MODELLING AND CONTROLLER DESIGN FOR POSITION TRACKING OF PNEUMATIC ACTUATOR SYSTEM

KHONG FAN HAO

UNIVERSITI TEKNOLOGI MALAYSIA

MODELLING AND CONTROLLER DESIGN FOR POSITION TRACKING OF PNEUMATIC ACTUATOR SYSTEM

KHONG FAN HAO

A project report submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Mechatronics and Automatic Control)

School of Electrical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

JULY 2022

DEDICATION

This thesis is dedicated to Professor Ts. Dr. Mohd Fua'ad Rahmat for his advice, faith and patience with me on my road toward this master thesis completion. It is also dedicated to myself, who had endured this research journey during the pandemic.

ACKNOWLEDGEMENT

While writing this Master's thesis, I received a palpable concern for morale and academics throughout my progress.

First and foremost, I would like to express my gratitude to both of my supervisors, Professor Ts. Dr. Mohd Fua'ad Rahmat and Ts. Dr. Noorhazirah Sunar from the Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), whose expertise was essential in figuring out my research and methodology uncertainty. Their perceptive feedback pushed me to improve my thinking and brought my research to a higher level.

I would also like to thank my beloved parents and peers for their moral support in completing my degree studies. Lastly, sincere thanks to those who accompanied me along my research journey, no matter its significant or small influences, because these made me who I am today.

ABSTRACT

To control a pneumatic actuator precisely is not a simple task, as the actuator system consists of many unknown and unpredictable non-linearity. In the worst case, it is prone to disturbances where the position tracking will be inaccurate. This thesis proposes an adaptive controller design for position tracking of the pneumatic actuator system, validated via a simulation study. Considering the mentioned problem, the proposed solution is an Extremum Seeking (ES) based PI(D) controller. This decision is based on the favour of current industry trends, that is, to maintain PID control structure while providing a model-free, data-driven approach and smart control scheme. A preliminary progression has been made to confirm the simulation model for the future controller design stage. The modelling methodology is carried out using the empirical method, and the selected model is $ARX331$ structure polynomial model. This is due to the consideration of the parsimonious / theoretical structure of the model and high validation accuracy. Additionally, the model is subjected only for simulation purposes and not for model-based controller design. The benchmark controller tuning using Ziegler-Nichols and IMC-PID approach is carried out to investigate the relationship of PID parameters to the performance of the pneumatic actuator system in position tracking. The proposed model-free online parameter optimization scheme using extremum seeking algorithm is applied on Proportional and Integral paths because it is found that these 2 paths are the primary source of affecting the transient performance response based on the investigation from the benchmark controller. The simulation validation test is carried out using 2 different types of input: step input of $50\ mm$, $100\ mm$, $150\ mm$, and square wave input of $\pm 50\ mm$ and $\pm 75\ mm.$ The learning ability of the proposed controller scheme was observed when the parameters of the ES-PI(D) controller would automatically tune without properly initialisation and provides a consistent response behaviour when subjected to different inputs. Besides, consistency in transient response and settling time is one of the most significant advantages of the proposed controller.

ABSTRAK

Pengawalan sistem penggerak pneumatik dengan tepat bukanlah sesuatu tugas yang mudah, kerana sistem tersebut mempunyai sifat tidak linear yang sukar dikenal pasti dan diramalkan. Dalam keadaan terburuk, ia terdedah kepada gangguan di mana penjejakan kedudukan akan menjadi tidak tepat. Oleh itu, tesis ini mencadangkan pelan penyelidikan yang jelas untuk mereka bentuk pengawal bagi penjejakan kedudukan sistem penggerak pneumatic dan divalidasi melalui kajian simulasi. Berdasarkan masalah yang disebutkan awal, penyelesaian yang dicadangkan ialah pengawal PID adaptif dengan algoritma pencarian ekstrem (ES). Keputusan ini adalah berdasarkan trend industri semasa, iaitu untuk mengekalkan struktur kawalan PID, pada masa yang sama, pendekatan tanpa model, kawalan pacuan data dan skim kawalan pintar digunakan. Perkembangan awal telah dibuat iaitu untuk mengesahkan model simulasi yang akan digunakan dalam peringkat reka bentuk pengawal akan dating. Metodologi pemodelan dijalankan menggunakan kaedah empirikal dan model yang dipilih adalah model polinomial struktur $ARX331$, ini disebabkan pertimbangan antara struktur parsimonious/teori model, dan ketepatan pengesahan yang tinggi. Selain itu, model ini tertakluk hanya untuk tujuan simulasi dan bukan untuk reka bentuk pengawal berasaskan model. Penalaan pengawal penanda aras menggunakan pendekatan Ziegler-Nichols dan IMC-PID dijalankan untuk menyiasat hubungan parameter PID terhadap prestasi sistem penggerak pneumatik dari segi pengesanan kedudukan. Skim pengoptimuman parameter bebas model dan dalam talian yang dicadangkan menggunakan algoritma pencarian ekstrem digunakan pada laluan Proportional dan Integral, kerana didapati bahawa 2 laluan ini adalah sumber utama yang mempengaruhi tindak balas sementara prestasi berdasarkan penyiasatan daripada pengawal penanda aras. Ujian pengesahan simulasi dijalankan menggunakan 2 jenis input yang berbeza: input langkah $50\ mm$, $100\ mm$, $150\ mm$, dan input gelombang persegi $\pm 50\ mm$ dan $\pm 75\ mm$. Keupayaan pembelajaran skema pengawal yang dicadangkan telah diperhatikan apabila parameter pengawal ES-PI(D) akan ditala secara automatik tanpa dimulakan dengan betul dan memberikan gelagat tindak balas yang konsisten apabila tertakluk kepada julat input yang berbeza. Selain itu, ketekalan dalam tindak balas sementara dan masa penyelesaian adalah salah satu kelebihan terbesar pengawal ES-PI(D).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ARX	-	Autoregressive Exogenous
DAQ	-	Data Acquisition
ES	-	Extremum Seeking
IMC	-	Internal Model Control
MSE	-	Mean Squared Error
PA	-	Pneumatic Actuator
PID	-	Proportional – Integral – Derivative Controller
SMC	-	Sliding Mode Control
UAV	-	Unmanned Aerial Vehicle
ZN	-	Ziegler – Nichols

LIST OF SYMBOLS

$\underline{\gamma}$	-	Adaptation gain
$e(t)$	-	Error signal / difference between $r(t)$ and $y(t)$
ω_h	-	High pass frequency
$\underline{\theta_0}$	-	Initial parameters
$u(t)$	-	Input signal / actuator valve's voltage
$\underline{\theta_{k,max}}$	-	Maximum saturation limit
$\underline{\theta_{k,min}}$	-	Minimum saturation limit
$y(t)$	-	Output signal / cylinder position
$\underline{\alpha}$	-	Perturbation amplitude
$\underline{\omega}$	-	Perturbation frequency
$r(t)$	-	Reference signal / desired cylinder position
T_s	-	Sampling time

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Problem Background

An actuator is a device that makes another machine / device to moves mechanically. There are 2 types of standard actuators: the linear actuator for straight motion and the rotary actuator for circular motion. All actuator requires a source of energy to operate. In industrial applications, there are 3 common energy sources: electric, hydraulic and pneumatic. The hydraulic and pneumatic sources are classified as fluidic sources too. The pneumatic actuator (PA) system refers to a series of pneumatic sourced interconnected components, including a pneumatic actuator, that results in a mechanical movement when operated. PA system is commonly found in manufacturing and automation industries to execute high frequency and repetitive mechanical motion.

Compared to electrical and hydraulic actuator systems, the PA system possesses some absolute advantages, such as providing a greener, cleaner and fail-safe environment (oil/spark free) and lower operation and maintenance costs. Due to these advantages, the PA system gradually becomes the standard solution in industry by replacing the electrical actuator system. However, controlling a PA system to perform precision position tracking is not easy compared to electrical actuators. It is mainly caused by high nonlinearities in the fluidic system; these nonlinearities include non-linear dynamics in compressible air, frictional properties and etc. Research about position/servo tracking of PA systems can be dated back to the 1990s and increased significantly by the 2010s when the control and automation field drew attention due to the introduction of Industry 4.0

1.2 Problem Statement

As stated previously, the advantages of a pneumatic actuator (PA)) systems are significant. They are cheaper, durable and safer compared to other actuator systems. However, one of the most significant issues in PA systems is the difficulty in executing precise position tracking. It is mainly caused by unpredictable system dynamics, especially in a system that uses fluid (pressurized air) sources. This led to a situation where model-based controller design or model-driven approach for position tracking of PAS becomes difficult as the model of PAS is not always accurate or available. Thus, a non-model-based controller design or data-driven approach might be an option for this situation.

Besides, the implementation of PID controller for PAS in the industry is still widely used, despite it being an 'old' technology in the eyes of a particular group. This is mainly caused by the practice of manual tuning, which is a time-consuming task that relies on an engineer's experience for fine-tuning. Therefore, following the emergence of adaptive control theory, it is possible to tune the optimal PID parameters in a closed-loop setting (direct / online tuning). To overcome these weaknesses, an optimal-based adaptive PID tuning control strategy for position tracking is proposed: Adaptive Extremum Seeking PID controller.

1.3 Research Goal

1.3.1 Research Objectives

The aim of the project is to design a controller for position tracking of the pneumatic actuator system. The specific objectives are shown below:

(a) To perform model identification of pneumatic actuator system using empirical modelling technique from secondary data.

(b) To design a controller for a pneumatic actuator system with the following features: Data-driven control, adaptive extremum seeking PID tuning, closed-loop system stability guaranteed.

(c) To compare the performance of the proposed controller with another rule-based controller.

1.3.2 Research Scopes

The scopes of the project are shown below:

(a) The simulation tool for this project is subjected to MATLAB/Simulink only.

(b) The Data Acquisition (DAQ) card used in this research is SCB-68 by National Instrument.

(c) The process rig consists of an air compressor, pneumatic cylinder, 2 pressure sensors, 1 electromagnetic displacement sensor and 1 control valve.

(d) This research work is limited to adaptive controller design only.

1.3.3 Research Limitation and Assumptions

The limitation and assumptions of the project are:

(a) For the ease of controller design, the noise from the system is assumed to be nearly zero.

(b) The supply pressure and temperature change throughout the position tracking process are constant.

(c) The nonlinear factors are ignored during modelling. They may be hysteresis, pressure change, frictional loss, etc.

REFERENCES

Abd. Rahman, R., He, L., & Sepehri, N. (2015). Design and experimental study of a dynamical adaptive backstepping–sliding mode control scheme for position tracking and regulating of a low-cost pneumatic cylinder. *Int. J. Robust Nonlinear Control, 26*(4), 853-875.

Azahar, M., Irawan, A., & Raja Ismail, R. (2021). Self-tuning hybrid fuzzy sliding surface control for pneumatic servo system positioning. *Control Engineering Practise, 113*, 104838-104857.

Beater, P. (2007). *Pneumatic Drives: System Design, Modelling and Control.* New York: Springer-Verlag Berlin Heidelberg.

Bittanti, S. (2019). *Model Identification and Data Analysis.* Hoboken, NJ, USA: John Wiley & Sons, Inc.

Bobal, V., Machacek, J., & Prokop, R. (1997). Tuning of Digital PID Controllers Based on Ziegler-Nichols Method. *IFAC Proceedings Volumes, 30*(21), 145-150.

Chen, Q., Tan, Y., Li, J., & Mareels, I. (2018). Decentralized PID Control Design for Magnetic Levitation Systems Using Extremum Seeking. *IEEE Access, 6*, 3059-3067.

Chen, Y., Tao, G., & Liu, H. (2019). High Precision Adaptive Robust Neural Network Control of a Servo Pneumatic System. *Applied Sciences, 9*, 3472-3488.

Choi, J., Krstic, M., Ariyur, K., & Lee, J. (2002). Extremum seeking control for discrete-time systems. *IEEE Transactions on Automatic Control, 47*, 318-323.

Giernacki, W., Horla, D., Baca, T., & Saska, M. (2019). Real-Time Model-Free Minimum-Seeking Autotuning Method for Unmanned Aerial Vehicle Controllers Based on Fibonacci-Search Algorithm. *Sensors, 19*(2), 312-341.

Gulati, N., & Barth, E. (2009). A Globally Stable, Load-Independent Pressure Observer for the Servo Control of Pneumatic Actuators. *IEEE/ASME Transactions on Mechatronics, 14*(3), 295-306.

Hazeleger, L., Beerens, R., & van de Wouw, N. (2021). Proportional–Integral–Derivative-Based Learning Control for High-Accuracy Repetitive Positioning of Frictional Motion Systems. *IEEE Transactions on Control Systems Technology, 29*(4), 1652-1663.

Khong, F., Rahmat, M., Sunar, N., Ramli, M., Jamaluddin, J., Ahmad, N., Nawawi, S., Ibrahim, S., & Md. Yunos, Y. (2022). Linear ARX modelling of pneumatic actuator system. In A. Shamsudin, A. Ahmad, & R. Abdul Rahim, *Sensor & instrumentation sysstem series 28* (pp. 125-145). Parit Raja, Batu Pahat, Johor: Penerbit UTHM.

Killingsworth, N. J., & Krstic, M. (2006). PID Tuning Using Extremum Seeking - Online, model-free performance optimization. *IEEE Control Systems Magazine, 26*(1), 70-79.

Ladaci, S., & Bensafia, Y. (2016). Indirect fractional order pole assignment based adaptive control. *Engineering Science and Technology, an International Journal, 19*, 518-530.

Lai, W. K., Rahmat, M. F., & Abdul Wahab, N. (2012). Modeling and Controller Design of Pneumatic Actuator System with Control Valve. *International Journal on Smart Sensing and Intelligent Systems, 5*(3), 624-644.

Landau, I. D., & Zito, G. (2020). Choice of the Input Sequence for System Identification. In *Digital Control Systems - Identification, design and implementation* (pp. 226-229). France: GIPSA-lab.

Lin, H.-T. (2017). A Novel Real-Time Path Servo Control of a Hardware-in-the-Loop for a Large-Stroke Asymmetric Rod-Less Pneumatic System under Variable Loads. *Sensors, 17*(6), 1283-1296.

Meng, D., Li, A., Tang, C., & Li, Q. (2018). Adaptive Dynamic Surface Control of Pneumatic Servo Systems with Valve Dead-Zone Compensation. *IEEE Access, 6*, 71378-71388.

Nazari, V., & Surgenor, B. (2016). Improved Position Tracking Performance of a Pneumatic Actuator using a Fuzzy Logic Controller with Velocity, System Lag and Friction Compensation. *International Journal of Control, Automation and Systems, 14*(5), 1376-1388.

Paz, P., Roux-Oliveira, T., Pino, A., & Fontana, A. (2019). Model-Free Neuromuscular Electrical Stimulation by Stochastic Extremum Seeking. *IEEE Transactions on Control Systems Technology, 28*(1), 238-253.

Ramezani, S., & Baghestan, K. (2019). Observer-based nonlinear precise control of pneumatic servo systems. *Proceedings of the Institution of Mechanical*

Engineers, Part E: Journal of Process Mechanical Engineering, 233(2), 165–176.

Ren, H.-P., Jiao, S.-S., Li, J., & Deng, Y. (2022). Adaptive neural network control of pneumatic servo system considering state constraints. *Mechanical Systems and Signal Processing, 162*, 1-17.

Ren, H.-P., Jiao, S.-S., Wang, X., & Li, J. (2020). Adaptive RBF Neural Network Control Method for Pneumatic Position Servo System. *IFAC PapersOnLine.* Berlin.

Roux-Oliveira, T., Costa, L., Pino, A., & Paz, P. (2019). Extremum Seeking-based Adaptive PID Control applied to Neuromuscular Electrical Stimulation. *Annals of the Brazilian Academy of Sciences, 91*(1), 1-20.

Salim, S. N., Rahmat, M. F., Faudzi, A. A., & Ismail, Z. H. (2014). Position control of pneumatic actuator using an enhancement of NPID controller based on the characteristic of rate variation nonlinear gain. *The International Journal of Advanced Manufacturing Technology, 75*, 181-195.

Skogestad, S. (2003). Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control, 13*, 291–309.

Sobczyk, M. R., Gervini, V. I., Perondi, E. A., & Cunha, M. (2016). A continuous version of the LuGre friction model applied to the adaptive control of a pneumatic servo system. *Journal of the Franklin Institute, 353*, 3021-3039.

Stojanovic, V., & Nedic, N. (2016). Identification of time-varying OE models in presence of non-Gaussian noise: Application to pneumatic servo drives. *International Journal of Robust and Nonlinear Control, 26*(18), 3974-3995.

Sulaiman, S. F., Rahmat, M. F., Faudzi, A., & Osman, K. (2016). Linear and Nonlinear ARX Model for Intelligent Pneumatic Actuator Systems. *Jurnal Teknologi (Sciences & Engineering), 78*(6), 21-28.

Sunar, N. (2017). *Parametric Controller Design For Electro-pneumatic Actuator System With Dead-zone.* Skudai, Malaysia: Ph.D. dissertation, Faculty of Electrical Engineering, Universiti Teknologi Malaysia.

Sunar, N. H., Rahmat, M. F., Ismail, Z. H., Mohd Fauzi, A. A., & Sy Salim, S. (2014). Model Identification and Controller Design for an Electro-pneumatic Actuator System with Dead Zone Compensation. *International Journal on Smart Sensing and Intelligent System, 7*(2), 798-819.

Valdiero, A. C., Ritter, C. S., Rios, C. F., & Rafikov, M. (2011). Nonlinear Mathematical Modeling in Pneumatic Servo Position Applications. *Mathematical Problems in Engineering, 2011*, 1-16.

Yang, H., Sun, J., Xia, Y., & Zhao, L. (2018). Position Control for Magnetic Rodless Cylinders With Strong Static Friction. *IEEE Transactions on Industrial Electronics, 65*(7), 5806-5815.

Zhao, J., Jing, W., & Wang, J. (2018). An indirect optimization scheme for tuning a fractional order PI controller using extremum seeking. *Mechatronics, 56*, 146-156.

Zhao, L., Xia, Y., Yang, Y., & Liu, Z. (2017). Multicontroller Positioning Strategy for a Pneumatic Servo System Via Pressure Feedback. *IEEE Transactions on Industrial Electronics, 64*(6), 4800-4809.

LIST OF PUBLICATIONS

Book Chapter

1. Khong, F., Rahmat, M., Sunar, N., Ramli, M., Jamaluddin, J., Ahmad, N., Nawawi, S., Ibrahim, S., & Md. Yunos, Y. (2022). Linear ARX modelling of pneumatic actuator system. In A. Shamsudin, A. Ahmad, & R. Abdul Rahim, *Sensor & Instrumentation System,* 28, 125-145. Parit Raja, Batu Pahat, Johor: Penerbit UTHM.