumatik semakin mendapat tempat bukan sahaja dalam industri malahan dalam bidang-bidang penyelidikan yang prominen seperti robotik dan kejuruteraan bio-medikal. Populariti ini boleh dikaitkan dengan kelebihan yang ditawarkan oleh penggerak otot seperti ciri-ciri keselamatan, kuasa penggerak yang tinggi dan faktor bentuk yang padat. Walau bagaimanapun, penggerak otot pneumatik mempamerkan ciri-ciri tidak linear yang ketara seperti fenomena hysteresis dan rayap. Justeru itu, kelemahan dinamik dan perubahan tingkah laku dengan masa sering kali membuat pencirian sistem dan kawalan gerakan satu usaha yang mencabar. Walau terdapat banyak sistem kawalan yang telah dicadangkan, rangka kerja sistem kawalan yang dicadangkan memerlukan model yang tepat dan juga pengetahuan yang mendalam berkaitan theori sistem kawalan moden di mana sistem kawalan sering kali menjadi tidak praktikal. Oleh itu, dalam penyelidikan ini, satu strategi kawalan praktikal yang dinamakan sebagai skema pengawal kaskad dengan pampasan suap depan dicadangkan untuk kawalan trajektori mekanisme PMA. Skema kawalan praktikal ini mempertimbangkan struktur yang mudah dan rangka kerja yang ringkas. Pengawal yang dicadangkan mempunyai elemen pengawal yang dibina melalui hubungan antara input dan keluaran yang boleh didapati melalui pencirian gelung terbuka. Seterusnya, prestasi penjejakan dinilai dan dibandingkan dengan pengawal PID melalui eksperimen. Hasil ujikaji menunjukkan bahawa sistem pengawal yang dicadangkan tidak menunjukkan ralat dalam keadaan mapan melalui pergerakan titik ke titik. Prestasi FFC lebih baik dalam penjejakan trajektori berbanding dengan pengawal PID dengan ralat penjejakan yang lebih tinggi di mana terdapat purata peningkatan bersamaan dengan 45 % dan 64 % dalam julat penjejakan maksimum dan julat kuadrat rata akar masing-masing. Begitu juga, dalam penilaian keteguhan pengawal terhadap perubahan jisim, prestasi pengawal yang dicadangkan adalah lebih teguh dengan penambahbaikan julat yang positif di mana 58 % dalam julat penjejakan maksimum dan 44% dalam julat kuadrat rata akar berbanding dengan pengawal PID.

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LIST OF SYMBOLS AND ABBREVIATIONS

α_o	- Initial braid angle
AFNTSMC	- Adaptive Fuzzy Non-Singular Terminal Sliding Mode Controller
AN-PID	- Advanced Nonlinear PID
ARX	- Auto-Regressive with Exogenous Input
ΔF	- Difference in force exerted by muscle
ΔP	- Difference in muscle pressure
D-FF	- Displacement feedforward element
D_o	- Initial diameter of muscle
DOF	- Degree of freedom
ε	- Length / contraction of muscle
E_{max}	- Maximum error
E_{rms}	- Root mean square error
$F(p,\varepsilon)$	- Force exerted in terms of supplied pressure and muscle length
FFC	- Feedforward Compensation with Cascaded control
FF-PID	- PID with feedforward control
FLC	- Fuzzy Logic Control
g	- Gravitational acceleration constant
I	- Integral element
J	- Moment of inertia
$K(p)$	- Spring coefficient in terms of supplied pressure
K_d	- Derivative gain
K_i	- Integral gain
K_p	- Proportional gain
K_{pp}	- Pressure gain
K_u	- Critical gain

K_v - Velocity gain

l - Length of arm

L - Length of muscle in inflated or deflated state

L_o - Initial length of muscle

M - Mass of load

MISO - Multiple Input Single Output

NN - Neural Network

P - Proportional element

PC - Pressure compensator element

PD - Proportional-Derivative element

P-FF - Pressure feedforward element

PI - Proportional-Integral element

PID - Proportional-Integral-Derivative element

φ - Total force exerted by muscle

PMA - Pneumatic Muscle Actuator

P_o - Nominal constant muscle pressure

P_u - Critical period

PWA - Piece Wise Affinity

RBFNN - Radial Basis Function Neural Network

SCARA - Selective Compliance Articulated Robot Arm

SMC - Sliding Mode Controller

sMPC - Switching Model Predictive Control

SOFC - Self-organizing Fuzzy Control

τ - Rotating torque of shaft

θ - Rotational displacement of shaft

$\dot{\theta}$ - Rate of change of angular displacement of shaft

$\ddot{\theta}$ - Rate of change of angular velocity of shaft

x - Nominal length / contraction of muscle

$\dot{x}$ - Rate of change of muscle length / contraction

VFF - Velocity feedforward element

LIST OF PUBLICATIONS

Journal:

1. Chong, S.H., Chan, C.Y., Sato, K., Sakthivelu, V., and Loh, S.L., 2017. Modified-PID Control with Feedforward Improvement for 1-Degree-of-Freedom Pneumatic Muscle Actuated System. *Jurnal Teknologi*, 79(5-2), pp. 51-57.

Conference:

1. Chan, C.Y., Chong, S.H., Tan, M.H., and Tang, T.F., 2017. Tracking Control of an Antagonistic Pneumatic Artificial Muscle Actuated System, using Enhanced-PID Control. In: *2017 Postgraduate Research Conference (PReCON).*
2. Tang, T.F., Chong, S.H., Chan, C.Y., and Sakthivelu, V., 2016. Point-to-Point Positioning Control of a Pneumatic Muscle Actuated System using Improved-PID Control. In: *2016 International Conference on Automatic Control and Intelligent System (I2CACIS).*

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter highpoints the background of the study, problem statement, objectives and the scopes of the project. Background of study is a brief exposition on the system that is being researched and the problem statement dictates the core issue that is to be addressed with this research. Meanwhile, the objectives serve as a benchmark while the scopes define the limits and boundaries of the project in overseeing the project upon completion.

1.2 Background

Predominantly, servo control in industrial applications has been limited to the usage of electrical and hydraulic actuators. However, in recent years, mechanical systems demands actuators of clean, compact form factor yet capable of yielding large power density. While electrical drives offers clean, reliable operation usually under high speed and low torque conditions, necessary transmision elements are needed to convert the power to a more suitable form. Hydraulic actuators, on the other hand provides a high power to weight ratio, however is subjected to leakage. Failure in catering to such criterias, leaving many researchers and users to consider pneumatic actuators. Lots of research work on novel actuators has been presented and among which is the pneumatic muscle actuators (PMA) shows a promising attributes that conforms with the requirements. PMAs have different nomenclature throughout past literatures such as braided muscle, McKibben muscle, netted muscle, paynter hyperboloid muscle and pneumatic artificial muscle (Kelasidi et al., 2011). In this thesis context, the actuator used would be known as the pneumatic muscle actuator.

Pneumatic muscle actuator is a contractile device manufactured with the inflatable pneumatic bladder of usually long synthetic or natural neoprene tube wrapped inside artificial mesh at a pre-defined angle (Kelasidi et al., 2011). The working principle of this actuator is similar to that of an inverse bellow (Repperger et al., 2006). During pressurisation, the pneumatic bladder expands and as a result from the expansion, the diameter of the mesh and bladder changes in the radial direction promoting shortening of the muscle in the longitudinal direction (Chang et al., 2006). Therefore, contraction or pulling force is generated upon inflation of the actuator. When operated, this fluid-driven actuator is capable of providing a striking resemblance to that of muscle-like properties notably the compactness and high power to weight ratio (Repperger et al., 2005). Apart from that, the operation of PMA can be done with minimal pressurized air consumption indirectly from the small and compact size of PMA alongside with the low costing of implementation and maintenance (Wickramatunge and Leephakpreeda, 2010). Besides, PMA offer a lower level of safety breach in the event of human interactions permitted by its inherent compliant behaviour (Coined as “soft actuator”) in which it is consider safer than electric or hydraulic drives producing the same force level (Tsagarakis and Caldwell, 2003). As a result, an increase in the deployment of this driver mechanism in industrial machinery(Zhu et al., 2008, 2009), medical applications (Chakravarthy et al., 2013), rehabilitation devices (Wong et al., 2012; Hussain et al., 2013) and robotics (Hosoda et al., 2008; Narioka and Hosoda, 2011).

Despite the advantages, there are few disadvantages where the usage of PMA is concerned. PMA intricately exhibits significant non-linear characteristics, creep phenomenon and hysteresis in which is attributed to the compressibility of operating medium, intrinsic properties of construction material and the geometric behaviour of PMA external mesh. These factors induce dynamic and time varying disturbances in the pressure response and thus cause vibratory motion to occur. Henceforth, these detriments limit the real time motion control of pneumatic muscle actuator in which deemed as a challenging effort and often inaccurate.

At present, numerous control methods have been proposed and established for PMA based mechanisms. Through classical control, the proportional-integral-derivative is widely used as it has simple design procedures and high applicability well suited for industry-based applications. However, they could not provide a robust performance in a highly nonlinear mechanism due to their linear structure. On the other hand, model-based control can yield an ameliorated result if only an accurate model is obtained. Henceforth, various model-free controller such as intelligent and hybrid control has been proposed and employed. This is because the complexity of control architecture can be simplified as well as system uncertainties and variations were accommodated. However, there is still a need for sufficient knowledge in control theory and the determination of exact model parameters has led to tedious and time-consuming design procedures. Therefore, in this research, a control strategy that employs a simple and practical framework will be put forward. The proposed control strategy will then be validated experimentally through a single degree of freedom vertical based antagonistic pneumatic muscle actuated system.

1.3 Problem Statement

PMA inherently possesses and exhibits substantial non-linear characteristics. These nonlinearity stems from the compressibility of operating medium, intrinsic properties of construction material and the geometric behaviour of PMA external mesh. While, these factors generally contribute to the difficulty in modelling and real time control, the different configuration of PMA used may include other factors such as the characteristics of the servo valve used as well as the infinite combination of forces that both muscles might exert for the same displacement in the case of an antagonistic construction. The above-mentioned factors are of more commonly known disadvantages of PMA. Specifically, in this research, few other issues were found and highlighted as follow. Figure 1.1 and Figure 1.2 shows the open loop system response and close loop uncompensated system response to multiple rectangular step input respectively through experimental works. In Figure 1.1, an asymmetric response can be observed. This indicates the muscles exhibits different dynamics during inflation and deflation process attributed with the high charging rate and low discharging rate of the proportional servo valve used. Also, the monotonous system response with the lack of overshoot indicates the system is rigid in nature. On the other hand, in Figure 1.2, the uncompensated system is incapable of reaching the desired reference input. These factors are detrimental to the system in which may induce a slow response during trajectory tracking that further degrades the positioning accuracy.

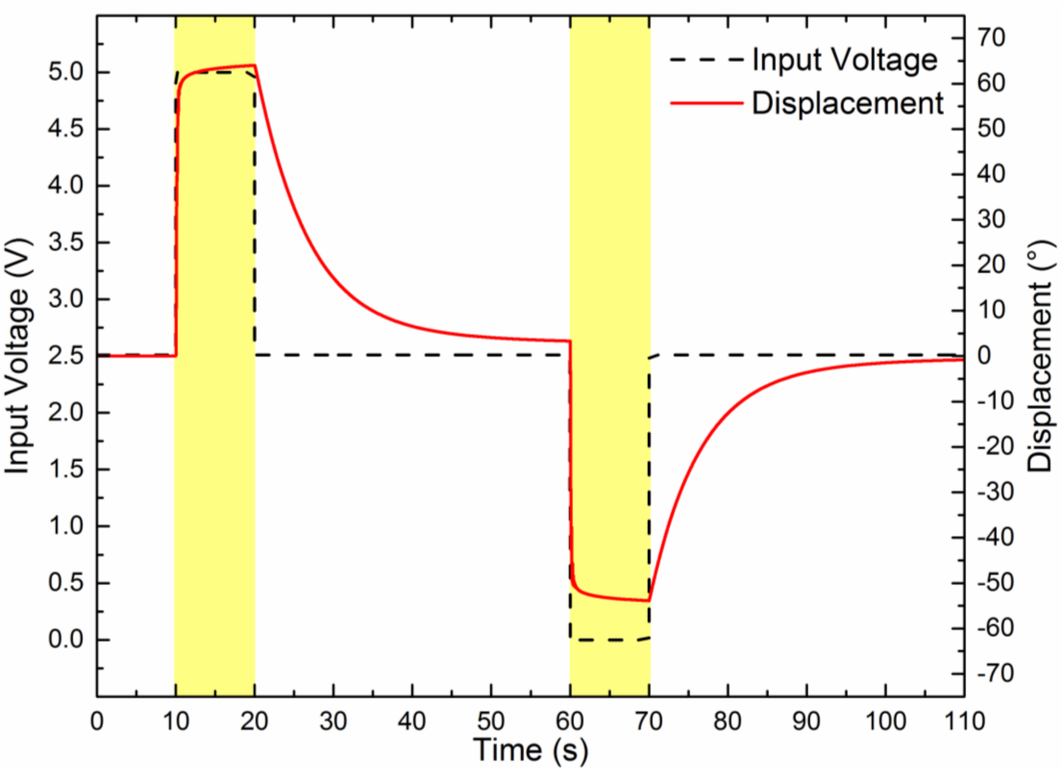

Figure 1.1: Open loop system response to rectangular input

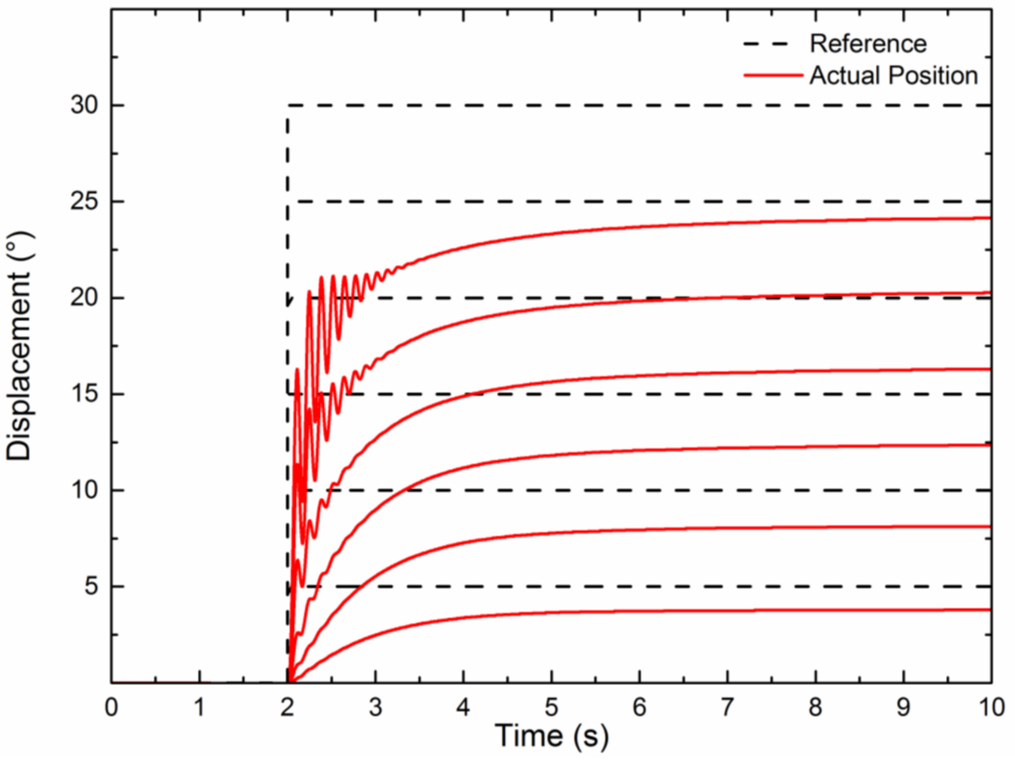

Figure 1.2: Uncompensated system response to different step input