DESIGN OF GAIN SCHEDULING PID CONTROLLER FOR PRECISE POSITIONING OF PNEUMATIC SYSTEM

This report submitted in accordance with the requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor's Degree of Manufacturing Engineering (Hons.)

by

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2022

DECLARATION

I hereby, declared this report entitled "Design of Gain Scheduling PID Controller for Precise Positioning of Pneumatic System" is the result of my own research except as cited in references.

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Date : 28 June 2022

APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfilment of the requirement for Degree of Manufacturing Engineering (Hons). The member of the supervisory committee is as follow:

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ABSTRAK

Kelebihan sistem penggerak pneumatik, seperti kos murah, keramahan alam sekitar, kebolehpercayaan tinggi, dan nisbah kuasa dan berat yang tinggi, adalah sebab penggunaannya meluas dalam industri automasi hari ini. Ciri-ciri ini menjadikan penggerak pneumatik nampaknya menjadi pilihan yang lebih sesuai dari sistem penggerak hidraulik dan motor servo elektrik untuk automatik. Walau bagaimanapun, mendapatkan kedudukan tepat adalah sukar bagi sistem pneumatik dengan perbezaan gangguan iaitu muatan dari 0kg hingga 9kg untuk projek ini kerana ketidaklinier pepejal penggerak pneumatik yang disebabkan oleh geseran dan kebolehmampatan udara. Solusinya, pengawal mesti digunakan untuk mengawal sistem untuk menyelesaikan kesulitan. Model sistem mesti diperoleh sebelum pengawal dapat dirancang. 'System Identifcation Toolbox' dalam MATLAB yang digunakan untuk mendapatkan model. Kemudian model disahkan dengan membandingkannya dengan data eksperimen. Selepas pengesahan model, pengawal PID akan dirancang diikuti dengan pengawal 'gain scheduling PID'. 'Gain Scheduling PID' dicipta dengan menggunakan MATLAB untuk mendapatkan ketepatan dalam kedudukan sistem dengan 'step input signal' yang dihasilkan. Lebih-lebih lagi, pengawal 'gain scheduling PID' sistem dapat meminimumkan 'error' dalam sistem. Oleh itu, tiga jenis pengawal dirancang dalam penyelidikan ini iaitu, (i) pengawal PID, (ii) 'manual-switching gain scheduling PID controller', dan (iii) 'auto-switching gain scheduling PID controller' untuk menganalisis dan membandingkan prestasi sistem. Selanjutnya, ketiga-tiga pengawal yang dirancang menganalisis dan membincangkan hasil respon pengawal dari segi analisis kedudukan tepat, analisis 'transient response', dan analisis 'integral of absolute error'(IAE). Dari hasil dan perbincangan yang dibuat, dapat disimpulkan bahawa 'auto-switching gain scheduling PID controller' menghasilkan hasil yang lebih baik dalam prestasi kedudukan yang tepat untuk sistem pneumatik. Pengawal PID hanya tidak dapat dibandingkan dengan dua pengawal yang lain kerana respon pengawal tersebut tidak stabil dan tidak dapat merakam apabila beban sistem lebih dari 1kg. Dengan membandingkan dua jenis pengawal 'gain scheduling PID', pengawal 'auto-switching gain scheduling PID' menghasilkan purata peningkatan yang signifikan sebanyak 42.79% purata daripada pengawal 'manual-switching gain scheduling PID'

ABSTRACT

The advantages of pneumatic actuator systems, such as cheap cost, environmental friendliness, high reliability, and high power-to-weight ratio, are the reason for their widespread use in the automation industry today. These characteristics make pneumatic actuators appear to be a viable option for hydraulic actuator systems and electric servo motors for automating tasks. However, obtaining precise positioning in the plant is challenging for pneumatic systems with the variance of disturbances which were loads from 0kg to 9kg for this research due to the solid nonlinearities of pneumatic actuators caused by friction and the compressibility of air. As a result, a controller must be used to control the system in order to solve the difficulties. The mathematical model of the system must be obtained before the controllers can be designed. Then System Identification toolbox in MATLAB software was used to obtain the model. Then the model was validated by comparing it with experimental data. After the model validation, the PID controller will be designed followed by the gain scheduling PID controller. The gain scheduling PID 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. Moreover, the gain scheduling PID controller of the system could be capable of minimizing the errors of the system. Thus, three types of controllers were designed in this research namely, (i) PID controller, (ii) manual-switching gain scheduling PID controller, and (iii) auto-switching gain scheduling PID controller in order to analyze and compare the performance of the system. Furthermore, all the three designed controllers analyzed and discussed the results of the controllers' performances in the terms of precise positioning analysis, transient response analysis, and integral of absolute error (IAE) analysis. From the results and discussions made, it can conclude that the auto-switching gain scheduling produced better results in precise positioning performance for the pneumatic system. The PID controller was simply non-comparative to the other two controllers as the responses of the controller were unstable and not able to record the system response with loads of more than 1kg. By comparing the two types of gain scheduling PID controllers, the auto-switching gain scheduling PID controller produced an average significant improvement of 42.79% than the manual-switching gain scheduling PID controller.

DEDICATION

For my beloved parents,

Srikanthan Gopal and Nirmala Devi Sevakrishnavelu,

my adored brother and sister, Danaraj and Elyni

for giving me moral support, money, cooperation, encouragement, and also understanding.

Love you all forever.

To my supportive supervisor

Ir. Dr. Lokman Bin Abdullah

For encouraging me and being my guidance

as the source of knowledge

throughout this project.

Thank you so much

ACKNOWLEDGEMENT

In the name of GOD, the most gracious, the most merciful, with the highest praise to God that I manage to complete this final year project successfully with ups and down but most importantly many lessons learned.

I would like to deliver my first and sincere gratitude to my supervisor for being the source of my knowledge, and for his encouragement and patience to guide me in the process of completion of this project. I truly appreciate the Ph.D. student, Mr. Khairun Najmi bin Kamaludin, who plays the role of mentor and puts the effort into assisting me in this project from the beginning until the end. A special huge thanks to the Faculty of Manufacturing Engineering at UTeM for giving me the chance to conduct the project solely.

I would like to deliver my significant gratitude to my family, my father Srikanthan Gopal, my mother Nirmala Devi Sevakrishnavelu, and my siblings for giving me a lot of support in the shape of moral, financial, and also motivational.

Finally, I want to express a big thanks to all of my friends who have been with me through my ups and downs either directly or indirectly for this project. My friends are the ones who dealt with my emotions and contributed much to the dimensions of critical thoughts in my research.

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LIST OF ABBREVIATIONS

ARMAX	AutoRegressive Moving Average with Exogenous input
ARX	AutoRegressive 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
NPID	Non-linear PID
OE	Output Errors
PD	Proportional-Derivative
PEM	Prediction Error Minimization
PI	Proportional-Integrational
PID	Proportional-Integrational-Derivative
PWM	Pulse Width Modulation
RMS	Root Mean Square
SISO	Single-Input Single-Output
SN-PID	Self-regulation Non-linear PID
ZOH	Zero Order Hold

CHAPTER 1
INTRODUCTION

1.1 Research Background

This research is about to model a design of the pneumatic system for precise positionings using a gain scheduling PID controller. Pneumatic was coined in the 1650s from the late ancient Greek word 'pneuma,' which meant "air." Pneumatic is an old antique technology used in the blowgun that was devised by ancient people for hunting purposes. The pressure created is roughly 1-3 psi, based on the capacity of the human lungs at the time. The first manually operated compressor is invented in approximately 3000 B.C. to assist in delivering air to ignite the fire(Trujillo, 2015). Pneumatic becomes more significant as we approach the bronze age when humans began to employ metal in their daily lives. After the 1950s, pneumatic systems were introduced into factories to replace human energy in the production line, and they are now widely used all over the world(Zhong & Zhao, 2019).

Pneumatic actuator systems are becoming more essential in the automation sector because of the lower cost, conveniently discovered material, high generating force, big power-to-weight ratio, and safe operation. Pneumatic systems are also environmentally benign and require less maintenance(Lee et al., 2002; Zhang et al., 2019). In the automation industry, pneumatic actuator systems are widely used in the food, aviation, and transportation industries. An air compressor, regulators, and gauges, as well as a check valve, buffer tank, feedlines, two-directional valves, and actuator, make up a pneumatic system. The pneumatic system is similar to the hydraulic system, except instead of hydraulic fluid, compressed air is used for the dynamic motion of the actuator whether its advances or retracts (Jang et al., 2012; Raghuraman et al., 2017).

Despite the fact that the pneumatic actuator system appears to be simple to operate technology with several benefits, it nevertheless has certain drawbacks in its use. The pneumatic actuator is difficult to regulate due to the friction and compressibility of the air. These issues lead the actuator to be unable to precisely reach the desired position, resulting in lag and delay in reaction(Nazari & Surgenor, 2016; Shilin et al., 2017). As a result of the drawbacks, a controller must be implemented to maximize the performance of the pneumatic actuator system. Since the use of pneumatic actuator systems in the industry has grown, researchers have created a variety of controllers.(Claeyssen et al., 2007; Lee et al., 2002; Yamaguchi et al., 2012).

Previous research on the pneumatic actuator system utilizing different methodologies such as conventional Proportional-Integral-Derivative (PID) controller and Fuzzy Logic controller began to gain attention and boost its study in the 1990s. PID controllers were first studied in 1998, but it wasn't until 2008 that they became popular in the pneumatic actuator positioning industry. With the help of various types of controllers, the performance of the pneumatic positioning actuator has greatly increased during the last 15 years(Mann et al., 1999). Nowadays in the industrial field, the PID controller is still the most widely used controller due to its simplicity and low cost, although it couldn’t be used to handle the highly non-linear system(Li et al., 2006).

Previous researchers have conducted similar studies to compare the performance of pneumatic actuators and have given ideas to improve actuator performance in nonlinear environments. However, the fundamental issue with pneumatic actuators is the dead zone and uncertainties in the system, such as cylinder and actuator friction, which persist even after previous researchers' controllers have been installed. As a result, ongoing research is required to analyze and resolve the issues.

1.2 Problem Statement

The pneumatic cylinders or actuators are driven by compressed air which produce and deliver by compressors to actuate to a specific position in the plant. The pneumatic positioning actuators have parametric errors due to the compressibility of air, causing the actuator to not reach the target position properly. It is hard to obtain precision in the positioning of pneumatic actuators due to high air compressibility, high nonlinearities, poor damping, friction, and wide dead zone (Sato et al., 2004; Sato & Sano, 2014). The system can benefit from a gain scheduling PID controller to overcome positioning uncertainties and improve system performance. As a result, System Identification must be utilized to correctly assess system models, and PID controllers must be developed using an acceptable approach for performance analysis and comparison along with gain scheduling PID controllers.

1.3 Objectives

The objectives of this research are as follows.

i. To obtain the system model of the pneumatic system.
ii. To design and develop a gain scheduling PID controller to obtain precise positioning of the pneumatic system.
iii. To analyze the performance of the gain scheduling PID controller in terms of steady-state error and system response.

1.4 Scope of Project

This project has some limitations as follows

i. 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. Gain scheduling PID controllers will be designed and simulated using the mathematical model.
ii. The experiment is carried out with variance of load weights. The available loads for the system are 0kg, 1kg, 2kg, 3kg, 4kg, 5kg, 6kg, 7kg, 8kg, and 9kg.
iii. The simulation and experimental tests should be conducted using MATLAB Simulink software.

iv. The experimental tests must be conducted using the pneumatic system hardware setup which was already set up completely.

1.5 Organization of Report

The analysis of all the gathered papers on the PID controller in the act of positioning the pneumatic actuator system is presented in the second chapter of this research study. With the use of connected works of literature, prior researchers' work, approaches, and accomplishments are evaluated, researched, and recognized.

Meanwhile, the third chapter starts with the workflow chart of the research. All the works are explained step-by-step in this chapter. The steps are divided into three phases for better research work understanding. Moreover, this chapter discussed the usage of MATLAB Simulink software, the experimental setup and its components, the utilization of system identification and transfer function, and lastly the PID controllers in detail.

The fourth chapter solely discussed the design of the controllers and their parameter tunings. There were three types of controllers were proposed and designed in this chapter. Then, chapter 5 presented the simulation and experimental results of all three controllers in terms of precise positioning analysis, transient responses, and integral of absolute error (IAE) analysis. The results were discussed in detail in the last section of Chapter 5. Conclusions were made in the last chapter by explaining the details of how the objectives were achieved at the end of the project. Recommendations and other needed elements also were discussed in Chapter 6.

CHAPTER 2
LITERATURE REVIEW

This chapter is about reviewing previous related research and project papers. The pneumatic actuator positioning system and the controllers to regulate the motions have been reviewed. The first section of this chapter is about the system models of pneumatic actuators and the modeling methods from several past research which are related to the system modeling of the pneumatic actuator system. Three types of PID-based controllers which are conventional PID controller, gain scheduling PID controller and fuzzy PID controller have been reviewed from previous studies in the next part of the chapter. The third part of this chapter is about reviewing the methods of controlling a pneumatic system with a gain scheduling PID controller and comparing it with a Fuzzy PID controller.

2.1 System Models of Pneumatic Actuator

There are a variety of methodologies for modeling the pneumatic actuator system that has come from various previous studies, and theoretical analysis is one of the most widely used approaches for obtaining the mathematical modeling of the pneumatic actuator system. A few assumptions must be established before the modeling can be built which are the gas volume flowing through the valve is constant, constant pressure of air supplied into the pneumatic actuator, constant volume, constant temperature, and applying the weight of the external load. Besides theoretical analysis, system identification is also a popular method for obtaining mathematical modeling of a pneumatic system. The greatest results in building the system controller would come from an accurate mathematical model of the pneumatic actuator system.

Significant research on modeling the pneumatic actuator system started conducted in 1956 based on a reviewed article on pneumatic actuator modeling (Shearer J.L, 1956). Shearer developed a theoretical model for the mass flow rate of air through a sliding plate proportional valve, which he then verified via an experimental model. A linear mathematical model of a double rod cylinder successfully developed by Shearer shows small motion about the mid-stroke position of a pneumatic cylinder.

In 1976, experiments on a low-pressure pneumatic actuator and load were conducted(Chitty & Lambert, 1976). The transient behavior of an actuator with load, operating in a particularly simple mode, was observed during an impulse test. Based on the findings, the nature of the actuator's expansion and compression processes is described. The findings are also being utilized to better understand the consequences of position leakage and friction in the system. The polytropic gas constant, as well as the friction and piston coefficients, are calculated numerically.

Two different approaches of formulae for pneumatic actuator modeling were proposed by a control system researcher named Sorli in 1999. The initial formulas were based on the thermodynamic transition of air, and simulations were run in MATLAB-Simulink. Meanwhile, another energy equation was incorporated into the second formula to account for the thermic exchange between the external atmosphere and the chambers(Sorli et al., 1999).

In 2000, a mathematical model of a double-acting pneumatic actuator system was introduced. 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 varied lengths of connecting tubes, the experiment provided a good outcome. The experiment took into account the impacts of nonlinear air flow via the valve, air compressibility in pneumatic cylinder chambers, air leakage between chambers, inactive volume at the end of the stroke, as well as time delay and attenuation in pneumatic lines. The mathematical model developed is employed in the construction of high-performance nonlinear force controllers, which have a variety of industrial applications. (Richer & Hurmuzlu, 2000).

A software tool was developed in 2003 which use to design and stimulate pneumatic actuator systems on the computer(Lin-Chen et al., 2003). That software tool is built with a library that contains five major categories of components together which are compressed air suppliers, cylinders, valves, control strategies, and miscellaneous parts such as connection hoses. This allows designers to quickly pick various components from the library to create a comprehensive pneumatic system. It also could simulate a designed pneumatic system in various operating modes. The graphic user interface (GUI) and animation techniques were adopted in designing software to create a user-friendly environment. Before the work of this researcher, pneumatic system components were divided into five major classes, and the combination of these components could be used to create a fully pneumatic system, from which a mathematical model of the system could be derived. Different component mathematical models have been created, and the combination of components will integrate the different mathematical models to create the overall system model.

A high-performance pneumatic force actuator system was also released in 2008, including simulation, animation, and program support. Double-acting pneumatic actuators controlled by proportional spool valves are one of the high-performance pneumatic actuator systems. Leakage between pneumatic chambers, time delay in pneumatic lines, the compressibility of air in cylinder chambers, and nonlinear air flow through the valve all influenced the real-time findings. It is required to build software aid for numerical issue solving due to the complexity of the pneumatic system model and partial differential equations theories. The engineering efficiency of the outputs is proved through simulation and program assistance in the MATLAB and Maple programming languages. (Dihovicni & Nedic, 2008).

Further study on the dynamic mathematical model of the pneumatic actuator system was conducted in 2005. The research system is controlled by on-off solenoid valves that use a pulse with modulation (PWM) technology to handle the temporal response of the opening and closing periods(Messina et al., 2005). The experimental inquiry offered a good foundation for testing the simulation model's performance. The capacity of the theoretical model to produce an accurate mean expectation of the actuator position less than 2 mm was demonstrated by simulation – experimental model comparisons. During the first five cycles, the model was tested several times during operation and initial circumstances. It is worthwhile to try out the proposed theoretical model for nonlinear dynamics events that are highly transient, as it may prove to be a useful tool for constructing control techniques without the need for expensive physical models.

A model of the rod-less pneumatic cylinder was developed in the year of 2011. Referring to the experimental data, the valve's dynamics were analyzed by producing the relationship graph between mass flow rate and input signal. During the charging and discharging processes, the heat transfer coefficient is also determined. The friction force in the pneumatic cylinder is formulated and calculated using the LuGre model. Experiments are used to gather data for the model's parameters. Finally, utilizing the open-loop step input response, the model is verified by comparing simulation results to experimental data. The finding shows that the experimental results are virtually identical to the theory's predictions(Meng et al., 2011).

Another study obtained the system model by applying system identification in MATLAB. The model structure utilized was state space from MATLAB's toolbox. The sample time of 0.01 seconds is used to capture input and output data. For parameter estimation, the Prediction Error Minimization (PEM) approach is applied. The model's parameter is determined, and the discrete state space equation is derived. With a sample time of 0.01 seconds, the continuous state space equation will be derived utilizing Zero Order Hold (ZOH) conversion methods(Syed Salim et al., 2014).

In 2018, researchers (Khairul et al., 2019) did research on obtaining a mathematical model of a pneumatic system utilizing the Real Laboratory Process. One of the libraries included in the MATLAB program is the Real Laboratory Process. At a sample interval of 0.01 seconds, a set of input and output data is gathered. For estimate and validation purposes, the obtained input and output data must be separated in the system identification process. The system model is estimated using the MATLAB library's system identification tools. There are also another four types of model structure as below:

I. AutoRegressive Moving Average with Exogenous input (ARMAX)
II. AutoRegressive with Exogenous input (ARX)
III. Box Jenkins (BJ)
IV. Output Errors (OE)

ARX was chosen by the researcher because it is the simplest model that incorporates the stimulus signal, and the order chosen is [3 3 1]. The model's validation will be the final stage in the system's identification. The ARX model structure uses Akaike's Model Validity Criterion. Only if the Best Fit is more than 90% is the model acceptable.

2.2 PID Controllers

Various type of controllers was 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). While researchers are using conventional PID controllers (Heidari & Homaei, 2014), some researchers hybrid the PID controller with gain scheduling or fuzzy logic(Dehghan, n.d.; Situm et al., 2004; Zhao et al., 1993).

2.2.1 Conventional PID Controllers

A Proportional–Integral–Derivative(PID) controller is a feedback-based control loop commonly used in industrial control systems and other applications that require constantly modulated control. The equation of the overall PID control function is :

$$K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt},$$

Where K_p, K_i, and K_d, all are non-negative, denote the coefficients for the proportional, integral, and derivative terms respectively. The equation of PID in the time domain is:

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

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 block, Integral block, and Derivative block are the three blocks that make up a PID controller(Jigang et al., 2017).

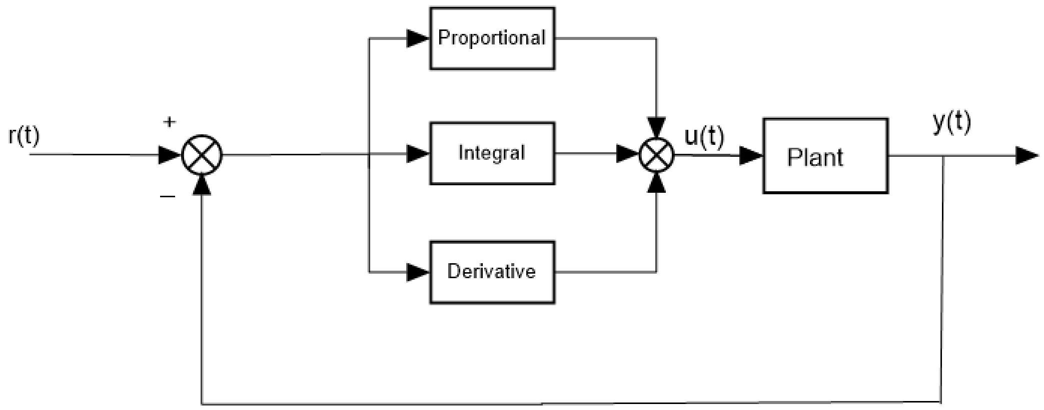

Figure 2.1: Structure of Conventional PID Controller

Because of its simplicity and low cost, it is the most extensively used controller in the world. Aside from PID controllers, there are also proportional controllers, PI controllers, and PD controllers that are also PID based. In the simulation, the PID-based controller has flawless performance in reducing overshoot and steady-state error, but in the real world, its performance is influenced by the plant's non-linearities. As a result, some researchers have previously conducted 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 controller 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 helps the controller eliminate overshoot issues. Based on (Gouda et al., 2000), Ziegler Nichol's tuning rules are used to adjust the parameters of the controller. 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 at the same time 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 PID-Based Controller

While the PID controller functions linearly, many manufacturing processes are nonlinear, making it difficult to regulate their operation. Consider common manufacturing processes like flow and temperature. As the process moves from one operational region to the next, the nonlinear behavior of these is exposed. When operating at one level of production vs another, the process variable responds disproportionately to a change in controller output. If the process has a wide range of operations, a single set of controller tuning settings will struggle to efficiently manage the process. After all, the PID has limitations. So that it needs to be improved the design of controllers with some other approaches to get better performance on the applied system. Gain scheduling is one of the typical methods for enhancing nonlinear process control. As a process transitions from one operating range to another, different controller tuning parameters are applied. The controller gains and time constant can then be more precisely aligned with the nonlinear dynamics of the operation.

According to a study, three series linked first-order pneumatic actuator systems with a couple of dead time equals a third-order pneumatic actuator system. Analog feedback with manipulatable proportional gain, Kp, was designed and used to the improve transfer function to reduce nonlinearities. The proportional gain value, Kp, was set to the greatest point of overshoot for the system. A third-order system may alternatively be thought of as a composite of three series-connected systems with some dead time in between. A PI controller was created utilizing the Chien-HronesReswick approach to compute controller settings based on this updated plant model. To avoid stiction, which might cause the system to stick and slip around the reference point, a weighting function was introduced to the controller. (Hamiti et al., 1996).

In the research done by researcher Lee in 2002, the tracking position control technique was presented, and the traditional PID controller was continually enhanced(Lee et al., 2002). It was divided into two control loops. The inner pressure control loop (PID + feedback linearization) and outer position control loop (PID + friction compensation) are the two control loops. The nonlinear observer and neural network were used to evaluate the friction compensators that were supplemented with PID. Because of the friction, traditional PID controllers are often unreliable and unsatisfying. The neural network is introduced to compensate for the friction. The proportional control valve translates an analog electrical input signal into a meaningful cross-sectional opening for pressure control design. The differential pressure is the input, and the position is the output for the controller design of position control utilizing neural networks. In comparison to conventional PID, which has a large overshoot, pressure control using PID, and feedback linearization decreased overshoot. The tracking errors, which are peak and RMS error, for the friction compensator were improved even with varying amplitudes and frequencies, whether employing a neural network or a nonlinear observer. When employing the neural network and testing with the step input, there is no improvement in the transient section since the peak error is significant.

Besides, a researcher focused on controlling the position of the pneumatic actuator(Papoutsidakis et al., n.d.). The system, however, is limited by the high air compressibility and friction force. The Kp, Ki, and Kd parameters of the traditional PID controller were tuned using the Zigler Nichols tuning method in this study. Initially, a P-controller was built, but when it achieved permanent oscillation, the positioning system refused to accept it. Then, to alleviate the issue, a PD-controller was implemented, which had an excellent result in lowering the rising time and eliminating oscillation. The PI-controller was then installed in the system, but regrettably, the system's rise time got worse than when the PD-controller was utilized, and the system's error remained constant. The PID-controller lowered the rising time and error the most of all the tested and simulated controllers, although the occurrence of overshoot rose as the time passed. An examination of the computed research revealed that the system's behavior provided the highest level of satisfaction, resulting in a model that could be evaluated in a simulation to assess performance. In this study, a classical PID, also known as an auto-selective classical PID (t-PID), was developed to offer the precision of the position accomplished in the simulation while also being very inexpensive. The suggested controller, on the other hand, was difficult to tune since it had to be verified in a simulation before being deployed in the real plant.

Next, according to the study by (Faudzi et al., 2012), the PI controller was employed in the study of intelligent pneumatic actuators (IPA) system, which demands higher control and precision. The nonlinear features, such as valve dead zone and mass flow rate parameters, were the most serious concern in the pneumatic actuators system. Because of the nonlinearities, the PI controller and pole placement feedback controller were used in this study. The pneumatic system was controlled by a PI controller, and feedback linearization proved that any single-input single-output (SISO) pneumatic system with a linearization load could be used. In other areas, input linearization with step-type disturbance rejection can be used to measure disturbance in static friction pneumatic actuators. In this work, the pole placement was done using a low-order linear approximation for a 2-axis pulse modulation width (PWM). The self-tuning control was used to place the poles, and it can be adjusted to fit any payload and time-varying parameters. In terms of transient response and steady-state error, this suggested technique is more stable than the PI controller for controlling the IPA system.

A study was undertaken in 2015 to improve the performance of pneumatic control valves using a PID controller. The performance of the proportional controller (P), the proportional-integral controller (PI), and the proportional-integral-derivative controller (PID) were examined in this study. The goal of the study was to achieve a maximum overshoot of unit step response of less than 10% and a settling time of fewer than 0.5 seconds. Without a controller, the unit step response of the old plant was roughly 901 percent overrun and 0.178s settling time. The P controller reduced the percentage of overrun to 89.6% while maintaining the same settling time. With a PI controller and a 1.78 second settling period, the percentage of overshoot is 9.09 percent. With a 0.32 second settling period, the PID controller reduced the overrun percentage to 5.53 percent. The PID controller was shown to be more reliable than the P and PI controllers in this investigation. When compared to a feedback path PID controller, a feedforward path PID controller showed a greater response characteristic(Heidari & Homaei, 2014).

A research proposal was made in 2019 about a PID to control an actuator with an on/off framework. The pulse width modulation (PWM) approach is utilized to regulate the valve using the PID controller. This approach is typically used on actuators that only have an on/off mode. The three parameters are utilized to reduce offset, reduce overshoot, and improve system stability. The proportional gain function boosted the system's sensitivity and decreased its time(t) constant, the integral gain function removed steady-state error, and the derivative gain function minimized overshoot and reduced settling time. In this controller design procedure, the second approach of Ziegler-Nichols tuning theories is used. The PID controller delivered signals to the PWM module, which then transmitted the analog signal to the solenoid valve, which controlled the amount of gas entering the cylinder(Thalia et al., 2019).

According to the research done in the year 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, K_e, the Popov stability criteria is used. When determining the value of K_e, chattering is also taken into account (max). The value of K_e 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).

A control system researcher Syed Salim then presented a Self-regulation Nonlinear PID (SN-PID) controller to solve the flaws in NPID. The goal of this research was to create a controller that would allow the actuator to achieve the specified displacement without overshooting. The range of variation (E_{max}) and rate of variation (α) 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_e 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).

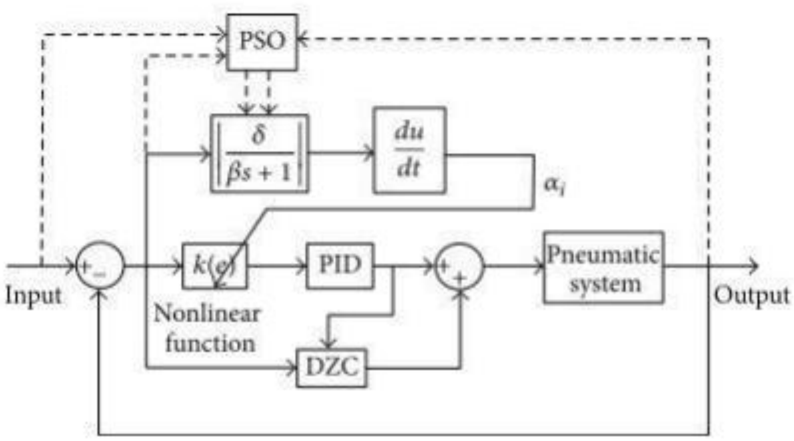

Figure 2.2: Block Diagram of SN-PID(Syed Salim et al., 2014)

In 2015, an improved nonlinear PID (ENPID) was proposed in follow-up research(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 when it came to monitoring the input trajectories. As a consequence, 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 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 of taking into account 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.

2.3 Summary

According to prior research, nonlinearities in the system, such as excessive air compressibility, frictional force, deadtime, and the dead band are the most prevalent difficulty in pneumatic actuator systems. Furthermore, the usage of these actuators is limited because of the pneumatics' requirement for outstanding performance in terms of durability, precision, and stability. 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 formulae. As a result, most academics have continued to favor control loops based on proportional integral derivatives (PID) controllers in recent years due to their simplicity and ease of understanding. 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.

CHAPTER 3
METHODOLOGY

In this chapter, the workflow of the research will be discussed in the first part. It is explained by providing a flowchart with a few processes from the start until the end of the research. The pneumatic system experimental setup of this research will be provided. The setup is mainly to perform data collection from the pneumatic plant. The method to obtain parameters for gain scheduling PID controller from the pneumatic system will be also explained in this chapter. The controller design of PID with gain scheduling methodology will be discussed in the last sub-topic of this chapter.

3.1 Workflow of Research

The flowchart shows the work to carry out step-by-step to complete the research. There are seven steps to be conducted divided into three phases. The first phase includes the finding of the problem statement and a literature review of related previous research papers. Phase 2 is about system modeling which includes system identification in MATLAB software, checking of parameters in the system modeling, and its validation via model. Controller designing steps take part in the last phase of the research flow which ends with the analysis of the controller.

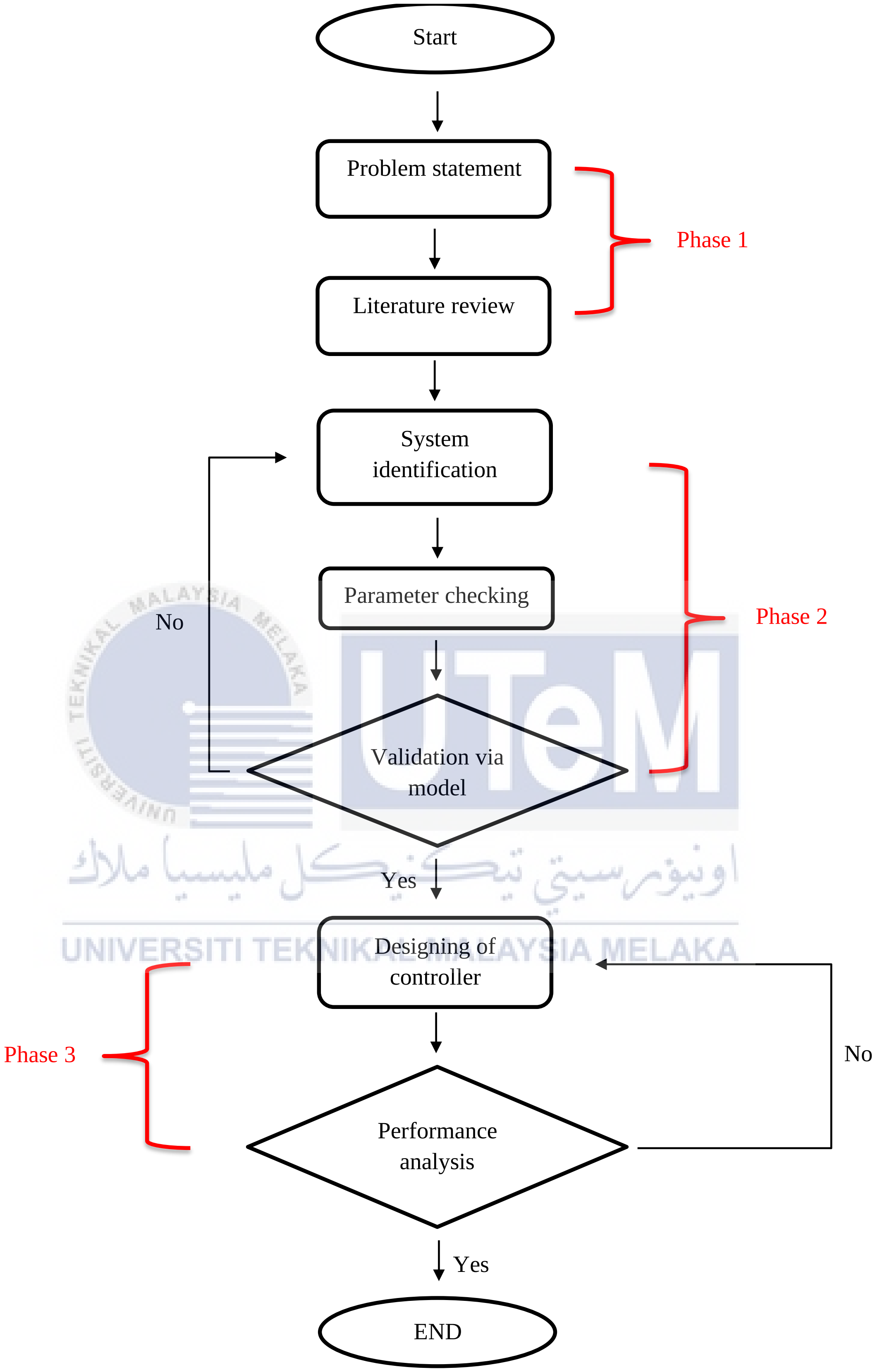

Figure 3.1: Work Flowchart of Research

3.1.1 Phase 1

The first phase of the project is to find the problem statements which lead to deciding the objectives to achieve through the research at the end. Problem statements also lead to finalizing the scope of the project. Moreover, phase 1 also includes a literature review to collect information on the data that have been encrypted in previous similar research. This helps to identify the issues and difficulties that have been faced by the previous researchers in the related projects.

3.1.2 Phase 2

Phase 2 is fully about the system modeling to achieve the first objective. In general, there are two methods to obtain the system model of the pneumatic system that has been used by researchers before which are mathematical modeling also known as physical derivation, and utilizing the system identification toolbox of MATLAB software. System identification was used in this study to get the needed models of the system by using the Single Input Single Output (SISO) approach. System identification is chosen because it identifies the parameters from the real pneumatic plant which will give higher accuracy than mathematical modeling. After system identification, the parameters were investigated and checked for model validation.

3.1.3 Phase 3

The last phase is the important stage of the project to achieve the other two objectives. Phase 3 solely includes designing controllers for the system model that obtain in phase 2. Then the controllers are implemented in the real system to conduct experimental tests. PID base controller with gain scheduling was designed initially with a try and error approach systematically to obtain results for the analysis of the controller’s performance.

3.2 Hardware Setup

A basic pneumatic system is connected up with an air compressor, Filter, Regulator & Lubricator unit (FRL unit), directional control valve with inlet and outlet ways, and actuator also known as a pneumatic cylinder. A controller is an additional component to the system to control the positioning performance of the actuator. The pneumatic system is started to function with the air compressor by supplying pressurized air into the pneumatic system. Then the pressurized air gets into the FRL unit. The main purposes of the FRL unit are to filter out the dust in the air to protect and make sure the system is sustainable longer, regulate the pressure of air that is needed upon the requirement of the system's function, and the lubricant applied to the air to prevent internal rusting of the actuator.

Then, the regulated pressurized air flow through the directional valve. The basic function of the valve is to control the air flow direction according to its 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 functions of other components.

The motion of the actuator is not consistent always as the users want. So, an external controller is used to control the whole pneumatic system to obtain the performance of the system that is needed by the users upon requirements. In this project, PID based controller with gain scheduling will be used to control the motion of the system's actuator. When it comes to the controller of the pneumatic system, positionings and accuracy are the elements that a user is concerned about the actuator.

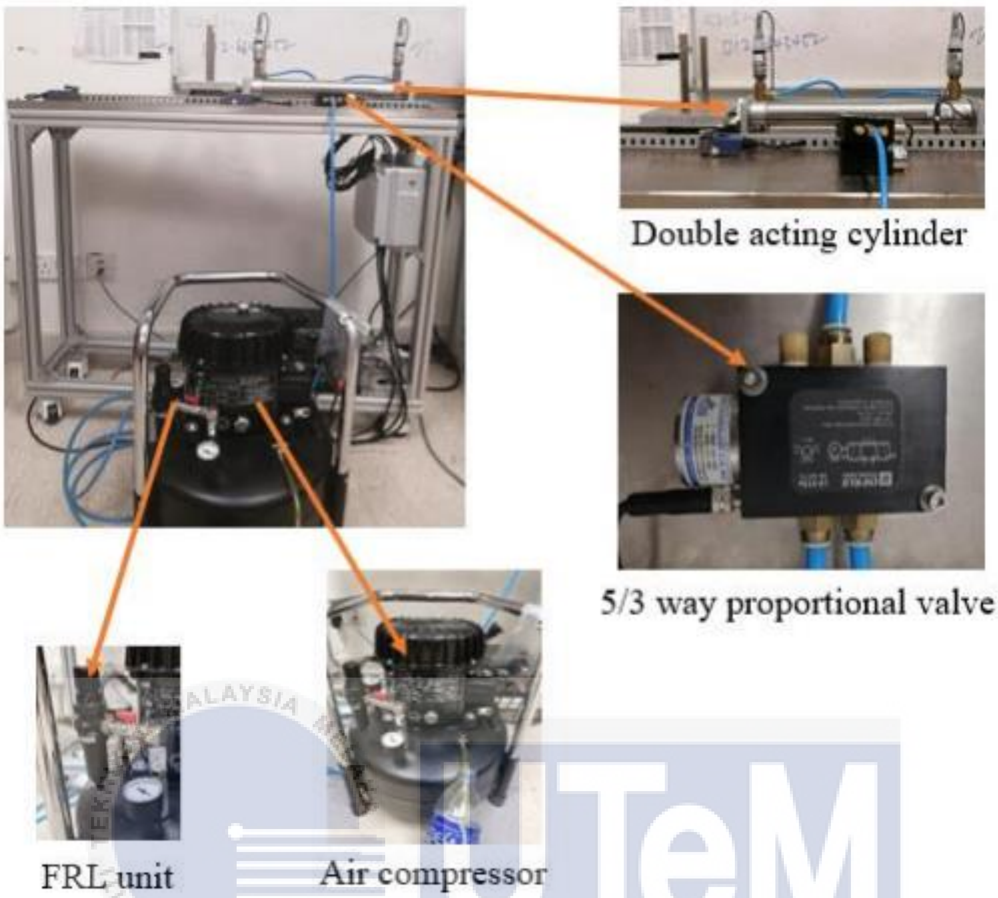

Figure 3.2: Components of Pneumatic Actuator System

Figure 3.3 below shows the complete experimental setup of pneumatic. It is made up of:

1. A personal desktop with MATLAB software
2. Air compressor
3. A single rod double-acting cylinder
4. Directional proportional valve
5. Pressure sensors

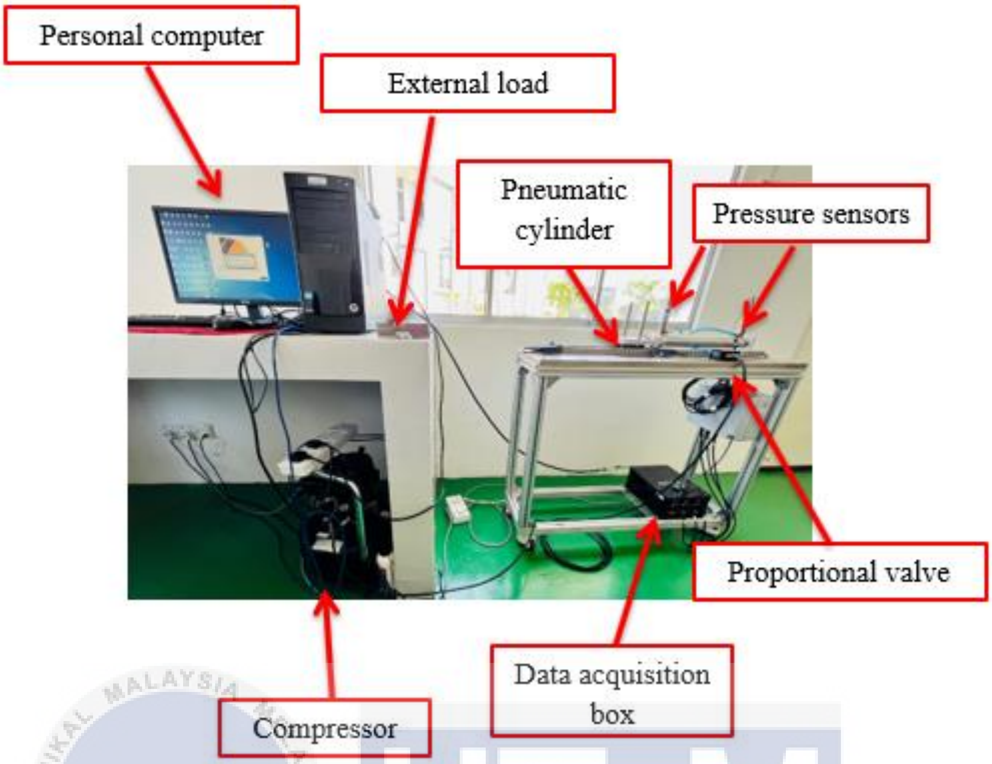

Figure 3.3: Experimental Setup of Pneumatic System

3.3 System Modelling

The system identification toolbox of MATLAB software will be used for the system modeling process since the model and parameters of the pneumatic actuator were undefined for the system with load variance from 0kg until 9kg. The block diagram that represents the pneumatic actuator system that will be 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 3.4.

Then the data will be collected and exported to the workspace of MATLAB software as presented in Figure 3.5. 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 best fit of more than 85% were selected for all the available loads of the system as shown in Figure 3.6. The obtained models will be shown in the next chapter.

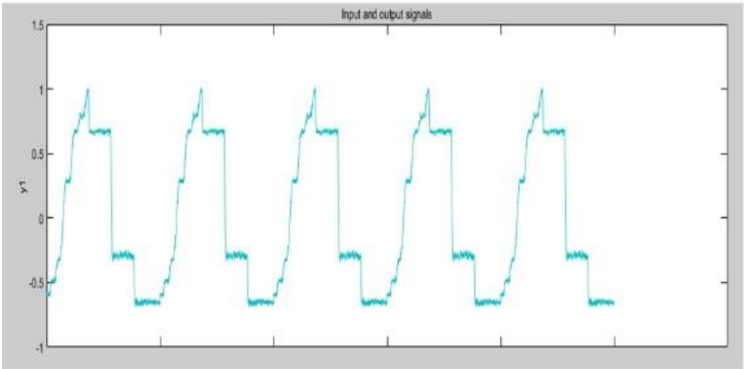

Figure 3.4: Sine Wave Input for System Identification

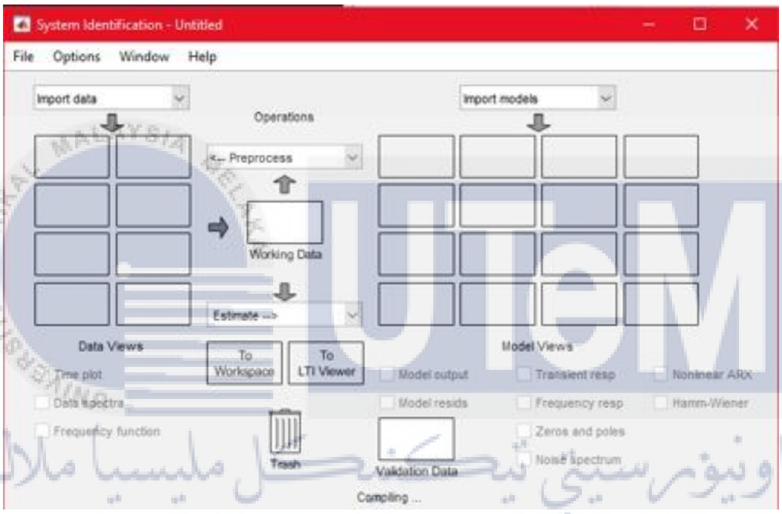

Figure 3.5: System Identification Toolbox to Import the Data

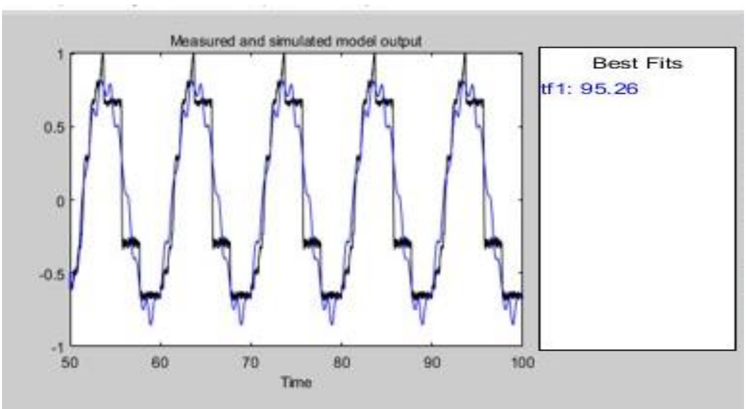

Figure 3.6: Sample of Best Fit Curve Percentage Output

3.4 MATLAB Simulink

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

3.5 PID Controller Design

PID base controllers are the most regular controller applied in the automation industry to control non-linear systems especially pneumatic systems. The nonlinear behavior is known as process transitions from one operating range to another. Initial set controller tuning parameters will struggle to regulate and control the motion of the nonlinear system. After all, PID-based controllers are linear controllers and have their limits in the process of moving. Thus, the controllers should have some modifications in their parameters to control a nonlinear system such pneumatic actuator positioning system.

There are many approaches for improving the controllers of nonlinear processes. Gain scheduling is one of the common approaches for PID-based controllers that have been used to regulate pneumatic systems. Gain scheduling involves tuning parameters of different controllers' applications as the process changes or transitions from one set of operating ranges to another. So, the controller gain can be aligned with the nonlinear dynamics of the process.

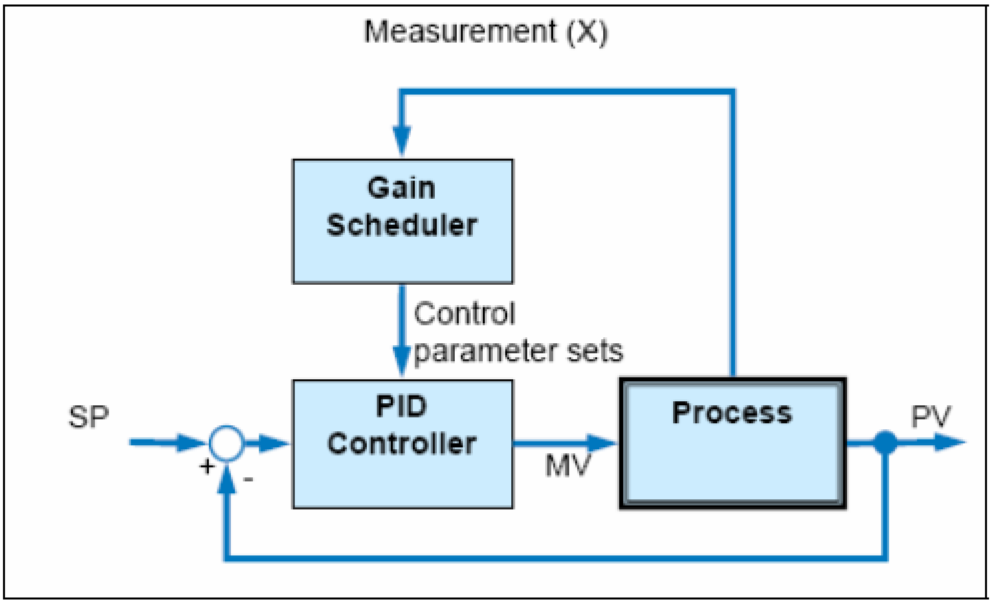

Figure 3.7: Basic Structure of Gain Scheduling PID Controller

There is various type of PID base controllers such as P, PI, PD, and PID controller. Different values of the proportional gain block (K_P), integral gain block (K_I), and derivative gain block (K_D) should fix respectively to the PID block. The simplest controller PID base controller is the P controller where only the proportional gain block (K_P) will be tuned and other blocks stay zero. For the PI controller, K_P will be tuned then follows by the tuning of Ki whereas K_D is left at zero. PD controller is contrary to PI controller; tuning of K_D will follow after K_P is tuned while K_I stays zero.

For PID controllers, all three blocks which are K_P, K_I, and K_D should be tuned to get zero error of steady-state and good transient response. Since the pneumatic system is highly nonlinear, the try and error technique should apply systematically to obtain the values of K_P, K_I, and K_D.

CHAPTER 4
CONTROLLER DESIGN

4.1 Introduction

The PID base controller is the most regular controller used and applied in the automation industry to achieve the favorable result in controlling position and continuing motion as the ultimate goal. However, a basic PID controller is often difficult to give good performance due to the presence of nonlinearities especially in pneumatic systems as position control performance is more rigorous when there is a change in the loads of the system. Therefore, the gain scheduling PID controller is designed, simulated, and tested to control the position and motion of the pneumatic actuator for multiple loads from 0 kg to 9 kg. The identified system of third-order transfer functions of the pneumatic plant from 0 kg until 9 kg were used as pneumatic systems for simulation as in Table 4.1 below.

Table 4.1: Transfer Functions of the System 0kg-9kg

Load(kg)	**Transfer function of the system**	**Best fit (%)**
0	$\frac{0.2882s^2 + 0.5213s + 0.02931}{s^3 + 0.2639s^2 + 0.01152s + 0.00008487}$	88.78
1	$\frac{-0.05631\, s^3 + 0.00688\, s^2 + 0.2289\, s + 0.1657}{s^3 + s^2 + 0.001779\, s + 0.001682}$	92.63
2	$\frac{0.04706\, s^2 + 0.2962\, s + 0.2491}{s^3 + 1.082\, s^2 + 0.08247\, s + 2.906e^{-6}}$	93.08
3	$\frac{0.03854\, s^2 + 0.2952\, s + 0.2567}{s^3 + 1.061\, s^2 + 0.06096\, s + 1.017e - 08}$	94.09
4	$\frac{0.06204\, s^2 + 0.3059\, s + 0.2439}{s^3 + 1.009\, s^2 + 0.009456\, s + 3.688e - 07}$	93.78
5	$\frac{-0.04438\, s^3 + 0.01251\, s^2 + 0.2427 + 0.1858}{s^3 + s^2 + 0.00076\, s + 0.00076}$	93.76
6	$\frac{0.0687\, s^2 + 0.3027\, s + 0.234}{s^3 + s^2 + 0.0001031\, s + 0.0001031}$	91.75
7	$\frac{0.04477\, s^2 + 0.2852\, s + 0.2404}{s^3 + 1.025\, s^2 + 0.02513\, s + 1.228e - 08}$	92.87
8	$\frac{0.04073\, s^2 + 0.2754\, s + 0.2347}{s^3 + 1.107\, s^2 + 0.1073\, s + 2.09e - 08}$	90.93
9	$\frac{0.2435\, s^2 + 0.2432\, s - 0.0002623}{s^3 + 0.2786\, s^2 + 0.001459\, s + 0.0003109}$	90.32

4.2 PID Parameter Tuning

The first step in designing the Gain Scheduling PID controller was to design a PID controller to ensure the PID gains were acceptable in achieving a stable system without external disturbances. In general, the PID gains were determined as presented in Figure 4.1.

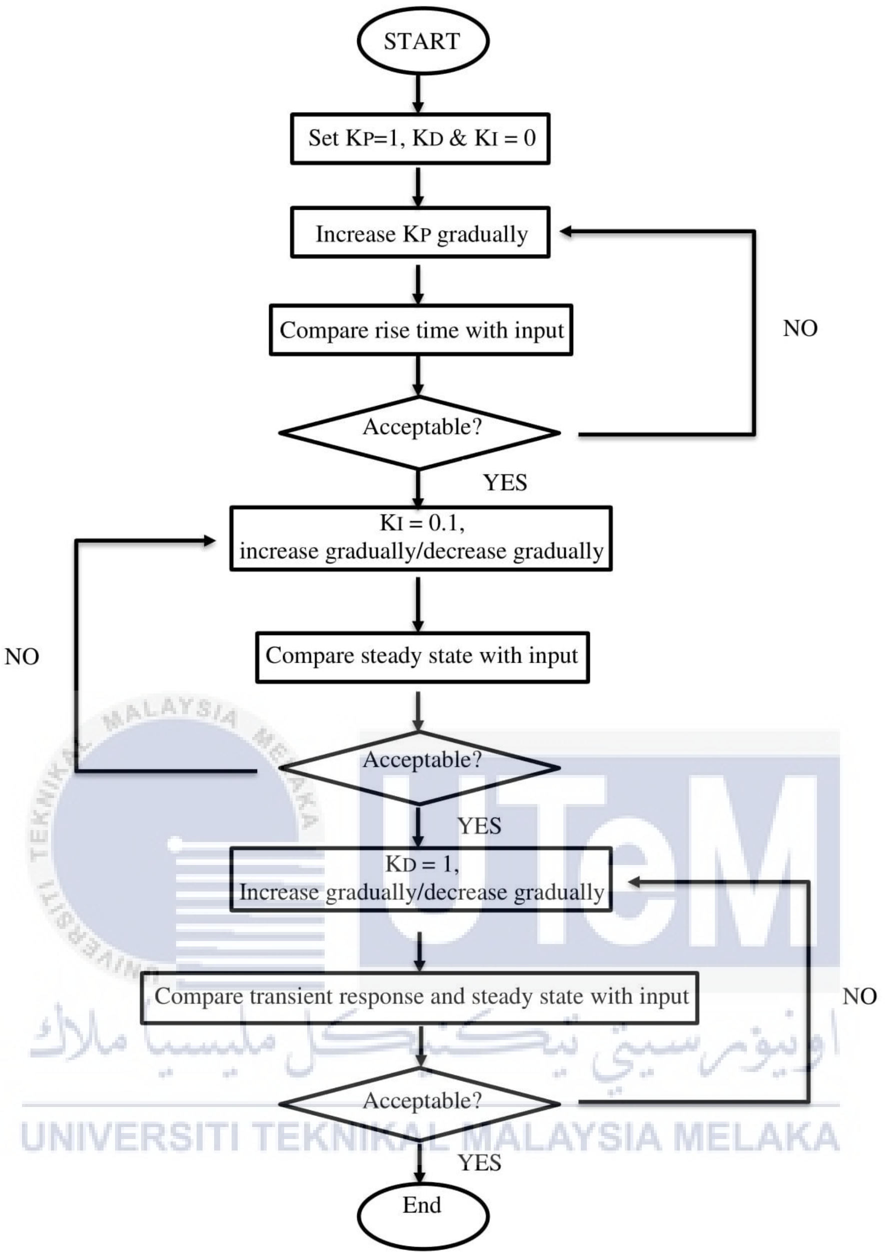

Figure 4.1: Flowchart of PID Parameter Tuning

This parameter tuning approach was applied in this research to ensure the stability of the pneumatic system without external disturbances after designing the PID controller. The control scheme of the PID controller was designed using MATLAB Simulink software. The control scheme and the control signal of the PID controller are shown in Figure 4.2 and Equation 4.1 respectively as stated below. Table 4.2 shows the gain parameters achieved upon PID tuning for the system without external loads. This control strategy was designed with the PID gains as indicated in Table 4.2 and the pneumatic system transfer function without loads as presented for 0kg in Table 4.1. A step form of signal generator discussed in section 5.2 was used as the input signal.

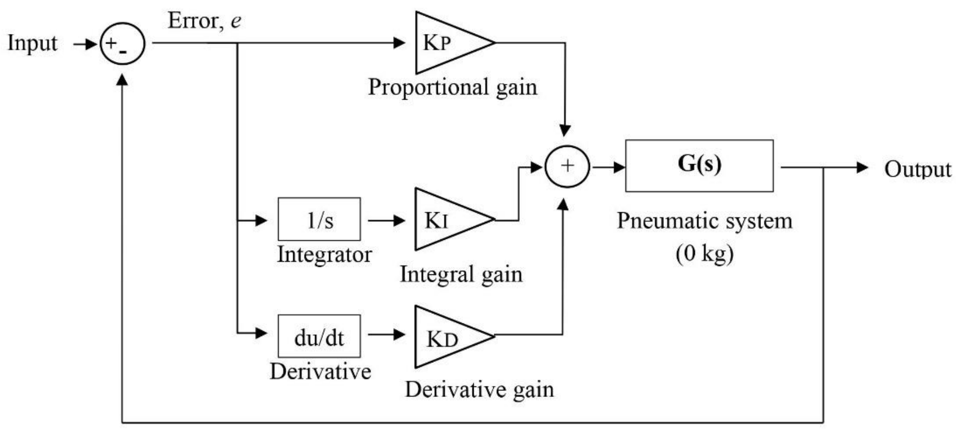

Figure 4.2: Structure of PID Controller

The control signal of the PID controller was derived as follows.

$$U_{PID} = K_P\, e(t) + K_I \int_0^t e(t)dt + K_D \frac{d}{dt} \quad (4.1)$$

where;

e(t) = Tracking error

K_P = Proportional gains

K_I = Integral gains

K_D = Derivative gains

Table 4.2: PID Gain Parameters

Gain parameters	Gain values
Proportional gain, K_P	10
Integral gain, K_I	0.235
Derivative gain, K_D	0.5

4.3 Gain Scheduling PID Controller

This section discusses the parameters for multiple external loads, and the gain scheduling PID controller structure. The gain scheduling PID controller structure is proposed in two different concepts of handling which are manual-switching gain scheduling PID and auto-switching gain scheduling PID. The detailed discussion is performed in section 4.3.1 and section 4.3.2 respectively. Later, the simulation and the experimental validations using these control schemes were performed in the next chapter.

The pneumatic system set up for this research is available for various external loads from 0 kg to 9 kg. The finalized PID gains of 0 kg may not acceptable and adaptive for other loads as there will be a difference in the disturbances of the whole system. Therefore, PID parameters need to be tuned individually for every external load so that it can be acceptable in terms of the stability of the system when the variance of loads is added to the system. The parameter tuning process is carried out using the PID controller scheme in Figure 4.2 with the various transfer function identified for external loads as presented in Table 4.1 in section 4.1. The procedure to tune the gains of the controller with external loads from 1 kg to 9 kg is illustrated in Figure 4.3 below. Load of 0 kg is excluded as it was already tuned in the PID controller previously. The PID parameters were determined for all the external loads as listed in Table 4.3 below.

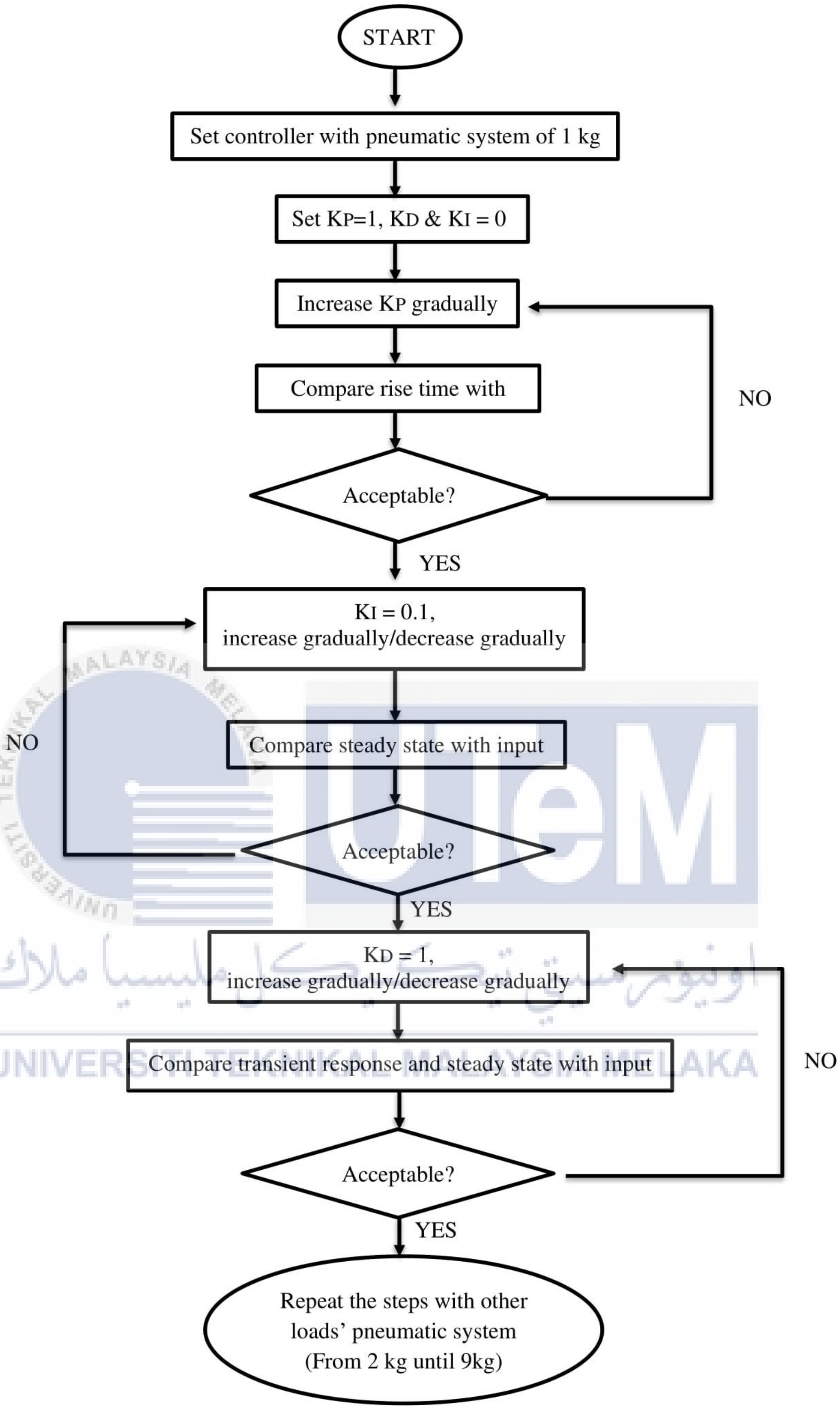

Figure 4.3 Flowchart of Gain Scheduling PID Parameter Tuning

Table 4.3: PID Gain Parameters for Various Loads

Gain parameters	Loads (kg)									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
K_P	10	8.5	8.5	8.2	7	6	5.6	4.6	4.6	4.5
K_I	0.235	0.234	0.220	0.250	0.275	0.230	0.230	0.210	0.220	0.230
K_D	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
IAE	1.978	2.093	2.466	2.684	3.085	3.065	3.342	3.528	3.502	3.402
SSE	0.04	0.48	0.37	0.05	0.63	0.09	0.06	0.81	0.49	0.20

4.3.1 Manual-switching Gain Scheduling PID Controller

Gain scheduling PID controller designed with multiple sets of PID parameters for the changes in the system. In this case, the manual-switching gain scheduling PID controller was proposed with ten sets of PID parameters which were tuned for multiple loads in the system from 0 kg to 9 kg. The control scheme of the manual-switching gain scheduling PID controller was designed using MATLAB Simulink software as shown in Figure 4.4. This control strategy incorporated two subsystem components embedded with the PID controller (displayed in blue color). The subsystem components were the proportional gains and integral gains for all the available loads for the pneumatic system. The subsystems were designed for proportional and integral gains separately as both parameters obtained different values while tuning. Derivative gains obtained the same values for all the loads as 0.5, so the parameter is constant. The PID gains as indicated in Table 4.3 were applied in the subsystems of the control scheme. The structure of the proportional gain subsystem and integral gain subsystem is designed with the multiport switch in MATLAB Simulink as presented in Figure 4.5 and Figure 4.6 respectively. The load input (displayed in green color) is the remote component of the controller to key in the load weight manually according to the system. Furthermore, the pneumatic system transfer functions as indicated in Table 4.1 from 0kg to 9kg were used in the control scheme accordingly. A step form of signal generator discussed in section 5.2 was used as the input signal.

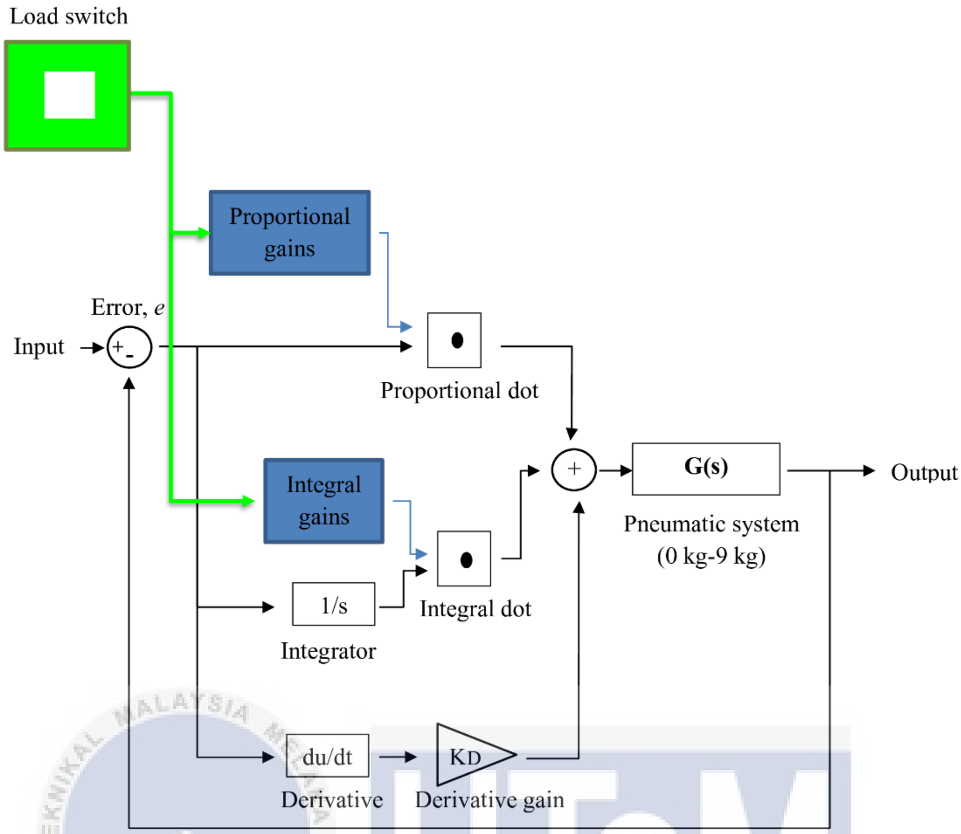

Figure 4.4: Structure of Manual-switching Gain Scheduling PID Controller

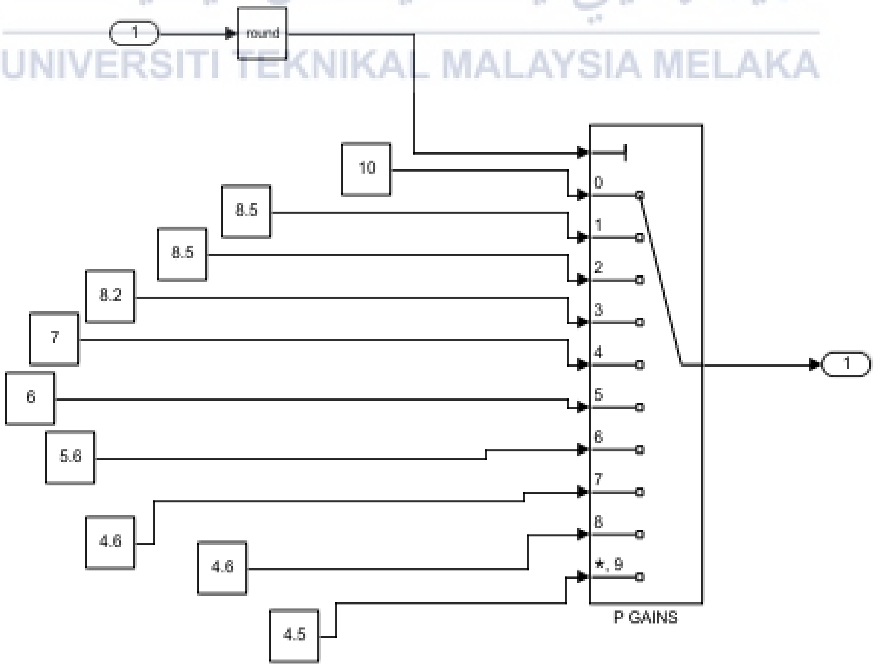

Figure 4.5: Structure of Proportional Gains Subsystem

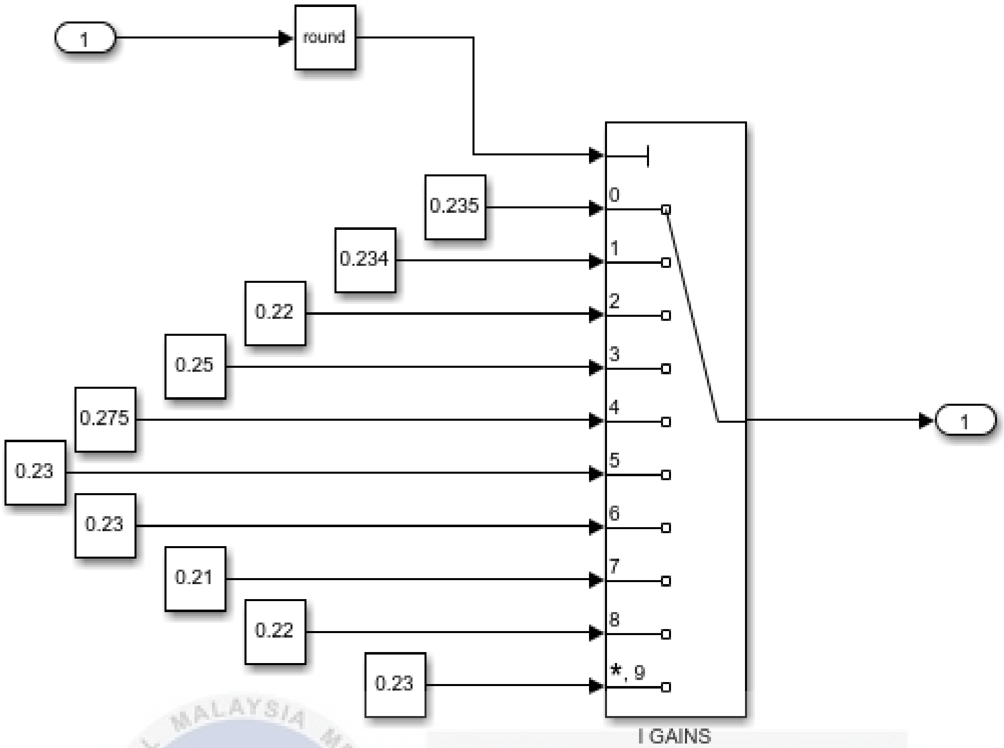

Figure 4.6: Structure of Integral Gains Subsystem

4.3.2 Auto-switching Gain Scheduling PID Controller

Auto-switching gain scheduling PID controller structure modified and updated from the manual-switching gain scheduling PID controller to achieve better performance of the system in the terms of stability with the changes of load in the run. The control scheme of the auto-switching gain scheduling PID controller is illustrated in Figure 4.7. This control strategy is designed with the same type of subsystems as in the manual-switching gain scheduling PID controller presented in Figure 4.5 and Figure 4.6. The remote component of the controller was the modified part of this controller. The manual load input of the previous controller was replaced with an auto switch (displayed in yellow color) in the control scheme.

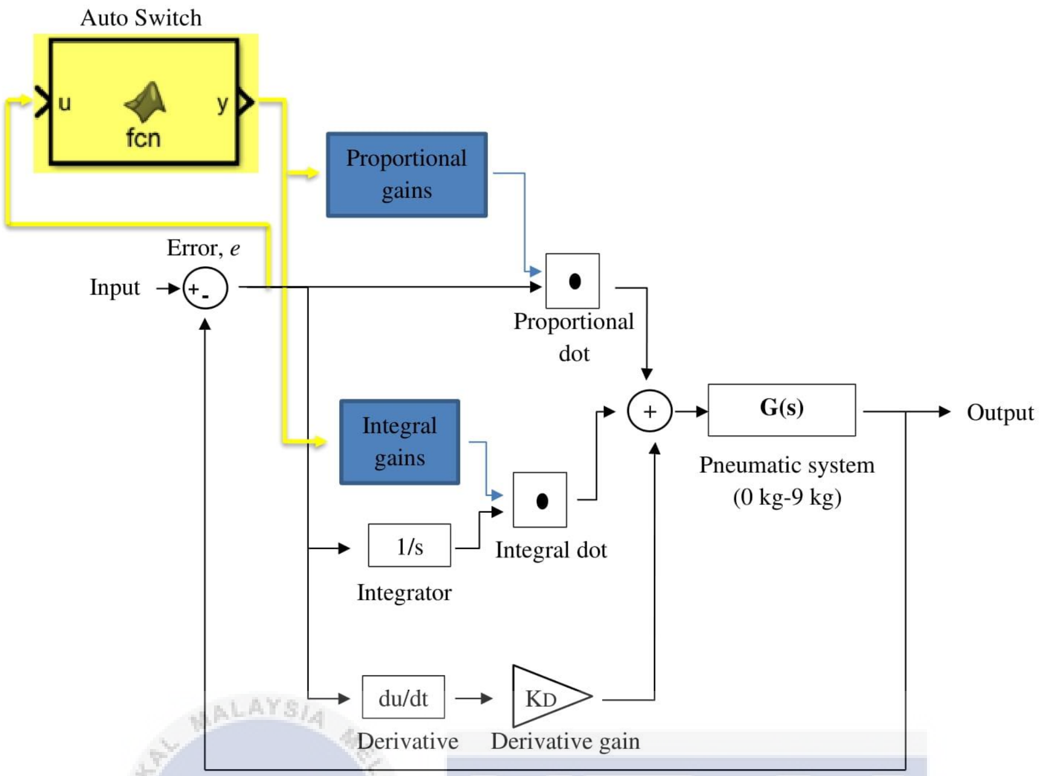

Figure 4.7: Structure of Auto-switching Gain Scheduling PID Controller

The auto switch is designed with the MATLAB Function component which transforms the generated program in MATLAB Editor to the function of MATLAB Simulink. The program generated in MATLAB Editor was by considering the error of the system for gain scheduling. There were 4 conditions to be taken into account to generate the program as shown in Table 4.4 below. There were also 6 different outcome possibilities of 'if' and 'and' cases followed by the 4 conditions but as presented in Table 4.5 below. The only gain of proportional taken count as it has the largest influence in the error of the controller while integral has very minor, and derivative has no influence on the error of the controller as both has a minimum and no difference in values respectively.

Table 4.4: Conditions of Error and Proportional Gains

Conditions	**Error**	**K_P**
1	Small	Small
2	Small	Large
3	Large	Small
4	Large	Large

Table 4.5: Outcome Possibilities of Condition Matching

Possibilities	Probabilities of Outcome of ‘if’ cases				
		Condition A		Condition B	Outcome
1		E=small; K_P=small		E=small; K_P=large	Same error
2		E=small; K_P=small		E=large; K_P=small	Same K_P
3	**‘If’**	E=small; K_P=small	**‘and’**	E=large; K_P=large	Different error & K_P
4		E=small; K_P=large		E=large; K_P=small	Different error & K_P
5		E=small; K_P=large		E=large; K_P=large	Same K_P
6		E=large; K_P=small		E=large; K_P=large	Same error

The possibilities with the outcome of the same error such as Possibility 1 and Possibility 2 were eliminated from the 6 possibilities because there will be no need to switch gains in gain scheduling if the errors of the system are constant. Similarly, Possibility 2 and Possibility 5 were eliminated as they provide the same gains of proportional where it takes as conventional PID controller; there is no function for gain scheduling. So, Possibility 3 and Possibility 4 are taken under consideration for generating the program coding of MATLAB Function. Possibility 3 is about using a larger value of proportional gains during large errors and a smaller value of proportional gains during small errors while Possibility 4 illustrates the usage of larger proportional gains during small errors and smaller values during large errors. The program of MATLAB Function generated as shown in Figure 4.8 Program 1 represented Possibility 3 and Figure 4.9 Program 2 represented Possibility 2. The letter ‘u’ in the program represented error while ‘f’ represented the address number of port in multiport switch of subsystems in Figure 4.5 and Figure 4.6 in section 4.3.1. Both programs of MATLAB Function run experimentally 5 times to record their average of Integral Absolute Error (IAE) for evaluation purposes as presented in Table 4.6. The lower the average IAE, the better the program to be used as the auto switch of the gain scheduling PID controller.

```
function y = fcn(u)

if abs(u) < 0.2
        f =9

elseif abs(u) < 0.4
        f =8

elseif abs(u) < 0.6
        f =7

elseif abs(u) < 0.8
        f =6

elseif abs(u) < 1.0
        f =5

elseif abs(u) < 1.2
        f =4

elseif abs(u) < 1.4
        f =3

elseif abs(u) < 1.6
        f =2

elseif abs(u) < 1.8
        f =1

else
        f =0

            end
y = f;
```

Figure 4.8: Program Coding 1 (for Possibility 3)

```
function y = fcn(u)

if abs(u) < 0.2
     f = 0

elseif abs(u) < 0.4
         f = 1

elseif abs(u) < 0.6
         f = 2

elseif abs(u) < 0.8
         f = 3

elseif abs(u) < 1.0
         f = 4

elseif abs(u) < 1.2
         f = 5

elseif abs(u) < 1.4
         f = 6

elseif abs(u) < 1.6
         f = 7

elseif abs(u) < 1.8
         f = 8

else
         f = 9

            end

y = f;
```

Figure 4.9: Programs Coding 2 (for Possibility 4)

Table 4.6: Average IAE of Programing

Program coding	IAE for Five Runs					Average IAE
	1	2	3	4	5	
1	1244	1203	1186	1237	1215	1217.0
2	1047	1063	1092	1035	1061	1059.6

Based on the result in Table 4.6, program coding 2 gives a lower average IAE value which means it is better than program coding 2. Therefore, programing coding 2 as in Figure 4.9 which represents larger values of proportional gain during small errors was selected as the auto switch for Auto-switching Gain Scheduling PID Controller. So, the auto switch will switch to the suitable gains automatically by referring to the errors of the system while running.

4.4 Summary

In summary, Chapter 4 illustrates a step-by-step procedure for the design of three types of controllers, namely, PID controller, manual-switching gain scheduling PID controller, and auto-switching gain scheduling PID controller. These controllers were designed and implemented numerically to develop the precise positioning performance of the pneumatic system. The novelty of the auto-switching gain scheduling PID controller lies in its control scheme itself in which a program-based switch generated from MATLAB Function is added to the controller to make gain selection adaptive to the error of the system. The main philosophy of the auto-switching gain scheduling PID controller approach is the selection of the gain embedded with the error of the system. The auto switch component of the controller is capable to select between any of the proportional gains and integral gains based on different values of error which could switch the gains on the run of the system. Results and discussion are discussed in the next chapter.

CHAPTER 5
RESULTS AND DISCUSSION

5.1 Introduction

This chapter emphasizes the input signal which defines the desired output, unit conversion of the system, results of the simulation, and experimental obtained using three different designed controllers named; (i) Proportional-Derivative-Integral (PID) controller, (ii) Manual-switching Gain Scheduling Proportional-Derivative-Integral (Manual-switching Gain Scheduling PID) controller, (iii) Auto-switching Gain Scheduling Proportional-Derivative-Integral (Auto-switching Gain Scheduling PID) controller. These controllers were tested with the variance of loads available for the system; from 0kg to 9kg of whole numbers. Each controller tested for three types of analyses: (i) precise positioning analysis, (ii) transient response analysis, and (iii) Integral Absolute Error (IAE). Moreover, the results of simulated and experimental works are presented and discussed according to four main sections results of PID controller, results of manual-switching gain scheduling PID controller, results of auto-switching gain scheduling PID controller, and comparisons of precise positioning and integral absolute error between the three designed controllers.

The first section presents the input signal for simulation and experimental tests. The second section presents the conversion of the unit of the pneumatic system for positioning measurements. Furthermore, the next three sections illustrate the results of three analyses for all the designed controllers respectively. Subsequently, in the last section, the comparison of three controllers is discussed in terms of positioning analysis, transient response, and integral absolute error analysis.

5.2 Input Signal

In this section, the use of an input signal for the three designed controllers; PID controller, manual switching gain scheduling PID controller, and auto-switching gain scheduling PID controller was discussed. A step form generated from the signal generator in MATLAB Simulink was used to test the effectiveness of the three designed controllers' performance. In the control system, the input is considered as the desired output to validate the positioning performance by comparing it to the actual output. The step input consisted of two parameters: step time and voltage. The setup of a step input is shown in Figure 5.1 below. The total time taken for the positioning evaluation was 50 seconds with a sample time of 0.01 seconds. The initial value is just to adjust the position of the actuator to the center point of the system before the step time. So, all the analysis will be made after the step time which is on the 20th second of the total time of the test. The pattern of the input signal is presented in Figure 5.2 and the details of the input signal is tabulated in Table 5.1 below.

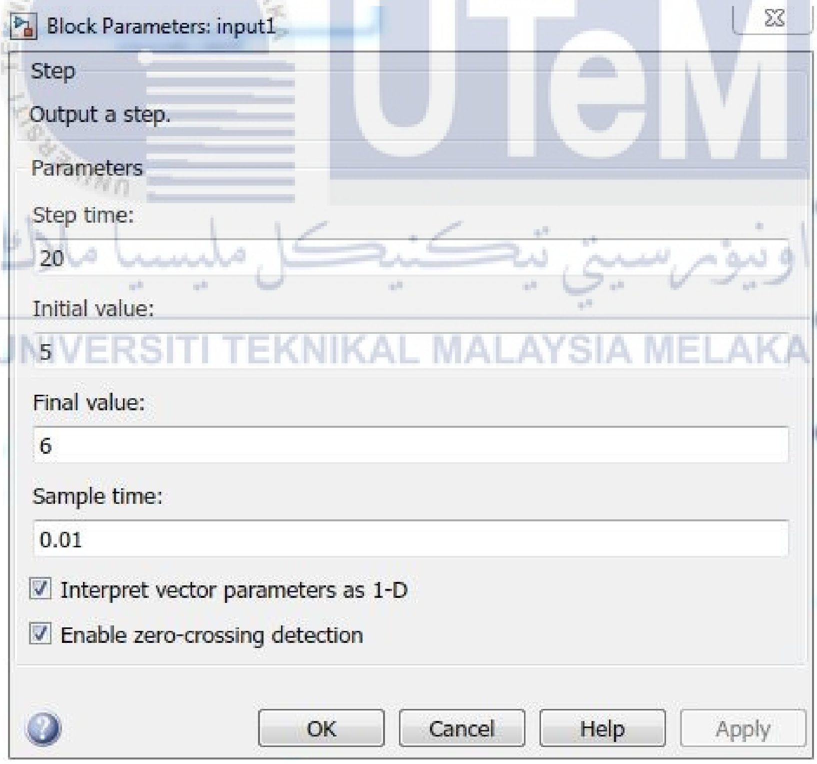

Figure 5.1 Step Input Block Setup

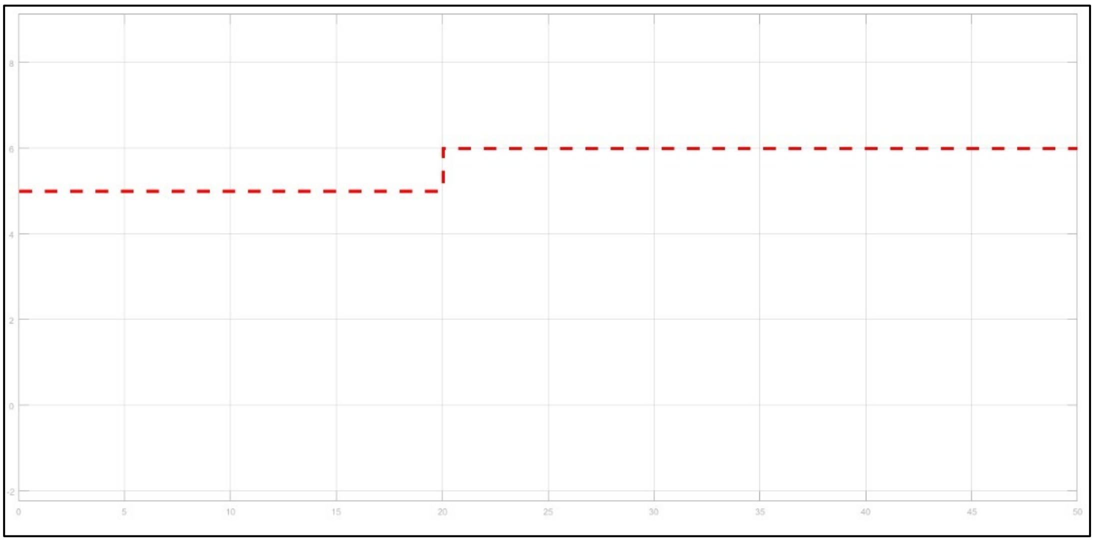

Figure 5.2 Pattern of the Input Signal

Table 5.1: Details of Input Signal

Input signal	
Type of input signal	Step input
Total time taken	50 seconds
Sample time	0.01 second
Step time	20
Initial voltage	5V
Final voltage	6V

5.3 Unit Conversion

In this section, the unit and its conversion were discussed. The input of the pneumatic system is configured in the unit of voltage while the positioning of the system can measure using units of displacement. The hardware setup consists of an encoder to measure positioning analysis in voltage which needs to convert to the unit of displacements as shown in detail on the second page of the data sheet of the actuator which is attached in Appendix A. Thus, the unit conversion was made through manual derivatives. Units of displacement consisted of millimeters, centimeters, meters, and kilometers. In this project, unit of millimeter was chosen as the range of the system's displacement is small. The specifications of the pneumatic actuator model ACTB-200-s01200 manufactured by Enfield Technology as presented in Table 5.2 of the system were taken to account for the unit conversion process(Kamarudin et al., 2018). The specification sheet of the pneumatic actuator was attached in Appendix A.

Table 5.2: Specification of the Pneumatic Actuator

Specification of the Pneumatic Actuator	
The total voltage of the actuator	10V
The total distance of the actuator	304.8 mm

So, the specifications were used to generate a conversion equation for the system. The conversion of the unit from the voltage (V) to millimeters (mm) was made as continuous equations from Equation 5.1 until Equation 5.3 below.

$$10\ \text{V} = 304.8\ \text{mm} \quad (5.1)$$

$$1\ \text{V} = \frac{304.8\ mm}{10\ V} \quad (5.2)$$

$$\varkappa\ \text{V} = \varkappa\ \text{V}\left(\frac{304.8\ mm}{10\ V}\right) \quad (5.3)$$

Along with the unit conversion, an adjustment was made in the positioning of the actuator, so the center of the actuator considers the origin point of the system as in Equation 5.4 below.

$$\varkappa\ \text{V} = \varkappa\ \text{V}\left(\frac{304.8\ mm}{10\ V}\right) - \left(\frac{304.8\ mm}{2}\right) \quad (5.4)$$

According to the input signal details as tabulated in Table 5.1 in section 5.2, the final voltage is 6V starting from the 20th second of the system response. The unit conversion of final voltage to millimeters before the adjustment made and after the adjustment made are as the Equation 5.5 and Equation 5.6 respectively. Unit conversion of final voltage after the adjustment as in Equation is used for all the analysis processes.

$$6\text{V}\left(\frac{304.8\ mm}{10\ V}\right) = 182.88\ mm \quad (5.5)$$

$$6V\left(\frac{304.8\,mm}{10\,V}\right)-\left(\frac{304.8\,mm}{2}\right)=30.48\,mm \tag{5.6}$$

5.4 Precise Positioning Analysis

This section solely presents the result of three designed controllers: PID controller, manual-switching gain scheduling PID controller, and auto-switching gain scheduling PID controller based on steady-state error for precise positioning analysis. The steady state of the controllers which is considered the actual output recorded the average position in the final 10 seconds of the output if it reached a steady state within the total time which is 50 seconds. The controller is considered unstable if the system was unable to reach steady-state within 50 seconds. The steady-state errors were then calculated from the difference between the desired output and actual output as presented in Equation 5.7. In addition, the percentage of steady-state errors were calculated using Equation 5.8. The percentage of steady-state error is a relative maximum steady-state error produced corresponding to the actual output of the input signal. The sample graph of simulation and experimental with the steady-state recorded region is shown in Figure 5.3 and Figure 5.4 respectively. The steady-state error results for PID controller, manual switching gain scheduling PID controller, and auto-switching gain scheduling PID controller are presented in section 5.4.1, section 5.4.2, and section 5.4.3 respectively.

$$\text{Steady state error (mm)} = \text{Desired output (mm)} - \text{actual output (mm)} \tag{5.7}$$

$$\text{\% Steady state error} = \left(\frac{\text{Steady−state error}}{\text{Actual output}}\right) \times 100 \tag{5.8}$$

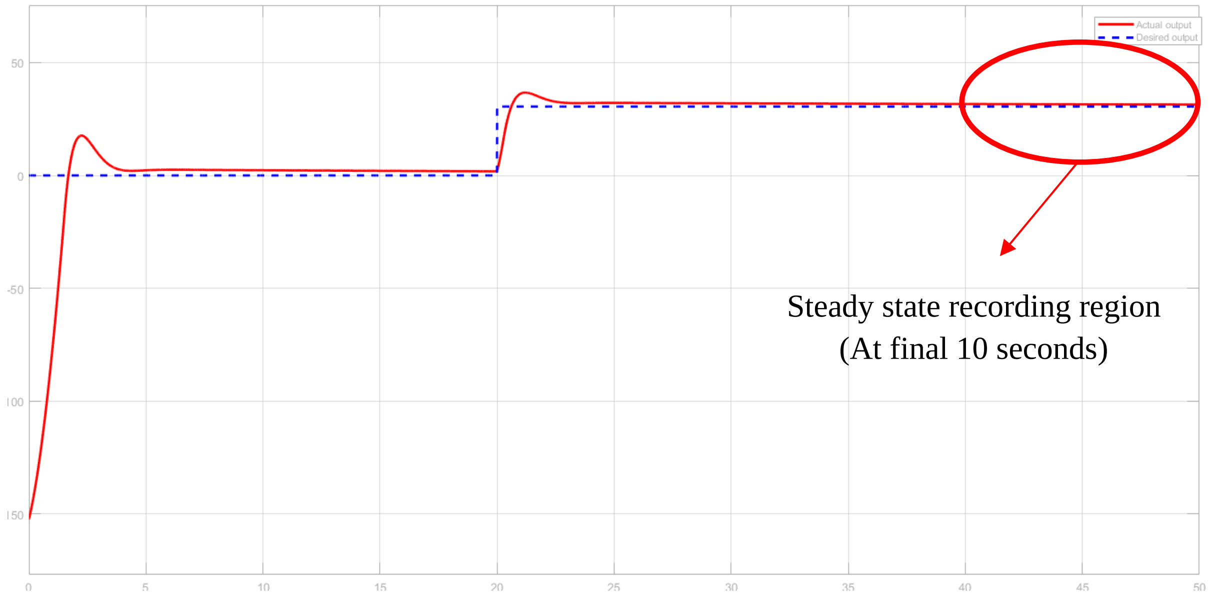

Figure 5.3 Sample Graph of Simulation Test for Steady State

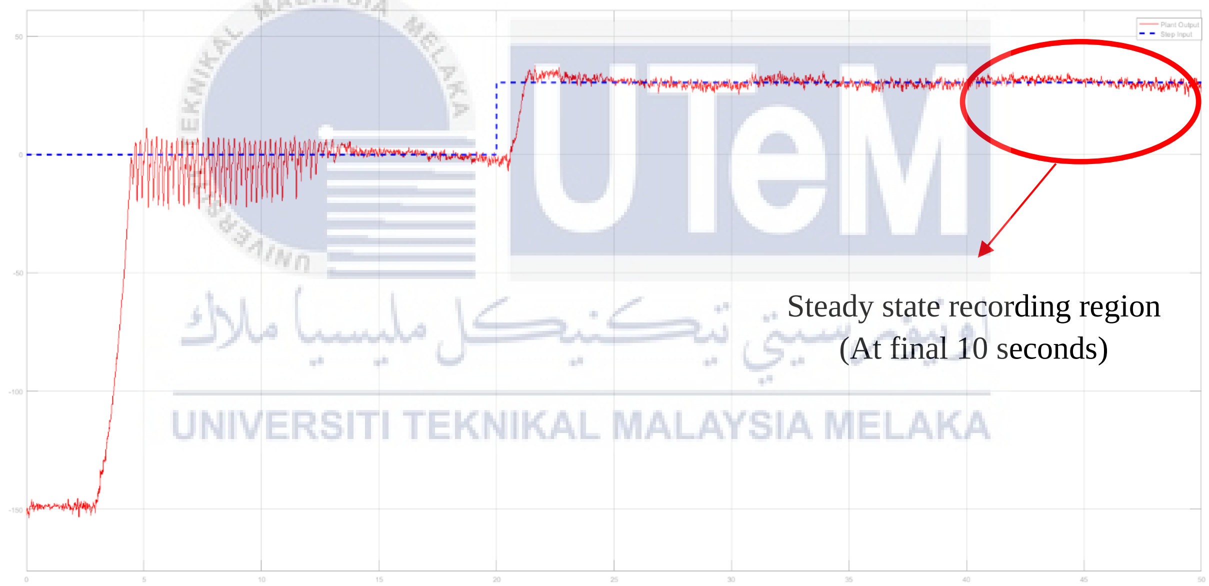

Figure 5.4 Sample Graph of Experimental Test for Steady State

5.4.1 PID Controller

The simulation and experimental results of precise positioning analysis for the PID controller are presented in section 5.4.1.1 and section 5.4.1.2 respectively.

5.4.1.1 Simulation Results

The simulations of the PID controller were performed using MATLAB Simulink software. A control structure of the designed PID controller is presented in Figure 4.2 in section 4.2. The gain values of the PID controller as tabulated in Table 4.2 in section 4.2 were used. Furthermore, transfer functions of 0kg until 9kg from Equation 4.1 until Equation 4.10 in Table 4.1 of section 4.1 were used as the pneumatic system of the structure for the testing of system controllers with all the available loads accordingly.

The simulation results of precise positioning analysis for PID controller are tabulated in Table 5.3 below. The steady-state recorded as the average of positions at the final 10 seconds of the total time as shown in Figure 5.3 of section 5.4, followed by the steady-state error which was obtained from the difference between the average of actual output (steady-state) and the desired output at the final 10 seconds as stated in Equation 5.5, in the unit of millimeters. In addition, the percentage of steady-state errors were calculated using Equation 5.6 in section 5.4.

Table 5.3: Precise Positioning Simulation Results of PID Controller

Precise positioning	Loads (kg)									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Desired output (mm)	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48
Actual output(mm)	30.48	30.62	Unstable							
Steady state error (mm)	0	0.14								
% Steady state error	0	0.46								

Desired output is 30.48 mm which is equivalent to 6 Voltages for simulation tests for PID controller without load and with external rounded loads of 1kg until 9kg. From the table of simulation results above, the PID controller gives zero steady-state error without a load in the system, and it gives 0.14 of steady-state error with 1kg of external load. The system was unstable with external loads of more than 1kg for simulation of the PID controller.

5.4.1.2 Experimental Results

The PID controller was tested using an experimental setup shown in Figure 3.3 in section 3.2. The experimental work was conducted using MATLAB Simulink software to run the system according to the input signal. Similar to simulation works, the PID parameters stated in Table 4.2 in section 4.2 were used for all the available loads for the system. In addition, there were changes in loads of the system in the experimental setup for testing each load. The experimental results of precise positioning analysis for PID controller are tabulated in Table 5.4 below.

The steady-state recorded as the average of positions at the final 10 seconds of the total time as shown in Figure 5.4 of section 5.4, followed by the steady-state error which was obtained from the difference between the average of actual output (steady-state) and the desired output at the final 10 seconds as stated in Equation 5.5, in the unit of millimeters. In addition, the percentage of steady-state errors were calculated using Equation 5.6 in section 5.4.

Table 5.4: Precise Positioning Experimental Results of PID Controller

Precise positioning	Loads (kg)									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Desired output (mm)	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48
Actual output (mm)	30.43	27.84	Unstable							
Steady state error (mm)	0.03	2.64								
% Steady state error	0.1	9.5								

Desired output is 30.48 mm which is equivalent to 6 Voltages for experimental tests for PID controller without load and with external rounded loads of 1kg until 9kg. From the table of the experimental result above, the PID controller gives a minor steady-state error without a load in the system which is equivalent to 0.03 mm, and it gives an unacceptable value of steady-state error with 1kg of external load which is equivalent to 2.64 mm. The system was unstable with external loads of more than 1kg for the experimental PID controller.

5.4.2 Manual-switching Gain Scheduling PID Controller

The results of precise positioning analysis for the manual-switching gain scheduling PID controller through simulation and experimental works are presented in section 5.4.2.1 and section 5.4.2.2 respectively.

5.4.2.1 Simulation Results

Simulation of the manual-switching gain scheduling PID controller was performed using MATLAB Simulink software, which is the same software used with the PID controller. In MATLAB Simulink software, a control structure of the manual-switching gain scheduling PID controller was designed as shown in Figure 4.4 in section 4.3.1. The manual-switching gain scheduling PID controller consisted of two subsystems as proportional gains and integral gains as presented in Figure 4.5 and Figure 4.6 respectively in section 4.3.1. In both subsystems, the gains of proportional and the gains of integral as tabulated in Table 4.3 in section 4.3 were injected into a multiport switch component according to the loads available in the system, which are from 0kg to 9kg of the whole number of loads. The value of the derivative gain of the system is the same for all loads which are 0.5. In addition, transfer functions of 0kg until 9kg as Equation 4.1 until Equation 4.10 in Table 4.1 of section 4.1 were used as the pneumatic system of the structure for the testing of system controllers without all loads accordingly. So, different transfer functions are used for different inputs of load in the load switch. Thus, different input of load in the load switch differs the selection of the gains in the subsystem for the controller.

The simulation results of precise positioning analysis for manual-switching gain scheduling PID controller are tabulated in Table 5.5 below. The steady-state was recorded as the average of positions at the final 10 seconds of the total time as shown in Figure 5.4 of section 5.4. Moreover, the steady-state error was obtained from the difference between the average of actual output also known as steady-state, and the desired output at the final 10 seconds as stated in Equation 5.5, in the unit of millimeters. In addition, the percentage of steady-state errors were calculated using Equation 5.6 in section 5.4.

Table 5.5: Precise Positioning Simulation Results of Manual-switching Gain Scheduling PID Controller

Precise positioning	Loads (kg)									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Desired output (mm)	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48
Average Steady state (mm)	30.48	30.48	30.48	30.49	30.51	30.52	30.53	30.55	30.56	30.56
Steady state error (mm)	0	0	0	0.01	0.03	0.04	0.05	0.07	0.08	0.08
% Steady state error	0	0	0	0.03	0.10	0.13	0.16	0.23	0.26	0.26

Desired output is 30.48 mm which is equivalent to 6 Voltages for simulation tests for manual-switching gain scheduling PID controller without load and with external rounded loads of 1kg until 9kg. From the table of simulation results above, the manual-switching gain scheduling PID controller gives zero steady-state error without load and with external loads of 1kg and 2kg in the system. Moreover, the controller gives values of steady-state error in the range from 0.01mm to 0.08mm with external loads from 3kg to 9kg. The system was stable for all the available loads with manual-switching gain scheduling PID controller for simulation works.

5.4.2.2 Experimental Results

The manual-switching gain scheduling PID controller was tested using an experimental setup shown in Figure 3.3 in section 3.2. The experimental work was conducted using MATLAB Simulink software to run the system according to the input signal. Similar to simulation works, the PID parameters stated in Table 4.3 in section 4.2 were used according to the loads carried by the actuator of the system which was already injected into the subsystem according to the number of loads. The parameters of PID gains differ for various loads. The experimental results of precise positioning analysis for manual-switching gain scheduling PID controller are tabulated in Table 5.6 below.

The steady-state was recorded as the average of positions at the final 10 seconds of the total time as shown in Figure 5.4 of section 5.4. The steady-state error was obtained from the difference between the average actual output (steady-state) and the desired output at the final 10 seconds as stated in Equation 5.5, in the unit of millimeters. In addition, the percentage of steady-state errors were calculated using Equation 5.6 in section 5.4.

Table 5.6: Precise Positioning Experimental Results of Manual-switching Gain Scheduling PID Controller

Precise positioning	Loads (kg)									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Desired output (mm)	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48
Average Steady state (mm)	30.48	30.47	30.45	30.48	30.52	30.44	30.51	30.52	30.47	30.48
Steady state error (mm)	0	0.01	0.03	0	0.04	0.04	0.03	0.04	0.01	0
% Steady state error	0	0.03	0.10	0	0.13	0.13	0.10	0.13	0.03	0

Desired output is 30.48 mm which is equivalent to 6 Voltages for experimental tests for manual-switching gain scheduling PID controller without load and with external rounded loads of 1kg until 9kg. From the table of the experimental result above, the manual-switching gain scheduling PID controller gives zero steady-state error without load, with external loads of 3kg and 9kg in the system. The controller gives values of steady-state error in the range from 0.01mm to 0.04mm for other external loads in the system overall. The system was stable for all the available loads with manual-switching gain scheduling PID controller for experimental works.

5.4.3 Auto-switching Gain Scheduling PID Controller

The results of precise positioning analysis for the manual-switching gain scheduling PID controller through simulation and experimental works are presented in section 5.4.3.1 and section 5.4.3.2 respectively.

5.4.3.1 Simulation Results

Simulation of the auto-switching gain scheduling PID controller was performed using MATLAB Simulink software, in which the same software was used with the PID controller and manual-switching gain scheduling PID controller. In MATLAB Simulink software, a control structure of the auto-switching gain scheduling PID controller was designed as shown in Figure 4.7 in section 4.3.2. The auto-switching gain scheduling PID controller consisted of two subsystems similarly to the manual-switching gain scheduling PID controller; proportional gains and integral gains as presented in Figure 4.5 and Figure 4.6 respectively in section 4.3.1. In both subsystems the gains proportional and the gains of integral used as the same as in manual-switching gain scheduling PID controller. The value of the derivative gain of the system is the same for all loads which are 0.5. In addition, transfer functions of 0kg until 9kg as Equation 4.1 until Equation 4.10 in Table 4.1 of section 4.1 were used as the pneumatic system of the structure for the testing of system controllers without load and with all available loads accordingly. In this controller, the error of the system influenced the selection of gains as the program of the MATLAB Function as presented in Figure 4.9 in section 4.3.2 connected as the switch for both subsystems.

The simulation results of precise positioning analysis for auto-switching gain scheduling PID controller are tabulated in Table 5.7 below. The steady-state was recorded as the average of positions at the final 10 seconds of the total time as shown in Figure 5.4 of section 5.4. Moreover, the steady-state error was obtained from the difference between the average of actual output also known as steady-state, and the desired output at the final 10 seconds as stated in Equation 5.5, in the unit of millimeters. In addition, the percentage of steady-state errors were calculated using Equation 5.6 in section 5.4.

Table 5.7: Precise Positioning Simulation Results of Auto-switching Gain Scheduling PID Controller

Precise positioning	Loads (kg)									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Desired output (mm)	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48
Average Steady state (mm)	30.48	30.47	30.48	30.48	30.48	30.50	30.49	30.46	30.48	30.47
Steady state error (mm)	0	0.01	0	0	0	0.02	0.01	0.02	0	0.01
% Steady-state error	0	0.03	0	0	0	0.07	0.03	0.07	0	0.03

Desired output is 30.48 mm which is equivalent to 6 Voltages for simulation tests for auto-switching gain scheduling PID controller without load and with external rounded loads of 1kg until 9kg. From the table of simulation results above, the auto-switching gain scheduling PID controller gives zero steady-state error without load and with external loads of 2kg,3kg,4kg, and 7kg in the system. Moreover, the controller gives values of steady-state error in the range from 0.01mm to 0.02mm with various external loads between 1kg and 9kg. The system was stable for all the available loads with auto-switching gain scheduling PID controller for simulation works.

5.4.3.2 Experimental Results

The auto-switching gain scheduling PID controller was tested using an experimental setup shown in Figure 3.3 in section 3.2. The experimental work was conducted using MATLAB Simulink software to run the system according to the input signal. Similar to simulation works, the PID parameters stated in Table 4.3 in section 4.2 were used in the subsystems of the controller while the derivative gain is 0.5. The parameters of PID gains differ for various loads. The experimental results of precise positioning analysis for auto-switching gain scheduling PID controller are tabulated in Table 5.8 below.

The steady-state was recorded as the average of positions at the final 10 seconds of the total time as shown in Figure 5.4 of section 5.4. The steady-state error was obtained from the difference between the average actual output (steady-state) and the desired output at the final 10 seconds as stated in Equation 5.5, in the unit of millimeters. In addition, the percentage of steady-state errors were calculated using Equation 5.6 in section 5.4.

Table 5.8: Precise Positioning Experimental Results of Auto-switching Gain Scheduling PID Controller

Precise positioning	Loads (kg)									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Desired output (mm)	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48	30.48
Average Steady state (mm)	30.47	30.48	30.48	30.49	30.48	30.49	30.48	30.48	30.48	30.49
Steady-state error (mm)	0.01	0	0	0.01	0	0.01	0	0	0	0.01
% Steady-state error	0.03	0	0	0.03	0	0.03	0	0	0	0.03

Desired output is 30.48 mm which is equivalent to 6 Voltages for experimental tests for auto-switching gain scheduling PID controller without load and with external rounded loads of 1kg until 9kg. From the table of the experimental result above, the auto-switching gain scheduling PID controller gives zero steady-state error with external loads of 1kg, 2kg, 4kg, 6kg, 7kg, and 8kg in the system. The controller gives values of steady-state error 0.01mm for other external loads in the system. The system was stable for all the available loads with auto-switching gain scheduling PID controller for experimental works. By observation, the auto-switching gain scheduling PID controller switches the gain parameter values by referring to the error of the whole system, not loads of the system. Thus, it shows the auto switch generated from the program of MATLAB Function is supporting the controller.

5.5 Transient Response Analysis

This section presents the simulation and experimental results of transient response analysis for three designed controllers: PID controller, manual-switching gain scheduling PID controller, and auto-switching gain scheduling PID controller in section 5.5.1, section 5.5.2, and section 5.5.3 respectively. As observed the simulation results of the controllers, the responses were counted as critically damped responses as the responses reached steady state without oscillating and underdamped(Paine & Sentis, 2015). The transient responses of the controllers recorded only after the 20th second of whole input signal which is for 50 seconds as first 20 seconds of the input signal is to adjust the position of the actuator to the center of the system. The transient response analysis contains six elements: (i) maximum overshoot, (ii) percentage overshoot, (iii) peak time, (iv) rise time, (v) settling time at 2%, and settling time at 5%. Value of maximum overshoot recorded the point that the response reached the peak position for simulation and experimental work of the controllers as shown in Figure 5.5 and Figure 5.6 respectively. Percentage of overshoot of the responses were calculated using Equation 5.9. Peak time is the time that recorded the maximum overshoot of the response. The rise time was defined as a time take for the response to rise from 5% to 95% of its steady state value as the responses were declared as critically damped system(Elmore, 2004). The settling time was defined as the time required for the response to reach the steady state within the given tolerance which are 2% and 5%. The position range of 2% tolerance for settling time was calculated using Equation 5.10 and followed by Equation 5.11 while the position range of 5% tolerance for settling time was calculated using Equation 5.12 followed by Equation 5.13.

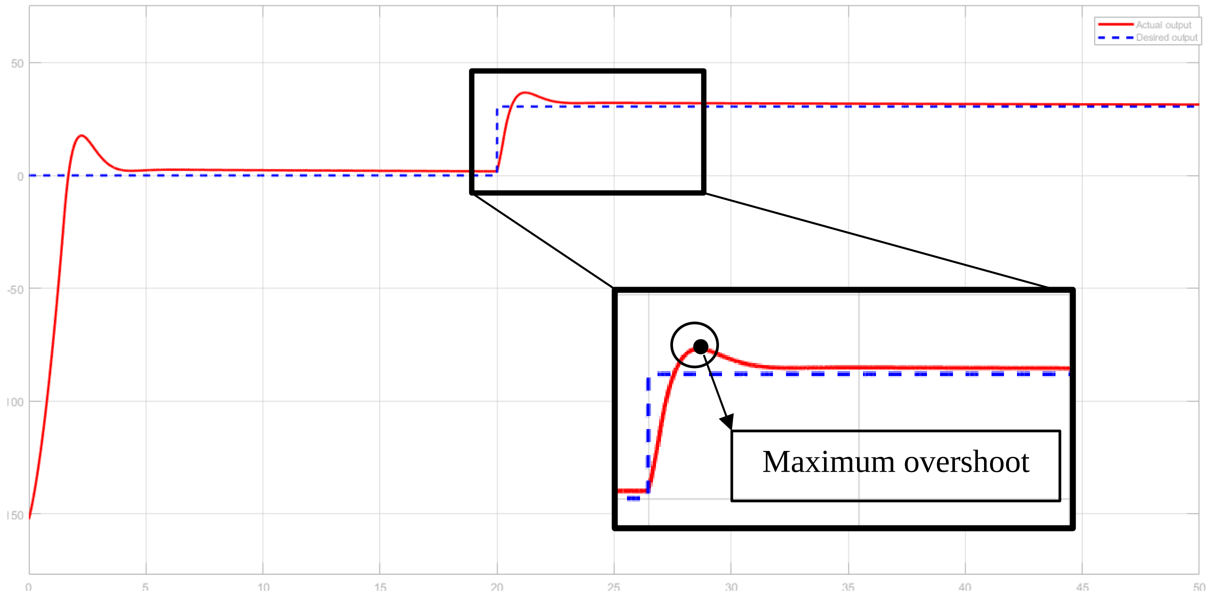

Figure 5.5 Sample Graph of Simulation Test for Maximum Overshoot

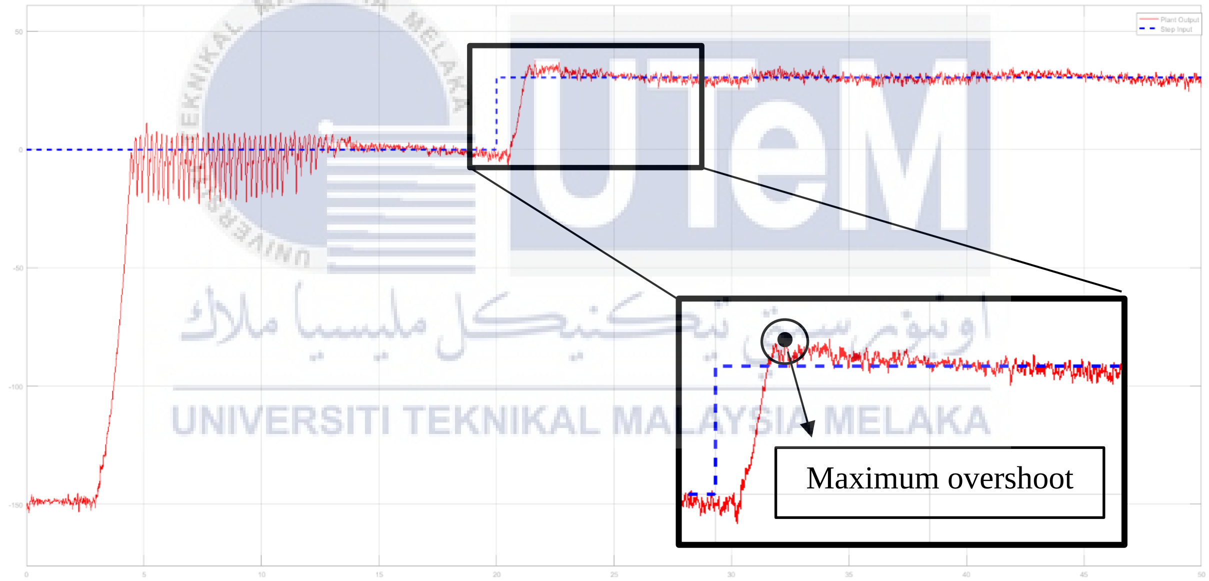

Figure 5.6 Sample Graph of Experimental Test for Maximum Overshoot

$$\% \text{ Overshoot} = \left(\frac{Maximum\ Overshoot - Desired\ Output}{Desired\ Output}\right) \times 100\% \quad (5.9)$$

Position range of 2% tolerance as follows:

30.48mm + 2% = 30.50mm (Upper limit) (5.10)

30.48mm – 2% = 30.46mm (Lower limit) (5.11)

Position range of 5% tolerance as follows:

30.48mm + 5% = 30.53mm (Upper limit) (5.12)

30.48mm – 5% = 30.43mm (Lower limit) (5.13)

5.5.1 PID Controller

The simulation and experimental results of transient response analysis for the PID controller are presented in section 5.5.1.1 and section 5.5.1.2 respectively.

5.5.1.1 Simulation Results

The simulations of the PID controller were performed using MATLAB Simulink software. A control structure of the designed PID controller as presented in Figure 4.2 in section 4.2. The gain values of the PID controller as tabulated in Table 4.2 in section 4.2 were used. Furthermore, transfer functions of 0kg until 9kg as from Equation 4.1 until Equation 4.10 in Table 4.1 of section 4.1 were used as the pneumatic system of the structure for the testing of system controllers with all the available loads accordingly. The results of transient response for simulation of PID controller are as in Table 5.9. The transient response of system loads of 2kg and above were not able to record as the system was unstable for the loads with the specific gain parameters.

Table 5.9: Transient Response Simulation Results of PID Controller

System Response		Loads of the system (kg)									
		0	1	2	3	4	5	6	7	8	9
Maximum overshoot		37.65	38.97	Unstable							
% Overshoot		23.52	27.85								
Peak time (thsec)		21.98	23.04								
Rise time, T_r (sec)		1.99	2.85								
Settling time, T_s (thsec) at	2%	24.39	30.81								
	5%	22.67	25.33								

5.5.1.2 Experimental Results

The PID controller was tested using an experimental setup shown in Figure 3.3 in section 3.2. The experimental work was conducted using MATLAB Simulink software to run the system according to the input signal. Similar to simulation works, the PID parameters stated in Table 4.2 in section 4.2 were used for all the available loads for the system. In addition, there were change in the loads of the system in the experimental setup for testing of each load. The experimental results of transient response analysis for PID controller are as tabulated in Table 5.10 below. The transient response of system loads more than 1kg were not able to record as the system was unstable for the loads with the specific gain parameters.

Table 5.10: Transient Response Experimental Results of PID Controller

System Response		Loads of the system (kg)									
		0	1	2	3	4	5	6	7	8	9
Max overshoot (mm)		37.73	49.66	Unstable							
% Overshoot		23.79	62.93								
Peak time (thsec)		21.94	23.52								
Rise time, T_r (sec)		2.14	3.71								
Settling time, T_s (thsec) at	2%	-	-								
	5%	24.87	28.14								

5.5.2 Manual Switching Gain Scheduling PID Controller

The simulation and experimental results of transient response analysis for the manual-switching gain scheduling PID controller are presented in section 5.5.2.1 and section 5.5.2.2 respectively.

5.5.2.1 Simulation Results

Simulation of the manual-switching gain scheduling PID controller was performed using MATLAB Simulink software, in which the same software used with the PID controller. In MATLAB Simulink software, a control structure of the manual-switching gain scheduling PID controller was designed as shown in Figure 4.4 in section 4.3.1. The manual-switching gain scheduling PID controller consisted of two subsystems as proportional gains and integral gains as presented in Figure 4.5 and Figure 4.6 respectively in section 4.3.1. In both subsystem the gains of proportional and the gains of integral as tabulated in Table 4.3 in section 4.3 were injected in a multiport switch component according to the loads available in the system, which are from 0kg until 9kg of whole number of loads. The value of derivative gain of the system is same for all loads which is 0.5. In addition, transfer functions of 0kg until 9kg as Equation 4.1 until Equation 4.10 in Table 4.1 of section 4.1 were used as the pneumatic system of the structure for the testing of system controllers without all loads accordingly. So, different transfer function used for different input of load in load switch. Thus, different input of load in load switch differs the selection of the gains in the subsystem for the controller. The simulation results of transient response analysis for manual-switching gain scheduling PID controller are as tabulated in Table 5.11 below.

Table 5.11: Transient Response Simulation Results of Manual-switching Gain Scheduling PID Controller

System Response		**Loads of the system (kg)**									
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Max overshoot (mm)		37.44	38.63	35.97	35.84	37.75	40.26	39.44	38.17	36.86	37.37
% Overshoot		22.83	26.74	18.01	17.59	23.85	32.09	29.40	25.23	20.93	22.60
Peak time (thsec)		21.83	22.78	21.69	21.51	22.37	24.83	24.15	23.72	22.00	22.29
Rise time, T_r (sec)		1.76	2.70	1.48	1.41	2.28	4.53	3.91	3.25	1.67	1.77
Settling time, T_s (thsec) at	**2%**	25.28	26.44	25.05	25.22	26.17	29.84	29.55	27.91	26.02	26.76
	5%	23.04	23.96	22.89	22.68	23.65	28.88	28.20	25.83	24.97	25.07

5.5.2.2 Experimental Results

The manual-switching gain scheduling PID controller was tested using an experimental setup shown in Figure 3.3 in section 3.2. The experimental work was conducted using MATLAB Simulink software to run the system according to the input signal. Similar to simulation works, the PID parameters stated in Table 4.3 in section 4.2 were used according to the loads carried by the actuator of the system which was already injected in the subsystem according to the number of loads. The parameters of PID gains differ for various loads. The experimental results of transient response analysis for manual-switching gain scheduling PID controller are tabulated in Table 5.12.

Table 5.12: Transient Response Experimental Results of Manual-switching Gain Scheduling PID Controller

System Response		**Loads of the system (kg)**									
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Max overshoot (mm)		37.12	36.98	37.25	37.28	38.66	39.04	39.77	36.49	37.33	37.58
% Overshoot		21.78	21.33	22.21	22.31	26.84	28.08	30.48	19.72	22.47	23.29
Peak time (thsec)		24.37	24.80	24.14	24.31	24.05	23.87	23.72	25.02	24.90	24.71
Rise time, T_r (sec)		3.72	4.20	3.83	3.61	3.55	3.29	3.74	4.58	4.57	4.07
Settling time, T_s (thsec) at	**2%**	-	-	-	-	-	-	-	-	-	-
	5%	26.11	27.07	25.97	25.99	26.03	25.96	25.66	27.15	27.10	27.02

5.5.3 Auto-switching gain scheduling PID Controller

The simulation and experimental results of transient response analysis for the auto-switching gain scheduling PID controller are presented in section 5.5.3.1 and section 5.5.3.2 respectively.

5.5.3.1 Simulation Results

Simulation of the auto-switching gain scheduling PID controller was performed using MATLAB Simulink software, in which the same software used with the PID controller and manual-switching gain scheduling PID controller. In MATLAB Simulink software, a control structure of the auto-switching gain scheduling PID controller was designed as shown in Figure 4.7 in section 4.3.2. The auto-switching gain scheduling PID controller consisted of two subsystems similarly as manual-switching gain scheduling PID controller; proportional gains and integral gains as presented in Figure 4.5 and Figure 4.6 respectively in section 4.3.1. In both subsystem the gains of proportional and the gains of integral used as the same as in manual-switching gain scheduling PID controller. The value of derivative gain of the system is same for all loads which is 0.5. In addition, transfer functions of 0kg until 9kg as Equation 4.1 until Equation 4.10 in Table 4.1 of section 4.1 were used as the pneumatic system of the structure for the testing of system controllers without load and with all available loads accordingly. In this controller, error of the system influenced the selection of gains as the program of the MATLAB Function as presented in Figure 4.9 in section 4.3.2

connected as the switch for both subsystems. The simulation results of transient response analysis for auto-switching gain scheduling PID controller are as tabulated in Table 5.13 below.

Table 5.13: Transient Response Simulation Results of Auto-switching Gain Scheduling PID Controller

System Response		Loads of the system (kg)									
		0	1	2	3	4	5	6	7	8	9
Max overshoot (mm)		37.24	37.44	37.07	37.90	37.11	38.26	37.93	36.85	37.72	37.22
% Overshoot		22.18	22.83	21.62	24.34	21.75	25.52	24.44	20.90	23.75	22.11
Peak time (thsec)		23.27	23.19	23.22	23.84	23.16	23.77	23.58	23.25	23.46	23.18
Rise time, T_r (sec)		2.92	2.90	2.88	3.39	2.85	3.26	3.04	2.98	3.00	2.81
Settling time, T_s (thsec) at	2%	26.17	27.37	26.64	26.57	26.77	27.85	27.22	26.83	26.94	26.44
	5%	25.51	25.30	25.47	25.59	25.13	26.15	25.90	25.72	25.88	25.51

5.5.3.2 Experimental Results

The auto-switching gain scheduling PID controller was tested using an experimental setup shown in Figure 3.3 in section 3.2. The experimental work was conducted using MATLAB Simulink software to run the system according to the input signal. Similar to simulation works, the PID parameters stated in Table 4.3 in section 4.2 were used in the subsystems of the controller while the derivative gain is 0.5. The parameters of PID gains differ for various loads. The experimental results of transient response analysis for auto-switching gain scheduling PID controller are tabulated in Table 5.14.

Table 5.14: Transient Response Experimental Results of Auto-switching Gain Scheduling PID Controller

System Response		Loads of the system (kg)									
		0	1	2	3	4	5	6	7	8	9
Max overshoot (mm)		36.61	37.04	36.85	37.22	37.34	37.68	36.84	37.16	36.20	36.33
% Overshoot		20.11	21.52	20.90	22.11	22.51	23.62	20.87	21.92	18.77	19.19
Peak time (thsec)		23.57	23.26	23.37	23.10	23.05	22.97	23.42	22.50	23.66	23.52
Rise time,(T_r) (sec)		2.90	2.77	2.84	2.61	2.59	2.32	2.86	2.08	2.98	2.74
Settling time, T_s (thsec) at	**2%**	-	-	-	-	-	-	-	-	-	-
	5%	25.27	25.15	25.22	24.97	24.80	24.51	25.64	24.35	25.47	25.30

5.6 Integral of Absolute Error Analysis

This section presents the results of Integral of Absolute Error (IAE) analysis for three designed controllers: PID controller, manual-switching gain scheduling PID controller, and auto-switching gain scheduling PID controller. IAE criterion is as in Equation 5.14. The IAE weights the error with time and hence emphasizes the error values over arrange of 0 to T, where T is the expected settling time(Girirajkumar et al., 2010.). IAE results able to obtain from experimental tests only. The indices of IAE of experimental tests for three controllers are as tabulated in Table 5.15. The IAE of the system loads of 2kg and above were not able to record as the system was unstable for the loads with the specific gain parameters.

$$I_{IAE} = \int_0^T |e(t)|dt \qquad (5.14)$$

Table 5.15: IAE Results of Three controllers.

Controllers	Integral of Absolute Error (IAE) Indices for System with Loads									
	0kg	**1kg**	**2kg**	**3kg**	**4kg**	**5kg**	**6kg**	**7kg**	**8kg**	**9kg**
PID	2.421	3.129	Unstable							
Manual-switching GS PID	2.364	2.093	2.466	2.684	3.085	3.067	3.142	3.047	3.251	3.229
Auto-switching GS PID	1.912	1.765	1.927	1.942	1.997	2.018	2.077	2.003	2.101	2.084

5.7 Discussion

This section discusses the results of the precise positioning analysis, transient response analysis, and integral of absolute error analysis in section 5.7.1, section 5.7.2, and section 5.7.3 respectively for the three controllers: PID controller, manual-switching gain scheduling PID controller, and auto-switching gain scheduling PID controller.

5.7.1 Discussions on Results of Precise Positioning Analysis

In this section, the experimental results of the precise positioning analysis for PID controller, manual-switching gain scheduling PID controller, and auto-switching gain scheduling PID are discussed extensively.

Firstly, the maximum load that the PID controller adapted for a stable response was 1kg. Based on the results in Table 5.4 in section 5.4.1.2, the PID controller gave smaller steady state error, 0.03mm when the system was without load than the system with the external load of 1kg which was 2.64 mm. The PID controller was unstable for the external load of 2kg and more. Thus, the study result can be concluded that the PID controller is precise in positioning for the system without load only and cannot be compared to other controllers for variance of the system loads.

The manual-switching gain scheduling PID controller and auto-switching gain scheduling PID were able to record the precise positioning results for variance for system loads which was 0kg, 1kg, 2kg, 3kg, 4kg, 5kg, 6kg, 7kg, 8kg, and 9kg. As observed the experimental results, the auto-switching gain scheduling PID controller produce the smaller percentage range of steady state error value than the manual-switching gain scheduling PID controller as illustrated in Figure 5.7. It was mainly contributed by the proposed control structure design. There was the load switch which specify the proportional gain and integral gain by referring the program of the MATLAB function. The MATLAB function made the load switch to switch in between any of the proportional gains and integral gains according to the error of the system in run. The gain selection of the auto-switching gain scheduling PID controller was based on the error of the system. Meanwhile, the gain selection of the manual-switching gain scheduling PID controller was based on the load of the system. These error-based gain selections were effectively adapted, in which the gains were switched based on the error of the system while running.

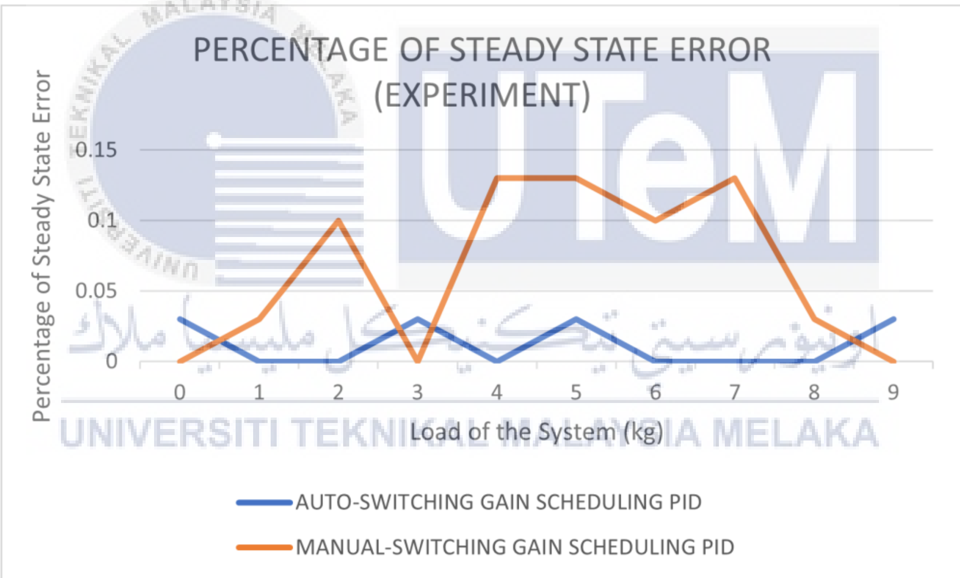

Figure 5.7: Percentage of Steady State Error Comparison

5.7.2 Discussions on Results of Transient Response Analysis

This section discusses the results of PID controller, manual-switching gain scheduling PID controller, and auto-switching gain scheduling PID controller according to the following observations of transient response elements.

a) Percentage of overshoot
b) Rise time, T_r (seconds)
c) Settling time, T_s (thsecond) at:
    i. 2%
    ii. 5%

The system response observation from experiment indicated that the PID controller able to give best response to the system without load while it produced unacceptable response for system with 1kg and unstable response for system with external loads of more than 1kg in terms of positioning and dynamic movements. Thus, the PID controller was not comparative to the other 2 controllers.

Firstly, the auto-switching gain scheduling PID controller produced smaller percentage range of overshoot than the manual-switching gain scheduling PID controller which was a similar discussion on the precise positioning analysis result previously. The comparison of overshoot percentage of both controllers illustrated in Figure 5.8. Secondly, the observation of rise time indicates the similar results as the percentage of overshoot where the auto-switching gain scheduling PID controller produced less rise time compared to manual-switching gain scheduling PID controller for all the loads available in the system as presented in Figure 5.9.

Thirdly, the settling time (T_s) at 2% of the input signal was able to record in simulation tests only for both controllers as the responses were not settled at 2% of the input signal in experimental runs. The study result can be concluded that the controllers are not settling to the steady state at the range of 2% of the input signal. Thus, settling time at 5% considered for the system response. The observation of settling time at 5% indicates that the response of the auto-switching gain scheduling PID controller is better than the manual-switching gain scheduling PID controller which is similar to the other comparisons of transient response element observations. The comparison of settling time at 5% as presented in Figure 5.10. This was due to the design structure of the auto-switching gain scheduling

PID controller. There was the load switch which determines the selection of the proportional gain and the integral gain by referring the program of the MATLAB function. The MATLAB function made the load switch to switch in between any of the proportional gains and integral gains according to the error of the system in run. The gain selection of the auto-switching gain scheduling PID controller was based on the error of the system. Meanwhile, the gain selection of the manual-switching gain scheduling PID controller was based on the load of the system. These error-based gain selections successfully adapted, in which the gains were switched based on the error of the system while running; thus, producing a better transient response of the system with variance of loads.

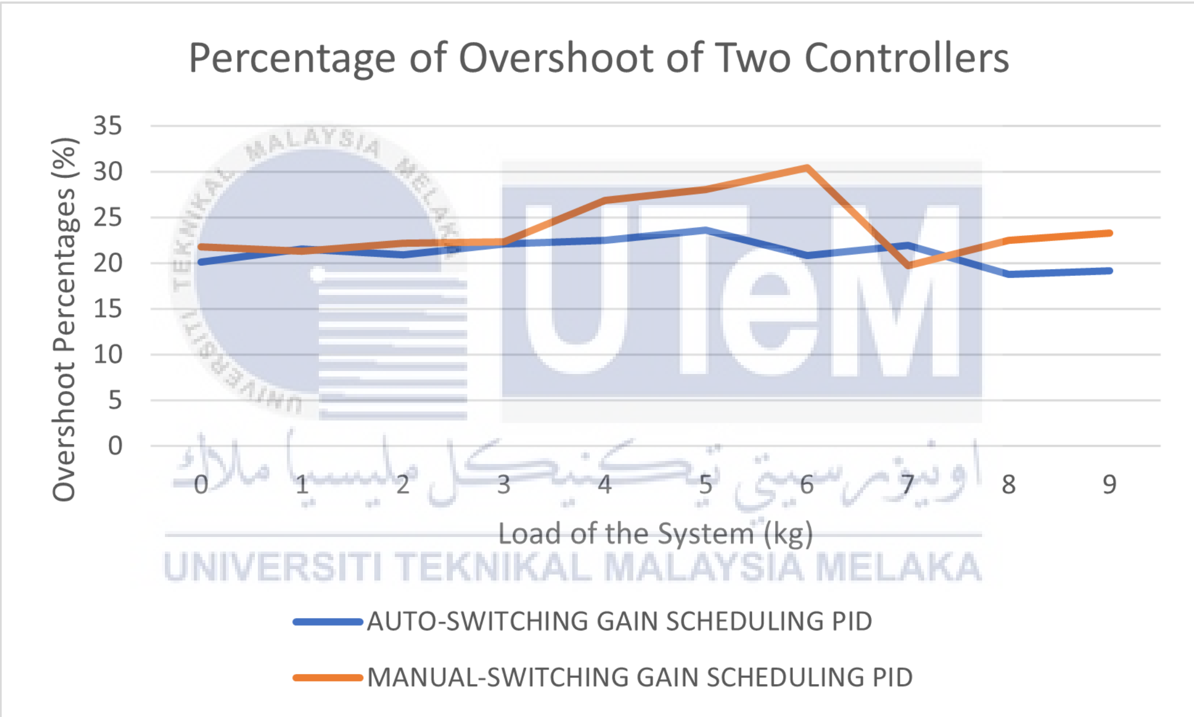

Figure 5.8: Percentage of Overshoot Comparison

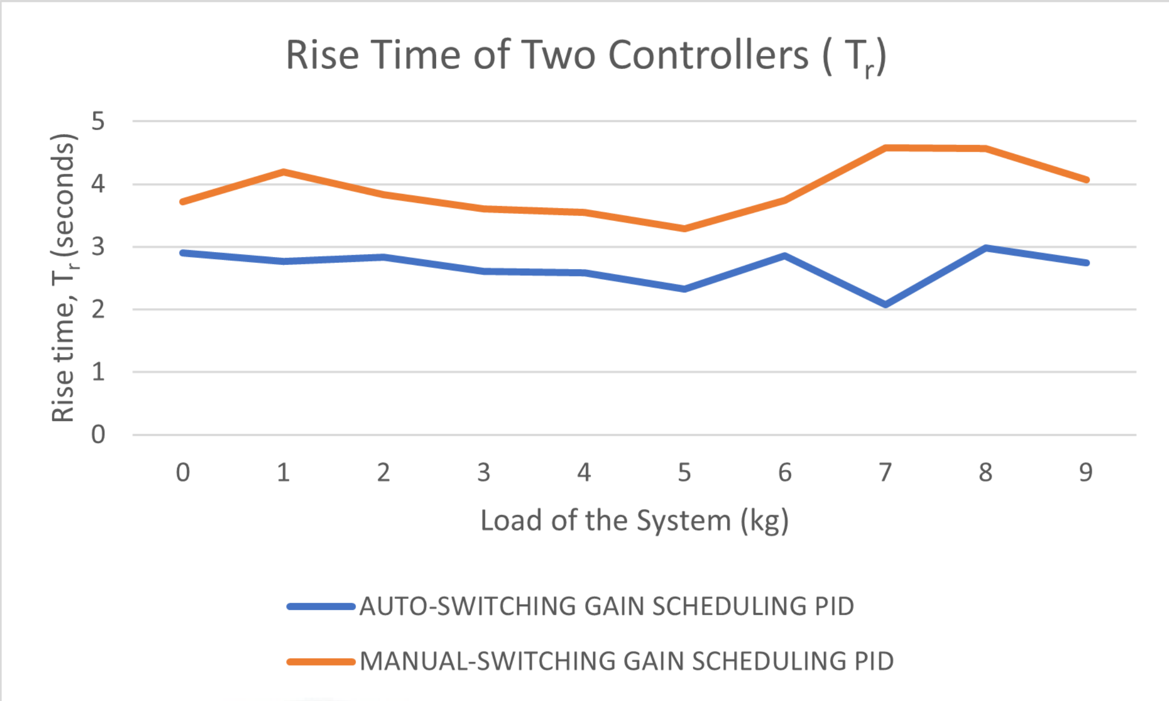

Figure 5.9: Comparison of Rise Time

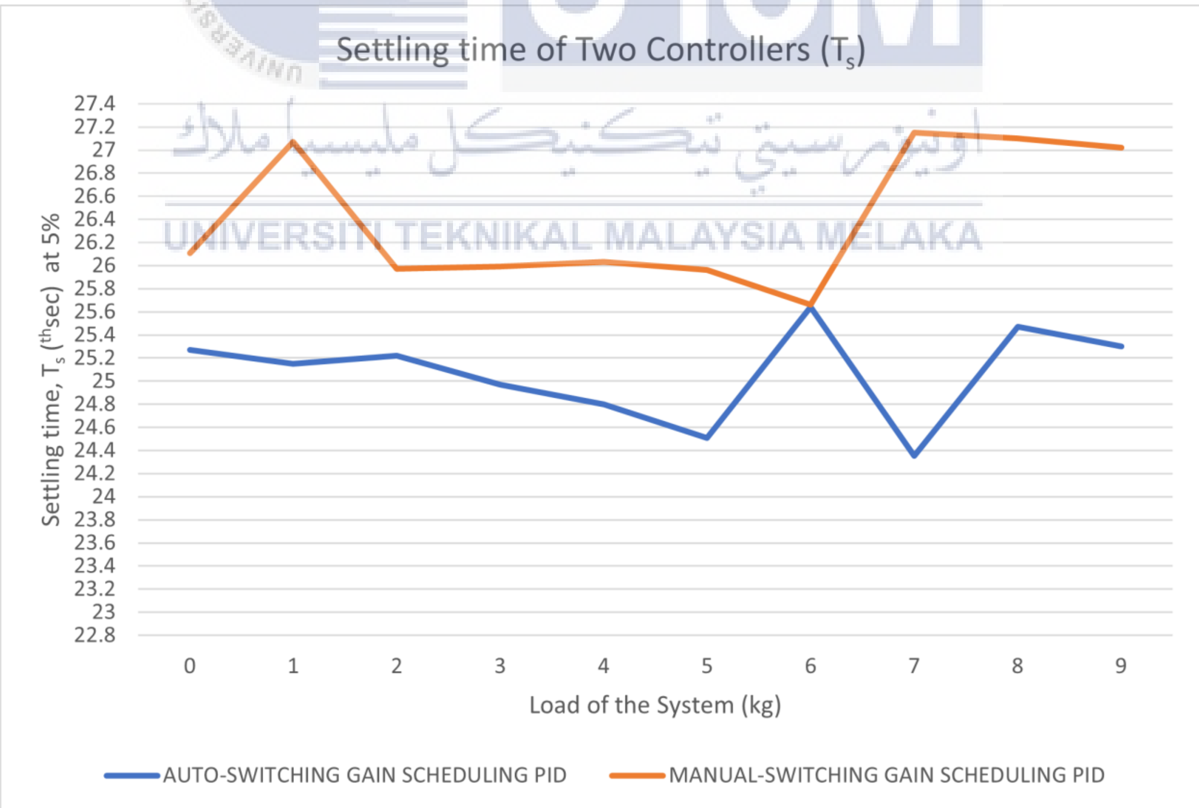

Figure 5.10: Comparison of Settling Time at 5%

5.7.3 Discussion on Results of Integral of Absolute Error Analysis

This section discusses the results IAE for the three controllers. The discussions were established with the error reduction from one controller to another for all the loads to obtain the percentage of improvements.

Similar to the precise positioning analysis and the transient response analysis measure, the IAE of PID controller was not able record for the loads 2kg and more as the response of the system was unstable. These results indicated that PID controller is adaptive for the system without load and not comparative for the system with variance of loads. By comparing the indices of IAE of both controllers, the auto-switching gain scheduling PID controller still produced more precision in positioning. This was due to the design structure of the auto-switching gain scheduling PID controller which provided an impact on reducing the IAE error. The error-based switch successfully adapted the switching function of the proportional gains and the integral gains before injecting to the system; thus, producing smaller indices of IAE which indicate the better performance of positioning of the system. The comparison of IAE indices for both controllers with variance of loads as presented in Figure 5.11.

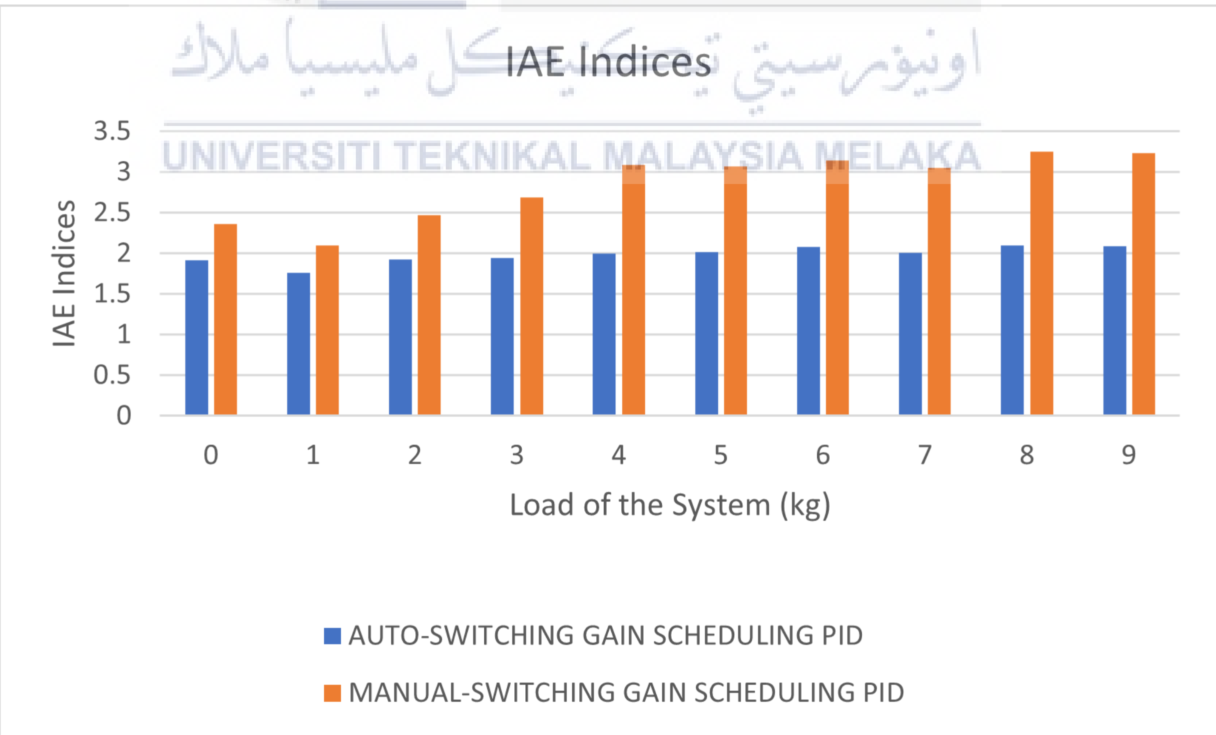

Figure 5.11: Comparison of IAE Indices

Moreover, the error reduction between manual-switching gain scheduling PID controller and auto-switching gain scheduling PID controller for all the available loads of the system were performed to obtain the improvement significance of the controllers based on IAE indices of both controllers as in Equation 5.15. The IAE indices of manual-switching gain scheduling PID controller were used as the reference of improvement between both controllers. The results of error reduction percentage of auto-switching gain scheduling PID controller from manual-switching gain scheduling PID controller for all the available loads are as tabulated in Table 5.16.

$$\% \text{ Error Reduction} = \left(\frac{IAE\ of\ Controller\ A - IAE\ of\ Controller\ B}{IAE\ of\ Controller\ B}\right) \times 100\% \qquad (5.14)$$

Where,

Controller A : Manual-switching gain scheduling PID controller

Controller B : Auto-switching gain scheduling PID controller

Table 5.16 : Error Reduction of Auto-switching Gain Scheduling PID Based on IAE Indices

System Loads (kg)	IAE		Error Reduction (%)
	Manual-switching	Auto-switching	
0	2.364	1.912	23.64
1	2.093	1.765	18.58
2	2.466	1.927	27.97
3	2.684	1.942	38.21
4	3.085	1.997	54.48
5	3.067	2.018	51.98
6	3.142	2.077	51.28
7	3.047	2.003	52.12
8	3.251	2.101	54.74
9	3.229	2.084	54.94

CHAPTER 6
CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This project explores the improvement of controller design in improving the positioning performance of the pneumatic system under the presence of load variance from 0kg until 9kg as the disturbance. The conventional PID controller is widely used in the industry owing to the simplicity of the design. However, the need to improve the PID controller is becoming increasingly crucial and has become the focus of many researchers. The reviews disclosed that the improvement made on the PID controller normally involved the modification of the controller structure. In that case, gain scheduling PID controller is widely known for compensating the positioning performance of the system with variance in the disturbance. However, this controller is still rarely applied to the machine tool application. Therefore, two different gain scheduling PID controllers with sets of proportional gain values and integral gain values which have been finalized through PID parameter tuning process and named as manual-switching gain scheduling PID and auto-switching gain scheduling PID for the pneumatic system. Both of the controllers vary in the component of switches only where manual-switching gain scheduling PID controller was used load switch to select the gains based on defined load of the system meanwhile, auto-switching gain scheduling PID controller was used auto switch to select the gains by referring to the error values of the system. This proposed controller is then analyzed and validated for positioning to verify the effectiveness on the system via the simulation and the experimental works.

A system models in the form of the third order transfer function of the pneumatic system was obtained via the system identification as discussed in detail in section 3.3. This system identification achieved more than 85% of best fit for the system with all the available loads where it obtained 10 sets of third order transfer function for 0kg until 9kg as presented in Table 4.1 in section 4.1; therefore, the system models were ready to be used for the simulation analysis and validation. The step-by step processes of parameter tunings of controllers were conducted in Chapter 4.

The simulation and experimental results of the three controllers; PID controller, manual-switching gain scheduling PID controller, and auto-switching gain scheduling PID controller were carried out and discussed in Chapter 5. The simulation was conducted with the system models in the form transfer function of the system with variance of loads while the experimental works was conducted on the real system by involving the hardware setup. These controllers were evaluated based on the three performance measures, namely precise positioning where steady state error taken into account, transient responses, and integral of absolute error (IAE). By considering IAE analysis, auto-switch gain scheduling PID controller produced significant improvement of 42.79% averagely for all the available loads of the system compared to manual-switching gain scheduling PID controller. The performance comparisons of the three controllers were made as presented in Table 6.1. The objectives of this project are successfully achieved as summarized in Table 6.2 below.

Table 6.1: Performance Comparison for Positioning of Three Controllers for P

Performance Comparison	PID	Manual-Switching Gain Scheduling PID	Auto-Switching Gain Scheduling PID
Adaptability to load variance	Reaches steady state without load and 1kg only.	Adaptive to load variance (0-9kg)	Adaptive to load variance (0-9kg)
SSE	Small errors without load only. Gives bigger error values with 1kg and more.	Small errors for all the available loads(0-9kg)	Obtains smallest range of errors for all the available loads(0-9kg)
IAE indices	Unable to record for all the loads due to unstable system response	Bigger indices	Smallest indices for all the loads compared to other controllers.

Table 6.2 Project Conclusion

Objectives	Descriptions
To obtain the system model of the pneumatic system	The first objective is successfully achieved by performing the four steps of system identification as discussed in detail in Chapter 3. Mathematical models in the form of third order transfer functions known as the system model is obtained with best fits of more than 85% of the system with all the available loads.
To design and develop gain scheduling PID controller to obtain precise positioning of the pneumatic system.	The second objective is successfully achieved through the design of the controllers, manual-switching gain scheduling PID controller and developed it into auto-switching gain scheduling PID controller via MATLAB Simulink software The design structures of the controllers discussed in detail in Chapter 4.
To analyze the performance of the controllers in terms of steady state error, and system response.	The final objective is successfully achieved when the three controllers were tested via the simulation and experimental works. In order to evaluate the effectiveness of the proposed controllers for positioning, three performance measures are used. a) Precise positioning analysis (steady state error) b) Transient response analysis - Overshoot and its percentage - Peak time - Rise time - Settling time at 2% and 5% c) Integral of absolute error analysis

6.2 Recommendations

After gone through this research, there are few recommendations suggested so be able to call attention to the important aspects need to be focus on for coming research topic about designing controllers for precise positioning for pneumatic system with variance in the disturbance. The first significant recommendation for this project is to look up to linearization approach when designing the gain scheduling PID controller. Linearization in gain scheduling able to produce more precision in positioning as it has wide selections of gain values in between the range of gain parameters that finalized through parameter tuning processes.

Furthermore, hybrid gain scheduling PID controllers are the controllers to look forward for precision in positioning of pneumatic system. Fuzzy rules and seasonings are one of the wide approaches to be embedded with gain scheduling PID controller to produce better performance. Moreover, the usage of filters should be considered when designing the controllers. The addition of filters into the system could remove the noise which will affect the response of the system.

6.3 Sustainability Elements

This research involved pneumatic system which being used widely in automation sectors. The usage of pneumatic actuators is keeping on increasing globally due to cheaper cost, easy maintenance, high durability, and high power-to-weight ratio. Although, pneumatic system has some drawbacks which need to compensate by designing various controllers. There are no limits for innovation of controllers for pneumatic system to improve the performance. The existed controllers of pneumatic system may contribute the upcoming controller designers to refer and develop it with either minor or major modifications.

6.4 Complexity of the Research

This research involves a unit conversion process where the input and output with the unit of voltage convert into unit of millimeter. The process done by referring to the specification of the pneumatic actuator which may give some offset during unit conversion as the pneumatic actuator is high in non-linearities as it uses compressed air. The existence of the offset and the significance of the offset during unit conversion were not able to detect and measure.

6.5 Lifelong Learning Element

PID controllers are well known for the simplicity of the structure where many other components add on and embed with the controller for different purposes. Modifications in PID controller may give huge impact on the system performances especially nonlinear systems such as pneumatic system. PID controllers are so effective on the performances of pneumatic system as the controller has parameters that control some responses of the system specifically as proportional gains are to control the rise time of the system response, integral gains are to compensate steady state error meanwhile, derivative gains are to reduce the overshoot of the system response.

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APPENDIX A

DATASHEET OF PNEUMATIC ACTUATOR

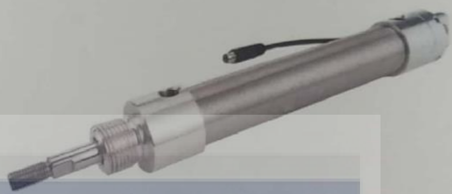
(Enfield Tech Model ACTB-200-S01200)

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



ETA Pneumatic Actuator

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

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.

Enfield Technologies
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f. +1 203 286 2414
toll free North America
1-800-504-3334
info@enfieldtech.com
www.enfieldtech.com

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

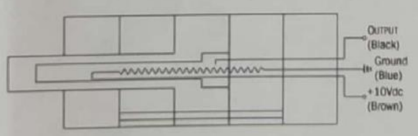
Cylinder Mounting:

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

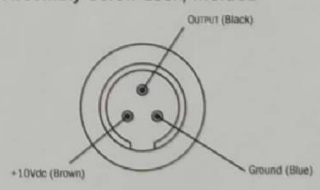
Notes:

- 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



²Wire 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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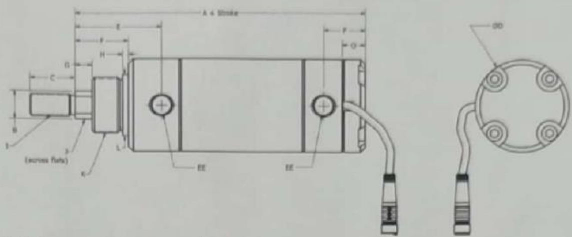
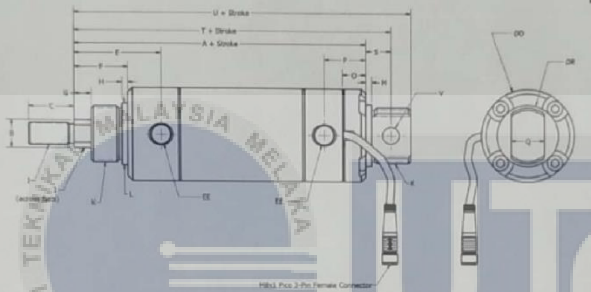
ENFIELD TECHNOLOGIES

ETA Series Pneumatic Linear Actuators
Datasheet

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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