DESIGN OF MODIFIED PID CONTROLLER FOR POSITIONING CONTROL OF PNEUMATIC SYSTEM

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APPROVAL

I declare that I have thoroughly reviewed this thesis, and in my assessment, it meets the necessary criteria in terms of its scope and quality to be awarded the Bachelor of Electronic Engineering with Honours.

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Date : 2 July 2024

DEDICATION

Only
my beloved father, Zainol Bin Mohd Rejab
my appreciated mother, NurSilah Binti Ahmad
for giving me moral support, money, cooperation,
encouragement and also understanding.
Thank You and I Love You All

To my supportive supervisor,
Ir. Assoc. Prof. Dr. Lokman Bin Abdullah
for encouraging me and being my guidance
as the source of knowledge
throughout this project.

Thank you.

ABSTRACT

The advantages of pneumatic actuator systems, such as low cost, excellent dependability and environmental friendliness, are the reason for their widespread use in the automation sector today. Because of these characteristics, pneumatic actuators seem like a good substitute for electric servo motors and hydraulic actuator systems when it comes to industrial automation. Nevertheless, solid nonlinearities of pneumatic actuators due to friction and air's compressibility make it difficult to achieve precise positioning in plants with the variety of disturbances. The objective of this research is to design a PID and modified Nonlinear PID controller to obtain the precise positioning of the pneumatic system. The mathematical model of the system must be obtained before the controllers can be designed. The model was then obtained by using the MATLAB software's System Identification toolbox. When transfer function acquires from the system identification, there are three types of PID-based controllers were designed in this research specifically, Nonlinear PID (NPID) controller, NPID with Particle Swarm Optimization (PSO) and lastly, Cascade controller. The controller that would be designed by using MATLAB should regulate the pneumatic actuator to obtain precision in the positioning of the system with the generated step input signal. The tuning of the gain parameter of each controller is done by doing the heuristic method. In addition, the performance of the controller in terms of positioning error and the system transient response must be analysed. Subsequently, the analysis from the simulation was validated by comparing it with experimental data. Minimising the maximum overshoot and steady-state error is the outcome of this study. In conclusion, in order to achieve the desired output with precise positioning, the design of an effective controller is essential. Based on the results and discussions, after comparison of all controllers, NPID with PSO provides a better steady state as well as transient response performance of the pneumatic actuator due to the advanced strategy, where the PSO is integrated into the NPID controller. The percentage improvement with respect to PID controller in terms of steady state error for NPID with PSO is 48.86%, NPID is 32.17%, followed by Cascade at only 1.21%. However, further improvements are still needed. It is recommended for future work, the usage of NPID controller should be considered to achieve a better robust tracking.

ABSTRAK

Kelebihan sistem penggerak pneumatik, seperti kos rendah, kebolehpercayaan yang sangat baik dan kemesraan alam sekitar, adalah sebab penggunaannya secara meluas dalam sektor automasi hari ini. Oleh kerana ciri-ciri ini, penggerak pneumatik kelihatan seperti pengganti yang baik untuk motor servo elektrik dan sistem penggerak hidraulik apabila ia berkaitan dengan automasi industri. Namun begitu, ketaklinearan pepejal penggerak pneumatik akibat geseran dan kebolehmampatan udara menyukarkan untuk mencapai kedudukan yang tepat dalam tumbuhan dengan pelbagai gangguan. Objektif penyelidikan ini adalah untuk mereka bentuk PID dan pengawal PID Tak Linear yang diubah suai untuk mendapatkan kedudukan tepat sistem pneumatik. Model matematik sistem mesti diperolehi sebelum pengawal boleh direka bentuk. Model tersebut kemudiannya diperoleh dengan menggunakan kotak alat Pengenalan Sistem perisian MATLAB. Apabila fungsi pemindahan diperoleh daripada pengenalan sistem, terdapat tiga jenis pengawal berasaskan PID telah direka dalam penyelidikan ini khususnya, pengawal PID Tak Linear (NPID), NPID dengan Pengoptimuman Kawanan Zarah (PSO) dan terakhir, pengawal Cascade. Pengawal yang akan direka bentuk dengan menggunakan MATLAB harus mengawal penggerak pneumatik untuk mendapatkan ketepatan dalam kedudukan sistem dengan isyarat input langkah yang dijana. Penalaan parameter keuntungan setiap pengawal dilakukan dengan melakukan kaedah heuristik. Di samping itu, prestasi pengawal dari segi ralat kedudukan dan tindak balas sementara sistem mesti dianalisis. Selepas itu, analisis daripada simulasi telah disahkan dengan membandingkannya dengan data eksperimen. Meminimumkan overshoot maksimum dan ralat keadaan mantap adalah hasil kajian ini. Kesimpulannya, untuk mencapai output yang diingini dengan kedudukan yang tepat, reka bentuk pengawal yang berkesan adalah penting. Berdasarkan keputusan dan perbincangan, selepas perbandingan semua pengawal, NPID dengan PSO memberikan keadaan mantap yang lebih baik serta prestasi tindak balas sementara penggerak pneumatik disebabkan oleh strategi lanjutan, di mana PSO disepadukan ke dalam pengawal NPID. Peratusan peningkatan berkenaan dengan pengawal PID dari segi ralat keadaan mantap untuk NPID dengan PSO ialah 48.86%, NPID ialah 32.17%, diikuti oleh Cascade pada hanya 1.21%. Walau bagaimanapun, penambahbaikan lanjut masih diperlukan. Adalah disyorkan untuk kerja masa hadapan, penggunaan pengawal NPID harus dipertimbangkan untuk mencapai penjejakan teguh yang lebih baik.

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LIST OF ABBREVIATIONS

ADRC	- Active Disturbance Rejection Controller
ARMAX	- Auto-Regressive Moving Average with Exogenous input
ARX	- Auto-Regressive with Exogenous input
BJ	- Box Jenkins
FRL	- Filter Regulator Lubricator
GUI	- Graphic User Interface
IAE	- Integral of Absolute Error
IPA	- Intelligent Pneumatic Actuator
MBSE	- Model-Based System Engineering
MN-PID	- Multi Non-linear PID
NADRC	- Nonlinear Active Disturbance Rejection Controller
NPID	- Non-linear PID
OE	- Output Errors
PD	- Proportional-Derivative
PEM	- Prediction Error Minimization
PI	- Proportional-Integrational
PID	- Proportional-Integrational-Derivative
PSO	- Particle Swarm Optimization
PWM	- Pulse Width Modulation
RMS	- Root Mean Square
SI	- System Identification
SISO	- Single-Input Single-Output
SN-PID	- Self-regulation Non-linear PID
ZOH	- Zero Order Hold

CHAPTER 1

INTRODUCTION

1.1 Research Background

The research is about designing a modified PID controller of a pneumatic system that can achieve accuracy in positioning the PID controller. Pneumatic was derived in the 1650s from the word "pneuma," which meant "air," in late ancient Greek. Pneumatic is an old antique technology utilised in the blowgun that was invented by ancient people for hunting purposes. The pressure generated is around 1-3 psi, based on the capacity of the human lungs at the time. The first manually operated compressor is invented in roughly 3000 B.C. to assist in delivering air to ignite the fire (Trujillo, 2015). The importance of pneumatics increases as we get closer to the Bronze Age, when people started using metal in their daily lives. Pneumatic systems were introduced into industries after the 1950s to replace labor-intensive manual labour on the production line, and they are currently widely used worldwide (Zhong & Zhao, 2019).

In the automation industry, pneumatic actuator systems are becoming more and more important because of their affordable price, easily found materials, large power-to-weight ratio, high generating force, and safe operation. Pneumatic systems are also environmentally benign and require less maintenance (Lee et al., 2002; Zhang et al., 2019). Pneumatic actuator systems are extensively utilised in the automation industry, particularly in the food, aviation, and transportation sectors. A pneumatic system consists of an air compressor, regulators, gauges, feedlines, buffer tank, check valve, two-directional valves and an actuator. The pneumatic system is similar to the hydraulic system, only instead of hydraulic fluid, compressed air is used for the dynamic motion of the actuator whether it advances or retracts (Jang et al., 2012; Raghuraman et al., 2017).

Subsequently, as evidenced by multiple published papers, further researchers conducted studies on this actuator. (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 this research, several developments have been recommended. In the meantime, pneumatics happens to be one of the actuators that are effectively utilised in a large variation of industrial applications which are robotics, CNC machines, the packaging industry, the food industry, plastic products, the automotive industry and other industries. Additionally, this also can be applied as an instrument for analysing human convenience like simplifying the investigation of chair patterns. (Faudzi et al., 2010)

The precise positioning of pneumatic actuators can be challenging to accomplish due to nonlinearities resulting from the compressibility of air, valve fluid flow properties, plus the highly nonlinear response of friction effects at nearly zero velocities (Keller and Isermann, 1993; Khayati et al., 2009). The precision and repeatability of the system are affected by the static properties of the mechanisms. High proportional gain is used in the system to enhance static performance is one of the unchallenging methods. Nevertheless, this technique can lessen its dynamic nature and lead to instability in the system. A suitable method should be studied to improve the system's performance.

The research findings indicate that the implementation of cascade PID controllers in pneumatic systems gives substantial advantages in establishing accurate and precise positioning control. The research emphasizes the efficiency of cascade controllers in boosting system performance, stability, and control precision (Dash, Puja et al., 2015; Kumbasar and Hagras, 2014; and Saravanakumar et al, 2017). The research focuses on the decoupling of position from stiffness, which is essential to establishing accurate control and manipulation capabilities in pneumatic systems (Minh et al., 2010; Giannaccini et al., 2017). The proposed (1+PD)-PID cascade controller for load frequency regulation in electric power systems, focuses on its potential to increase system performance and stability (Çelik et al., 2021). The study highlighted the application of PID-based cascade controllers with feedforward compensators based on dynamic models for accurate and precise positioning control in pneumatic systems (Saravanakumar et al., 2017).

Consequently, the pneumatic positioning system's performance has been increased constantly. Nonetheless, it works with slightly complex controllers that incorporate several parameters with sophisticated mathematical formulae. Hence, the majority of industries still implement control loops based on PID controller due to their simplicity even if it can be challenging to handle highly nonlinear systems. The pneumatic positioning systems have been carried out in this study using a new control technique. In the beginning, the Nonlinear PID controller was created to serve as evidence that the controllers with conventional PID are still applicable and may operate better when some enhancement is applied to this controller. Further improvement of this controller is investigated and designed to provide the system with greater efficiency.

1.2 Problem Statement

Control systems' intended performance characteristics are often expressed in terms of the transient response, steady-state error, stability, robustness, and disturbance rejection. The pneumatic cylinders or actuators are driven by compressed air which is produced and delivered by compressors to actuate to a specific position in the plant. It exhibits high nonlinearities, and their models inevitably contain parametric uncertainties due to high friction forces, the compressibility of air, poor damping ability and a dead band of the spool movement which is difficult to manage and requires an appropriate controller for better performance. Hence, it is challenging to control the pneumatic actuator in order to obtain the desired performance since the output is not directly proportional to the input. Furthermore, the pneumatic system is difficult to achieve precise positioning because of parametric errors due to the compressibility of air. The system can benefit from a Nonlinear PID controller to achieve precise positioning and improve the system performance.

In addition, it is certainly difficult in ensuring the controller’s effectiveness in both virtual and real plant of pneumatic system. To address these challenges, a systematic and iterative approach involving simulation, modelling refinement, and experimental validation is often necessary. Advanced control techniques and adaptive control strategies may also be employed to enhance the controller's robustness in dealing with uncertainties and variations in both virtual and real-world environments.

1.3 Objectives

The objectives of this research are as follows.

i) To design a PID controller and modified Nonlinear PID controller to obtain precise positioning of the pneumatic system.
ii) To analyse the controller performance in terms of positioning error (steady state) and the system's transient response.
iii) To validate the designed controller through simulation using MATLAB Simulink software and experimental work using real plant of pneumatic system.

1.4 Scopes of the Research

i) The simulation and experimental tests should be conducted using MATLAB Simulink software.
ii) Using the System Identification toolbox in MATLAB, determine the mathematical model of the pneumatic actuators system. Experimental data will be used to confirm the results' validity.
iii) The experimental tests must be conducted using the pneumatic system hardware setup.
iv) The proposed Nonlinear PID controller's performance will be analysed and compared to the performance of the proposed PID controller system.

1.5 Thesis Organization

Chapter 1
Provide an overview of this project, including the problem statements, objectives, and the scope of the project. The pneumatic system and PID controller serve as essential components for this study.

Chapter 2

Concentrate on the literature review for the content that has been discussed in Chapter 1. The analysis of all the obtained articles on the PID controller in the act of positioning the pneumatic system is presented in the second chapter. The project relies on utilising several sources such as journals, books, and previous research to serve as references and provide guidance in order to successfully complete the assignment. Each of these parts is described according to this finding.

Chapter 3

Describe and analyse the methodology that has been utilised for the purpose of completing this project. The following chapter begins with the workflow chart of the research. Each of the works is discussed sequentially in this chapter. The steps have been divided into three phases to enhance research work understanding. Additionally, the third chapter also analyses the use of the MATLAB Simulink program, the experimental setup and its components, the use of the transfer function and system identification, and finally a detailed discussion of PID controllers.

Chapter 4

Explain the outcome produced and the limitations of the project. Every address is focused on the outcome as well as the performance of the developed system. This chapter mainly discussed the design of the controllers and their parameter tunings.

Chapter 5

Analyse the conclusion of the implementation of this study. Moreover, this chapter also addresses the suggestion for this system for future development or adjustment. It is shown the simulation and experimental outcomes of all the three controllers in terms of accuracy in positioning analysis and transient responses analysis.

CHAPTER 2

LITERATURE REVIEW

This chapter focuses on reviewing previously published research and project papers that are relevant to the topic at hand. The pneumatic actuator positioning system and the controllers for motion regulation have been analysed. The beginning of this chapter focuses on the system models of pneumatic actuators and the system identification utilised in previous research that related to the system modelling of the pneumatic actuator system. The following part of this chapter provides an overview of three types of PID-based controllers including the basic PID controller, nonlinear PID controller, and lastly a cascade PID controller which the review is based on earlier studies. The final part of this chapter concentrates on studying the techniques for regulating a pneumatic system using different kind of PID controller and make comparison between all of the controllers.

2.1 System Models of Pneumatic Actuator

Several strategies have been developed for modelling the pneumatic actuator system based on previous research. Theoretical analysis is a commonly used methodology for gaining the mathematical model of the pneumatic actuator system. Before constructing the model, some assumptions need to be made. These include the constancy of the gas volume flowing through the valve, the constant pressure of air supplied to the pneumatic actuator, constant volume, constant temperature, and the inclusion of the weight of the external load. In addition to theoretical study, system identification is a widely used approach for obtaining a mathematical model of a pneumatic system. An accurate mechanical model of the pneumatic systems would lead to the most significant outcomes in constructing the system controller.

In 1999, control system researcher, Sorli offered two alternative formula approaches for describing pneumatic actuators. The basic formulations were based on the thermodynamic transition of air, and simulations were carried out in MATLAB-Simulink. At the same time, another energy equation was introduced into the second formula to account for the thermic exchange between the external atmosphere and the chambers(Sorliet al., 1999).

A mathematical model of a double-acting pneumatic actuator system was introduced back in 2000. The detailed model is controlled by proportional spool valves. After system identification, numerical simulation, and model validation trials for two types of pneumatic cylinders and varying lengths of connecting tubes, the experiment yielded a positive result. The experiment takes into account the effects of air compressibility in pneumatic cylinder chambers, air leakage between chambers, nonlinear air flow through the valve, inactive capacity at the end of the stroke, along with time delay and attenuation in pneumatic lines. The mathematical model established is applied in the creation of high-performance nonlinear force controllers, which have a variety of industrial applications. (Richer & Hurmuzlu, 2000).

In 2003, a software programme was developed which use to design and simulate pneumatic actuator systems on the computer (Lin-Chen et al., 2003). The software tool is designed using a library that contains five important classifications of components combined which are compressed air suppliers, cylinders, valves, control strategies, and various components such as connecting hoses. This allows designers to simply pick numerous parts from the library to develop a comprehensive pneumatic system. It also could simulate a designed pneumatic system in various operating modes. The graphic user interface (GUI) and methods of animation have been used in designing software to give an uncomplicated environment. In a previous study by this researcher, parts of the pneumatic system were divided into five primary classes, and the combination of these parts would be employed to construct a fully pneumatic system, from which a mathematical model of the system was able to be developed. Some component mathematical models have been developed, and the combination of components will integrate multiple mathematical models to generate the overall system model.

Additionally, a high-performing pneumatic force actuator system was introduced in 2008, encompassing simulation, animation, and program support. Double-acting pneumatic actuators controlled by proportional spool valves are one of the high-performance pneumatic actuator systems. The compressibility of air in cylinder chambers, nonlinear air flow through the valve, time delay in pneumatic lines, and leakage between pneumatic chambers all had an impact on the real-time results. It is needed to construct software aids for numerical issue solving due to the intricacy of the pneumatic system model and partial differential equations theories. The engineering efficiency of the outputs is proved by simulation and program help in the MATLAB and Maple programming languages. (Dihovicni & Nedic, 2008).

In 2011, A model of the rod-less pneumatic cylinder was constructed. According to the experimental data obtained, the valve's dynamics were evaluated by generating the relationship graph between mass flow rate and input signal. During its charging and discharging cycles, the heat transfer coefficient is also determined. The friction force in the pneumatic cylinder is formulated plus calculated with the LuGre model. Experiments are used to acquire data for the model's parameters. Finally, applying the open-loop step input response, the model gets verified by comparing simulation outcomes to experimental data. The finding reveals that these experimental results are nearly identical to the theory's predictions (Meng et al., 2011).

Another study obtained the system model by performing system identification in the software namely MATLAB Simulink. The model structure adopted was state space from MATLAB's toolbox. The sample time of 0.01 seconds is utilised to gather input and output data. For parameter estimation, the Prediction Error Minimization (PEM) technique is utilised. The model's parameter is established, and the discrete state space equation is generated. With a sample time of 0.01 seconds, the continuous state space equation will be determined via Zero Order Hold (ZOH) conversion techniques (Syed Salim et al., 2014).

Researchers used the Real Laboratory Process to generate a mathematical model of a pneumatic system in 2018 (Khairul et al., 2019). One of the libraries included in the MATLAB application is the Real Laboratory Process. At a sample interval of 0.01 seconds, a collection of input and output data is gathered. For estimation and validation reasons, the obtained input and output data must be split in the system identification process. The system model is estimated using the MATLAB library's system identification tools. Four additional types of model structures are also available, as indicated in the list below:

i) AutoRegressive Moving Average with Exogenous input (ARMAX)

ii) AutoRegressive with Exogenous input (ARX)

iii) Box Jenkins (BJ)

iv) Output Errors (OE)

The researcher selected the order [3 3 1] for ARX because it is the simplest model that includes the stimulus signal. The model's validation will be the final stage in the system's identification. The ARX model structure uses Akaike's Model Validity Criterion. The model turns out to be satisfactory only if the best fit percentage exceeds 90%.

2.2 Control the Strategies for Pneumatic Positioning Control System

The primary goal of this research is to control the positioning of the pneumatic system. Several types of controllers were applied in the pneumatic actuator system to get a high rate of efficiency in the positioning precision of the actuator. Many research studies have been carried out in the past few years on controlling the position of actuators in the pneumatic system. By referring to the previous research, it shows that most of the controller designs are based on PID controllers although there are many other different types of controllers(Hamdan & Gao, 2000; Nalawade & Gawade, n.d.; Oguntosin et al., 2017; Syed Salim et al., 2014; Thalia et al., 2019; Valdiero et al., 2011). The reported controllers used to control the positioning of the cylinder stroke are the Proportional-Integral-Derivative (PID) controller, Nonlinear PID (NPID) controller, NPID with PSO controller and Cascade controller.

2.2.1 Control the Positioning of Pneumatic System based on Proportional-Integral-Derivative (PID) Controller

The Proportional-Integral-Derivative (PID) controller is the most popular control approach in industries based on the studies. According to (K. J. Åström and T. Hägglund, 2000), PID controllers are applied in almost 90 percent of the controllers used in the industry today. Furthermore, the PID controller's strengths in the industry include its simplicity, understandability, reliability, and robustness (M. E. S. M. Essa, 2014). The PID controller consists of three major parameters which are proportional, integral, and derivative. The key challenge with its use is choosing the most optimal value of the controller parameters (K_p, K_i and K_d). Figure 2.1 illustrates a PID-controlled closed-loop system.

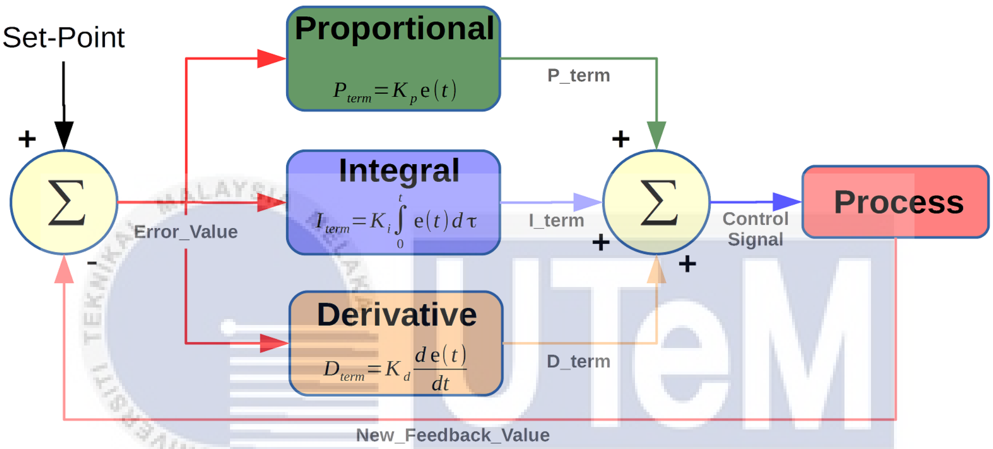

Figure 2.1: Close-loop Block Diagram of PID Controller (The Engineering Concept, 2018)

A feedback-based control loop called a Proportional-Integral- Derivative (PID) controller is often used in industrial control systems as well as other applications which require continuously modulated control. The Equation of the overall PID control function is:

$$\text{PID} = K_p e(t) \; + \; K_i \int_0^t e(t)d\tau \; + \; K_{p\frac{d}{dt}} e(t) \tag{2.1}$$

Where *Kp*, *Ki*, and *Kd*, all are non-negative, denote the coefficients for the proportional, integral, and derivative terms respectively. The Equation of PID in the time domain is:

$$u(t) = K_p e(t) + \frac{Kp}{Ti} \int_0^t e(t)dt + \; K_P T_d(e) \frac{de(t)}{dt} \tag{2.2}$$

The output signal is u(t), while the error signal is e(t). Td is the time differential constant, whereas Ti is the time integral constant. The Proportional, Integral, and Derivative blocks are the three blocks that make up a PID controller (Jigang et al., 2017).

Due to its simplicity and inexpensive cost, it is the most extensively used controller in the world. Other than PID controllers, there are other proportional controllers, PI controllers, and PD controllers that are also PID based. Although the PID-based controller performs excellently in the simulation in terms of reducing overshoot and steady-state error, the non-linearities of the plant have an impact on its performance in the actual world. As a result, certain researchers have already done research to improve or modify the performance of PID-based controllers (Hamiti et al., 1996). Some researchers compare the P, PI, and PID controllers.

Parameters of conventional PID controllers require precise adjustment to obtain optimal performances even though it is efficient and reliable. An algorithm of tuning is needed to adjust the controller parameters. Tuning algorithms help the controller eliminate overshoot issues. Based on (Gouda et al., 2000), Ziegler Nichol's tuning rules are used to adjust the controller's parameters. These are predicated on meeting the response conditions of a hypothetical linear low-order system, and so have limited utility outside of the specific region of plant operation where the tuning was done. Conventional PID would give a reasonable response while there are very high chances of getting the overshoot. Thus, a certain amount of robustness of the PID controller is lost, requiring it to be re-tuned. When the plant has nonlinear features, conventional PID controllers require three tuning parameters that are difficult to optimize a priori and, in any case, are only suitable for a narrow range of plant responses.

2.2.2 Control the Positioning of Pneumatic System based on Nonlinear PID (NPID) Controller

The position of pneumatic systems plays an essential part in numerous industrial applications. In order to accomplish accurate and efficient positioning, the implementation of a control system such as a Nonlinear PID (Proportional-Integral-Derivative) controller has been analysed. The objective of this literature review is to synthesize the research findings on the positioning of pneumatic systems using Nonlinear PID controller and identify knowledge gaps for future research. By addressing these knowledge gaps, researchers can enhance the understanding and application of Nonlinear PID control for accurate and efficient positioning of pneumatic systems.

According to the research done in 2012, the nonlinear PID controller is a combination of a traditional PID controller plus a nonlinear gain block. This NPID controller was represented by a new equation. To establish the maximum value and range of automatic gain adjustment, Ke, the Popov stability criteria is used. When determining the value of Ke, chattering is also considered (max). The value of Ke changes as the number of mistakes changes. If there was no fault, the NPID controller was a conventional PID controller, according to the research. Aside from that, it was an NPID controller with greater performance and lower steady-state error than a traditional PID controller. Even when the stroke position changed, the NPID performed admirably (M. F. Rahmat, 2012). Figure 2.2 shows the block diagram of the researcher.

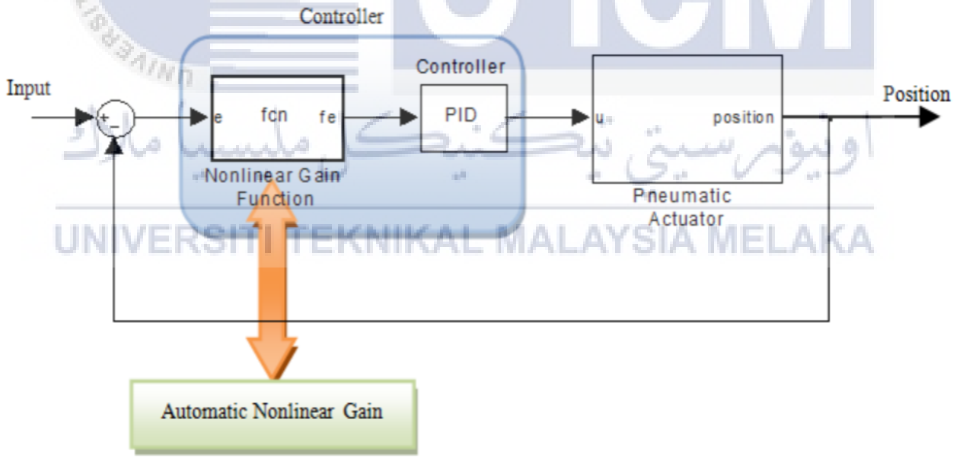

Figure 2.2: Block Diagram of the N-PID Control System (M. F. Rahmat, 2012)

Moreno presented an innovative PID-type motion controller designed specifically for a quadrotor. The controller was extensively analysed, and detailed suggestions for setting the gain were provided. Experimental results compared the performance of the PID-based system with a sliding-mode controller and the novel nonlinear PID-type method. The introduced approach displayed higher tracking accuracy in the presence of disturbances in one of the actuators (Moreno-Valenzuela et al., 2018).

A control system researcher, Syed Salim then presented a Self-regulation Nonlinear PID (SN-PID) controller to solve the flaws in NPID. This research aimed to create a controller that would allow the actuator to achieve the specified displacement without overshooting. The range of variation (Emax) and rate of variation (a) are two factors that must be set in a nonlinear PID. To solve the challenges of collecting the parameters, a change was developed to obtain them automatically. For enhanced controller flexibility, the researcher modified the rate variation parameter to an online produced technique. Because the rate variation parameter is automatically modified, the value of K, is now automatically updated. As a result, self-regulation is another name for this function. This controller is represented by a simple equation. For the to produce automatically, the relationship between and is calculated in advance using the particle swarm optimization approach. When compared to the NPID controller developed by M. Rahmat in 2012, this researcher's controller has been shown to have superior steady-state response and 2.2 times better transient response. When the external load applied to the system is less than 28kg, the SN-PID can maintain satisfactory performance (Syed Salim et al., 2014). Figure 2.3 demonstrates a block diagram of the SN-PID Control System.

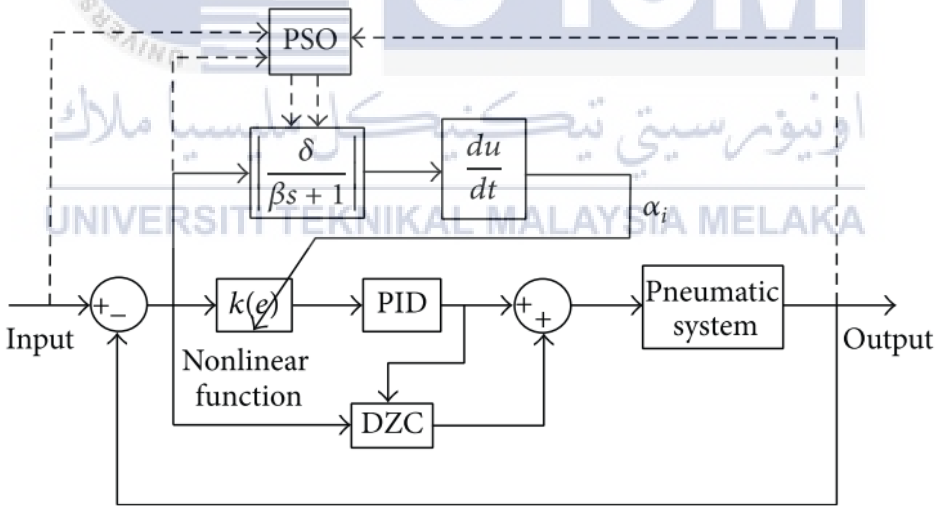

Figure 2.3: Block Diagram of the SN-PID Control System (Syed Salim et al., 2014)

An improved nonlinear PID (ENPID) was proposed in follow-up research back in year 2015 (Salim et al., 2015). The multi-nonlinear (MN-PID) controller and the self-regulation (SN-PID) controller are the two control techniques used in the controller. To circumvent the valve's dead band, dead zone compensating was used. In addition, to boost tracking performance, the feedforward path was implemented. In the MN-PID, fuzzy was utilized to modify the rate variation of the nonlinear gain, ax, whereas, in the SN-PID, the gain was created online by the equation, as indicated in the previous work (Syed Salim et al., 2014). Both MN-PID and SN-PID performed well in this investigation regarding monitoring the input trajectories. Consequently, when compared to NPID, the suggested controller showed no improvement, but when compared to prior research that employed a step input, it clearly improved. The performance of the system with the suggested controller was tested with a range of amplitude and frequency, but no difference was found, indicating that the proposed control techniques were able to adjust to rapid changes.

In 2022, An issue commonly encountered in industrial applications is the use of linear compensators, which do not match the extremely nonlinear properties of pneumatic systems. Due to this factor, a Double Nonlinear Hyperbolic compensator and two types of Triple Nonlinear Hyperbolic Proportional-Integrator-Derivative (PID) compensators have been designed to deal with the system's nonlinearity. Both Double and Triple Nonlinear Hyperbolic PID demonstrate a good steady-state error performance in comparison to the basic PID compensator, as proven through simulation and experimental analysis. The performance of each nonlinear compensator in the transient response remains uncompromised while delivering a greater steady state. This Double Nonlinear Hyperbolic PID compensator demonstrates outstanding performance in determining the precise position during experimental analysis. Nevertheless, The Triple Nonlinear Hyperbolic PID has better performance in the analysis of Integral Absolute Error (IAE) (Kamaludin, K. N., Abdullah, L., Salim, S. N.S., Rahmat, M. F., 2022). The PSO algorithm aims to identify the optimal parameter configuration that reduces error and enhances the reaction time and stability of the pneumatic actuator (Bai, 2010).

2.2.3 Control the Positioning of Pneumatic System based on NPID with PSO Controller

Particle Swarm Optimization (PSO) is a computer technique that draws inspiration from the collective behaviour of birds flocking or fish schooling. The process optimizes a problem by repeatedly attempting to enhance candidate solutions based on a specified measure of quality (Bai, 2010). Moreover, the PSO algorithm proves extremely valuable for optimizing the parameters of NPID controllers, which include the proportional, integral, and derivative gains, as well as any nonlinear parameters. This ensures that the control system operates at its optimum performance.

A combination of an NPID (Nonlinear Proportional-Integral-Derivative) controller and Particle Swarm Optimization (PSO) is an advanced control approach used to achieve accurate positioning of pneumatic systems (Li et al., 2020). Pneumatic systems, which utilize compressed air to produce mechanical motion, possess inherent nonlinearity and complexity in their control due to the presence of frictional forces and compressibility.

By combining PSO with an NPID controller, the control system of a pneumatic actuator is able to autonomously adapt its parameters to get the most efficient performance. This combination enables improved management of the nonlinear dynamics and uncertainties present in the pneumatic system, leading to enhanced accuracy in positioning control (Ye et al., 2017). The PSO algorithm aims to identify the optimal parameter configuration that reduces error and enhances the reaction time and stability of the pneumatic actuator (Bai, 2010).

2.2.3 Control the Positioning of Pneumatic System based on Cascade PID Controller

The positioning of pneumatic systems plays an essential part in numerous applications, such as manipulators, electro-hydraulic position servo systems, and pneumatic pressure controlling systems. The application of cascade PID controllers has been widely studied to enhance the performance of these systems. This literature review examines the research findings related to the positioning of pneumatic systems utilising cascade PID controllers, highlighting the integration and synthesis of the findings, identifying knowledge gaps, and suggesting potential future research areas. The integration and synthesis of these findings reveal the effectiveness of cascade PID controllers in improving system performance, such as frequency response, load frequency control, transient response speed, tracking accuracy, and robustness. The review also identifies knowledge gaps and suggests potential future research directions, including adaptive control strategies, optimization algorithms, hybrid control schemes, real-time implementation, advanced modelling techniques, robustness and fault tolerance, and energy efficiency.

The research highlights the betterment of performance achieved through the cascade controller design, emphasizing the importance of optimized control strategies in maintaining system stability (Çelik et al., 2021). In 2018, the researcher proposed the design and implementation of a digital fractional order PID controller using the optimal pole-zero approximation method for a magnetic levitation system. The study focuses on the cascaded PI-FOPID controller, fine-tuned using the Gorilla Troops Optimizer (GTO), which offers improved maximum overshoot/undershoot and settling time compared to other optimization techniques.

In another work, the author presented a nonlinear robust tracking control strategy to overcome the servo pneumatic positioning system's tracking problem (Ramírez, 2018). As a feedback state, the findings underlined the need to consider the pressure, velocity, and position changes between the chambers of a pneumatic cylinder. This research was successful in simulation and was applied in a real-world pneumatic system and a global simulation model. There were two aspects to the control approach. Firstly, as an inner loop, a proportional controller is used to measure the difference in pressure between the chambers of the pneumatic cylinder. The second is independent feedback and feedforward; it means feedforward serves as a pre-filter for the reference position trajectory and feedback for the difference between the intended and actual states. The greatest tracking error was determined to be around 2 mm, and the steady-state error was less than 1 mm, which is better than the previous study's finding of 5 mm.

Ali devised a cascaded PI-fractional order PID. The study demonstrates the effectiveness of the controller in enhancing the frequency response and highlights the use of the Gorilla Troops Optimizer for fine-tuning the controller parameters (Ali et al., 2021). Next, in 2018, a researcher proposed a fuzzy fractional-order PID controller for a fractional model of a pneumatic pressure system. The research presents a model-free, data-driven method for safe tuning of PID cascade controller gains based on Bayesian optimization, outperforming relay feedback autotuning and ensuring stability (Al-Dhaifallah et al., 2018).

2.3 Summary

According to prior research, nonlinearities in the system, such as excessive air compressibility, and frictional force are the most prevalent difficulty in pneumatic actuator systems. Previous researchers have built numerous controllers to overcome those challenges. Proportional integral derivatives (PID) based controllers are the most extensively utilized controllers in pneumatic actuator systems. According to the results of the literature study, research into these actuators surged in the 1990s as a result of the introduction and implementation of several control schemes into the system. Then, in the early 2000s, researchers came up with a slew of sophisticated control tactics, and the field's research grew even more intense. However, the majority of the studies that were recommended for control measures contained complex factors and mathematical formulas. As a result, most academics have continued to favour control loops based on proportional integral derivatives (PID) controllers in recent years due to their simplicity and ease of understanding. This study has selected the use of a Nonlinear PID (NPID) controller and will compare it with a cascade PID controller. Nonlinear PID controllers are designed to handle systems with nonlinearities. It can be more effective in controlling processes where the relationship between the input and output is nonlinear. Moreover, nonlinear controllers can offer robustness against variations and uncertainties in the system. This is the most important control application choice accessible because of its basic structure (just three parameters to consider), even if it may have problems coping with highly nonlinear systems. Lastly, Overall, the NPID controller with PSO optimization provides a reliable solution for accurately controlling the position of pneumatic systems. It effectively addresses the inherent nonlinearities of these systems and ensures precise control by optimizing the controller's parameters.

CHAPTER 3

METHODOLOGY

The first part of this chapter will focus on the research workflow. A flowchart outlining the different processes involved in conducting the research, from start to end, is shown to help clarify the process. The flowchart in Figure 3.1 shows the progress of the analysis. The experimental setup for the pneumatic system in this research will be provided. The primary purpose of the setup is to gather data from the pneumatic plant. This chapter will also provide an explanation of the procedure for obtaining parameters for positioning the PID controller from the pneumatic system. The pneumatic Actuator system's mathematical model was obtained from a System Identification (SI) approach in the MATLAB software. The techniques employed in the design of the modified proportional integral derivative (PID) controller are described.

3.1 Workflow of Research

The flowchart illustrates the work to be carried out sequentially to accomplish the research. There are eleven steps to be conducted divided into four phases. The first phase covers the problem statement and a literature review of related existing research articles. The second phase focuses on system modelling, which involves system identification in MATLAB software, data collection and model structure selection, model estimation and validation, and system modelling checking parameters. Moreover, the third phase includes the controller designing steps, which end with the simulation test and analysis. The final stage is the comparison between all the controllers. Figure 3.1 illustrates the work flowchart for the methodology framework.

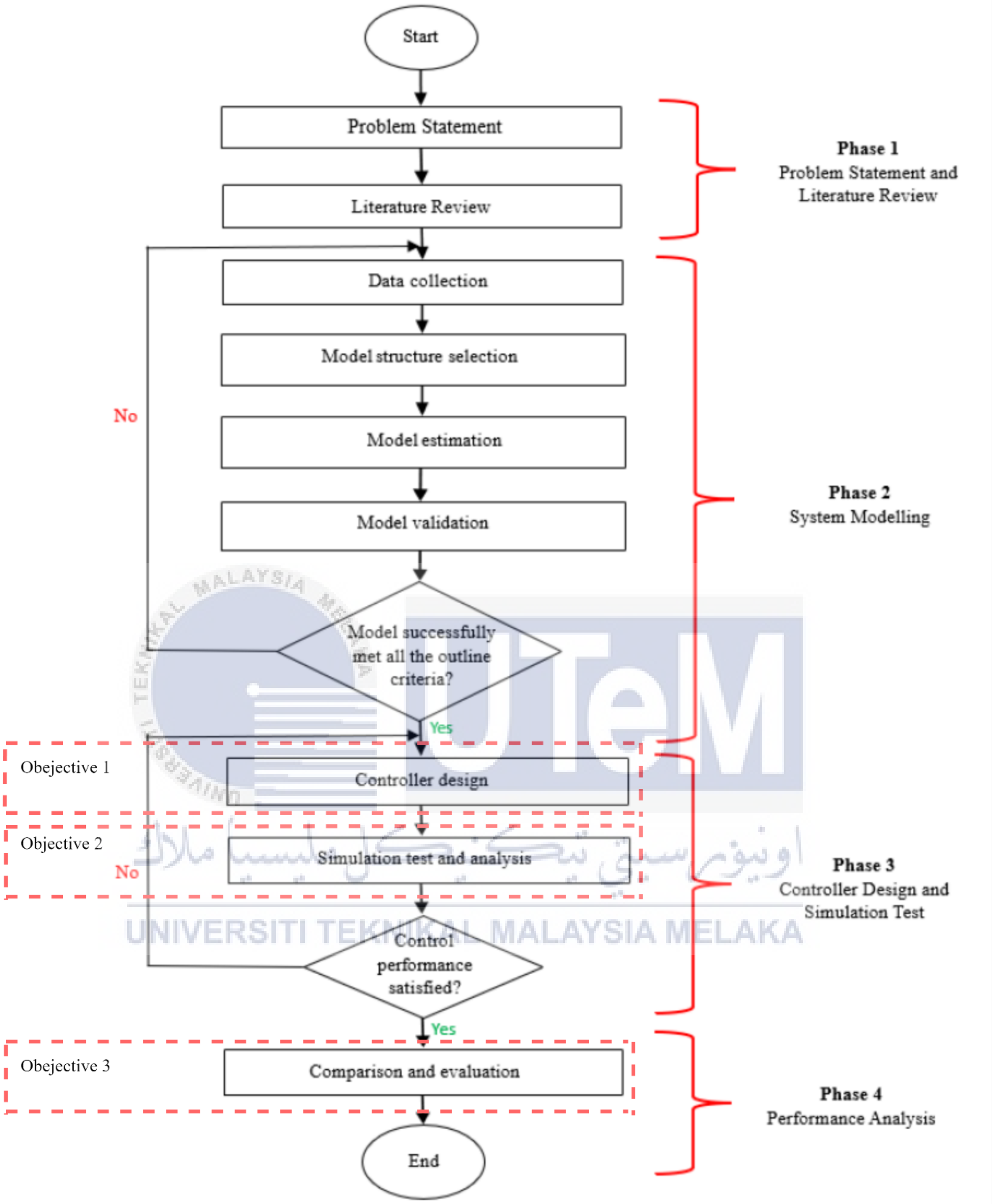

Figure 3.1: Work Flowchart for Methodology Framework

3.1.1 Phase 1

Based on Figure 3.1, the first phase of the project is to identify the problem statements which leads to determining the research objectives. Additionally, scope of project must be defined to limit the area of research. Furthermore, it also includes a literature review to collect information on the data that have been written in earlier similar research. This method is able to recognise the problems and difficulties that earlier researchers in related disciplines had to deal with.

3.1.2 Phase 2

In order to design a controller in a simulated environment, a mathematical model must be obtained. In the second stage, the measured input and output data from the actual experimental procedure of the pneumatic positioning control system were imported by reference into the MATLAB system identification tool. System identification was utilised in this project to develop the desired models of the system by utilising the Single Input Single Output (SISO) method. System identification is used because it identifies the parameters from the real pneumatic plant which will deliver greater precision. After system identification, the parameters have been examined and evaluated for model validity. The identified models were evaluated using the criteria stated in the system identification approach to demonstrate their validity as representing the genuine pneumatic system used in this study. The most appropriate and accurate model structure was implemented to represent the actual pneumatic system employed in this study.

3.1.3 Phase 3

In the third phase, designing controllers for the system model that is obtained in Phase 2. The controllers are then implemented in the real system to conduct experimental tests for validation purposes. Design the PID controller, Nonlinear PID controller and Cascade controller. Integrated PSO into NPID controller. Tuning the parameter of each controller using the heuristic method to obtain the results. Tuning the gain parameter until it reaches a steady state with minimum error and optimizing the transient response.

3.1.4 Phase 4

At the final of the phase, the performance of both controllers in controlling the positioning of pneumatic (based on simulation tests) was analysed in terms of Steady State Error (ess) and transient response: 1) Settling time (Ts), 2) Rise time (Tr), 3) Peak time (Tp), 4) Overshoot ($\%OS$).

3.2 Hardware Setup

A pneumatic system consists of an air compressor, a filter, a regulator, a lubricator unit (FRL unit), a directional control valve with inlet and outlet ways, and an actuator, which is sometimes referred to as a pneumatic cylinder. A controller is the main component of the actuator's positioning performance. The pneumatic system is beginning to work with the air compressor by supplying pressured air into the pneumatic system. Subsequently, the compressed air enters the Filter-Regulator-Lubricator (FRL) unit. The primary objectives of the FRL unit are to eliminate airborne dust particles to enhance the system's longevity and sustainability, control air pressure according to the system's operational needs, and apply lubrication to the air to avoid damaging the actuator. Figure 3.2 shows the experimental setup of pneumatic systems.

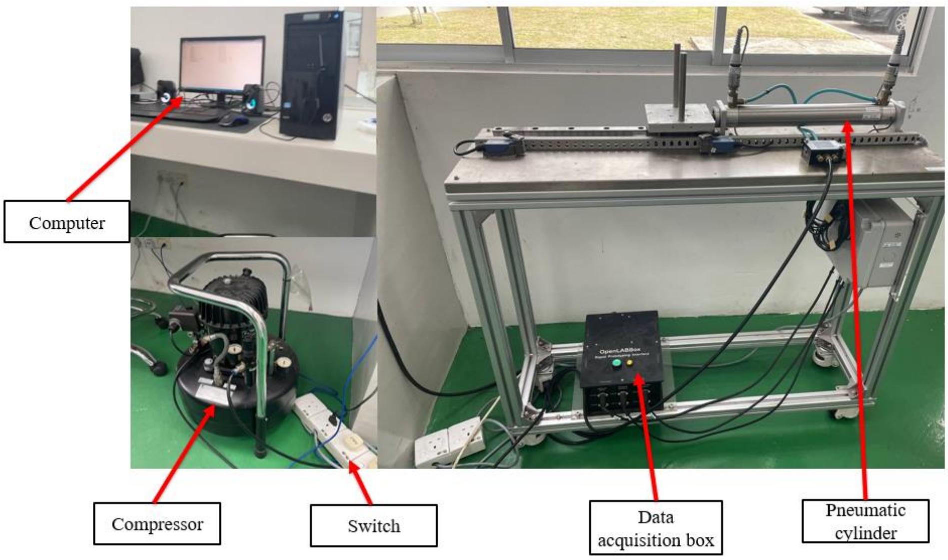

Figure 3.2: Experimental Setup of Pneumatic Systems

Afterwards, the control signal is applied to the 5/3-way valve as the control mechanism of the system. The basic function of the valve is to control the air flow direction according to the inlet and outlet of the air in the pneumatic system. After that, the actuator is the acting component of the pneumatic system according to the pressure of air and the functions of other components.

The actuator's motion lacks consistency according to user preferences. An external controller is employed for controlling the complete pneumatic system to accomplish what is needed for system performance as stated by the users' requirements. The project will utilise a Nonlinear PID-based controller to control the movement of the actuator in the system. Regarding the controller of the pneumatic system, the user's primary concerns are the actuator's position and precision. Figure 3.3 illustrates a schematic diagram of a pneumatic positioning system from a previous researcher (M. F. Rahmat, 2012).

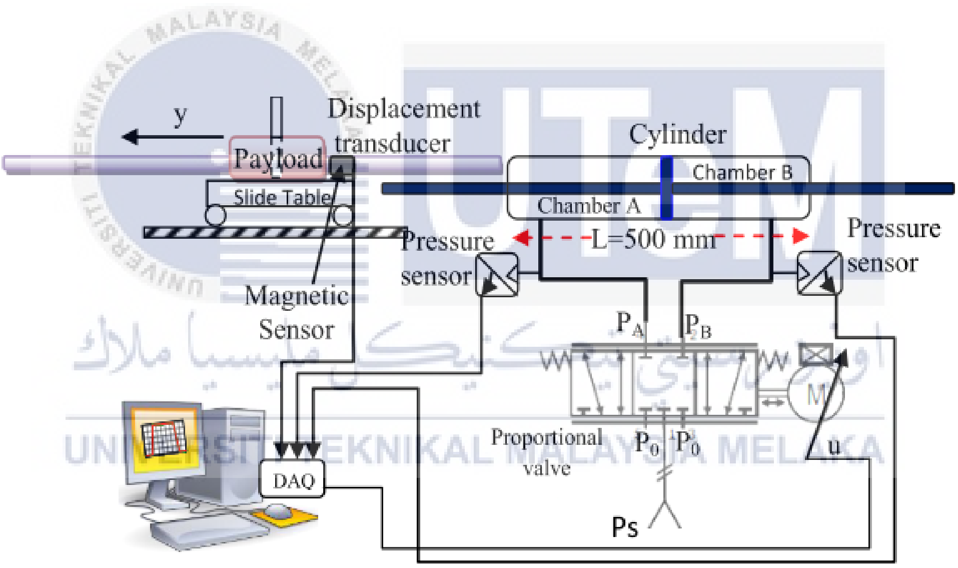

Figure 3.3: Schematic Diagram of Pneumatic Positioning System (M.F Rahmat, 2012)

Figure 3.4 demonstrates the components of pneumatic actuator systems. The system consists of (i) 5/3 way proportional control valve; (ii) double acting with double road cylinder; (iii) data acquisition card; (iv) pressure sensor; (v) Computer; and (vi) air compressor. A pneumatic cylinder, measuring 170 mm in diameter, is securely attached to the base. It has a stroke length of 400mm on both sides. The piston rod is attached to the carriage on one side, pushing an inertial load along the guiding rails. The displacement transducer is positioned in parallel with the rail on which the carriage is attached. The data acquisition and control routines built-in MATLAB Simulink using real-time workshops are run by a PC equipped with a PCM card. Two pressure sensors are positioned on opposite sides of the cylinder, enabling the precise measurement of the difference in pressure between the two chambers. Figure 3.4 shows the components of a pneumatic actuator system that have been captured in the lab employed to verify the proposed technique.

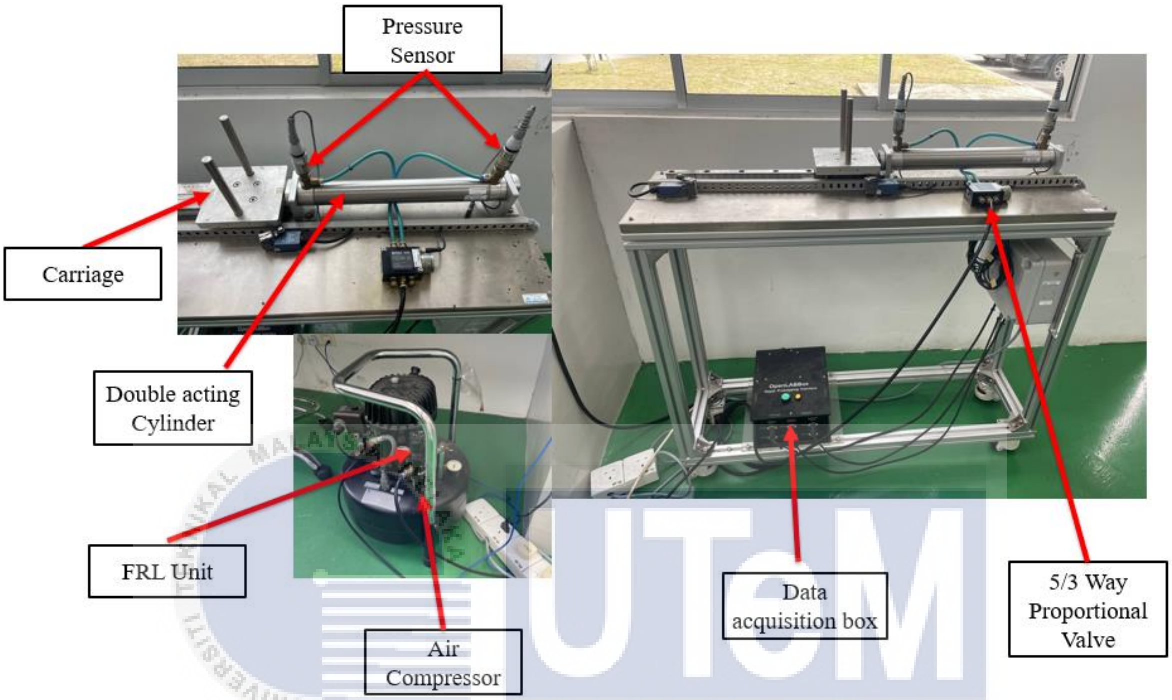

Figure 3.4: Components of Pneumatic Actuator Systems

3.3 System Modelling

The system identification toolbox of MATLAB software will be used for the system modelling process since the model and parameters of the pneumatic actuator were undefined for the system. The block diagram representing the pneumatic actuator system used for the experiment will be drawn in MATLAB Simulink. Recording of the system model's estimation will be conducted from the experiments works on the pneumatic actuator system with sine wave input and constant sampling time as shown in Figure 3.5.

Then, the data will be collected and exported to the workspace of MATLAB software as presented in Figure 3.6. The data range to be used will be selected by employing a system identification toolbox from MATLAB software. The general transfer function model and its respective parameters will be chosen. The models that resulted in the best fit of more than 90% were selected from the system, as shown in Figure 3.10.

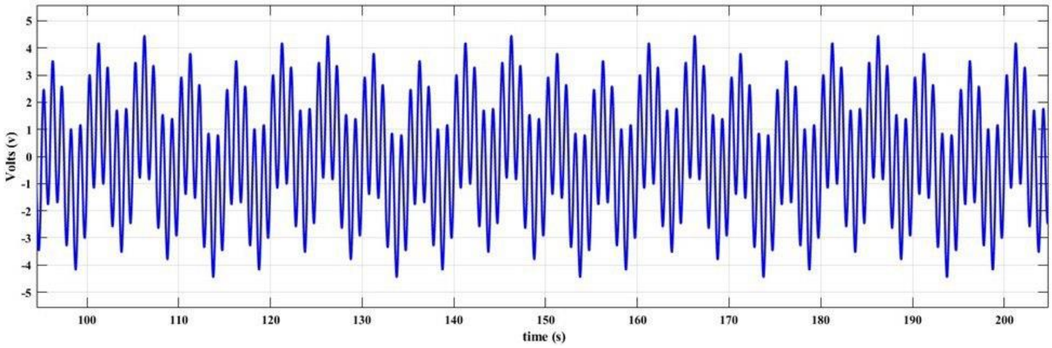

Figure 3.5: Sine Wave Input for System Identification

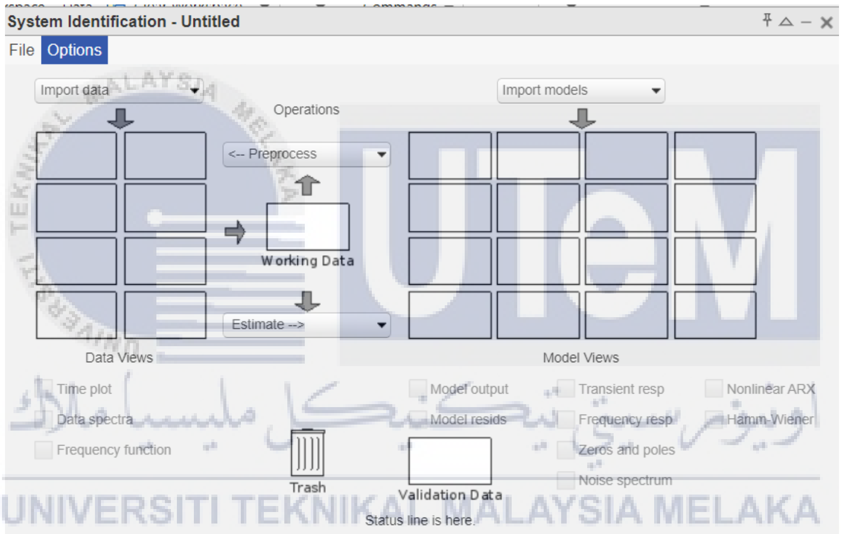

Figure 3.6: System Identification Toolbox to Import the Data

Figure 3.6 illustrates a system identification toolbox to import the data from MATLAB software that will be used to choose the data range to be used. The generic transfer function model and its corresponding parameters will be chosen. The transfer function models are chosen as the estimation function, as shown in Figure 3.7. Next, Figure 3.8 indicates the software will display the estimate functions window, allowing the user to input the parameters for the required number of poles and zeros to be added. Double-clicking on the chosen output model pops up the transfer function. As shown in Figure 3.9, this step will prompt the data or model information.

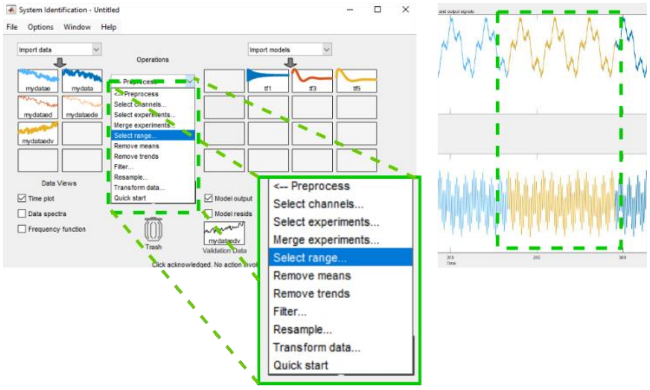

Figure 3.7: Selecting Data Range from System Identification

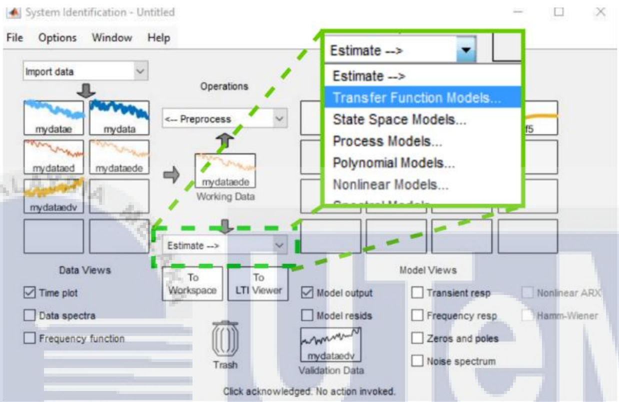

Figure 3.8: Selecting Transfer Function Model

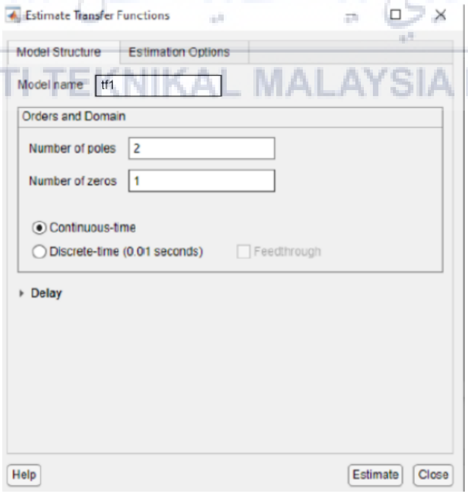

Figure 3.9: Data Input Information

System identification is the process of using measurable input-output data to determine a dynamic system's mathematical model or parameters. Due to all of its integrated features and resources, MATLAB is a popular tool for system identification tasks. After gathering, the data will be moved to the MATLAB workspace. The data range will be chosen with a system identification toolbox provided by MATLAB. The general transfer function model and the associated parameters will be chosen. The models demonstrating the best fit will be selected. Table 3.1 shows the transfer function and its best fits of the system that were gained from system identification using MATLAB software. These outstanding transfer and best-fit functions are appropriate for the project.

Table 3.1: Transfer Function and Best Fits

No.	**Transfer Function of the System**	**Best Fit %**
1.	$\frac{0.2311s^2 + 2.844s + 1.946}{s^3 + 3.415s^2\ 0.9866s + 0.03526}$	91.02
2.	$\frac{-0.03514s^2 - 1.057s + 1.159}{s^3 + 0.1008s^2 + 6.33s + 0.5494}$	81.81
3.	$\frac{2.348s + 0.1902}{s^3 + 2.356s^2 + 0.03633s + 0.08559}$	78.30

To assess the preciseness of the controller's model, the System Identification technique involves generating transfer functions using the actual plant's schematics. Additionally, it gives the best match percentage for the model that is displayed on the right side of the simulated model output that has been shown in Figure 3.10. It shows the best match was achieved at a rate of 91.02%. It can be applied to this project since the best fit is more than 90%. According to (Abdullah et al., 2021), research shows high precision in the model since the model fit over 90% is achieved. Equation 3.1 represents the chosen transfer function, demonstrating the simulated model that best fits the data.

$$G(s) = \frac{0.2311s^2+2.844s+1.946}{s^3+3.415s^2\ 0.9866s+0.03526} \tag{3.1}$$

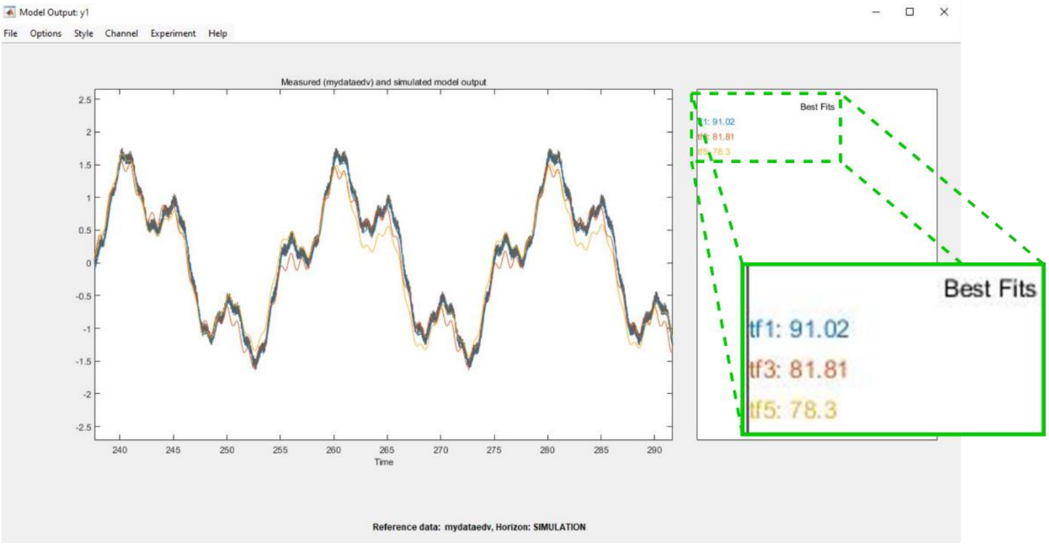

Figure 3.10: Best Fit of Estimated Transfer Function

3.4 MATLAB Simulink

MATLAB Simulink software is one of the essential aspects of this study. Simulink is a block diagram environment software to design systems with domain models, simulate before proceeding to hardware setup, and deploy the system into hardware setup. Model-based systems engineering (MBSE) is the application of models to support the whole system lifecycle. Simulink bridges development from requirements and system architecture to technical component design, implementation, and testing This software is used throughout the research to design the controllers, simulate, and implement them into the real system. Figure 3.11 illustrates the software of MATLAB Simulink.

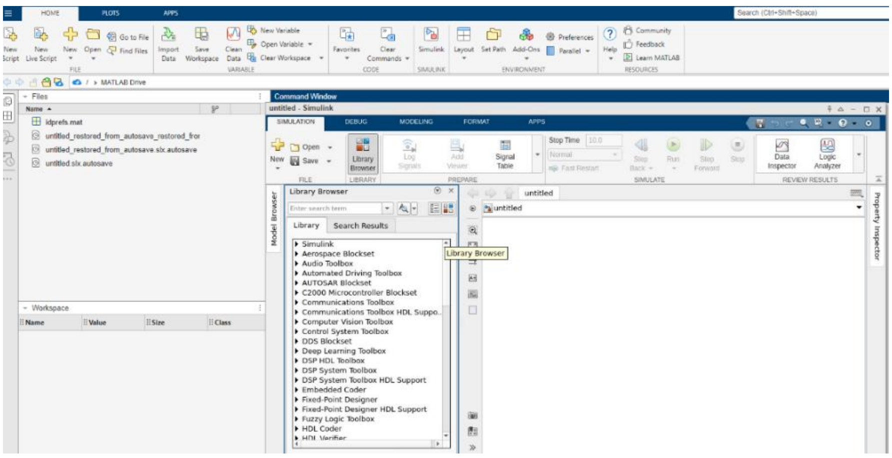

Figure 3.11: MATLAB Simulink Software

3.5 Controller Design

The traditional PID controller emphasizes a clear design technique in order to get the advantageous result in managing the position and continuous motion as its final goal. However, when the position control operates more rigorously, this sort of controller is generally difficult to give better performance due to the presence of nonlinearities particularly in pneumatic systems. In an attempt to overcome this difficulty, several control mechanisms have been examined by researchers. However, numerous of these control strategies are not applied in industries as they prefer to use PID controller due to its simplicity, low cost and ease of operate (Bharathi, M., 2012). In this paper, the PID controller that incorporates automatic nonlinear was designed, simulated and tested to control the position and tracking of a pneumatic actuator. The nonlinear function is utilised to accommodate the nonlinearity in addition to solving the deficiencies in traditional PID controllers. The proposed controller's control performance was then compared to the Cascade-type controller.

3.5.1 Proportional-Integral-Derivative (PID)

PID is a combination of "Proportional Integral Derivative." A PID controller consists of three basic parameters: proportional (P), integral (I), and derivative (D). Each parameter has its own function, and all three of these parameters mainly determine the performance of a PID controller. Proportional response to the current error. Integral addresses accumulated past errors. Derivatives anticipate Future error. Controller is a widely Used feedback control system that plays a crucial role in regulating and stabilizing various process. Various type of controller was applied in pneumatic system to obtain a high rate of efficiency in the positioning of pneumatic system. Moreover, it is effectively Minimize the error between a desired setpoint and the actual output of a system.

Figure 3.12 shows the closed-loop block diagram of a PID controller. Equations 3.2 through 3.4 describe the P, I, and D controller basic equations, while Equation 3.5 describes the PID controller's basic equation.

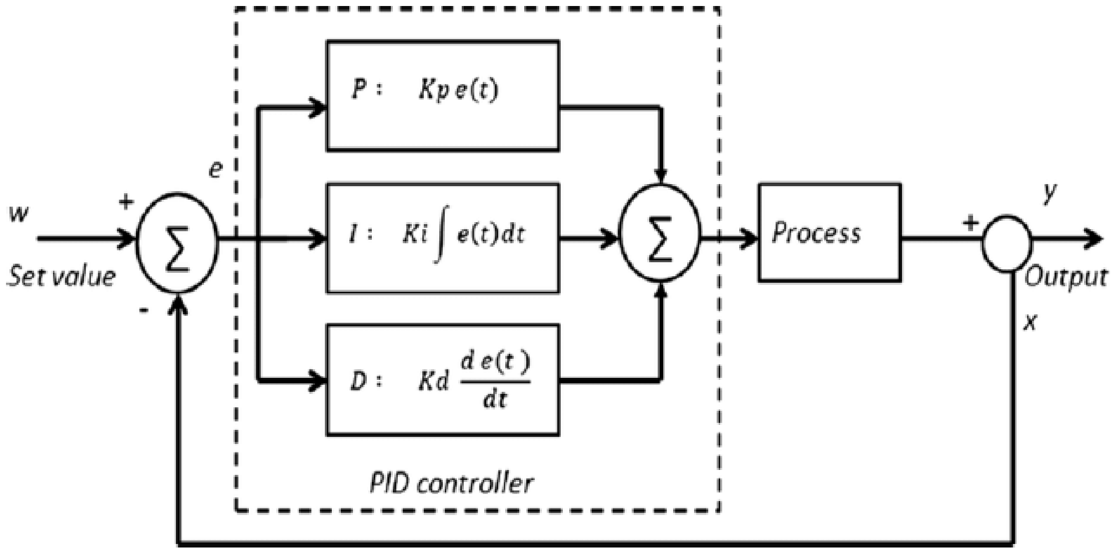

Figure 3.12: The Closed-Loop Block Diagram of PID Controller (A. Hanif Halim, 2017)

$$\text{P} = K_p e(t) \tag{3.2}$$

$$\text{I} = K_i \int_0^t e(t) d\tau \tag{3.3}$$

$$\text{D} = K_{d\frac{d}{dt}} e(t) \tag{3.4}$$

$$\text{PID} = K_p e(t) \ + \ K_i \int_0^t e(t) d\tau \ + \ K_{d\frac{d}{dt}} e(t) \tag{3.5}$$

3.5.2 Nonlinear PID Controller

This controller is a type of Proportional-Integral-Derivative (PID) controller that incorporates nonlinear elements to improve its performance in controlling complex systems. Traditional PID controllers are widely used in industrial applications to regulate the behaviour of systems by adjusting control inputs based on the error signal, which represents the difference between the desired setpoint and the actual system output. Nonlinear PID controllers aim to enhance the adaptability and robustness of the control system by introducing nonlinearity into the control algorithm. This can be particularly useful when dealing with systems that exhibit nonlinear behaviour, uncertainties, or varying dynamics.

Better position tracking performance and fast response times have been achieved by using the PID controller effectively. subsequently, it has a basic structure with many types of tunning methods available that are more efficient as well. By tuning the PID gain K_p, K_i and K_d, steady state and transient response such as rising time, overshoot, settling time, and peak time error able to obtain a better performance. Nevertheless, obtaining satisfactory performance for these systems is difficult for PID controllers. Hence, the PID controller combines with nonlinear gain to form the NPID controller, which was developed to govern the pneumatic position tracking. Equation 3.6 shows the NPID controller.

$$u(t) = K_p k(e) e(t) + K_i k(e) \int_0^t e(t)dt + K_d k(e) \frac{d}{dt} e(t) \quad (3.6)$$

A wide variety of options are available for the nonlinear gain *k*. Therefore, as a function of error *e*, nonlinear gain *k* has been used. Figure 3.13 illustrates the simulation model of NPID controller.

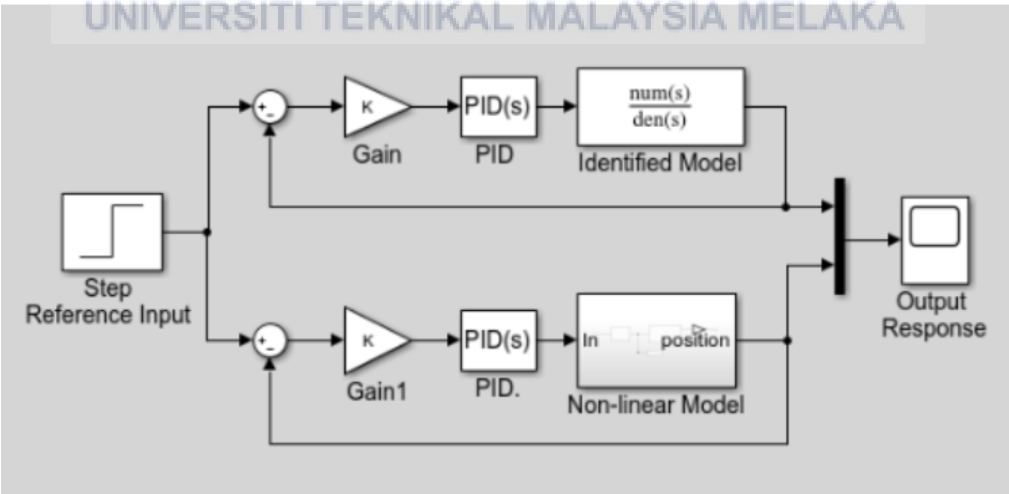

Figure 3.13: Simulink Model with NPID Controller (Nisar Z, 2021)

3.5.3 Cascade PID Controller

A Cascade PID controller is a control system architecture that involves using multiple PID controllers in series to control a single process or system. This arrangement is often employed when a control system exhibits complex dynamics or has multiple interacting variables. The Cascade PID controller consists of two or more PID controllers arranged in a cascaded (sequential) manner. The primary (outer) controller regulates the setpoint for the secondary (inner) controller. Tuning a Cascade PID controller involves tuning both the primary and secondary controllers. This controller is generally utilised to accomplish rapid rejection of disturbance before it propagates to the other parts of the plant. This basic controller system has two control loops (inner and outer) as represented in Figure 3.14.

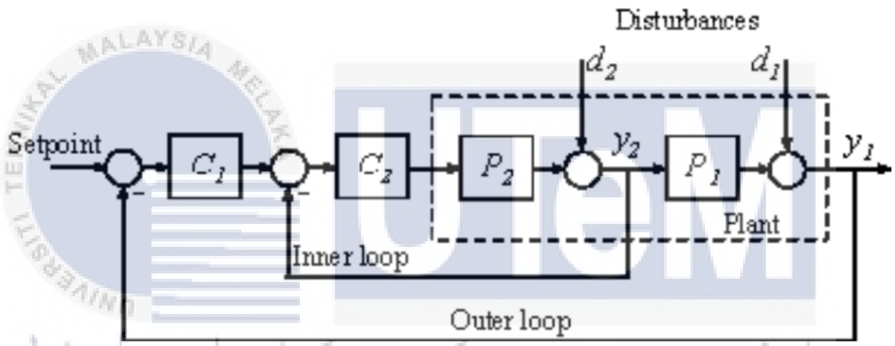

Figure 3.14: Block Diagram of Cascade Controller (Chengyi Guo, 2007)

Controller *C1* in the outer loop is the primary controller that regulates the primary controlled variable *y1* by setting the set-point of the inner loop. Controller *C2* in the inner loop is the secondary controller that rejects disturbance *d2* locally before it propagates to *P1*. For a cascade control system to function properly, the inner loop must respond much faster than the outer loop. It's worth noting that the effectiveness of a Cascade PID controller depends on the specific characteristics of the controlled process. Proper tuning and understanding of the system dynamics are crucial for achieving the desired control performance.

In 2017, a hierarchy controller called cascade was suggested in the research. The experiment showed the effectiveness of cascade control in improving the assistance modulation and positioning capabilities. This actuation technique offers several advantages, but it also has inherent limits due to the existence of nonlinearities, like backlash and friction in the cables. These nonlinearities make it challenging to accurately predict while controlling the dynamics between the device and the user. The citation is from a study conducted by Binh Khanh Dinh, (2017).

An active disturbance rejection controller (ADRC) is initially designed to implement a resilient cascade control system for precise position control of a pneumatic servo system. This system is typically characterised by uncertainty, nonlinearity plus disturbance. The control system being suggested includes inner and outer control loops. Specifically, a linear ADRC is employed to control the valve position in response to the dynamics of a linear spool valve within the inner loop. Next, a nonlinear ADRC (NADRC) was created to control the position of a nonlinear pneumatic actuator subsystem within the outer loop. Both the LADRC and NADRC algorithms incorporate linear and nonlinear extended state observers (ESO), accordingly. The ESO has the capability to accurately predict both unfamiliar nonlinear dynamics and external disturbances, thereby enhancing the robustness of the ADRC against uncertainty and disturbances in the system. The outcomes of the simulation effectively showcase the efficacy and robustness of the designed cascade control system. By using the Lyaunov method, it is proved that the stabilities of the inner and outer control loops. (Mandali, A., Dong, L., 2022).

3.6 Tunning of Controllers

All the controllers have finalized the tuning process. The objectives of the project are incapable of being achieved by only tuning that was chosen during the simulation phase. The process of altering the gains for the controllers like K_p, K_i and K_d is the main focus of this chapter.

3.6.1 PID Controller

The beginning phase of developing the Nonlinear PID controller was to design a PID controller to guarantee the PID gains were satisfactory in achieving a stable system without external disruptions. In overall, the PID gains were determined as indicated in Figure 3.15.

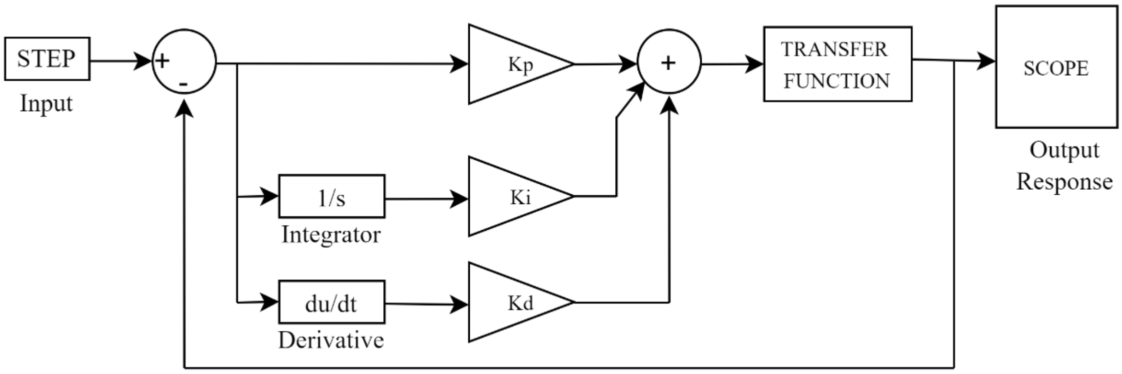

Figure 3.15: Structure of PID Controller

In this research, after designing a parameter tuning approach was used to ensure the stability of the pneumatic system without any external disturbances. The tool for designing the PID controller is MATLAB Simulink software. Tuning the value of K_p, K_i and K_d are crucial in order to achieve the desired output with satisfactory transient response. Fundamentally, three control blocks form a PID controller: proportional (P), integral (I), and derivative (D) (Solihin et al., 2011). The control scheme and control signal of the PID controller can be seen in Figure 3.15. Equation 3.7 shows the control signal of the PID controller accordingly.

$$\mathrm{U}_{PID} = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} \tag{3.7}$$

where,

$e(t)$ = Tracking error

K_p = Proportional Gains

K_i = Integral Gains

K_d = Derivative Gains

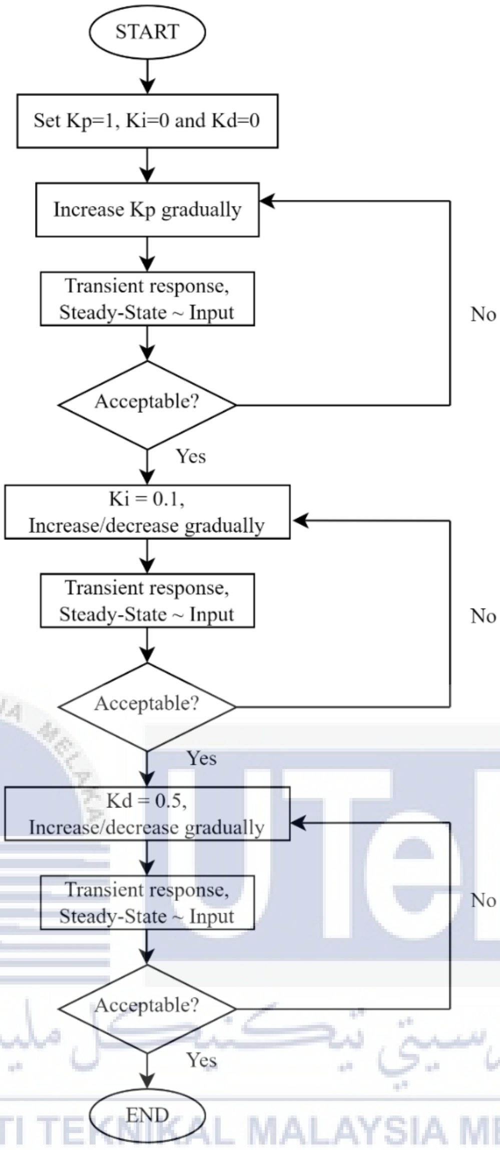

Figure 3.16: Flowchart of PID Parameter Tunning

The flowchart illustrates steps that control the system's response to an input by modifying the proportional (K_p), integral (K_i), and derivative (K_d) gains of the PID controller. Moreover, the K_p, K_i and K_d gains define how much the controller considers the present error, cumulative error over time, and the rate of the error change, correspondingly. Ultimately, by repeatedly altering the K_p, K_i and K_d gains until the system's response matches the desired input, the flowchart can be used as a guide to tune a PID controller. Table 3.2 shows the PID controller data value of tuning the gain parameter K_p, K_i and K_d by using the Heuristic Method.

Table 3.2: Simulation Tuning of Tuning K_p with a Constant Value of K_i = 0, K_d = 0

K_p	Steady-State (mm)	Steady-State Error (mm)
1	30.58	49.42
2	35.86	44.14
3	40.05	39.95
4	43.70	36.3
5	48.02	31.98
6	53.81	26.19
7	59.47	20.53
8	63.16	16.84
9	64.01	15.99
10	66.54	13.46
11	66.89	13.11
12	67.44	12.56
13	68.48	11.52
14	68.07	11.93
15	72.05	7.95
16	71.19	8.81
17	72.05	7.99
18	71.07	8.93
19	71.53	8.47
20	71.60	8.40

Table 3.3: Simulation Tuning of Tuning K_i with a Constant Value of K_p = 15, K_d = 0

K_i	Steady-State (mm)	Steady-State Error (mm)
0.10	77.06	2.934
0.11	73.9	6.61
0.12	77.03	2.94
0.13	75.17	4.29
0.14	75.18	4.82
0.15	74.94	5.06
0.16	77.49	2.51

0.17	76.55	3.44
0.18	78.31	1.69
0.19	78.13	1.87
0.20	78.17	1.83
0.21	81.72	-1.72
0.22	77.47	2.53
0.23	78.71	1.29
0.24	78.69	1.31
0.25	79.36	0.64
0.26	80.82	-0.82
0.27	78.97	1.03
0.28	80.58	0.58
0.29	80.69	-0.69
0.30	81.10	-1.10
0.31	82.81	-2.81

Table 3.4: Simulation Tuning of Tuning K_d with a Constant Value of K_p = 15, K_i = 0.28

K_d	Steady-State (mm)	Steady-State Error (mm)
0.05	77.58	2.42
0.06	77.13	2.87
0.07	77.70	2.30
0.08	77.13	2.87
0.09	78.21	1.78
0.10	79.33	0.67
0.11	79.46	0.53
0.12	80.91	-0.91
0.13	81.17	-1.17
0.14	82.75	-2.75

The process of determining the appropriate tuning gains during simulation for the PID controller relies on the flowchart shown in Figure 3.16. This flowchart outlines the procedures involved in tuning the K_p, K_i and K_d gains. The initial tuning gains of K_p are established by setting K_i and K_d to 0. The selected value for the K_p tuning parameter in Table 3.2 is 15 mm. This occurs because when the tuning exceeds 15 mm, it offers the lowest steady-state error.

Afterwards, the tuning gains of K_i are determined by assigning K_p value of 15 mm, and K_d remain the same, which is 0. The selected value for the tuning parameter K_i in Table 3.3 is 0.28 mm. The variations in steady-state error during the tuning process of K_d can be documented in Table 3.4. Any tuning beyond 0.11 results in an escalation of the steady-state inaccuracy and unstable system.

3.6.2 Nonlinear PID Controller

The NPID controller is an improved version of the conventional PID controller, designed specifically for improving the efficiency of pneumatic positioning systems. This controller modifies the traditional PID control method to more effectively control the nonlinearities present in pneumatic systems. The NPID controller includes a non-linear gain to overcome the limitations of the conventional PID. Implementing a significantly high gain to achieve a rapid response can result in overshooting. The inclusion of a nonlinear gain in the control system prevents the overshoot by altering the control action in response to the rate at which the error is changing. The general transfer function of the PID controller is shown in Equation 3.8:

$$G_{pid}\,(s) = K_p + \frac{K_i}{s} + K_d\,s \qquad (3.8)$$

where K_p, K_i and K_d are the gain values for proportional (P), Integral (I) and Derivative (D) components of the controller (Li et al., 2006, Padhan and Majhi, 2012). After tuning the parameters for K_p, K_i and K_d for the PID controller, an additional two tuning parameters are needed to create the NPID controller, which are e_{max} and KO. KO is the rate of variation for the nonlinear gain, while e_{max} is the maximum value of error. Equation 4.6 captures the overall representation of the NPID controller. Figure 3.17 illustrates the structure of the NPID controller.

$$NPID\ transfer\ function, G_{npid}(s) = \left[K_p\,.\ K_e\right] + \left[\frac{K_i}{s}\,.K_e\right] + \left[K_d S.K_e\right] \qquad (4.6)$$

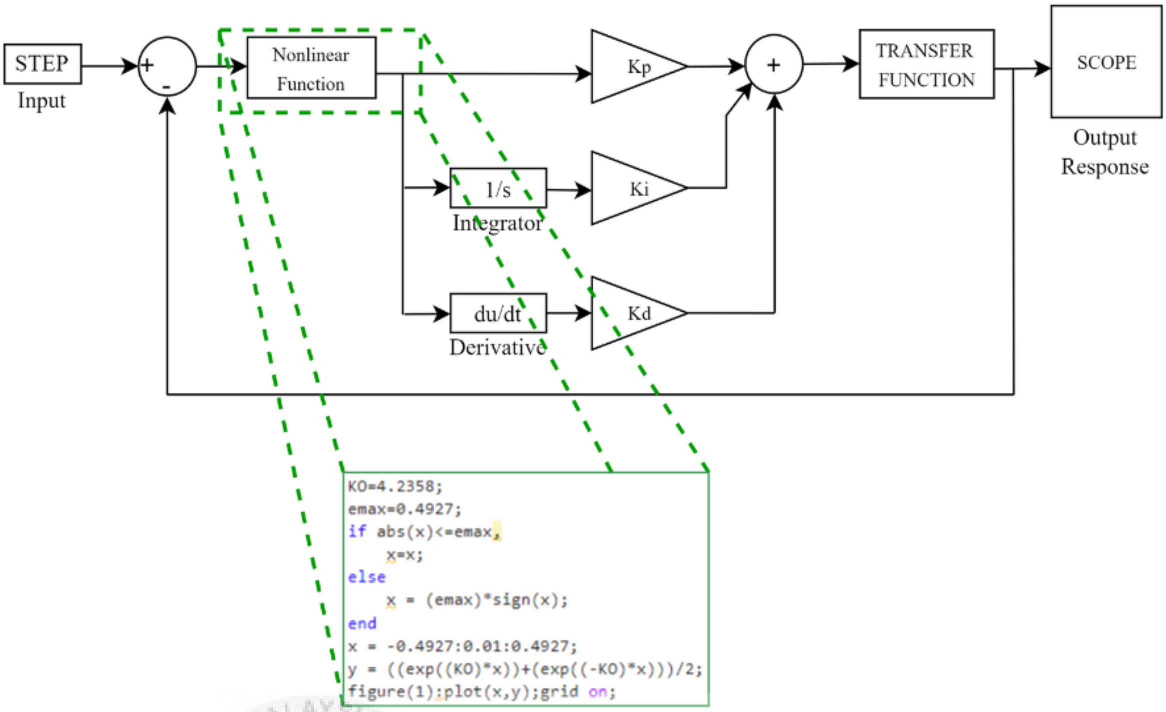

Figure 3.17: Structure of NPID Controller

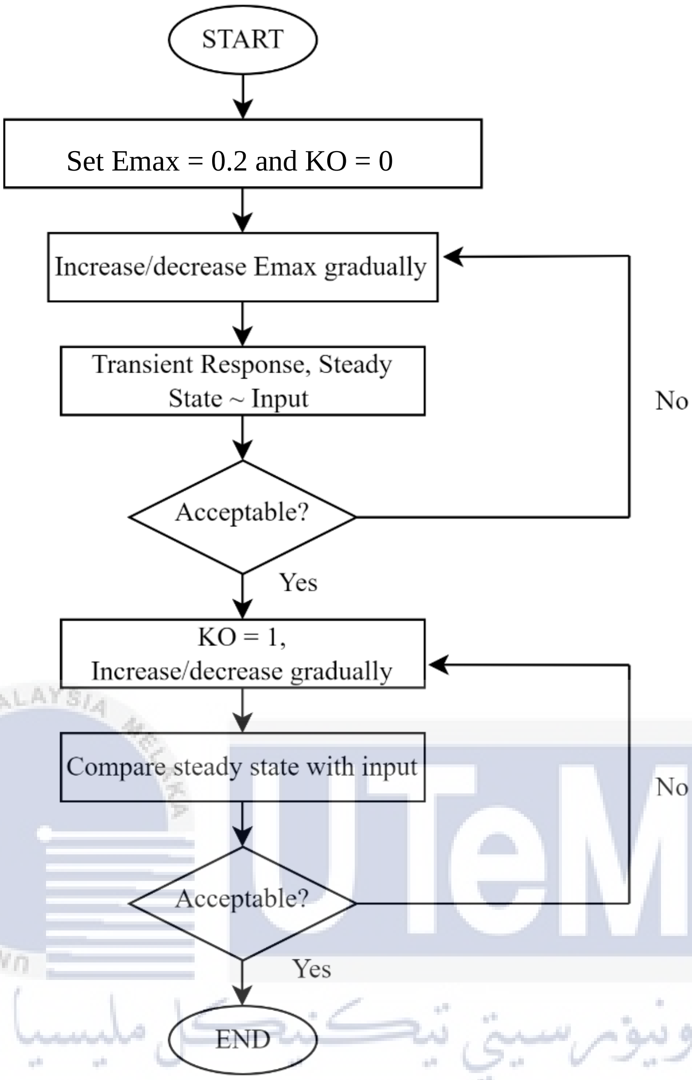

Figure 3.18: Tuning Flowchart NPID Controller

The flowchart shows the steps that control the system's response to an input by modifying the e_{max} and KO gains of the NPID controller. This controller only alters those parameters with the same value of K_p, K_i and K_d that were gained after tuning the PID controller. Eventually, by repeatedly altering the e_{max} and KO gains until the system's response matches the desired input, the flowchart can be used as a guide to be tuning the NPID controller.

Table 3.5 shows the simulation for NPID controller data value of tuning the gain parameter for e_{max} and KO. The parameter K_p is 15, K_i is 0.28 and K_d is 0.11. The parameter of K_p, K_i and K_d remain constant from the previous simulation of a PID controller. KO and e_{max} are tuned using a heuristic approach based on Popov stability criterion (Seraji, 1998).

Table 3.5: Simulation Tuning of e_{max} with a Constant Value of KO = 4.24

e_{max}	Steady-State (mm)	Steady-State Error (mm)
1.0	88.65	-8.65
0.9	86.26	-6.26
0.8	84.21	-4.21
0.7	82.34	-2.34
0.6	81.07	-1.07
0.5	79.39	0.61
0.4	78.78	1.22
0.3	77.42	2.58
0.2	76.43	3.58

Table 3.6: Simulation Tuning of KO with a Constant Value of e_{max} = 0.5

KO	Steady-State (mm)	Steady-State Error (mm)
1.0	73.25	6.75
1.5	74.11	5.89
2.0	74.56	5.44
2.5	72.02	7.98
3.0	74.65	5.35
3.5	72.38	7.62
4.0	78.89	1.17
4.10	76.14	3.86
4.20	77.93	2.07
4.21	78.24	1.76
4.22	79.12	0.88
4.23	79.01	0.99
4.24	79.74	0.25
4.25	80.67	-0.67
4.26	81.13	-1.13
4.27	81.18	-1.18
4.30	82.88	-2.88

According to (M. F. Rahmat, 2012), the value of KO is often tuned after tuning the value of e_{max}. The procedure of determining the proper tuning gains during simulation for the NPID controller utilizes the flowchart shown in Figure 3.18. The following flow chart illustrates the steps involved in altering the e_{max} and KO gains. Based on the tuning result shown in Table 3.6, the KO value is 4.24 by assigning the e_{max} value of 1.0. When KO values are exceeding 4.24, which will increase the steady-state error (SSE) value. Subsequently, the e_{max} value is set to 0.5 when KO is 4.24. When increasing or decreasing the e_{max} value of 0.5, the SSE value will become greater. Figures 3.19 show how nonlinear gain K_e and different errors, e, relate to one another. The Figures clearly show that K_e is exponentially proportional to the error, e. The value of the nonlinear gain, K_e, increases rapidly in parallel with the error, e. Furthermore, since the nonlinear gain K_e equals 1, the controller functions as a linear PID controller when an error, e, is 0. This indicates the nonlinear gain, K_e will function only in the presence of errors. Figure 3.19 illustrates the graph of nonlinear gain, K_e against error, e.

Figure 3.19: Graph of Nonlinear Gain, K_e against error, e

3.6.3 Cascade Controller

A positioning system that combines proportional and proportional-integral control in a two-level structure is a control system architecture known as a Cascade controller. This configuration has two layered control loops which are an inner loop for controlling velocity and an outer loop for controlling position. These loops are utilized to control the position of a system accurately, for instance, a motor or an actuator. For this scenario, an outside position control loop employs a Proportional-Integral (PI) controller, while an inner velocity control loop employs a Proportional (P) controller. To accomplish the ideal efficiency, responsiveness and stability, it is essential to calibrate the Cascade controller of a positioning system. Besides, when the system is properly calibrated, it is able to precisely track the required position while maintaining optimal control over velocity. However, the modification of the Cascade controller includes adding the value of K_d following to K_p, while maintaining K_i at 0.

To obtain a desirable transient response and a steady-state output with minimum error, it is vital to fine-tune the PK_p, PK_i, VK_p, and VK_i values for the four blocks of the Cascade controller. Determining the values of K_p, K_i and K_d is challenging due to the significant nonlinearity displayed by the system. Therefore, the values of K_p, K_i and K_d are determined through a systematic process of heuristic method, which is now utilized in the industry. The diagram in Figure 3.20 shows the display of the Cascade Simulink block diagram. Figure 3.21 illustrates the tuning approach applied for the Cascade controller.

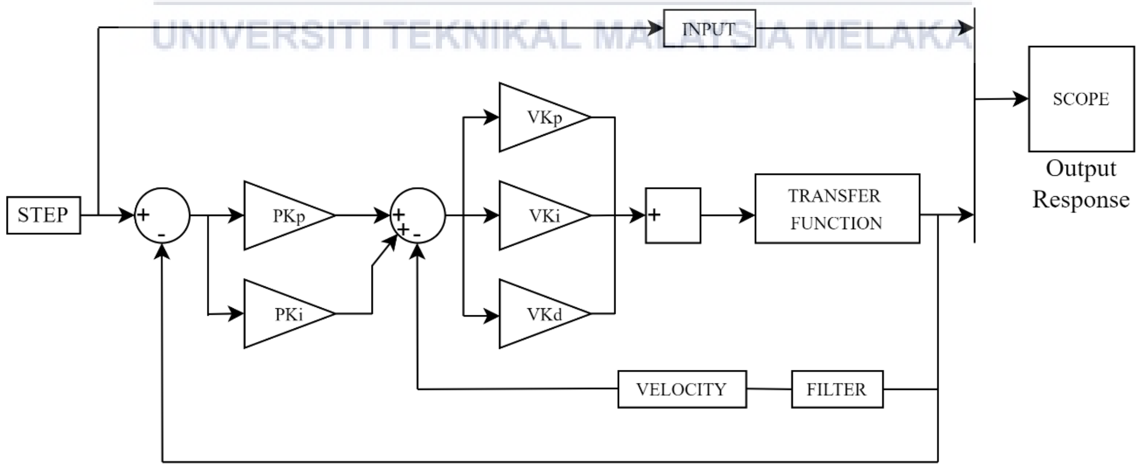

Figure 3.20: Structure of Cascade Controller

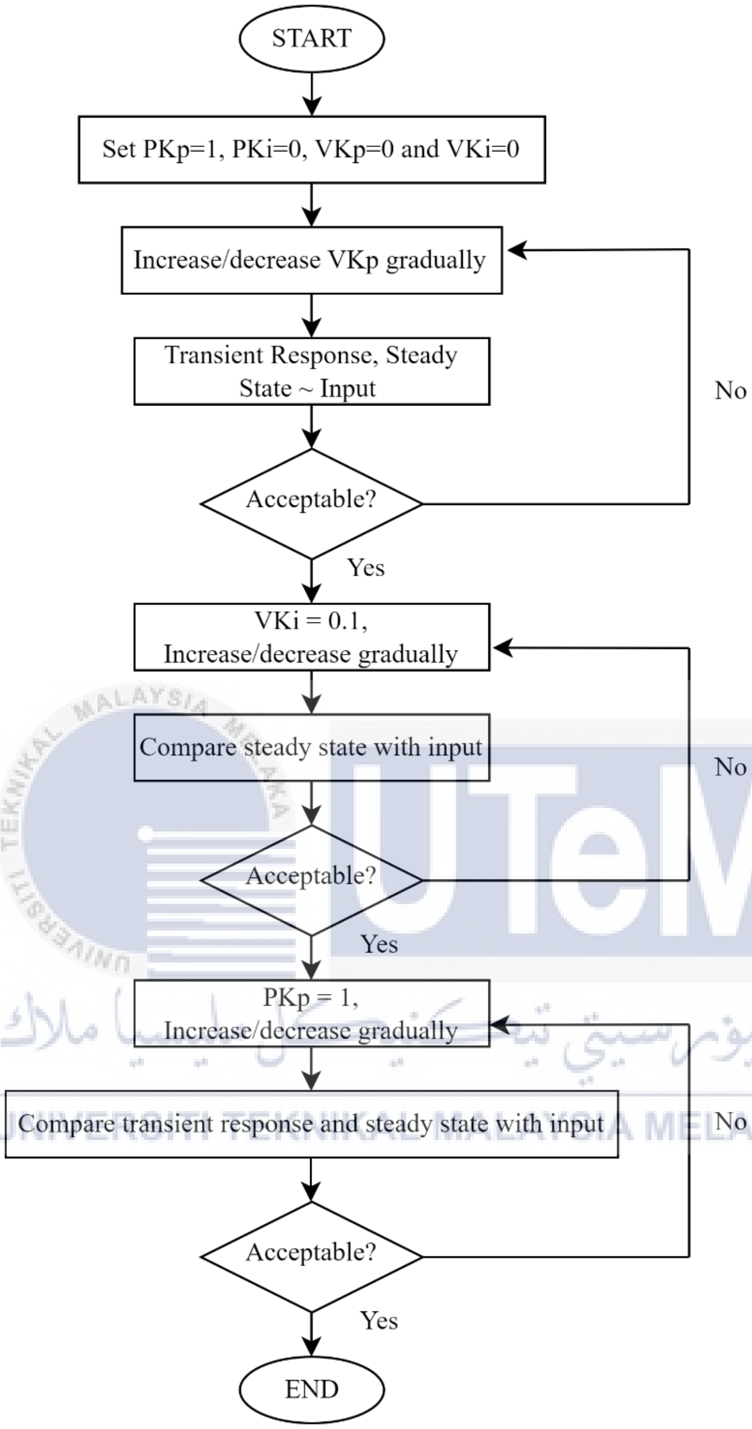

Figure 3.21: Tunning Flowchart Cascade PID Controller

The Flowchart shows steps that control the system's response to an input by modifying the gain parameter of PK_p, PK_i, VK_p, and VK_i of the Cascade controller. Plus, the PK_p, VK_p and VK_i gains define how much the controller considers the present error, cumulative error over time, and the rate of the error change, correspondingly. Ultimately, by repeatedly altering all those gains until the system's response matches the desired input, the flowchart can be used as a guide to tune a Cascade controller. Table 3.7 demonstrates the Cascade controller data value of tuning the gain parameter for VK_p, VK_i, PK_p, and PK_i by using the heuristic method.

Table 3.7: Simulation Tuning of VK_p with a Constant Value VK_i and PK_i=0, PK_p=1

VK_p	Steady-State (mm)	Steady-State Error (mm)
0.5	74.70	5.29
1.0	77.51	2.49
1.5	78.96	1.04
2.0	80.78	-0.78
2.5	81.58	-1.58
3.0	81.81	-1.81

Table 3.8: Simulation Tuning of Tuning VK_i with a Constant Value of VK_p=2, PK_p=1, PK_i=0

VK_i	Steady-State (mm)	Steady-State Error (mm)
0.1	78.68	1.40
0.2	79.15	0.85
0.3	80.74	-0.74
0.4	81.01	-1.01
0.5	82.72	-2.72
0.6	84.11	-4.11

Table 3.9: Simulation Tuning of PK_p with a Constant Value of VK_p = 2, VK_i = 0.3, PK_i=0

PK_p	Steady-State (mm)	Steady-State Error (mm)
1.0	80.69	-0.69
1.5	82.16	-2.16
2.0	85.94	-5.94
2.5	88.84	-8.84
3.0	89.43	-9.43

Table 3.10: Simulation Tuning of PK_i with a Constant Value of VK_p = 2, VK_i = 0.3, PK_p=1

PK_i	Steady-State (mm)	Steady-State Error (mm)
0	80.69	-0.69
0.1	86.83	-6.83
0.2	87.83	-7.83
0.3	89.43	-9.43

The Flowchart shown in Figure 3.21 is used to determine the proper tuning gains for the Cascade controller during simulation. The steps necessary to tune the VK_p, VKi, PK_p, and PK_i gains are shown in this flowchart. Setting PK_p to 1, VK_i to 0, and PK_i to 0 establishes the initial tuning gains of VK_p. In Table 3.7, the VK_p tuning parameter has a chosen value of 2.0. This happens as a result of the tuning increasing the SSE value beyond 2.0.

Following that a VK_p value of 2.0, PK_p value of 1, PK_i, and VK_d value of 0 is assigned to calculate the tuning gains of VK_i. In Table 3.8, the tuning parameter VK_i has a selected value of 0.3. Table 3.8 describes the alterations in steady-state error that occurred during the VK_i tuning process. Increases in tuning above 0.3 lead to an increase in the steady-state error. Consequently, VK_i = 4.1 is chosen due to its small steady-state error.

The PK_p tuning is achieved by assigning the values VK_p = 2.0, VKi = 0.3, and VK_d = 0 and PK_i = 0. The selected value for the tuning parameter PK_p in Table 3.9 is 1.0. Setting the proportional gain PK_p to a value greater than 1.0 results in an elevation of the steady-state error.

Afterwards, tuning the parameter PK_i where VK_p = 2.0, VK_i = 0.3, and VK_d = 0 and PK_p = 1. The selected value for the tuning parameter PK_i in Table 3.10 is 0. If the value of PK_i is increased, the steady state will become higher.

Since the derivative gain K_d is usually used in the outer loop of a Cascade P-PI control system to control the desired value of the inner loop, the value of VK_d = 0 stays constant. To swiftly alter the procedure, the inner loop mainly involves the use of integral and proportional terms. Conversely, the outer loop's derivative action is more sensitive to larger changes and doesn't need to be adjusted as carefully as the inner loop. This is because the stable and highly tuned inner loop significantly increases the stability of the outside loop, whereas the outer loop responds to system changes more slowly. Therefore, although it is important to pay attention to K_d in the outer loop, its tuning may be less crucial compared to the parameters of the inner loop to achieve optimal control system performance.

3.7 Summary

The related research approach is discussed and covered in this chapter. The model of the system is acquired through MATLAB/Simulink software's System Identification Toolbox. The model fits are 91.02% which is above 90%. Insert the transfer function to run the simulation of each controller. The design will be analyzed and validated through experiments. An effective controller's design is essential to achieve precise positioning.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will discuss the simulation results of the controller based on a specific set of inputs. The measured parameters are steady state and transient response. The input signal that specifies the desired output, the system's unit conversion, the simulation and experimental results gathered through four different designed controllers which are the Proportional-Derivative-Integral (PID) controller, the Nonlinear Proportional-Derivative-Integral (NPID) controller, the NPID with PSO controller and the Cascade controller are emphasized in this chapter. Every controller underwent two different kinds of analyses. Firstly, precise positioning analysis and secondly, transient response analysis. Additionally, four main sections are used to present and discuss the results of the simulated and experimental works: results of the PID controller, results of the NPID controller, results of the NPID with PSO controller, results of the Cascade controller, and comparisons of the four designed controllers' precise positioning and transient response analysis.

The input signal for the simulation and experimental tests is shown in the first section. The pneumatic system's unit conversion for positioning measurements is shown in the second section. The next part then displays the controllers' overall tuning. In addition, positioning analysis and transient response analysis results for each of the modified controller are shown in the next three sections, respectively. Eventually, the comparison of three controllers will be addressed in terms of positioning analysis, and transient response analysis in the final section.

4.2 Input Signal

This section focused on the application of an input signal for the four specified controllers which are PID controller, NPID controller, NPID with PSO controller and Cascade controller. The performance of the four proposed controllers was tested using a step form generated by the signal generator in MATLAB Simulink. By comparing the input to the actual output, the control system verifies the positioning performance. The input is considered as the desired output. The step input was defined by two parameters which are the step time and voltage. Figure 4.1 illustrates the step input block setup. With a sample time of 0.01 seconds, the positioning evaluation took 35 seconds in total. The initial value is used for coordinating the actuator with the centre point of the system before the step time. Thus, the analysis will be performed during the 20th second of the total time test period. The input signal's pattern is displayed in Figure 4.2, while the specific details of the input signal are presented in Table 4.1.

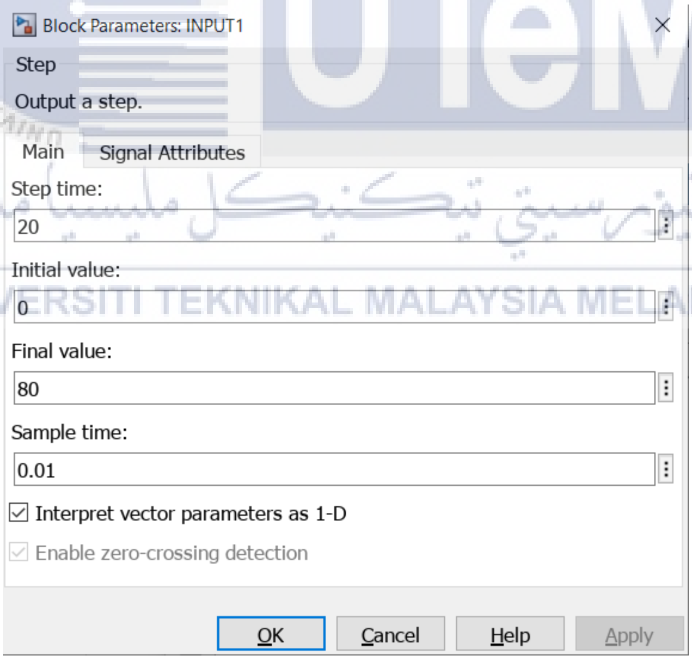

Figure 4.1: Step Input Block Setup

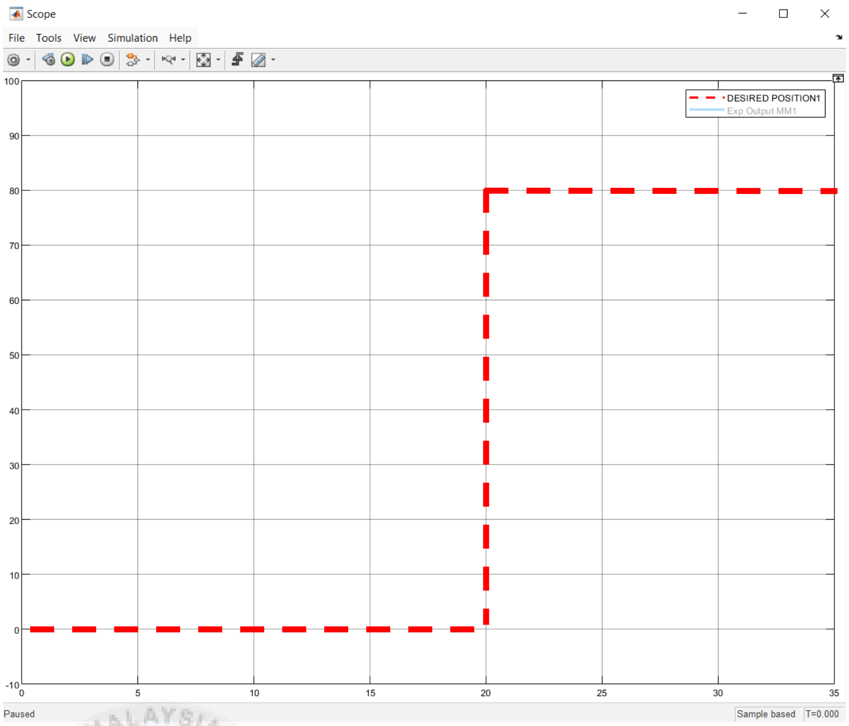

Figure 4.2: Pattern of the Input Signal

Table 4.1: Details of Input Signal

INPUT SIGNAL	
Type of Input Signal	Step Input
Total Time Taken (sec)	15
Sample Time (sec)	0.01
Step Time (sec)	20
Stroke Input (mm)	80

4.3 Unit Conversion

The unit and its conversion were addressed in this section. The pneumatic system's input is set up in voltage units, whereas the system can measure displacement in displacement units for positioning. Furthermore, the hardware configuration includes an encoder for positioning analysis in voltage, which must be converted to displacement units as detailed on the actuator's data sheet's second page, which is attached in Appendix A. Hence, manual derivatives were used to convert the units. There were four different units of displacement which are millimetres, centimetres, metres, and kilometres. Since the system's displacement range is lower, the millimetre was selected as the unit of measurement for this project. For the unit conversion process, the Enfield Technology pneumatic actuator model ACTB-200-s01200 parameters listed in Table 4.2 of the system were considered (Kamarudin et al., 2018). Appendix B contained the pneumatic actuator's specification document. Table 4.2 contains the pneumatic actuator's specifications.

Table 4.2: Specification of the Pneumatic Actuator

Specification of the Pneumatic Actuator	
Total Voltage of Actuator	10 V
Total Distance of Actuator	12 inches

Therefore, a conversion equation for the system was generated using the specifications. From Equation 4.1 to Equation 4.3, the conversion of the unit of measurement was continuously converted from voltage (V) to millimetres (mm).

$$10\ \text{V} = 304.8\ \text{mm} \tag{4.1}$$

$$1\ \text{V} = \frac{304.8\ mm}{10\ V} \tag{4.2}$$

$$x\ \text{V} = x\ V\left(\frac{304.8\ mm}{10\ V}\right) \tag{4.3}$$

4.4 System Stability Analysis

The consideration of stability in control systems is an essential element of control engineering, particularly when considering Nonlinear PID controllers. Moreover, it is a graphical representation of a function, W(jω), shown on the complex plane. The transfer functions of the control system's nonlinear element (N(s)) and linear portion (G(s)) are used to generate this function. The system's stability is evaluated by analysing the location of the Popov plot in relation to a designated reference line. The Popov criterion states that the system is stable if the entire plot is located to the right or below the line (Seraji, 1998).

The Popov criterion is a graphic technique that establishes a condition for stability. It is sufficient but not essential. This indicates that a system that fails the Popov criterion is certain to be unstable, whereas a system that succeeds the criterion could still be unstable (A. Maddi & A. Guessoum and D. Berkani, 2014). Some other factors to take into account regarding the Popov Criterion are firstly, it may be used with a large range of nonlinearities, including memory-related ones. Next, it can be employed to examine systems that possess parameters that change over time. Thirdly, the implementation of this approach may result in significant computing costs, especially when dealing with complex systems. In general, the Popov criterion is an effective tool for evaluating the stability of control systems that contain nonlinear components, such as Nonlinear PID controllers.

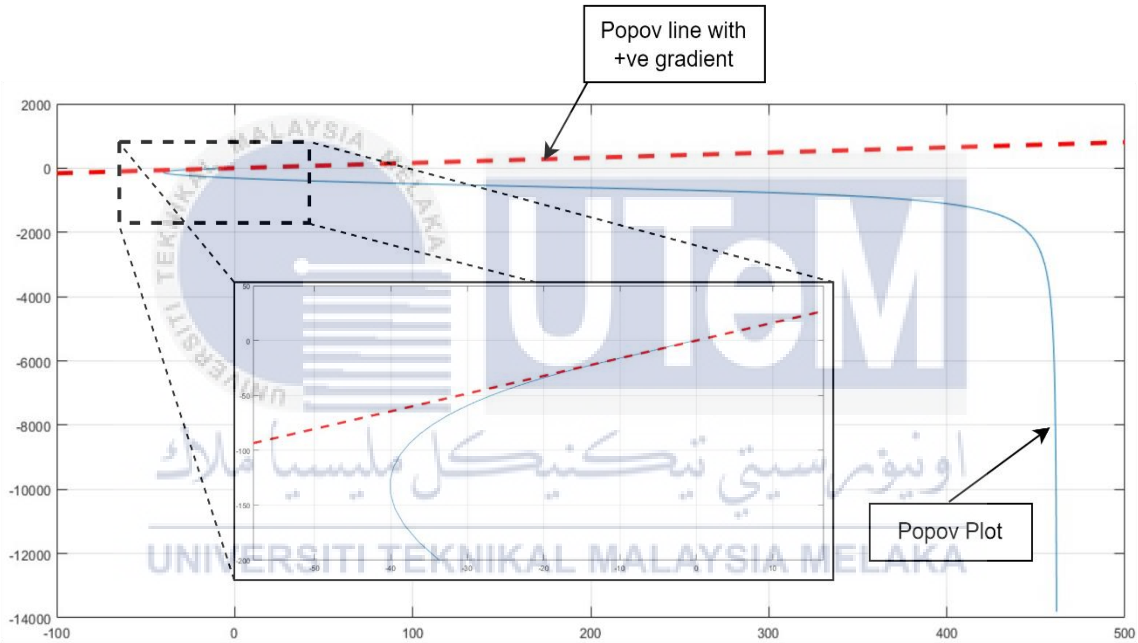

Figure 4.3: Stability Analysis Graph

Based on Figure 4.3, the system is considered stable because the Popov Plot (blue colour) lies below the Popov line (red colour). This shows that the transfer function and the gain parameter for the NPID controller is in stable state. The aim is to maintain traditional PID control's simplicity while adding nonlinear features to improve control performance (Seraji, n.d.).

4.5 Tunning Gains of Controller

Table 4.3 contains a list of the selected tuning parameters that were applied throughout the experimental phase. The gains of each controller were modified to allow a comparison between the simulation and the experimental graphs. This technique displays a minor difference between the simulation and the experimental graphs when applying identical gain values to a controller.

Table 4.3: Experimental Tuning Gains of Controllers

Controller	Gains								
	K_p	K_i	K_d	e_{max}	KO	PK_p	PK_i	VK_p	VK_i
PID	15	0.28	0.11	-	-	-	-	-	-
NPID	15	0.28	0.11	0.50	4.24	-	-	-	-
NPID with PSO	15	0.28	0.11	0.49273	4.235773	-	-	-	-
CASCADE	-	-	-	-	-	1.0	0	2.0	0.3

4.6 Positioning and Transient Response Analysis

Positioning Analysis involves assessing and improving how accurately a pneumatic system can reach and maintain a desired position. Pneumatic systems utilize compressed air to create motion and are commonly used in industrial automation because of its simpleness and dependability.

Transient response analysis is essential in evaluating the functionality of control systems. It describes how a system behaves when it moves from one state to another, especially after a disturbance or setpoint change, from an initial state to a desired final state. Important parameters in transient response analysis are rise time, settling time, peak time, and overshoot. Studying and optimizing these characteristics is critical for designing an effective controller. Plus, transient response analysis is crucial for designing and evaluating control systems. Different controllers have varying transient response characteristics, with NPID controllers and optimization approaches like PSO showing significant promise in increasing system performance (Haeri, M., & Farzanehfard, M. R., 2002).

Moreover, the simulation entails constructing a virtual representation of the pneumatic system to anticipate its performance under different circumstances. This includes modelling, control algorithms and software tools. For modelling, creating mathematical representations of system components such as cylinders, valves, sensors, and others. Next, control algorithms implement and test different control strategies like PID, NPID, NPID with PSO and Cascade. The software tools for utilizing the simulation are MATLAB/Simulink software.

When it comes to experimental, it involves real-world testing of the pneumatic system to validate and refine the control strategies. This includes machine setup, sensors and actuators, data collection and validation. Building a physical system with all the necessary components is essential for machine setup. In order to measure the position, use the sensors and actuators to adjust it. Afterward, recording the system's response to various inputs is vital in data collection. In the end, to validate the designed controller, comparing experimental results with simulation to identify discrepancies and refine models.

Both simulation and experimental approaches are crucial for effective positioning control in pneumatic systems. Simulation allows for extensive testing and development with minimal risk, while experimental validation ensures that the system performs reliably in real-world conditions. Together, it will enable the development of robust and precise control systems for pneumatic applications.

4.6.1 PID Controller

PID Controller is a basic and benchmark controller for positioning control of the pneumatic system. The simulation and experimental results of precise positioning analysis and transient response analysis for the PID controller are presented in the Tables 4.4 and 4.5. The graph shows the comparison between simulation and experimental illustrated in Figure 4.4.

Table 4.4: Positioning Analysis of PID Controller

Performance Parameter	Simulation	Experimental
Desired Output (mm)	80.00	80.00
Actual Output (mm)	79.46	80.71
Steady-State Error, SSE (mm)	0.538	0.706
% Steady-State Error, SSE (%)	0.673	0.883

Table 4.5: Transient Response Analysis of PID Controller

Performance Parameter	Simulation	Experimental
Rise Time, Tr (sec)	0.851	1.463
Maximum Overshoot, Cmax (mm)	14.965	0
% Overshoot, %OS (%)	18.706	0
Peak Time, Tp (sec)	1.388	0
Settling Time, Ts (sec)	4.844	7.15

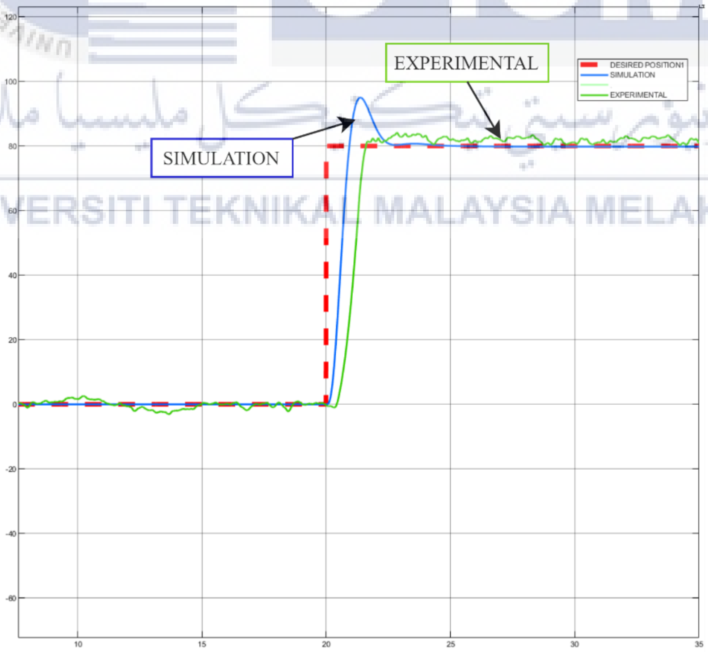

Figure 4.4: Step Response of Simulation and Experimental of PID

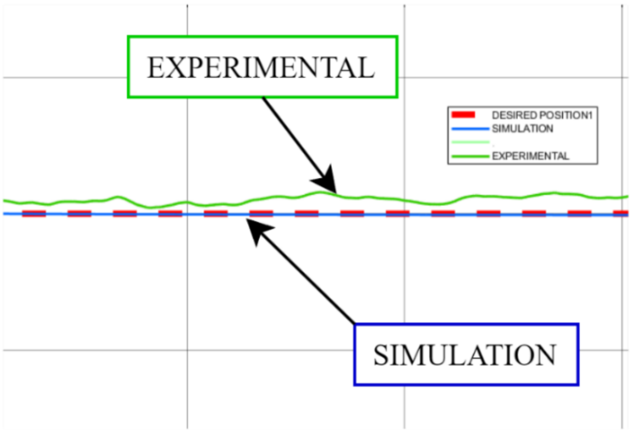

Figure 4.5: Close up Steady-State of PID

Based on the analysis data presented in Tables 4.4 and 4.5, the experimental results show a slightly higher steady-state error and a longer settling time compared to the simulation results. The experimental results also achieved zero overshoot, whereas the simulation results had a significant overshoot. There are two step responses in the graph, the blue colour represents the simulation results, and the green colour indicates the experimental results.

4.6.2 Nonlinear PID Controller

Tables 4.6 and 4.7 show the simulation and experimental results of the NPID controller's transient response analysis and precise positioning analysis. Figure 4.6 depicts a graph that compares simulation and experimental step response.

Table 4.6: Positioning Analysis of PID Controller

Performance Parameter	Simulation	Experimental
Desired Output (mm)	80.00	80.00
Actual Output (mm)	79.74	79.52
Steady-State Error, SSE (mm)	0.257	0.479
% Steady-State Error, SSE (%)	0.322	0.599

Table 4.7: Transient Response Analysis of PID Controller

Performance Parameter	Simulation	Experimental
Rise Time, Tr (sec)	0.844	1.124
Maximum Overshoot, Cmax (mm)	9.482	0
% Overshoot, OS (%)	11.852	0
Peak Time, Tp (sec)	1.229	0
Settling Time, Ts (sec)	4.618	3.480

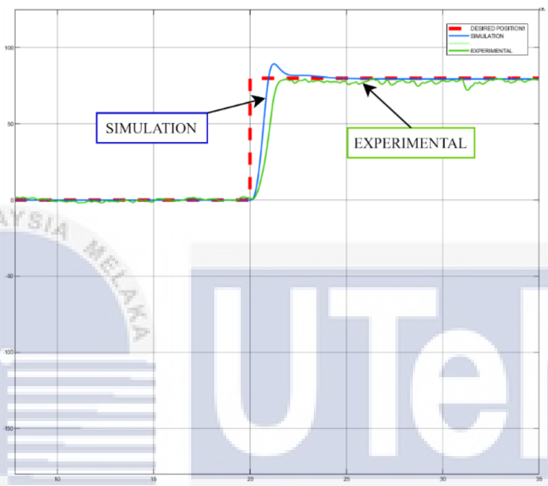

Figure 4.6: Step Response of Simulation and Experimental of NPID Controller

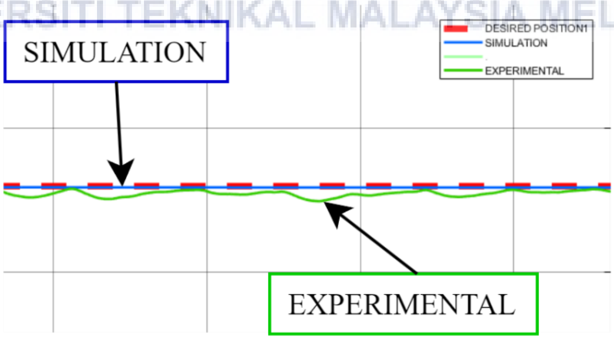

Figure 4.7: Close up Steady-State of NPID Controller

The experimental results indicate a somewhat larger steady-state inaccuracy and a short settling time compared to the simulation results, based on the analysis data displayed in Tables 4.6 and 4.7. While the simulation results showed a considerable overshoot, the experimental results likewise achieved 0% overshoot and peak time. The graph shows two step responses: the green colour indicates the experimental results, while the blue colour reflects the simulation results. The NPID controller with the nonlinear gain significantly improves transient response compared to the traditional PID. The pneumatic positioning system performs remarkably well, even under variable load conditions (Syed Salim et al., 2014).

4.6.3 NPID with PSO Controller

An optimization system named Particle Swarm Optimization (PSO) is inspired by the social behaviour of fish schools and flocks of birds (Kennedy, et.al.,1995). By continuously enhancing potential solutions in relation to a specified fitness or quality criterion, it is utilized to locate the most effective solutions in a search space. Combining the NPID controllers with PSO leads to an excellent control process where the capabilities of both systems are utilized. The main objective of PSO, in this case is to optimize the parameters of the NPID controller to obtain the optimal performance. The simulation and experimental findings of precise positioning analysis and transient response analysis for the NPID with PSO controller are shown in the Tables 4.8 and 4.9. The graph displays the disparity between simulation and experimental illustrated in Figure 4.8.

Table 4.8: Positioning Analysis of NPID with PSO Controller

Performance Parameter	Simulation	Experimental
Desired Output (mm)	80.00	80.00
Actual Output (mm)	80.18	80.36
Steady-State Error, SSE (mm)	0.179	0.361
% Steady-State Error, SSE (%)	0.224	0.452

Table 4.9: Transient Response Analysis of NPID with PSO Controller

Performance Parameter	Simulation	Experimental
Rise Time, Tr (sec)	0.508	0.889
Maximum Overshoot, Cmax (mm)	0	0
% Overshoot, %OS (%)	0	0
Peak Time, Tp (sec)	0	0
Settling Time, Ts (sec)	1.534	3.21

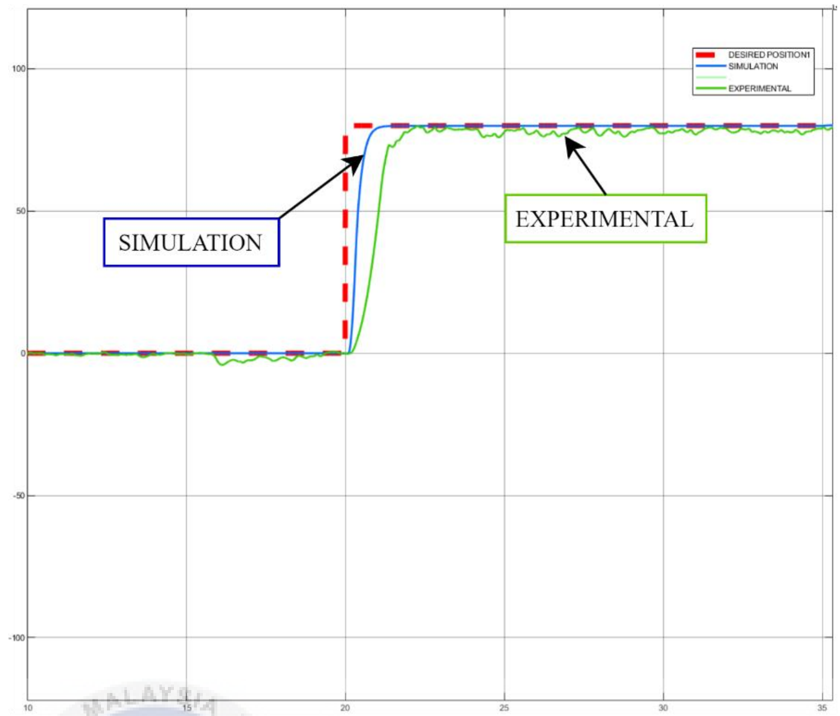

Figure 4.8: Step Response of Simulation and Experimental of NPID with PSO Controller

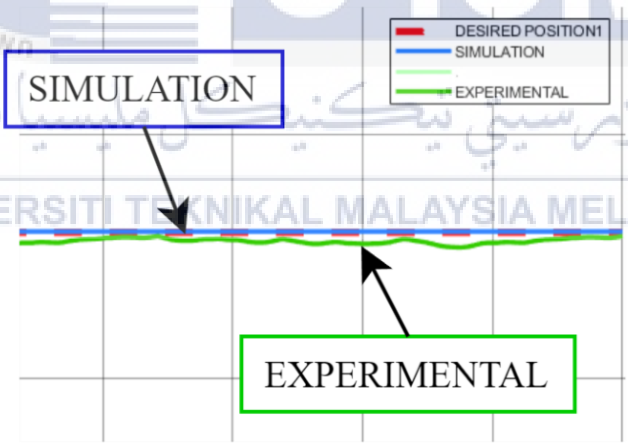

Figure 4.9: Close up Steady-State of NPID with PSO

The experimental results indicate a somewhat larger steady-state inaccuracy and a short settling time compared to the simulation results, based on the analysis data displayed in Tables 4.8 and 4.9. There was no overshoot in the experimental data either. However, there was a noticeable overshoot in the simulated results. The graph depicts two step responses in which the green colour indicates the experimental results, while the blue colour represents the simulation results. PSO draws inspiration from the collective behaviour of natural swarms. The fractional orders provide finer control over the system's dynamics, allowing for more precise tuning of the response (Muftah et al., 2022).

4.6.4 Cascade Controller

Cascade controller is just an additional controller to make a comparison between PID and NPID controller for steady state analysis and transient response analysis. The simulation and experimental results of the transient response analysis and precise positioning analysis of the NPID controller are displayed in Tables 4.10 and 4.11. A graph comparing the step response from simulation and experiment is shown in Figure 4.10.

Table 4.10: Positioning Analysis of Cascade Controller

Performance Parameter	Simulation	Experimental
Desired Output (mm)	80.00	80.00
Actual Output (mm)	80.69	79.30
Steady-State Error, SSE (mm)	0.689	0.697
% Steady-State Error, SSE (%)	0.861	0.872

Table 4.11: Transient Response Analysis of Cascade Controller

Performance Parameter	Simulation	Experimental
Rise Time, Tr (sec)	3.989	2.037
Maximum Overshoot, Cmax (mm)	10.278	0
% Overshoot, %OS (%)	12.847	0
Peak Time, Tp (sec)	7.791	0
Settling Time, Ts (sec)	15.979	10.242

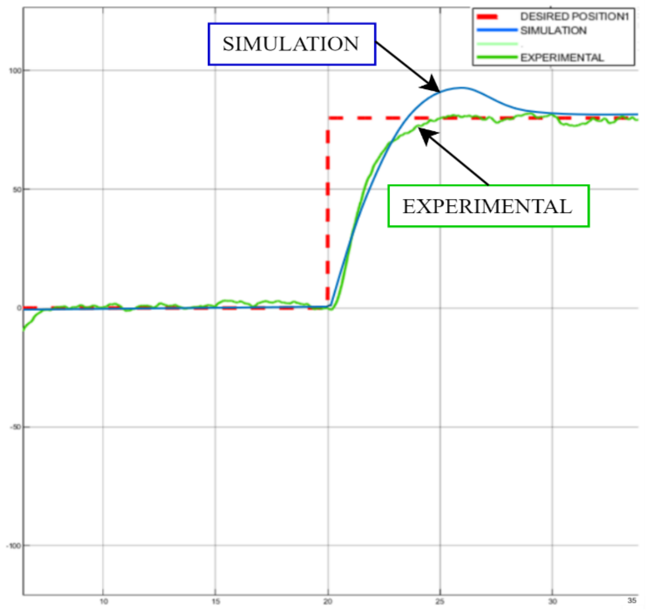

Figure 4.10: Step Response of Simulation and Experimental of Cascade Controller

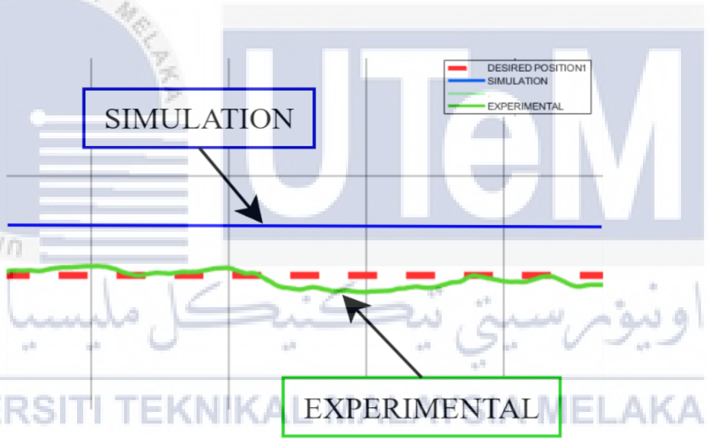

Figure 4.11: Close up Steady-State of Cascade Controller

Based on the analysis data presented in Tables 4.10 and 4.11, the experimental results show a slightly higher steady-state error and a long settling time. The outcomes of the experiment accomplished 0% overshoot and peak time, despite the simulated results displaying a significant overshoot. The graph illustrates two step responses. Firstly, the simulation results are represented in blue colour. Secondly, the experimental data are shown in green colour.

4.7 Simulation Comparison

The step input is applied to the compensated system. Figure 4.12 illustrates the simulation for both the steady-state and the transient response of all the controllers that were examined. Figure 4.14 shows a simulation result in a detailed view of all the controllers. There are four colours to differentiate each controller. Blue colour represents PID controller, green colour displays NPID controller, yellow colour indicates the Cascade controller and lastly, black colour represents NPID with PSO controller. The steady state is represented in Figure 4.13 in close up view meanwhile Figure 4.12 demonstrates the transient response performance of the controllers.

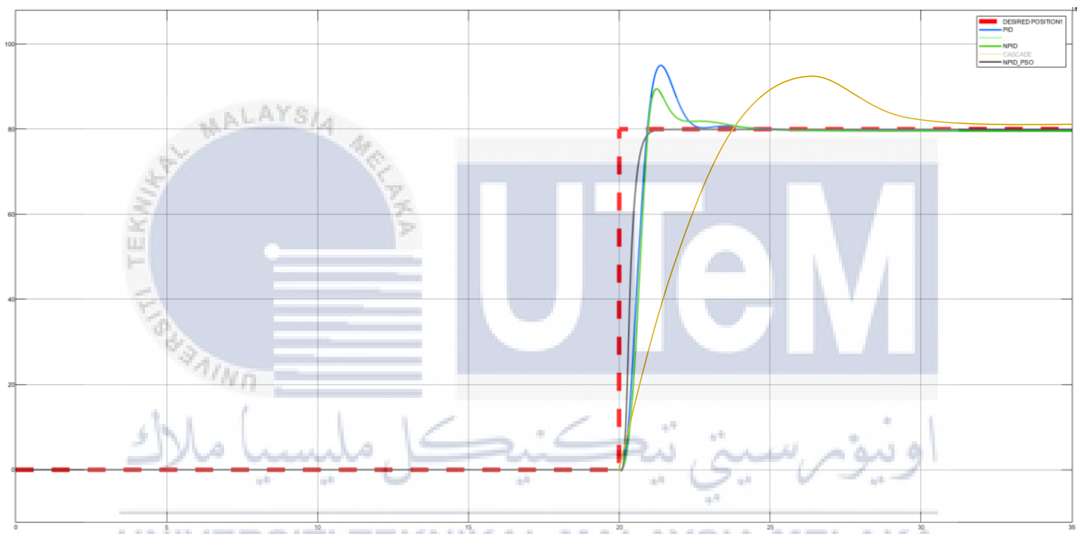

Figure 4.12: Simulation Graph for all Controllers

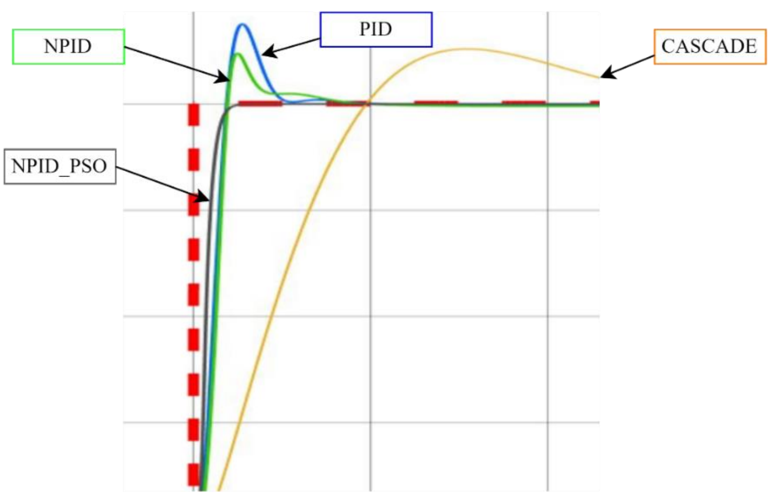

Figure 4.13: Close up Transient Response Performance

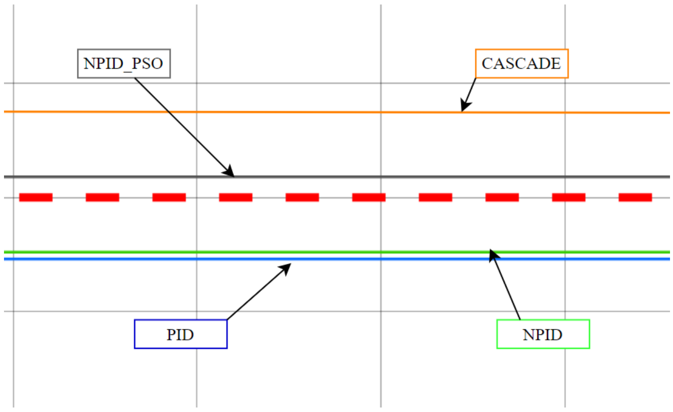

Figure 4.14: Close up Actual Position of all Controllers

Table 4.12 depicts the steady-state performance and the percentage of steady state error of PID, NPID, NPID with PSO and Cascade controller for simulation.

Table 4.12: Simulation Results of Steady-State Performance

Parameter	**CONTROLLER**			
	PID	**NPID**	**NPID with PSO**	**CASCADE**
Desired Output (mm)	80	80	80	80
Actual Output (mm)	79.46	79.74	80.18	80.69
Steady-State Error, SSE (mm)	0.538	0.2572	0.1795	0.689
% Steady-State Error, SSE (%)	0.673	0.322	0.224	0.861

The data displayed in Table 4.12, NPID with PSO, indicates higher steady-state performance during simulation configurations. The Cascade controller has the most steady-state inaccuracy. During the experiment, the Cascade controller offers better steady-state performance, even with a minor difference. Table 4.13 illustrates the transient response performance of all the controllers for simulation.

Table 4.13: Simulation Results of Transient Response Performance

Parameter	**TRANSIENT RESPONSE PERFORMANCE**			
	PID	**NPID**	**NPID with PSO**	**CASCADE**
Rise Time, Tr (seconds)	0.851	0.844	0.508	3.989
Maximum Overshoot, Cmax (mm)	14.965	9.482	0	10.278
Percentage Overshoot, %OS (%)	18.7063	11.8525	0	12.8475

Peak Time, Tp (seconds)	1.388	1.229	0	7.791
Settling Time, Ts (seconds)	4.844	4.618	1.534	15.979

The transient response of all the controllers can be validated in Figure 4.13 Compared to the other controllers, the PID controller demonstrates the largest overshoot, both in terms of percentage overshoot and maximum overshoot.

4.8 Experimental Comparison

This section focusses on the comparison of experimental results for PID, NPID, NPID with PSO and Cascade controller. Figure 4.15 displays both the steady state and transient response performance. It also shows a detailed view of transitory reaction. The colour of each controller remains same as simulation. The acquired data exhibits noticeable "noise" in comparison to the simulation, primarily caused by the encoders' noise and external or internal disturbances affecting the actual plant.

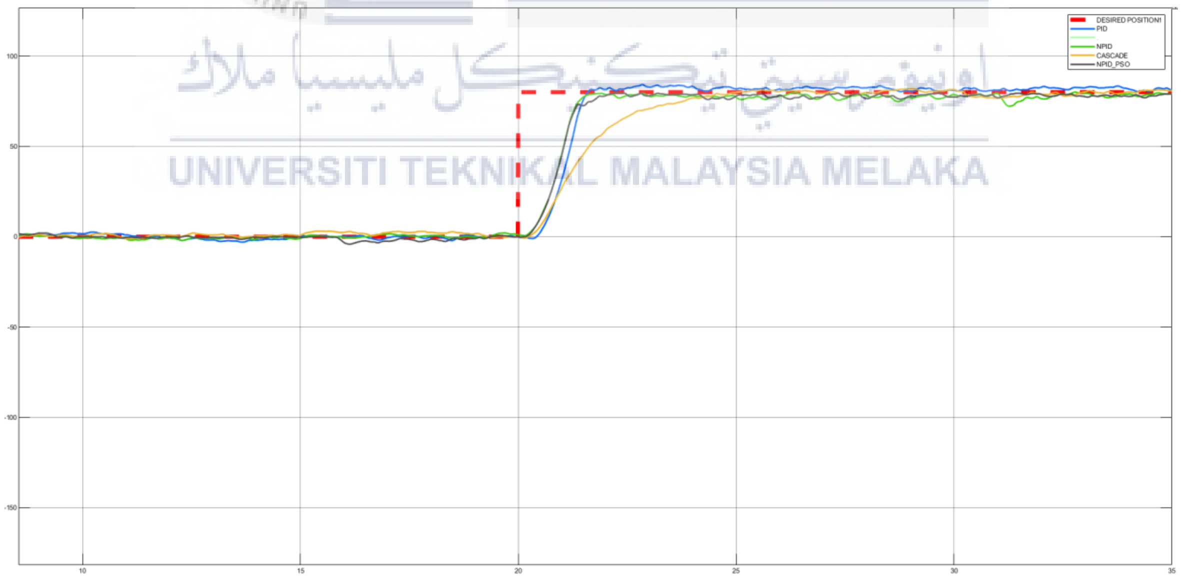

Figure 4.15: Experimental Results of All Controllers

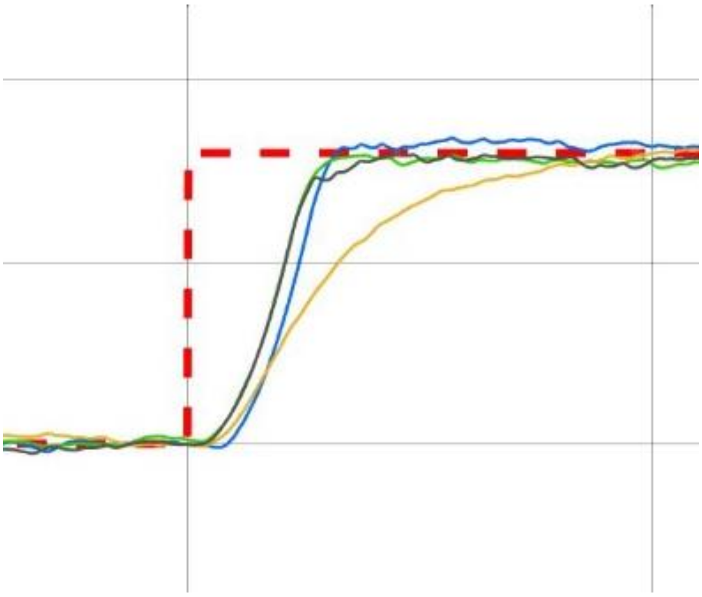

Figure 4.16: Close up Experimental Transient Response Performance

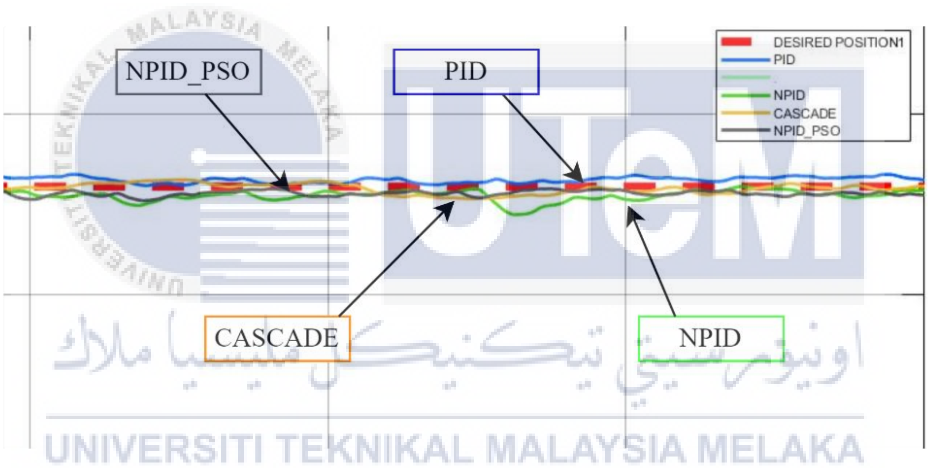

Figure 4.17: Close up Actual Position of all Controllers

Figure 4.16 demonstrates that all the controllers have a similar transient reaction in comparison to one another except for the Cascade controller. The NPID with PSO controller exhibits superior transient response compared to the other controllers, followed by the NPID controller, PID controller and lastly Cascade controller. The settling time appears to be slightly degraded, but it is expected that the steady-state inaccuracy will improve. Figure 4.17 illustrates the actual output in relation to the desired output. All al of the controllers shows the steady state is nearly close to the desired output during the experimental. During the experiment, NPID with PSO appears to be the finest controller in terms of steady state, resulting in more favourable steady state conditions. The data is organized and presented in Table 4.14.

Table 4.14: Experimental Results of Steady-State Performance

Parameter	**Controller**			
	PID	**NPID**	**NPID with PSO**	**CASCADE**
Desired Output (mm)	80	80	80	80
Actual Output (mm)	80.71	79.52	80.36	79.3
Steady-State Error, SSE (mm)	0.7065	0.4792	0.3613	0.6979
% Steady-State Error, SSE (%)	0.883	0.599	0.452	0.872

The NPID with PSO controllers exhibited outstanding steady-state performance, achieving the lowest percentage of steady-state error. The Cascade controller demonstrates marginally lower steady-state performance in comparison to the other three controllers. Table 4.15 shows the transient response analysis for all controllers.

Table 4.15: Experimental Results of Transient Response Performance

Parameter	**Transient Response Performance**			
	PID	**NPID**	**NPID with PSO**	**CASCADE**
Rise Time, Tr (seconds)	1.463	1.124	0.889	2.037
Maximum Overshoot, Cmax (mm)	0	0	0	0
Percentage Overshoot, %OS (%)	0	0	0	0
Peak Time, Tp (seconds)	0	0	0	0
Settling Time, Ts (seconds)	7.15	3.48	3.21	10.242

The result shows that there is no overshoot and peak time for the experimental. Therefore, the percentage overshoot for all controllers is 0. NPID with PSO shows a greater transient response performance. The observation of the settling time of the nonlinear controllers is also conducted. The Cascade controller exhibits the most extended settling time, which is considered unfavourable in a system. During the simulation process, there is no disturbance or noise. This also can cause the percentage overshoot to be higher and lower settling time. Therefore, the speed of achieving the desired output is faster than during the experiment.

4.9 Discussion

In terms of simulation and experimental approaches, this section presents detailed evaluation results on the performance of PID, NPID, and NPID with PSO and Cascade controllers. The data comparison between the experimental and simulation shows a difference of more than 10%, as shown in Table 4.16. Disturbances that occur during experiments, whether internal or external, lead to discrepancies in results. The encoder produces a high level of noise. These changes impact the system's overshoot and steady-state error. In simulations, it is an ideal condition, where there are no disturbances, the system can operate smoothly, and the shortened settling time results in extreme overshoot. The percentage discrepancy between the results from the controllers' experiments and simulations is shown in Table 4.17. Equation 4.7 is used to compute the percentage difference between the simulation and experimental parameter values.

$$Percentage, \% = \left|\frac{Experiment - Simulation}{Simulation}\right| X\ 100 \qquad (4.7)$$

Table 4.16: Simulation and Experimental Data of each Controller

Parameter	Controllers							
	PID		NPID		NPID with PSO		CASCADE	
	Simulation	Experiment	Simulation	Experiment	Simulation	Experiment	Simulation	Experiment
Steady-state Error, SSE (mm)	0.538	0.707	0.257	0.479	0.179	0.361	0.689	0.698
% Steady-state Error	0.673	0.883	0.322	0.599	0.224	0.452	0.861	0.872
Rise Time, Tr (sec)	0.851	1.463	0.844	1.124	0.508	0.889	3.989	2.037
Settling Time, Ts(sec)	4.844	7.15	4.618	3.480	1.534	3.210	15.979	10.242
Max Overshoot (mm)	14.965	0	9.482	0	0	0	10.278	10.242

Table 4.17: Percentage Difference between Simulation and Experimental

Performance Parameter	Controller			
	PID	NPID	NPID with PSO	CASCADE
Steady-state Error, SSE (%)	31.41	86.38	101.68	1.31
Rise Time, Tr (%)	47.61	24.64	109.25	35.90
Settling Time, Ts (%)	71.92	33.18	42.86	48.93

In both simulation and experimental, NPID with PSO has better performance than the other controllers because of the combination with the PSO. The nonlinear function of the NPID that was optimized allows the enhancement of the controller producing a better performance in the final steady-state position. This approach exhibits more adaptivity in a controller to achieve the desired output. The percentage improved steady-state performance of all the controllers is presented in Figure 4.18 based on the data tabulated in Table 4.16. PID controller is a basic and benchmark controller for positioning control of a pneumatic system. Equation 4.8 demonstrates how to acquire the percentage improvement with respect to the PID controller.

$$Percentage\ Improvement\ (\%) = \left[\frac{Improved\ Value - Benchmark\ Value}{Benchmark\ Value}\right] \text{X } 100 \qquad (4.8)$$

Table 4.18: Percentage Improved of Steady-State Performance with Respect to PID Controller

Performance Parameter	NPID	NPID with PSO	CASCADE
Steady-State Error, SSE (%)	48.86	32.17	1.21

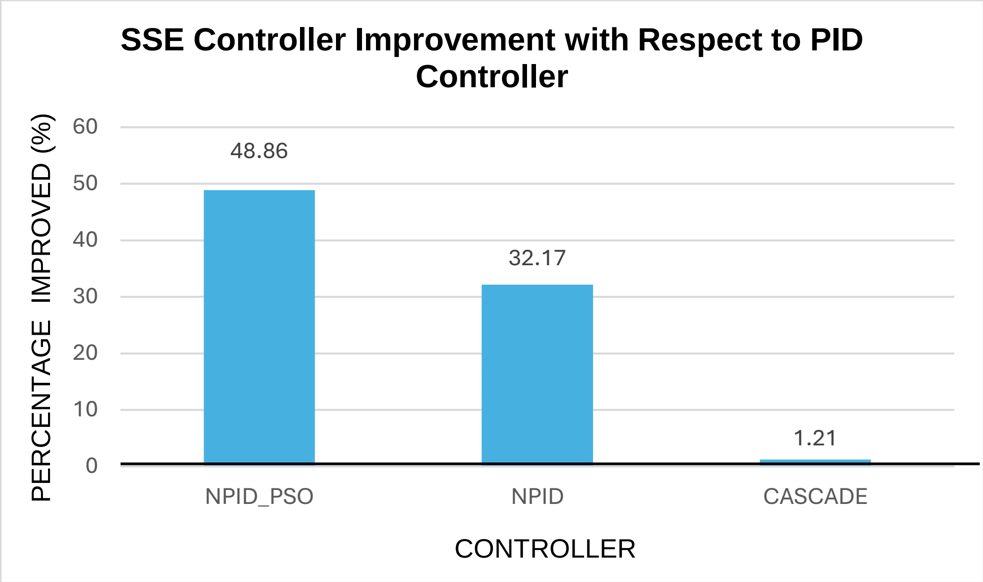

Figure 4.18: Percentage Improvement for SSE Controller

Based on the data above, as for steady-state performance, NPID with PSO has the highest percentage improvement which is 48.86%. This is followed by the NPID controller at 31.17%, and the smallest percentage improvement goes to the Cascade controller, at 1.21%. The percentage improvement of settling time and rise time with respect to the PID controller is presented in Figures 4.19 and 4.20 based on the calculated data in Table 4.19.

Table 4.19: Percentage Improved of Transient Response

Performance Parameter	NPID	NPID with PSO	CASCADE
Settling Time, Ts (%)	55.10	24.76	-43.24
Rise Time, Tr (%)	39.23	23.17	-39.23

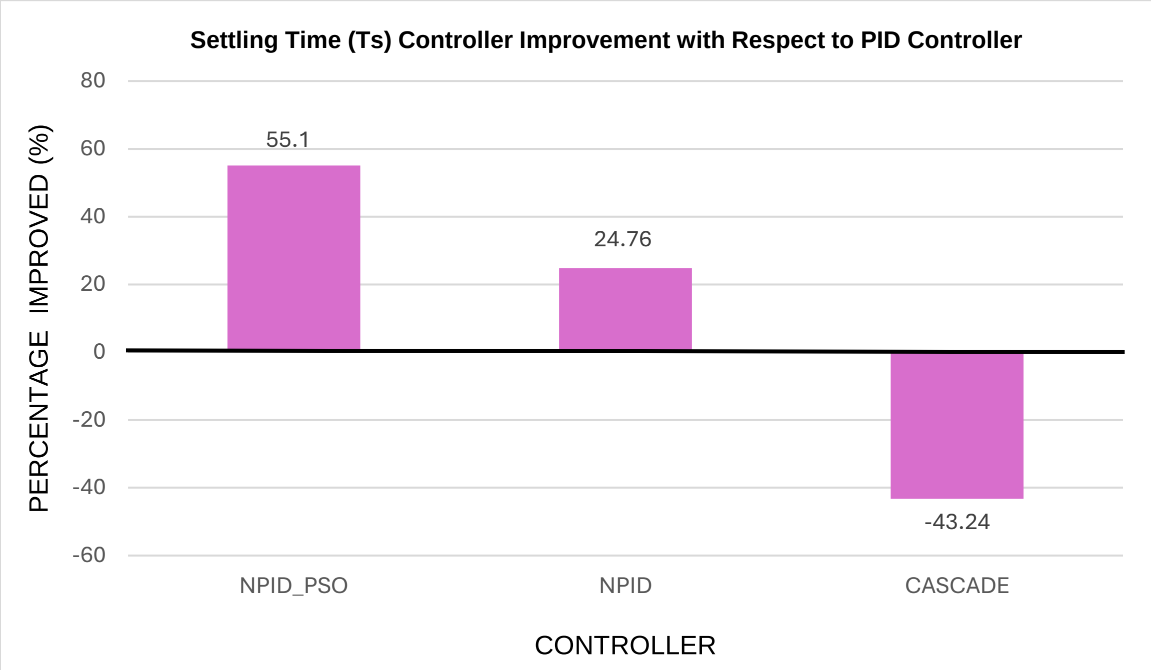

Figure 4.19: Percentage Improvement for SSE Controller

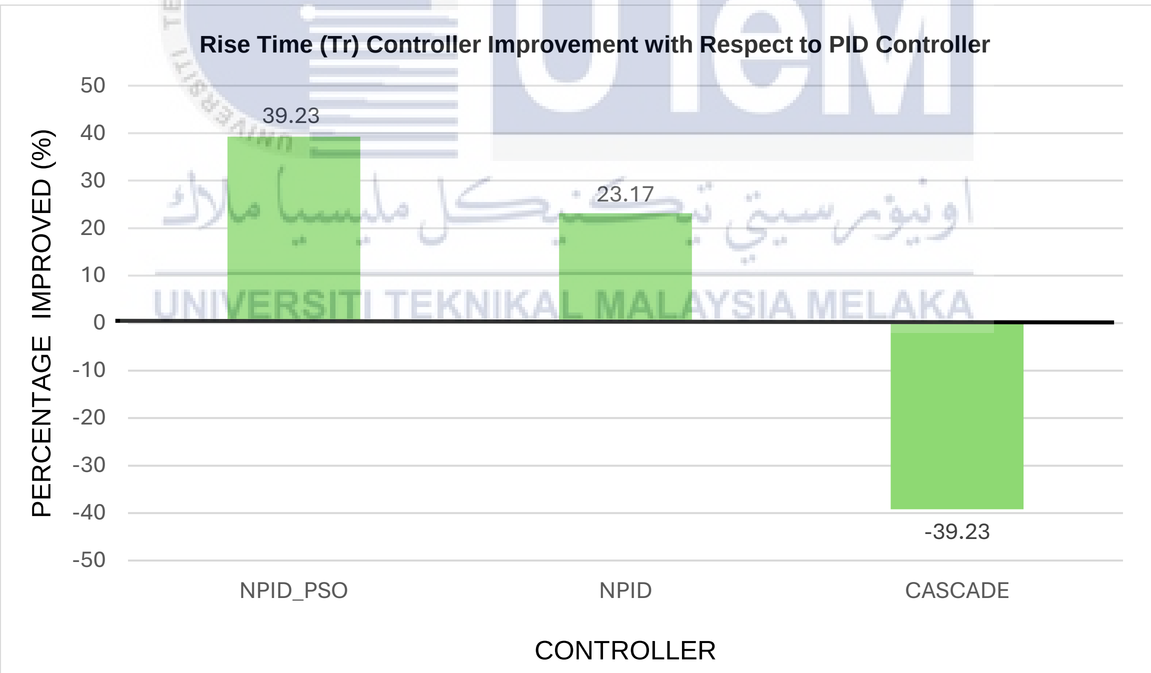

Figure 4.20: Percentage Improvement for Settling Time

NPID with PSO has the highest percentage improved compared to the other controller. Cascade controller did not have an improvement for both settling time and rise time. This is because, during the experiment, the actuator will have internal and external disturbances or noise (the encoder produced a high level of noise) that causes the controller to have a slower speed in achieving the desired output.

4.10 Summary

This chapter presents the analysis and the experimental validation results that validate the effectiveness of the PID, NPID, NPID with PSO, and Cascade controllers. The analysis process involves comparing the steady-state position and transient response whilst the validation is performed on the experimental plant of the NPID controller with other controllers, specifically PID, NPID with PSO, and Cascade. The performance parameter was assessed by comparing the steady-state error, percent overshoot, settling time, and rise time to establish the ideal controller performance in a system. Based on the results and statistics, it has been observed that NPID with PSO exhibits improved performance in terms of both steady-state performance as well as transient response.

CHAPTER 5

CONCLUSION

This chapter provides a summary of the project's overall conclusion, with a specific emphasis on the results and discussion gained from the final year project titled 'Design of Modified PID Controller for Positioning Control of Pneumatic System'. Additionally, it involves the objectives that were achieved as outlined in Chapter 1.

5.1 Conclusion

The objective of this study is to prove that the NPID controller has improved performance in both steady-state and transient responses. The proper transfer function for the system can be derived by System Identification. The minimal requirement for the model fit in System Identification is a number surpassing 90%. System models in the form of third order transfer function of the pneumatic system acquired via the System Identification is discussed in detail in Chapter 3, Section 3.3. Consequently, the system models were ready to be used for the simulation analysis and validation. The NPID controller is built by setting it up with a nonlinear function. In order to attain the result performance, optimizing the NPID controller with the usage of PSO is able to enhance the controller, producing a better performance in the final steady state. One technique to analyse the performance of the NPID controller is by making a comparison with other controllers, especially PID, which are the basic controller and Cascade controller.

The gain tuning (K_p , K_i and K_d) has been performed by an iterative process of heuristic method for each of the controllers. The common gain tuning of PID controller normally creates an enormous overshoot, and hence current stochastic approaches such as Particle Swarm Optimization (PSO) are utilized to improve the performance of traditional methods (Solihin et al., 2011). The appropriate tuning of controllers is essential for accomplishing high-performance control of various dynamic systems. In recent years, numerous methods have been presented to tune the gain parameters of PID controllers, aiming to improve the transient response and minimize steady-state error. The selection of gain adjustment is based on determining the lowest steady-state error performance. The selected gain is applied in both simulation and experimental analysis of the controllers. Comparisons can be made between the gains of all the controllers during both the simulation and experimental phases.

The controller that exhibits the lowest steady-state error, percent overshoot, settling time, and rise time data is considered the most effective controller for precise control placement. The results indicate that the NPID with PSO controller displays a better transient response for both simulation and experimental. Meanwhile a CASCADE controller has the lowest transient response performance due to the complexity of the controller. Conversely, NPID with PSO demonstrates greater steady-state performance between all of the controllers. The disparity between the data of the NPID and NPID with PSO controllers is minimal. The objective of this project is successfully achieved as summarized in Table 5.1.

Table 5.1: Project Conclusion

Objective	Conclusion
To design a PID controller and modified Nonlinear PID controller to obtain precise positioning of the pneumatic system.	• Successfully designed the PID and NPID controller.
To analyse the controller performance in term of positioning error (steady state) and the system's transient response.	• Achieved the steady-state error where it is lower than 2%. • Accomplish the minimization of the maximum overshoot. • Gain a better assessment of the controller's effectiveness in the rise time and settling time.

To validate the designed controller through simulation using MATLAB Simulink software and experimental work using real plant of pneumatic system.	• Accomplished by conducting a thorough comparison between the simulation and experimental results. • Experimental results nearly match the simulation results. • Simulation shows the correct order of the controller's performance ranking, validated during the experimental stage.

5.2 Recommendation

It is highly advised to include the improvement of the controller as one of the topics in the Control System course. The use of NPID controllers has become more prevalent in complex control systems due to its ability to handle nonlinearities and increase system performance. When integrated with optimization algorithms involving PSO, the efficiency and effectiveness of NPID controllers can be considerably improved. It is strongly encouraged for applications demanding reliable and precise control in the presence of nonlinearities and dynamic changes. By combining the features of both NPID controllers and PSO, students may achieve optimal control solutions that match the demanding needs of modern automated and robotic systems.

In addition, when designing the controllers, the use of the filters should be considered. The addition of filters into the system could remove the noise, which will affect the system's response. Lastly, The Self-regulating Nonlinear PID (SN-PID) controller are the controller to look forward to obtain precise positioning of pneumatic system.

5.3 Sustainability Design and Development

This study focused on the application of pneumatic systems, which are frequently utilized in the field of automation. Pneumatic actuators are experiencing a global increase in utilization due to low price, ease of maintenance, excellent durability, and high power-to-weight ratio. Despite its disadvantages, the pneumatic system can be improved by inventing alternative controllers to compensate for it. There are many possibilities for innovating controllers for pneumatic systems in order to enhance performance. The current controllers of pneumatic systems may contribute to the upcoming controller designers to refer and develop it with either minor or major modifications.

5.4 Complexity

This research includes a procedure for converting the input and output values from the unit of voltage to the unit of a millimetre. The process is done by referring to the specification of the pneumatic actuator, which may give some offset during unit conversion. The pneumatic actuator is high in non-linearities as it uses compressed air. The existence and importance of the offset in unit conversion could not be detected and measured.

5.5 Life Long Learning and Basic Entrepreneurship Development

PID controllers are well recognized for the simplicity of design, where various other components add on and integrate with the controller for different reasons. Modifications in PID controllers may offer tremendous impact on the system performances particularly nonlinear systems like a pneumatic system. PID controllers are so effective in the performances of pneumatic systems as the controller has parameters that control some responses of the system, specifically as proportional gains to control the rise time of the system response, integral gains compensate steady state error meanwhile, derivative gains to reduce the overshoot of the system response.

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APPENDIX A

Gantt Chart PSM 1

Activities	Weeks														
PSM 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Submission of FYP title															
Introduction															
Discuss about the project								**S**							
Summary of article								**E**							
Background and problem statement								**M**							
Submission of Chapter 1															
Literature Review															
Draft of Literature Review															
Methodology															
Draft of Methodology								**B**							
Submission Chapter 3								**R**							
Submission Abstract								**E**							
Draft poster presentation								**A**							
Important Deadline															
Logbook								**K**							
Poster Presentation															
Final report PSM 1															

APPENDIX B
Data Sheet of Pneumatic Actuator
(Enfield Tech Model ACTB-200-S012000)

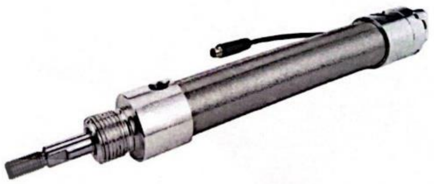
ENFIELD® TECHNOLOGIES

ETA Series Pneumatic Linear Actuators
Datasheet
page 1 of 3

Product Overview
The ETA Series is an economical pneumatic linear actuator that contains an internal Linear Resistive Transducer (LRT). It is ideal for applications where traditional magnetic position sensing is not acceptable. Additionally, the ETA Series is conducive where variations in cylinder stroke and speed are required or where an application calls for continuous position sensing

Features:
- Ideal for applications where traditional magnetic position sensing is not acceptable.
- Continuous position monitoring

Standard Specifications:
- 303 stainless steel piston rods
- 304 stainless steel cylinder tube
- Aluminum head and caps
- Maximum pressure rating is 250 PSIG



ETA Pneumatic Actuator

Component	Description
Piston Rod	303 Stainless steel rod is ground, polished, and roller burnished for a hard mirror finish.[1]
Rod Thread	Roll-formed rod threads.
Rod Bushing	Sintered bronze rod bushing.
End Caps	High strength aluminum alloy.
Ports	Full-flow porting and rectangular slots on the piston-mating surface enable the air to work against a larger piston for easy breakaways (even at low pressures).
Tube	304 Stainless steel.
Piston	High strength aluminum alloy piston.
Piston Seals	Low friction Buna N "U" cups piston seals.
Rod Seal / Wiper	Buna N "U" cup rod seal.
Cylinder Lubrication	Pre-lubricated.
Linear Resistive Transducer (LRT) Probe	Anodized aluminum probe with a reinforced threaded flange and thread seal. The probe processes infinite resolution, with a non-linearity of ±1 % of full stroke. ±0.001" mechanical repeatability. Rated for 10 million cycles, temperature range -40 °F to 250 °F.
Linear Resistive Transducer (LRT) Wiper	LTR Wiper is precision molded assembly that is rated for more than 1000 linear miles of travel.
3 Pin Connector	M8, 3 pin, Nano male connector, IP65 standard.

[1] The 1-1/16" bore is chrome plated 1050 steel.

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How to Order

Act1b 106 s0600

Cylinder Type
Act1b = ETA Series

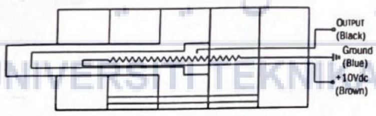
Cylinder Bore (Dia.)
150 = 1.50"
200 = 2.00"

"Standard" Full Inches of Stroke
s0600 = 6.00
s01200 = 12.00

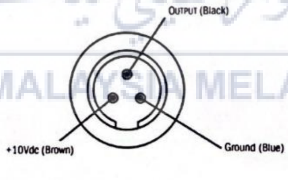
Cylinder Mounting:
- All models are Front Nose mount and include Rear Pivot mount (uninstalled).

Notes:
- For non-standard stroke lengths; contact factory.
- Consult factory for NFPA or ISO/VDMA actuator models and options.
- A-M8-3P-*M-F cable required for each Actuator ordered (sold separately).

ETA LRT Circuit Diagram



M8, Round Connector- Cable Assembly Screw-Lock, Molded



[2]Wire colors correspond to Enfield Technologies' A-M8-3P-*M-F (sold separately).

toll free North America
1-800-504-3334
info@enfieldtech.com
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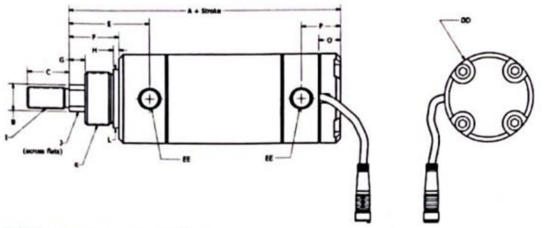
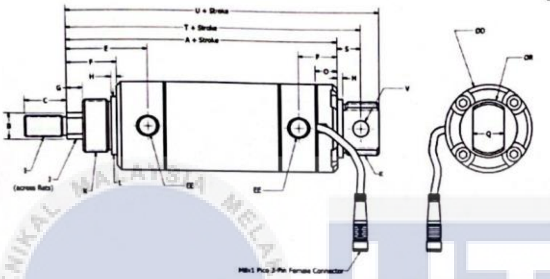
Cylinder Dimensions





	1.5" Bore	2.0" Bore
A	4.88	5.46
B	0.50	0.63
C	0.88	1.00
D	1.56	2.08
E	1.72	1.92
F	1.13	1.188
G	0.31	0.38
H	0.09	0.13
I	7/16-20 UNF	1/2-20 UNF
J	0.44	0.50
K	1 1/8-12 UNF	1 1/4-12 UNF
L	1.125	1.375
O	0.41	0.50
P	0.83	0.93
Q	0.63	0.75
R	1.125	1.375
S	0.56	0.56
T	5.44	6.02
U	5.91	6.46
V	0.38	0.38
EE	1/4 NPTF	1/4 NPTF

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