# CONTROL OF A PNEUMATIC ACTUATOR SYSTEM USING ENHANCED NONLINEAR PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER ALGORITHM

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*To my beloved family*

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*Syed Najib Syed Salim, Skudai*

## ABSTRACT

Pneumatic actuators offer several advantages such as low cost, simple to maintain, high power to weight ratio, fast motion, free from overheating and reliable. Due to these advantages, this actuator continues to generate significant research interests and it has been promoted as an alternative to hydraulics and electric servo motors in many automated tasks. However, it exhibits high nonlinearities due to high friction forces, compressibility of air and dead band of the spool movement in the valve. These nonlinearities make an accurate position difficult to achieve and it requires an appropriate controller for better performance. This thesis presents a new approach to control the pneumatic positioning system. The mathematical modeling is a crucial part to be established before the control algorithm can be designed. Initially, the modeling of the system is presented based on physical derivation. The parameters of the system are identified, and comparison between system identification by means of the MATLAB software is performed. The result obtained from the modeling process is validated with experimental data. Subsequently, two new controller techniques are proposed based on the enhancement of the Nonlinear Proportional Integral Derivative (N-PID) controller. The first technique is called Multi-rate Nonlinear PID (MN-PID), which is performed by utilizing the characteristics of rate variation in nonlinear gain. Fuzzy logic is used to perform this task. Meanwhile, for the second technique, a Self-regulation Nonlinear (SN) function, is introduced to reprocess the error signal to continuously generate the values for rate variation. The proposed controllers are implemented to the system, and their performances are analyzed for both cases, with and without load. Simulation and experimental tests are conducted with different input, namely step, multistep, sinusoidal and S-curve waveforms to evaluate the performance of the proposed techniques. The existing techniques that include PID, N-PID, and Sliding Mode Control (SMC) are also tested to the system as a comparison. The results indicate that the system with MN-PID and SN-PID exhibits improvement of dynamic performance criterion exceeding $34\%$ and $59\%$, respectively. In addition, both techniques succesfully provide fast response without overshoot where the rise time reduces more than $87\%$. It proves that the novel initiative is capable of examining and identifying the characteristics of rate variation based on a new controller that was derived from N-PID controller. Moreover, the system performance is successfully accomplished for each position and direction as well as under various loads.

# ABSTRAK

Penggerak pneumatik menawarkan beberapa kelebihan seperti murah, mudah diselenggara, berkuasa tinggi terhadap nisbah berat, pantas, bebas lampau panas dan tahan lasak. Dengan kelebihan ini, penggerak ini terus mendapat perhatian dalam penyelidikan yang signifikan dan ia merupakan alternatif kepada hidraulik dan motor servo elektrik dalam kerja-kerja pengautomatan. Namun, ia mempamerkan ketaklelurusan yang tinggi disebabkan daya geseran yang tinggi, mampatan udara dan jalur-mati pergerakan kili dalam injap. Ketaklelurusan ini menyukarkan kedudukan yang tepat dicapai dan memerlukan pengawal yang sesuai untuk prestasi yang lebih baik. Tesis ini membentangkan pendekatan baru untuk mengawal sistem kedudukan pneumatik. Permodelan matematik adalah perkara utama yang perlu dibuat sebelum pengawal dapat direkabentuk. Mulanya, pemodelan sistem diperolehi berdasarkan terbitan fizikal. Parameter-parameter bagi sistem ini dikenalpasti dan perbandingan dengan teknik pengenalpastian sistem dilaksanakan melalui perisian MATLAB. Keputusan yang diperolehi disahkan dengan data amali. Seterusnya, dua teknik pengawal baru dicadangkan melalui penambahbaikan terhadap pengawal Tak lelurus Berkadar Kamiran Terbitan (N-PID). Teknik pertama dipanggil pengawal Pelbagai Kadar Tak lelurus PID (MN-PID), dilaksana menggunakan ciri-ciri kadar variasi yang terdapat dalam gandaan tak lelurus. Logik kabur digunakan untuk melaksanakan tugas ini. Manakala, untuk teknik yang kedua, Fungsi Pengaturan-kendiri Tak lelurus (SN) diperkenalkan untuk memproses semula isyarat ralat bagi menjana kadar variasi. Pengawal-pengawal yang dicadangkan ini dilaksanakan pada sistem dan prestasi bagi kes tanpa beban dan dengan beban dianalisa. Ujian simulasi dan amali dijalankan dengan masukan yang berbeza iaitu isyarat langkah, pelbagai langkah, sinusoidal dan lengkuk-S bagi menilai prestasi. Teknik-teknik yang sedia ada termasuk PID, N-PID dan Kawalan Ragam Lincir (SMC) juga diuji pada sistem sebagai perbandingan. Keputusan menunjukkan sistem dengan MN-PID dan SN-PID mempamerkan peningkatan kriteria prestasi dinamik masing-masing melebihi $34\%$ dan $59\%$. Selain itu, kedua-dua teknik berjaya mengurangkan masa menaik melebihi $87\%$. Ia membuktikan inisiatif baru ini mampu memeriksa dan mengenalpasti ciri-ciri kadar variasi berdasarkan pengawal baru yang telah diterbitkan dari pengawal N-PID. Selain itu, prestasi sistem berjaya dicapai untuk setiap kedudukan dan arah serta bagi sistem di bawah beban yang berbeza-beza.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| A/D | – | Analogue to digital |
| ANNC | – | Adaptive neural network compensator |
| ARMA | – | Auto-regressive moving-average |
| BP | – | Back-propagation |
| D/A | – | Digital to analogue |
| DSP | – | Digital signal processing |
| DZC | – | Dead zone compensator |
| EKF | – | Extended kalman filter |
| FAT | – | Function approximation technique |
| FF | – | Feed forward |
| FMRLC | – | Fuzzy model reference learning control |
| FNN | – | Fuzzy neural network |
| FRL | – | Filter regulator lubricator |
| GM | – | Gain margin |
| HIL | – | Hardware in the loop |
| IAE | – | Integrated absolute error |
| LVDT | – | Linear variable differential transformer |
| MISO | – | Multiple-input single-output |
| MNF | – | Multi-rate nonlinear function |
| MN-PID | – | Multi-rate nonlinear proportional-integral-derivative |
| MRAC | – | Model reference adaptive controller |
| MRE | – | Mixed-reality environment |
| MRFT | – | Modified relay feedback test |
| MSSC | – | Multiple-surface sliding controller |
| NLSE | – | Nonlinear least square error |
| NPID | – | Nonlinear proportional-integral-derivative |
| PEM | – | Prediction-error minimization |
| PID | – | Proportional-integral-derivative |

| | | |
|---|---|---|
| PIDVF | – | PID with velocity feed-forward and feedback |
| PM | – | Phase margin |
| PSO | – | Particle swarm optimization |
| PWM | – | Pulse-width modulation |
| RLS | – | Recursive least squares |
| RLS-FGS | – | Robust loop shaping-fuzzy gain scheduled control |
| RMSE | – | Root mean square error |
| RTWT | – | Real-time windows target |
| SMC | – | Sliding mode control |
| SMCL | – | Sliding mode control linear |
| SMCN | – | Sliding mode control nonlinear |
| SMVSC | – | Sliding-mode variable-structure controller |
| SNF | – | Self-regulation nonlinear function |
| SN-PID | – | Self-regulation nonlinear proportional-integral-derivative |
| ZOH | – | Zero order hold |
| ZPETC | – | Zero phase error tracking controller |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $A$ | – | Piston Area |
| $A_v$ | – | Effective orifice area |
| $B$ | – | Damping coefficient |
| $C_f$ | – | Orifice discharge coefficient |
| $C_V$ | – | Valve constant |
| $F_c$ | – | Coulomb friction |
| $F_f$ | – | Friction force |
| $F_L$ | – | External force |
| $F_s$ | – | Static friction |
| $k$ | – | Specific heat ratio |
| $L$ | – | Piston stroke |
| $P_1$ | – | Pressure inside Chamber 1 |
| $P_1$ | – | Pressure inside Chamber 2 |
| $P_{cr}$ | – | Critical pressure |
| $P_o$ | – | Ambient pressure |
| $P_S$ | – | Supply pressure |
| $P_u$ | – | Upstream pressure |
| $P_d$ | – | Downstream pressure |
| $R$ | – | Gas constant |
| $T$ | – | Temperature |
| $V$ | – | Volume of each chamber |
| $x$ | – | Piston position |
| $X_{spool}$ | – | Spool displacement |
| $z$ | – | Dynamics of the internal state |
| $\Delta e$ | – | Change of position error |
| $\gamma_i$ | – | Estimate value of specific heat ratio for charging process |
| $\gamma_o$ | – | Estimate value of specific heat ratio for discharging process |
| $c_1$ | – | Learning factor |

| | | |
|---|---|---|
| $c_2$ | – | Learning factor |
| $G_{best}$ | – | Global best |
| $itr$ | – | iteration |
| $k(e)$ | – | Nonlinear gain |
| $k(e, \alpha_x)$ | – | Multi sector bounded of nonlinear gain |
| $P_{best}$ | – | Personal best |
| $S$ | – | sensitivity function |
| $W(K)$ | – | Performance criteria |
| $\omega_c$ | – | Crossover frequency |
| $\omega_B, \omega_{BT}$ | – | Bandwidth |
| $\hat{y}$ | – | Experimental value of data |
| $y$ | – | Estimate value of output |
| $y_m$ | – | Mean value of experimental data |
| $z$ | – | Dynamics of the internal state |
| $\alpha$ | – | Rate of variation of nonlinear gain |
| $\delta \, and \, \beta$ | – | SNF parameter |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Pneumatics is a branch of technology that deals with mechanical properties of gases such as pressure and density. They are categorized under fluid power control and apply the principles of using compressed gas as a source of power to perform a variety of tasks. One of the benefits of fluid power is an easy way in which the delivered power can be controlled. They can also be used in many tasks. For pneumatic actuator especially, it can be used in explosive environments because air does not generate sparks. It also poses no health hazard and can easily be stored and vented into the atmosphere. The ability to operate at a high number of cycles per workday is also one of the advantages of this drive. Besides, pneumatic actuator is also considered for low-cost, high power-to-weight ratio and ease of maintenance (Mohd Faudzi *et al*., 2014; Noor *et al*., 2011; Taghizadeh *et al*., 2010).

In early 1900s, pneumatic drives were mostly applied in pneumatic hammers such as in shipyards and on construction sites. The difficulty of obtaining a good performance in terms of accuracy and stability has greatly limited the use of this actuator in many applications. Thus, research on this component is rarely performed for decades until there is a demand to be applied in the automation industry circa 1950s. In the next few years following that, this actuator is then used in most of the industrial automation, such as spraying, drilling, squeezing, and packaging. Subsequently, the theoretical and experimental analyses of proportional directional control valves, cylinders, and mechanical parts have been reported by Shearer (Beater, 2007).

Works on this actuator are then continued by other researchers as evident in several published papers (Atkinson, 1972; Backe', 1986; Burrows, 1966; Burrows, 1969; French and Cox, 1990; Kawamura *et al*., 1989; Liu and Bobrow, 1988;

Noritsugu, 1985; Salihi and Weston, 1983). Based on these studies, a number of improvements had been suggested. Subsequently, pneumatics became one of the actuators that are appropriately used in a wide variety of industrial applications including robotics, CNC machines, packaging industry, food industry, plastic products, automotive industry and other industries. Moreover, it also be utilized as a tool to study human convenience, such as, to facilitate investigation of chair shapes (Faudzi *et al.*, 2010).

Pneumatic actuators are subject to nonlinearities in which the precise position of this actuator is difficult to achieve due to compressibility of the air, valve fluid flow characteristics and the highly nonlinear behavior of friction effects at near-zero velocities (Keller and Isermann, 1993; Khayati *et al.*, 2009). The static properties of the mechanisms influence the system in terms of accuracy and repeatability. One of the simple approaches to improve the static performance is the used of high proportional gain in the system. However, this approach can degrade its dynamic characteristic and tend to cause instability to the system. Thus, an appropriate technique should be examined to provide better performance to the system.

Research on pneumatic positioning control has increased in the 1990s when many control techniques were been examined on the system such as PID control, PD plus, sliding mode control, robust control, adaptive control, and PWM control (Reznik *et al.*, 2000; Richer and Hurmuzlu, 2001b; Shen *et al.*, 1998; Wang *et al.*, 1999). Subsequently, advanced control strategies were aggressively investigated and applied beginning in the early of 2000s onward such as researches conducted in (Bone and Ning, 2007; Hassan and Kothapalli, 2010; Kaitwanidvilai and Olranthichachat, 2011; Khayati *et al.*, 2009; Lu and Hwang, 2012; Ning and Bone, 2005b; Osman *et al.*, 2014; Taghizadeh *et al.*, 2010).

Consequently, in the last 10 years, the performance of pneumatic positioning system has been continuously improved. However, it deals with quite complicated controllers that involve many parameters with complicated mathematical equations. Thus, most industries still employ the control loops based on Proportional-Integral-Derivative (PID) controller because of its simplicity even though it is difficult to deal with highly nonlinear systems. In this research, a new control technique has been performed to manage the pneumatic positioning systems. Initially, the Nonlinear PID controller was designed to provide evidence that the controllers with the conventional PID are still relevant and can perform better when some improvement is applied to this controller. Further enhancement of this controller is examined and designed in order to provide the system with a better performance.

## 1.2 Problem Statement

Industrial pneumatic actuators are highly nonlinear, and their models inevitably contain parametric uncertainties, making it difficult to determine its dynamics. This is caused by compressibility of the air, significant mechanical friction, poor damping ability and the proportional valve dead zone problems. Therefore, it is hard to control the pneumatic actuator to achieve the desired performance because the output is not directly proportional to the input. It becomes more challenging when the speed, robustness and accuracy of the system are set as a goal to be achieved simultaneously. There are many control techniques proposed by previous researchers such as sliding mode control, fuzzy logic control, adaptive control, and robust control. However, most of the studies did not take into account all these three issues concurrently. Thus, there is a gap that can be studied to achieve this goal especially when applied in the industry.

In order to apply in industry, there are several constraints that have to be taken into account in designing the controller. One of the constraints is the complexity of the design which causes the processor unable to finish processing all data that is time consuming. Furthermore, the complexity of the controller design also makes the maintenance of the system difficult. Besides, the cost of the controller design should be considered. In practice, most industries are more concern to upgrade the existing controller rather than to change it. Based on this fact, a control technique will be identified and developed to satisfy certain performance objectives, including fast response with good transient response, an accurate position, disturbance rejection, stability and insensitivity to parameter uncertainty as well as easiness to apply in industries.

## 1.3 Research Objectives

The following are the objectives of this research:

1. To identify the mathematical model that represents a pneumatic actuator system by using the physical parameter estimation approach and the system identification technique.

2. To develop the suitable control technique for pneumatic positioning system that will provide:

    a) Good performance for both transient and steady state response

    b) Robustness to the variation of load and pressure

    c) Practical application in industry

3. To analyze and evaluate the pneumatic positioning system performance in terms of position, accuracy and robustness. Comparison between the existing control techniques will be presented.

## 1.4 Research scope and limitation

The following are the scope of the research:

1. Identify the mathematical model of pneumatic actuator system based on physical parameter estimation by taking into accounts its dynamic characteristics and friction. The validation will be performed with experimental data. The comparison of the model with system identification is also presented.
2. The proposed control design will be simulated based on the system modelled and verified to the real plant. The experiments are conducted based on different distances with a maximum of 460 mm. The performance of the system with the proposed techniques is analyzed and compared to the existing methods. Conventional PID and Nonlinear PID controller are used as a benchmark in this research.
3. Robustness analyses are examined based on the variation of load starting from 3.1 kg up to 36.5 kg. Besides, the performance due to the changing pressures is one of the matters that is investigated in this research. In this case, the pressure supply will be varied either increases or decreases around 1.5 bars. The nominal pressure is set to 6 bars.

The theoretical modelling of the pneumatic system is the most important part to be established before the control algorithm can be designed. In order to get an accurate model, the identification process performed is based on hardware-in-the–loop simulation environment of Real-time Workshop and System Identification toolbox in MATLAB/SIMULINK. The parameters of the plant that are not provided by manufacturer will be estimated using nonlinear least square method. Subsequently, to verify the model, the plant is then identified through system identification in which the state space model is used as a model structure of the system.

For the controller design, a variety of techniques is applied. It is necessary to ensure that the proposed approach must be appropriate, affordable, and easy to operate as well as able to be applied in industries. Based on these reasons, most of the industries prefer to use the PID controller in which it has the desired features. However, the performance achieved is an important thing that should be considered. Thus, the proposed technique will lead to study how to improve this conventional technique so that it can perform better in controlling the position of the pneumatic system that includes nonlinear elements. The recommended technique is able to produce a good performance and achieve the objectives outlined. Comparison with existing technique will be implemented and evaluated to prove that the improvement of performance is significant.

## 1.5 Contributions of the Research

In achieving the objectives that have been assigned, this reasearch provides the following contributions:

1. Development of an enhanced Nonlinear PID controller by including the new control algorithm called the Multi-rate Nonlinear Function (MNF) to improve the performance of pneumatic positioning system.
2. A new control algorithm, named Self-regulation Nonlinear Function (SNF) has been introduced to overcome the difficulties in determining the rules on Multi-rate Nonlinear Function (MNF).
3. Application of Particle Swarm Optimization technique (PSO) in determining the parameters involved in SNF.
4. These techniques are able to provide fast response without overshoot and achieve better steady state performance as well as robust to the variation of load and pressure.

## 1.6 Thesis Outline

This thesis is organized as follows:

Chapter 2 provides a literature review regarding the pneumatic positioning system. The study begins by looking on how the system is modelled by previous researchers. The techniques on how to model the friction are also reviewed. Subsequently, the control techniques that have been used are described. In order to investigate the improvements that had been achieved, the discussion is broken into some categories. This chapter ends with a summary and some proposal on how to further improve the system.

Chapter 3 deals with the modeling of pneumatic positioning system. The modeling will be elaborated by estimating the parameters of the pneumatic actuator, and then the performance is compared to the model obtained from System Identification. The experimental setup to perform the data collection is also provided in this chapter. The methods on how to determine the parameters of the plant model based on a combination of empirical curve fitting and theoretical analysis are explained in detail. Subsequently, a comparison between simulations and experimental are conducted for validation. In addition, the preliminary design procedure of the controller that will be employed in designing the proposed control technique is also included.

Chapter 4 describes two proposed techniques namely Multi-rate Nonlinear PID and Self-regulation Nonlinear PID controller that control the position of the pneumatic actuator. The design of these controllers includes the determination of the parameters involved, and this is discussed in detail. Besides, the stability of the system is shown in this chapter via the Popov Plot analysis.

In Chapter 5, the results of the system controller by the proposed techniques are demonstrated and analyzed through simulation and followed by experimental work. The performances of these techniques are examined based on several circumstances. First the simulation and experimental are performed based on various reference trajectories including step response with different distance and direction, sinusoidal and S-curve trajectory. The performance obtained from these results will be compared to the other techniques based on the same test rig. Subsequently, the results with the variation of payload and supply pressure are also provided in this chapter for the purpose to analyze the robustness of the proposed techniques. The robustness of the proposed techniques is compared to the other techniques.

Chapter 6 summarizes the findings and conclusions on the research. Recommendations for future work are also provided.

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