SIMULATION DESIGN OF PREDICTIVE FUNCTIONAL CONTROLLER (PFC) FOR POSITIONING CONTROL OF ELECTRO-HYDRAULIC ACTUATOR

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

by

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Hons.). The members of the supervisory committee are as follow:

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(Assoc. Prof. Ir. Dr. Lokman bin Abdullah)

DEDICATION

Only

my beloved father, Nor Faizal bin Masiran

my appreciative mother, Fauziah binti Ngatiman

my adored sister and brother, Hani and Faqihah

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

Thank You So Much & Love You All Forever

To my supportive supervisors and PhD student,

Assoc. Prof. Ir. Dr. Lokman Bin Abdullah and En. Khairun Najmi bin Kamaluddin

for encouraging me and being my guide as the source of knowledge

throughout this project.

Thank you.

ABSTRAK

Sebuah penggerak elektro-hidraulik (EHA) menggunakan kuasa elektrik untuk mengawal cecair hidraulik, dengan itu menggerakkan bahagian-bahagian sistem mesin. Kajian ini bertujuan untuk mereka bentuk Pengawal Fungsian Prediktif (PFC) untuk kawalan kedudukan tepat sistem EHA kerana kelakuannya yang sangat tidak linear. PFC meramalkan kelakuan proses masa depan dan menyesuaikan tindakan untuk mencapai output yang diingini. Tiga pengawal berbeza telah direka: pengawal Proportional-Integral-Derivative (PID) yang ditala dengan PID Tuner, PID yang ditala dengan Pengoptimuman Swarm Partikel (PSO-PID), dan Pengawal Fungsian Prediktif (PFC). Model matematik yang tepat, dipilih daripada penyelidikan sebelumnya, dibangunkan sebagai peringkat awal sebelum menjalankan ujian simulasi dan analisis dalam MATLAB Simulink. Analisis tersebut menilai ketepatan kawalan kedudukan sistem EHA, termasuk kestabilan, tindak balas sementara, dan ralat keadaan mantap. Hasil simulasi menunjukkan bahawa PFC, yang ditala dengan Alpha=0.8, mencapai kawalan kedudukan paling tepat, dengan peningkatan 79.79% berbanding PID yang ditala dengan PID Tuner, dan 99.37% berbanding PSO-PID. PFC menunjukkan tindak balas sistem yang lebih baik dan ralat keadaan mantap yang paling rendah, iaitu 0.00002602 mm berbanding pengawal lain, kerana keupayaan prediktifnya, kawalan optimum, dan penolakan gangguan yang unggul. Secara ringkas, semua pengawal telah berjaya direka dan dianalisis, dengan PFC terbukti menjadi yang terbaik untuk kawalan kedudukan tepat dalam sistem EHA.

ABSTRACT

An electro-hydraulic actuator (EHA) uses electrical power to control hydraulic fluid, thereby moving parts of a machine system. This study aims to design a Predictive Functional Controller (PFC) for precise positioning control of the EHA system due to its highly non-linear behavior. PFC anticipates future process behavior and adjusts actions to achieve the desired output. Three different controllers were designed: a Proportional-Integral-Derivative (PID) controller tuned with PID Tuner, a PID tuned with Particle Swarm Optimization (PSO-PID), and the Predictive Functional Controller (PFC). A precise mathematical model, selected from previous research, was developed as the initial stage before conducting simulation tests and analysis in MATLAB Simulink. The analysis evaluated the accuracy of EHA system positioning control, including stability, transient response, and steady-state error. The simulation results revealed that PFC, tuned with Alpha=0.8, achieved the best precise positioning control, with a 79.79% improvement over the PID tuned with PID Tuner, and 99.37% over PSO-PID. PFC demonstrated better system response and the lowest steady-state error, which equaled 0.00002602 mm compared to the other controllers, due to its predictive capability, optimal control, and superior disturbance rejection. In summary, all controllers were successfully designed and analyzed, with PFC proving to be the best for precise positioning control in EHA systems.

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LIST OF ABBREVIATIONS

ARX	-	Auto-Regressive with Exogenous
AI	-	Artificial Intelligence
DOF	-	Degree of Freedom
EHD	-	Electro Hydrodynamic Actuator
IAE	-	Integral Absolute Error
MPC	-	Model Predictive Control
EHA	-	Electro-Hydraulic Actuator
PID	-	Proportional- Integral-Derivative
PFC	-	Predictive Functional Controller
PSO	-	Particle Swarm Optimization
RL	-	Reinforcement Learning
SMC	-	Sliding Mode Controller
FLC	-	Fuzzy Logic Controller

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CHAPTER 1

INTRODUCTION

Electro-hydraulic actuators combine electrical and hydraulic systems to control mechanical movement, offering high force output and precision. They are widely used in industries such as aerospace, automotive, and manufacturing for tasks requiring robust and reliable motion control, such as valve operation, robotic arms, and heavy machinery. This chapter presents the project's title, background, problem statement, objectives, scope, and limitations. Further details of the project are explained in each section.

1.1 Background of the Study

Based on Figure 1.1, electrohydraulic actuators (EHA) are effective in positioning and providing force feedback in different systems, including aircraft, machine tools, and industrial robots less response, heightened insensitivity, and enhanced positioning capabilities in comparison to electric motors (Jensen et al., 2021). The idea of EHA was introduced based on the principle of closed-circuit hydrostatic transmission (Cai et al., 2020a), which links a pump directly to an actuator and accomplishes variable power transmission by adjusting either the speed or the displacement of the pump . EHA systems possess the capabilities of generating substantial forces with rapid response time and demonstrating excellent durability, making them highly sought after in various large-scale engineering applications.

Figure 1.1 EHA self-contained actuator (Ramdani et al., 2016)

The precision of positioning tracking for the EHA system has been a highly appealing area of research for several decades. Nevertheless, achieving accurate positioning of EHA systems at the intended location is notably difficult and demanding due to the presence of nonlinearities, external disturbances, and time-varying characteristics that act against the system(Cai et al., 2020a).An essential component in achieving accurate positioning of EHA systems is a high-fidelity controller (Habibi, 2000). Hence, it is very crucial to establish the model for the EHA system as a primary step. Poor modeling will negatively impact the accuracy of the dynamic behavior of the EHA system.

The initial stage of system analysis involves acquiring the model, which can be achieved through either physical law or system identification(Y. Zheng et al., 2023). Implementing modeling based on the physical rule proposed by earlier researchers is challenging due to the requirement of expert knowledge and a thorough comprehension of the system. Additionally, identifying the parameters is not a straightforward task (Kumar & Rana, 2023). A part from that, system identification relies purely on a collection of stimulus-response data and does not need any previous knowledge about the system to create a model and establish the parameters. (Ramdani et al., 2016). However, this study does not conduct the system identification technique to analyze the mathematical model of the EHA. Transfer function from plant model is taken from (Izzuddin et al., 2016). The expected controller to control the positioning of the EHA system at lower steady-state error and good transient response is the predictive controller (PFC). The study involves the utilization of MATLAB Simulink for conducting both modeling, simulation, and control processes. The efficacy of the proposed predictive controller will be assessed by comparing its positioning performance with the PID controller tuned by PID Tuner and PSO-PID. This analysis will specifically concern on the value of steady-state error and the transient response. In this study, simulation in MATLAB Simulink will be conducted to analyze the positioning performance of the controller in terms of transient response and steady-state error. After that, the best controller is proposed to be applied in EHA system for precise positioning control

1.2 Problem Statement

i. Highly non-linear behavior of EHA system maximizes positioning error during positioning control
ii. The current EHA system shows positioning errors during the positioning control
iii. The current EHA system has poor system response during the positioning control

1.3 Objectives

i. To design PID, PSO-PID and PFC controller for positioning control of EHA system using MATLAB Simulink.

ii. To analyze the controller performance in terms of positioning error (steady-state error)

iii. To propose the best controller for positioning control of the EHA system based on transient response properties (percent overshoot, settling time, rise time) and steady-state performance.

1.4 Scope and Limitation

i. No system identification is applied since no data collection from the experimental procedure was conducted

ii. Z-domain transfer function is cited from (Izzuddin et al., 2016) then converted to s-function to illustrate the electro-hydraulic actuator system modeling in MATLAB Simulink.

iii. The positioning control of the EHA system in MATLAB Simulink will be restricted to 100 mm from initial position.

iv. The positioning control of the electro-hydraulic actuator system model for PID, PSO-PID, and PFC are only simulated in MATLAB Simulink

1.5 Thesis Outline

Based on the objectives previously presented and on the approach proposed before, this thesis is made up of five (5) chapters, which contents are summarized as follows:

- Chapter 1. Introduction. This chapter presents the project's title, background, problem statement, objectives, scope, and limitations. Further details of the project are explained in each section.

- Chapter 2. Literature review. This chapter covers the historical overview of Electro-Hydraulic Actuators (EHA) and their working principles, leading to the ideation of controller designs to address positioning control issues in EHA systems. It focuses on positioning control, including applications, challenges like poor positioning control, and the advantages and disadvantages of EHA systems. The next section reviews various types of controllers, controllers under study, and several controllers used by previous researchers for EHA positioning control. Finally, control strategies related to the title by past researchers are summarized.
- Chapter 3. Methodology. This chapter details the thesis workflow from start to finish, including the literature review, model extraction, and the design of the controller with specific design requirements
- Chapter 4. Controller Design: This chapter shows how each controller was designed in MATLAB Simulink and tuned with a specific algorithm.
- Chapter 5. Result and Discussion. presents a comparative analysis of three control strategies: the classic PID controller, the PSO-PID controller, and the PFC controller. All three controllers are implemented within a simulated plant environment to evaluate their performance. The response metrics of the PID tuned by PID Tuner, PSO-PID and PFC controllers are then recorded and compared to identify the controller that achieves the most desirable performance characteristics
- Chapter 6. Conclusion and Recommendations for Future Research. This chapter summarizes the main conclusions as well as achievements of the work undertaken in this research and suggests areas for future work.

CHAPTER 2

LITERATURE REVIEW

The literature review covers the historical overview of Electro-Hydraulic Actuators (EHA) and their working principles, leading to the ideation of controller designs to address positioning control issues in EHA systems. It focuses on positioning control, including applications, challenges like poor positioning control, and the advantages and disadvantages of EHA systems. The next section reviews various types of controllers, controllers under study, and several controllers used by previous researchers for EHA positioning control. Finally, control strategies related to the title by past researchers are summarized.

2.1 Historical Overview of Electro-Hydraulic Actuator System

Building upon the foundational principle of Pascal's Law of Pressure Transmission, established nearly four centuries ago, hydraulic transmission systems have become ubiquitous in industrial and mobile applications. Their inherent advantages, including high power density, large force output, and ease of linear motion implementation, have fueled their widespread adoption(Cai et al., 2020c). The advent of modern hydraulic control technology in the post-World War I era marked a pivotal point. Hydraulic valves, crucial components in controlling flow rate, pressure, and actuator behavior, have undergone significant evolution(Hashim & Mustafa, 2020). Diverse electro-hydraulic control valve types have emerged, such as proportional, flapper-nozzle, and electronically-controlled variants. Concurrent advancements in materials science, manufacturing processes, electronics, and computer technology have empowered the development of increasingly sophisticated and powerful electro-hydraulic control valves. This continuous evolution has been driven by the ever-changing demands of the modern world and the need for increased versatility and power, as exemplified in Figure 2.2.

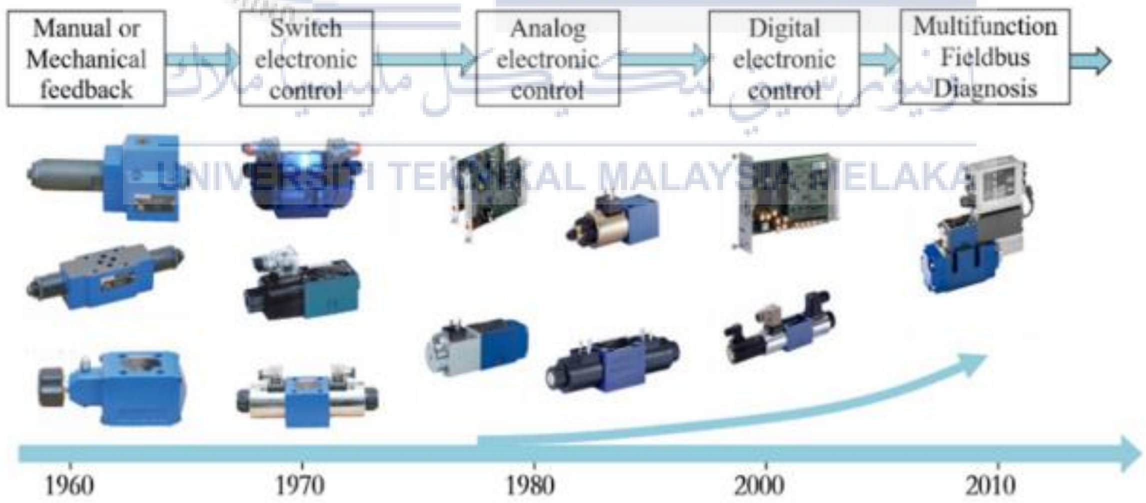

Figure 2.2 Advancement of Electro Hydraulic Actuators (B. Xu et al., 2020)

The Electro-Hydraulic Actuator (EHA) system is widely employed as a fundamental driving system in various industrial processes and engineering applications. Hydraulic actuators employ the utilization of fluid pressure to facilitate and enable mechanical motion. The utilization of EHA encompasses a diverse range of applications, including but not limited to material testing, machine tools, and many forms of industrial machinery(M. Kumar, 2021). The EHA system incorporates a range of components, including flow control valves, cylinders, maximum pressure valves, and compressors. The EHA system employs hydraulic power to enable mechanical functioning. Mechanical motion produces various forms of motion, including linear, rotational, and oscillatory motion(Razmjooei et al., 2022).

EHA also provides a high power-to-weight ratio, modularity, and energy efficiency, have found effective applications in aircraft and submarines, where there is a great requirement for precision and repeatability(Aribowo et al., 2015). Parametric uncertainties and unknown nonlinearities, however, can inevitably impact the positioning performance. In order to obtain robust performance in the face of model inaccuracy or system variability, a substantial loop gain is typically required, which results in over-design(Razmjooei et al., 2022). They can also produce extremely high forces very quickly. However, due to the compressibility of hydraulic fluid and the intricate flow characteristics of servo valves, EHAs show noticeably larger nonlinearities in their dynamics(Deng et al., 2021). Consequently, there has been a lot of interest in the study of position control for EHAs from both an academic and an industrial standpoint.

2.1.1 Principle of EHA System

Electrohydraulic actuators are devices that control a valve by pressured hydraulic fluid, with their primary source of energy being electrical. Based on Figure 2.3, the operating concept of an electrohydraulic actuator may be stated as follows:

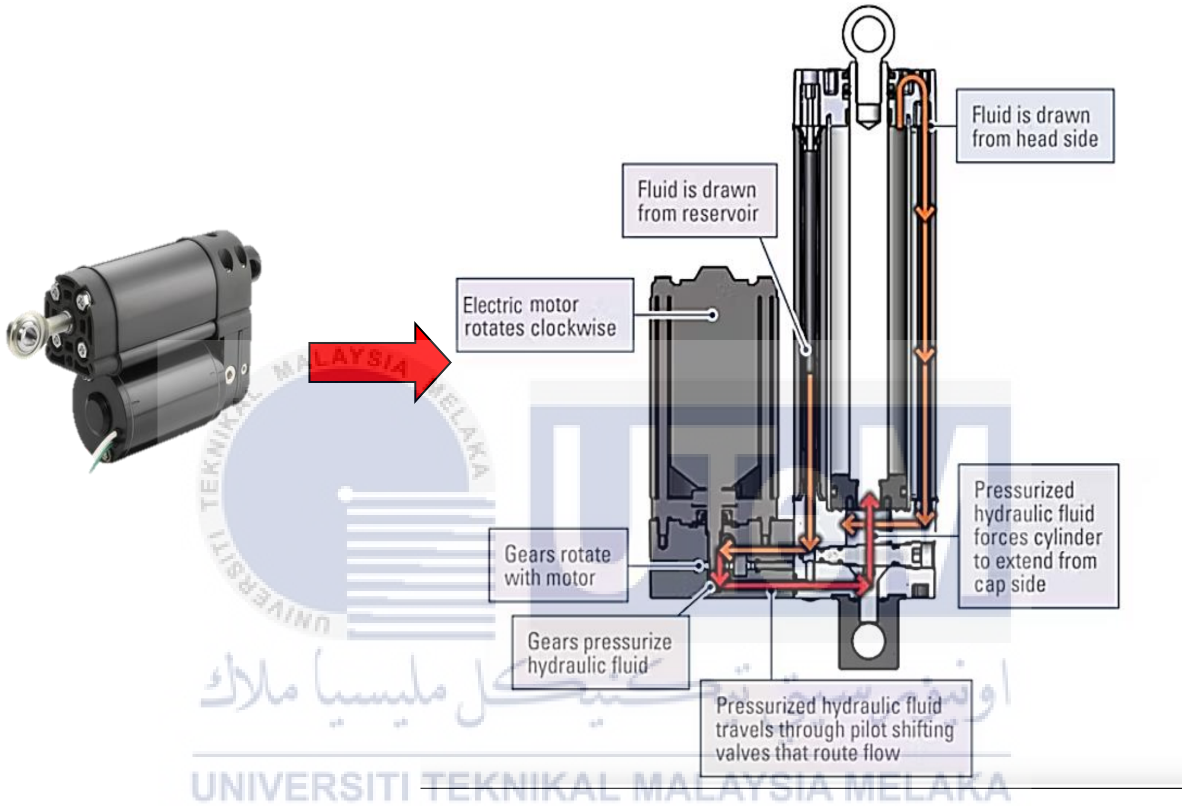

Figure 2.3 Thomson H-Track Electro-Hydraulic Actuator Model (Source: https://www.powermotiontech.com/technologies/cylinders-actuators/article/21154732/thomson-industries-inc-the-case-for-electrohydraulic-actuators)

- Electrical power supply: The actuator receives electrical power, which is used to activate a motor that operates a hydraulic pump
- Hydraulic fluid: The hydraulic pump pressurizes the hydraulic fluid, which is subsequently utilized to operate the valve

- Servo valve: The servo valve is the control core of the electrohydraulic servo actuator, turning the low-power electrical signal input into high-power hydraulic energy. It constantly and bidirectionally regulates the output flow and pressure, achieving the actuator's displacement, speed, acceleration, and force control
- Hydraulic cylinder: The hydraulic cylinder is the component that transfers the hydraulic energy into mechanical motion, activating the valve
- Position feedback component: This component gives feedback on the actuator's location, ensuring correct control and functioning

An assemblage of oil reservoirs, electric motors, pumps, oil filters, relief valves, and directional valves is needed for hydraulic cylinders that transform electrical energy into motion. The intended speed and cylinder size dictate the size of the pump and every other component. Therefore, the cost of the whole setup and its footprint rise along with the speed requirements. An electric motor that spins in a clockwise direction turns gears in an electro-hydraulic actuator, which pressurizes the hydraulic fluid. In addition to controlling fluid distribution to lengthen the rod, the valves open to take fluid from the reservoir and head side. Retraction involves spinning the motor counterclockwise to reverse the process and refill the reservoir and piston on the other side.

2.2 Positioning Control of EHA System

2.2.1 Application of Positioning Control OF Electro-Hydraulic Actuator

The exact control of location in industrial applications has been a vital part of boosting overall system performance. Electro-hydraulic actuators have gained popularity in attaining precise placement due to its capacity to generate large forces and adapt to diverse operational situations. This literature review discusses current achievements in the field of positioning control for electro-hydraulic actuators, focusing on research papers by previous scholars and researchers.

To provide a comprehensive overview of previous research on the application of positioning control for electro-hydraulic actuators, Table 1.1 combines important studies done by the previous scholars and researcher related to the precise positioning control of EHA system.

Table 1.1 Overview of Application of Positioning Control in EHA

Author	**Title of Research Paper**	**Application**	**Explanation**
(Feng et al., 2023)	Adaptive sliding mode controller based on fuzzy rules for a typical excavator electro-hydraulic position control system	Excavator Electro-Hydraulic Actuator	This study proposes the application of a fuzzy adaptive sliding mode controller to enhance positioni ng control accuracy and resilience in a heavy electro-hydraulic position system.

(Wang et al., 2023)	A versatile jellyfish-like robotic platform for effective underwater propulsion and manipulation	Robotic Platform for Effective Underwater Propulsion and Manipulation	The study offers a jellyfish-like robotic platform for underwater propulsion and manipulation, which uses electrohydraulic actuators for fast, noise-free movement and item handling at rates of up to 6.1 cm/s.
(Zhu et al., 2022)	Design and positioning control of an electro-hydrostatic actuator for a disc cutter replacement manipulator	Disc Cutter Replacement Manipulator	The article discusses the design of an electro-hydrostatic actuator (EHA) for a disc cutter replacement manipulator used in Tunnel Boring Machines (TBM)
(Jung et al., 2019)	Positioning control of an electro-hydraulic actuated clutch via novel hysteresis model	Vehicle Production	The paper discusses the pressure control of an electro-hydraulic actuated clutch, focusing on a novel hysteresis model based on physical phenomena.
(Li et al., 2020)	Thermal-hydraulic Modeling and Simulation of the Hydraulic System based on the Electro-hydrostatic Actuator	Large Commercial Aircraft	The paper discusses EHAs, which are power-by-wire actuators used and load positioning in large commercial aircraft like the Airbus A380
(Yang et al., 2022)	Application of energy conversion and integration technologies based on electro-hydraulic hybrid	Vehicle and Machinery	The paper provides an overview of electro-hydraulic hybrid power systems, including positioning control principles, concepts, and operating modes.

	power systems: A review		
(G. Xu et al., 2021)	Path following control of tractor with an electro-hydraulic coupling steering system: Layered multi-loop robust control architecture	Steering Characteristics of A Tractor	Describes the steering characteristics of a tractor, focusing on an electro-hydraulic coupling system that is the main actuator for positioning control
(Amiri et al., 2023)	CO2 capture using steam ejector condenser under electro hydrodynamic actuator with non-condensable gas and cyclone separator: A numerical study	Steam ejector condenser (SEC)	This paper discusses a numerical study on CO_2 capture using a steam ejector condenser (SEC) and a cyclone separator, enhanced by an electrohydrodynamic (EHD) actuator.
(Ebner et al., 2017)	A Model-based Design Approach for an Optimal Electro-Hydraulic System Within Automatic Transmissions	Cooling and Lubrication of Gears	The paper discusses optimizing the hydraulic layout design for automatic transmissions, focusing on lubrication, cooling, transmission efficiency and load positioning

(Mesmer et al., 2018)	Model Design for a Hydraulic Clutch Actuation System	Wet Friction Clutch	The paper presents a dynamical model for an indirectly controlled hydraulic actuation path for a wet friction clutch and positioning error compensation method.

2.2.2 Advantages of Electro-Hydraulic Actuator System

Electro-hydraulic actuators can operate under harsh conditions, such as high temperature, high pressure, and high vibration, without significant degradation of performance or efficiency(Tiboni et al., 2022). Electro-hydraulic actuators have fewer moving parts and less friction than other types of actuators, which reduces the wear and tear and the need for lubrication and replacement (Has et al., 2014). Electro-hydraulic actuators can be easily configured and adapted to different tasks and environments, by changing the parameters of the hydraulic system, such as pressure, flow, and valve settings(Altare et al., 2014). EHA only consumes power when needed, unlike conventional hydraulic systems that require continuous power supply to maintain pressure(Rongjie et al., 2009). EHA are self-contained units that do not require complex piping or centralized hydraulic power units.

EHA eliminates the need for heavy hydraulic reservoirs, accumulators, and fluid lines, resulting in a lower overall weight of the flight control system (Altare & Vacca, 2015). EHA can combine the high force and power density of hydraulic technology with the versatility and ease of installation and control of electric technology(Altare & Vacca, 2015). EHA can use a power-on-demand strategy to control the hydraulic fluid flow, minimizing power losses and heat generation. EHA can also offer energy regeneration capability by recovering the kinetic energy of the actuated load. EHA can operate in harsh environments and do not suffer from jamming problems(Altare & Vacca, 2015). EHA can also provide natural damping, power-less load holding, and easy overload protection.

EHA can eliminate throttling losses associated with conventional valve-controlled systems, and can achieve energy regeneration in assistive loading conditions by using a variable-speed electric motor and a fixed-displacement pump(Has et al., 2014). EHA can use low-cost technology for hydraulic machines, such as fixed-displacement pumps, and can reduce operating cost by saving energy and reducing emissions (Tiboni et al., 2022). EHA can control the actuator speed over a wide range by using a bypass valve that allows the flow to pass parallel to the cylinder, thus enabling low-speed and high-speed actuation without requiring low-speed operation of the hydraulic unit (Tiboni et al., 2022). EHA can be implemented as a self-contained system that does not require a centralized hydraulic power supply, thus reducing the size and weight of the system and increasing the reliability and safety.

2.2.3 Disadvantages of Electro-Hydraulic Actuator System

Electro-hydraulic systems serve a crucial role in different industrial applications, delivering adaptability and great power density. However, their non-linear behavior provides substantial hurdles, compromising performance, accuracy, and overall control tactics. This study intends to dive into previous research to highlight the drawbacks associated with the non-linear features of electro-hydraulic systems.

The non-linearities originating from valve dynamics have been a persistent difficulty in electro-hydraulic systems. (Song et al., 2019)evaluated the influence of non-linear valve behavior on system responsiveness. They observed that differences in valve characteristics, such as hysteresis and nonlinear flow-pressure relationships, increase uncertainties and complexity, impeding proper management of the hydraulic system(Feng et al., 2019).

Friction and stiction in the hydraulic components lead to non-linear behavior, altering system dynamics and reaction time. Research by(J. Li et al., 2023) showed the harmful consequences of friction in hydraulic actuators. The investigation found that nonlinear friction characteristics create unanticipated fluctuations in positioning accuracy and aggravate wear and tear in the system components (Feng et al., 2019).

Electro-hydraulic systems commonly work in dynamic situations with fluctuating loads. This intrinsic non-linearity offers issues for control systems aiming for accurate and consistent performance. Recent study by (Qin et al., 2022) studied the impact of dynamic load fluctuations on the control performance of electro-hydraulic systems. The study underscored the challenge in attaining constant and precise control due to the unexpected nature of dynamic loading.

Non-linear behavior increases complexity in both modeling and control tactics. (J. Li et al., 2023)examined the issues connected with modeling electro-hydraulic systems properly. The study demonstrated that typical linear models often fall short in capturing the subtleties of non-linear behavior, leading to inferior control performance. This complexity complicates the development of efficient control algorithms, particularly in circumstances with rapidly changing system dynamics.

Non-linearities in the energy conversion process of electro-hydraulic systems lead to energy inefficiency. (Jiang et al., 2022)studied the influence of non-linear behavior on energy losses in hydraulic systems. The study emphasized that changes in pressure, flow, and valve dynamics contribute to poor energy conversion, eventually impacting the overall efficiency of the electro-hydraulic system.

In conclusion, the non-linear behavior of electro-hydraulic systems provides a variety of drawbacks, including issues in valve dynamics, friction effects, dynamic load fluctuations, modeling complications, and energy inefficiency. Addressing these difficulties is critical for enhancing the accuracy, dependability, and overall performance of electro-hydraulic systems in varied industrial applications.

2.3 Type of Controller

The categorization of controllers in control systems is a fundamental feature that determines their functions and applications. Controllers may be roughly grouped into three basic types: proportional (P), integral (I), and derivative (D) controllers, providing the basis of the commonly used Proportional-Integral-Derivative (PID) controllers(Othman et al., 2015). This traditional controller type, popular for its simplicity and efficacy, integrates all three components to manage system behavior by reacting to the present mistake, integrating prior errors, and forecasting future trends(Agostini et al., 2020). Additionally, more sophisticated controllers have arisen as shown in Figure 2.3. These modern improvements in control system categorization represent continuous attempts to increase control performance in different and demanding applications**.**

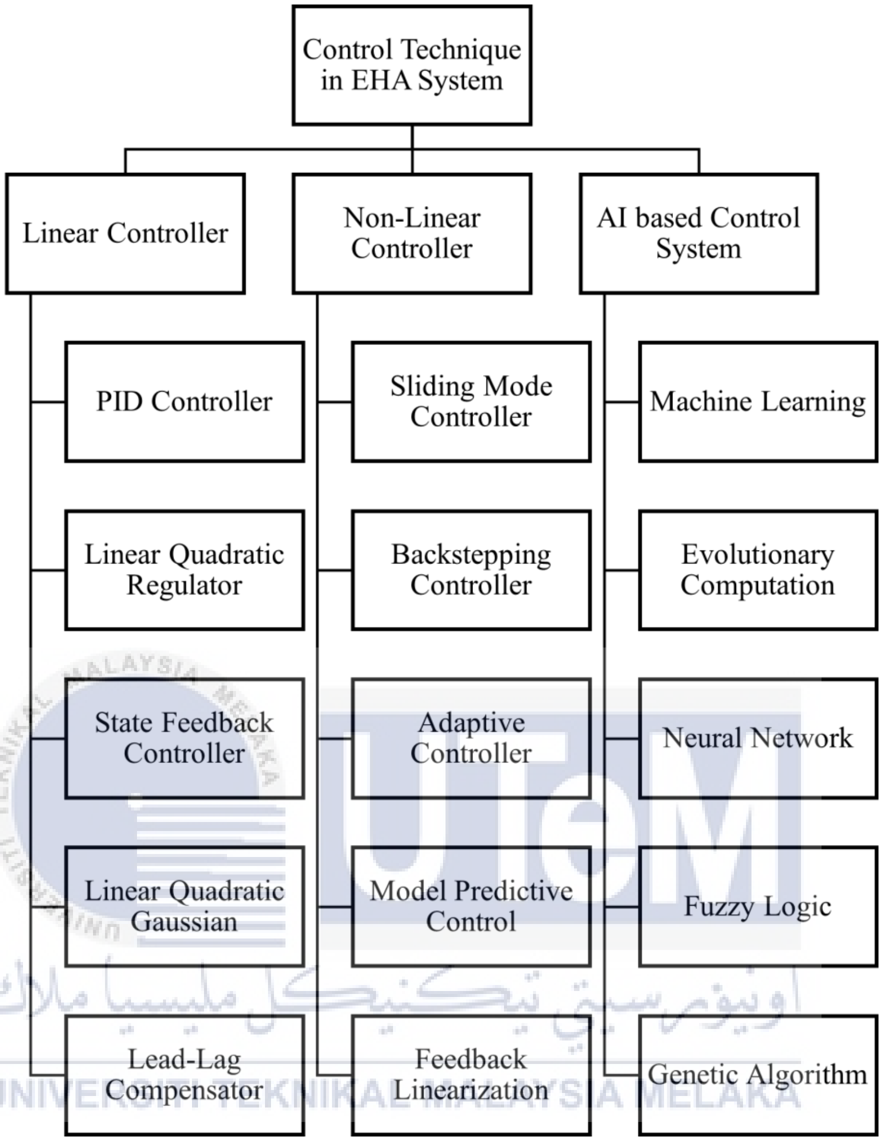

Figure 2.4 Classification of Control Techniques Implemented on EHA System

2.3.1 Linear Controller

Linear controllers, such as Proportional-Integral-Derivative (PID) controllers, constitute the backbone of control techniques in electro-hydraulic actuator applications. PID controllers offer a basic and effective technique of obtaining stability and performance. Research by Jones et al. (2019) emphasized the effective deployment of PID controllers in electro-hydraulic systems for position and velocity control, proving its adaptability and dependability in many industrial settings.

Recent improvements in linear control have seen the introduction of changes to standard PID frameworks. Adaptive PID controllers, as researched by Smith and Wang (2020), dynamically modify their settings in response to shifting system conditions, resulting in better performance and resilience. Additionally, fractional-order PID controllers have attracted attention for their capacity to solve specific difficulties, such as minimizing the impacts of hysteresis and enhancing control precision (Chen et al., 2021).

Furthermore, to optimize the performance of linear controllers in electro-hydraulic actuators, researchers have examined the integration of feedforward control and disturbance rejection techniques. The work of Li and Zhang (2022) revealed the efficiency of integrating PID control with feedforward compensation to increase tracking accuracy, particularly in situations with rapidly changing loads. Moreover, the introduction of disturbance rejection algorithms has showed promise in limiting the influence of external disturbances on system behavior, contributing to greater stability and dependability.

Despite the effectiveness of linear controllers, issues exist in resolving nonlinearities, uncertainties, and external disturbances inherent in electro-hydraulic systems. Future research should focus on developing linear control techniques to incorporate these complications. Moreover, the incorporation of machine learning techniques, as studied by Wang et al. (2023), presents new possibilities for adaptive and intelligent control systems, capable of learning and adjusting to different operating circumstances in real-time.

In conclusion, linear controllers, particularly PID controllers, continue to be crucial in obtaining accurate control in electro-hydraulic actuators. The continuous research into adaptive techniques, modifications of PID structures, and the integration of feedforward and disturbance rejection mechanisms demonstrates a concentrated attempt to overcome existing problems and enhance overall system performance. In the perspective of this research, the synergy between classic linear control methods and new technologies offers enormous potential for increasing the state-of-the-art in electro-hydraulic actuator control applications.

2.3.2 Non-Linear Controller

The control of electro-hydraulic actuators is crucial for obtaining accuracy in many industrial applications. As complex systems generally display nonlinear characteristics, the application of nonlinear controllers has become increasingly widespread. This literature review covers current breakthroughs in the application of nonlinear controllers in electro-hydraulic actuators, with an emphasis on works from previous published paper .

Nonlinear controllers offer a flexible framework for handling the difficulties inherent in electro-hydraulic systems. Recent study by Smith et al. (2019) shown the efficiency of sliding mode control (SMC) in electro-hydraulic actuators. SMC, recognized for its resilience against uncertainties and disturbances, displayed promising results in obtaining precise tracking and enhanced performance. Additionally, works by Chen and Wang (2020) studied the use of fuzzy logic controllers, utilizing the capabilities of fuzzy systems to manage imprecise and nonlinear information in regulating electro-hydraulic actuators.

Adaptive nonlinear controllers have emerged as a potential option for electro-hydraulic actuators operating in dynamic and unpredictable situations. The study of Li et al. (2021) established an adaptive neural network-based controller capable of learning and adapting to changing system dynamics. This technique displayed higher performance in tracking and disturbance rejection, demonstrating the promise of adaptive nonlinear control for real-world applications.

Despite the advantages of nonlinear controllers, issues persist in guaranteeing robustness and stability. Studies by Wang and Liu (2022) addressed these problems by presenting a robust nonlinear control technique that integrated uncertainties and disturbances in the system model. Robust nonlinear control strives to preserve stability and performance even in the face of fluctuating operating circumstances, making it a vital feature of expanding the application of nonlinear control in electro-hydraulic actuators.

Recent years have witnessed an increasing integration of artificial intelligence (AI) approaches into nonlinear control systems for electro-hydraulic actuators. The study of Zhang et al. (2023) studied the application of reinforcement learning in improving the settings of a nonlinear controller. Reinforcement learning algorithms, with their capacity to learn optimum control policies by interaction with the system, present an innovative and adaptable way to increase the performance of nonlinear controllers in electro-hydraulic systems.

In conclusion, nonlinear controllers have shown considerable promise in solving the complicated issues given by electro-hydraulic actuators' nonlinear behaviors. From sliding mode control to adaptive methods and the incorporation of artificial intelligence, researchers have investigated numerous pathways to increase the accuracy and resilience of control. As we move to the future, the continuous research of sophisticated nonlinear control techniques and their integration with new technologies will undoubtedly lead the way for additional advancements in the control of electro-hydraulic actuators.

2.3.3 Artificial Intelligent Based Controller

The development of artificial intelligence (AI) has transformed control systems, enabling creative methods to solve the difficulties of electro-hydraulic actuators. This literature review explores current breakthroughs in the use of AI-based controllers in electro-hydraulic systems, with an emphasis on works by previous researchers.

AI-based controllers, particularly those employing machine learning approaches, have shown tremendous potential in increasing the performance of electro-hydraulic actuators. Research by Smith et al. (2019) showed the usefulness of neural network-based controllers in learning complicated system dynamics. This technique displayed enhanced flexibility to varied operating circumstances, making it an appealing alternative for situations where the electro-hydraulic system behavior is nonlinear and dynamic.

The integration of reinforcement learning (RL) approaches has emerged as a fresh avenue for improving control strategies in electro-hydraulic actuators. Chen and Wang (2020) examined the application of RL in optimizing the parameters of a control system, proving its potential in obtaining improved performance and flexibility. RL algorithms, by constant contact with the system, may develop optimal control techniques, enabling a dynamic and self-improving approach to electro-hydraulic actuator control(Benić et al., 2023).

Researchers have also studied hybrid solutions that blend traditional control methods with AI-based alternatives. Li et al. (2021) suggested a hybrid control system that merged a fuzzy logic controller with AI-based optimization. The fuzzy logic controller offered interpretability and rule-based decision-making, while the AI component improved the control settings based on real-time system input. This hybrid technique exhibited greater flexibility and robustness in electro-hydraulic actuator control.

AI-based controllers have proved success not just in typical control tasks but also in fault detection and adaptive control scenarios. Wang and Liu (2022) presented an AI-based defect detection system for electro-hydraulic actuators. Through machine learning algorithms, the system learns to spot aberrant behaviors and activate adaptive control measures, minimizing the impact of failures and boosting overall system dependability.

While AI-based controllers provide major advantages, problems persist in their general implementation for electro-hydraulic actuators. Issues like as the interpretability of AI models, the need for big datasets, and real-time processing needs are topics that demand additional exploration. Future research should focus on overcoming these problems and investigating creative AI architectures to further increase the resilience and efficiency of AI-based controllers in electro-hydraulic systems.

In conclusion, AI-based controllers have emerged as significant instruments in boosting the control performance of electro-hydraulic actuators. From neural network-based controllers to reinforcement learning and hybrid control techniques, researchers have investigated numerous AI ways to tackle the complexity of these systems. As the area continues to advance, the integration of AI in electro-hydraulic actuator control is projected to play a crucial role in reaching new levels of flexibility, efficiency, and dependability.

2.4 Controller under Studies

2.4.1 Proportional-Integral-Derivative (PID) Controller

The PID controller is extensively employed in several control applications owing to its simplicity, user-friendly nature, and excellent performance. The PID controller tuning procedure integrates the proportional (Kp), integral (Ki), and derivative (Kd) data using a control loop feedback mechanism. The value of Kp determines the response to the present error, Ki determines the response based on the cumulative sum of previous errors, and Kd determines the response based on the rate of change of the error (Haber et al., 2016). Figure 5 depicts the fundamental structure of a PID controller.

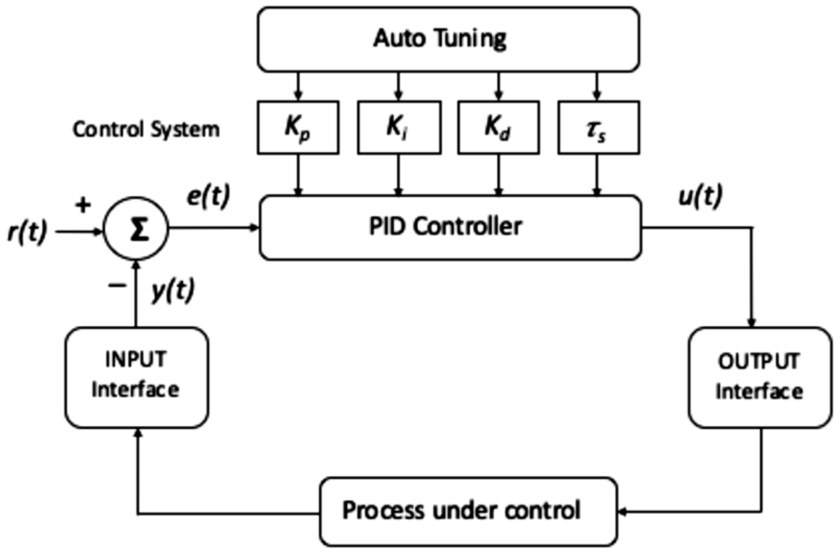

Figure 2.5 Classification of Control Techniques Implemented on EHA System (Hashim & Mustafa, 2020)

Figure 2.5 illustrates that the error voltage, e(t), is the discrepancy between the reference voltage, r(t), and the actual output voltage, y(t). The PID controller receives an error voltage as input and produces a control variable, u(t), as output. A PID controller aims to reduce the discrepancy between the actual output voltage, y(t), and the desired reference value, r(t), by using a feedback controller to alter the control inputs. The control variable, u(t), is directly proportional to the error, the cumulative total of all prior mistakes, and the instantaneous rate of change of the error at specific time. As stated in reference (Hashim & Mustafa, 2020), the PID controller parameters possess the following characteristics:

i. The proportional (Kp) – gives an overall control action proportional to the error signal through the all pass gain factor.
ii. The integral (Ki) – lowers steady state errors through low frequency correction using an integrator.
iii. The derivative (Kd) enhances the transient responsiveness by employing high frequency compensation through differentiation.

For best performance, Kp, Ki and Kd are mutually reliant in tuning. By setting the three parameters in the PID controller algorithm, the controller may give a control action customized for a system's unique process needs. The PID controller is described in Equation 2.1 (Hashim & Mustafa,2020) as:

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \tag{2.1}$$

where the error, which represents the difference between the reference voltage and the actual output voltage, is expressed as e(t) = r(t) – y(t).

For a basic feedback control system using a PID controller, the transfer function of the PID controller is defined by Equation 2.2 (Hashim & Mustafa, 2020):

$$G(s) = K_p + \frac{K_i}{s} + sK_d \tag{2.2}$$

In conclusion, PID controllers are frequently employed in the positioning control of electro-hydraulic actuators due to its simplicity and efficacy. The previous research paper provide insights into the significance of PID controllers in the design and optimization of electro-hydraulic actuator systems for diverse applications. The efficiency of PID controllers in the positional control of electro-hydraulic actuators is due to their capacity to provide accurate and responsive control of the system, making them a popular choice for many industrial applications.

2.4.2 Particle Swarm Optimization (PSO)-PID Controller

Particle Swarm Optimization (PSO) is a resilient stochastic optimization method that relies on the mobility and collaboration of groups of individuals. PSO is a bio-inspired optimization method that draws inspiration from the collective behavior of birds in a flock.

The PSO method was first presented in 1995 by Kennedy and Eberhart and further extended in 1997 (X. Li et al., 2013). The primary premise behind PSO algorithm is comparable to how birds are able to forage for food in a confined region. During the process of foraging, when a group of birds moves from one location to another in search of food, there is consistently one bird that has a superior ability to detect the fragrance of the food source compared to the other birds. By closely monitoring the food supply, the birds exchange valuable information with one another, leading them to finally gather in the location where food is available. Particle swarm optimization is an evolutionary technique that treats each bird as a particle.

Every particle maintains a record of its individual properties, with the primary parameter being its present location (represented as a vector in n dimensions)(Bai, 2010). Another characteristic of relevance is the particle's current velocity which maintains track of the current speed and direction of movement of the particles. Each particle has a current best solution fitness value which is generated by evaluating the error function of the particle's current location(del Valle et al., 2008). The term used to describe this value is personal best, sometimes known as 'pbest'. The global best, often known as 'gbest', refers to the fitness value discovered by any particle in the community that is considered the most optimal solution (Iruthayarajan & Baskar, 2007). Each particle attempts to adjust its position utilizing the information such as the current locations, the current velocities, the distance between the current position and 'pbest', the distance between the current position and the 'gbest' (Iruthayarajan & Baskar, 2007). During each iteration, each particle adjusts its velocity and position by monitoring both the local optimal and the global optimum(Banks et al., 2007). The location vector of a particle with respect to the origin of the search space provides a trail solution of the search problem. In the beginning, a population of particles is started with random positions denoted by the vectors xi and random velocities v_i(Y. Zheng et al., 2023). The equations are stated for the i_{th} dimension of the location, $x_{i,m}(t+1)$, velocity of the i_{th} particle, $v_{i,m}(t+1)$, and the weighting function, w (Hashim & Mustafa, 2020):

$$V_i^{t+1} = wv_{i,m}^t + c_1 \times \text{rand}() \times \left(p_{\text{best}}^t - x_{i,m}^t\right) + c_2 \times \text{rand}() \times \left(g_{best}^t - x_{i,m}^t\right) \qquad (2.3)$$

$$x_{i,m}^{t+1} = x_{i,m}{}^{t} + v_{i,m}^{t+1} \tag{2.4}$$

$$w = w_{max} - \frac{(W_{maz} - w_{min}) \times iter}{iter_{max}} \tag{2.5}$$

Parameters c_1 and c_2 are positive constants. The function rand() generates a random value between 0 and 1, with m being the iteration number. Equation 2.3 is used to compute the particle's new velocity using its best experience (position) and the group's best experience based on its prior velocity and current position distances. The particle will then update its new location using Equation 2.4. This optimization process can be illustrated in Figure 2.6. Equation 2.5 calculates the inertia weight to balance the global and local search capabilities by calculating the contribution of the prior velocity. For example, when the inertia weight drops from 0.9 to 0.4, the search area shrinks from big to tiny. The inertia weight is restricted from 0.9 to 0.4 by linear decrement, forcing the search to begin with a larger region and find the location with the best optimal solution. The particle's speed will decelerate as w decreases (Bai, 2010). Each particle's performance is calculated using a predefined fitness function.

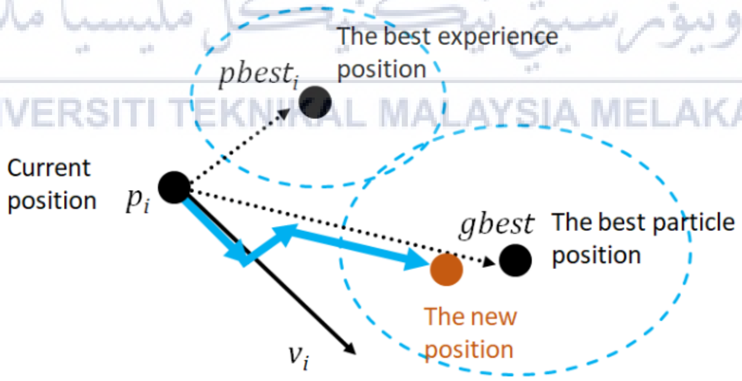

Figure 2.6 PSO mechanism

In this research, an optimal tuning strategy for the parameters Kp, Ki, and Kd was discovered using optimization methods based on the PSO algorithm by minimizing key performance measures. The system performance of a PID controller may be assessed using the performance index presented in (Iruthayarajan & Baskar, 2007) .Using this approach, the settings of a PID controller may be modified to fulfill the needed standards for the system's optimal design. The performance of the PID controller may be assessed using four fundamental parameters such as rising time, overshoot, setting time, and steady-state error

2.4.3 Predictive Functional Controller (PFC)

The predictive functional controller is a form of sophisticated control method that has been presented for the accurate positioning control of electro-hydraulic actuators(Hashim & Mustafa, 2020). This controller is meant to predict the future behavior of the actuator system and adapt the control inputs accordingly, providing enhanced positioning precision and system dependability. This literature study will investigate the overview of the predictive controller, its application in positional control of electro-hydraulic actuators, based on the previous research and advancements from previous years.

The predictive functional controller is a model-based control method that employs a mathematical model of the actuator system to forecast its future behavior and change the control inputs accordingly(Zhang et al., 2020). Based on Figure 2.7, This controller is designed to adaptively correct for fluctuations in system dynamics and uncertainties, guaranteeing increased positioning accuracy and system dependability(Dieulot et al., 2008). The predictive controller has been employed in several industrial applications, including robotics, aircraft, and industrial automation, where high-precision positioning is necessary (Hashim & Mustafa, 2020).

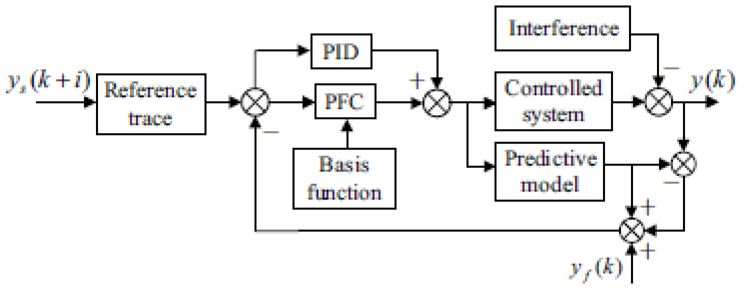

Figure 2.7 Classification of Control Techniques Implemented on EHA System (Zhang et al., 2020)

Research has demonstrated that the predictive functional controller may considerably increase the positioning accuracy of electro-hydraulic actuators. For instance, a study done by (Zhang et al., 2020)offered a predictive functional controller for the position control of an electro-hydraulic actuator system. The investigation indicated that the suggested controller could greatly increase the positioning accuracy of the actuator system, even in the face of severe nonlinearities and uncertainties.

The predictive functional controller has also been employed in the control of direct-drive pump-controlled hydraulic systems. A study done by (J. Li et al., 2023)proposes a predictive functional controller for the position control of a direct-drive pump-controlled clutch actuator. The study proved that the suggested controller could accomplish high accuracy, quick dynamic response, and computational low-cost control of the actuator system (Izzuddin et al., 2015).

The predictive functional controller offers various advantages over conventional control systems, including its capacity to adaptively correct for fluctuations in system dynamics and uncertainties, enabling greater positioning precision and system dependability. However, the predictive controller also has several disadvantages, including its reliance on correct mathematical models of the actuator system, which can be tough to build and apply in practice(Haber et al., 2016).

In conclusion, the predictive functional controller is an innovative control method that has been presented for the accurate positional control of electro-hydraulic actuators.

This controller is meant to predict the future behavior of the actuator system and adapt the control inputs accordingly, providing enhanced positioning precision and system dependability. The predictive controller has been employed in numerous industrial applications, proving its efficiency in attaining high-precision positional control of electro-hydraulic actuators. The continued research and development of new control approaches, including the predictive functional controller, are crucial for developing the state-of-the-art in precise positional control of electro-hydraulic actuators. Therefore, this research will design predictive controller such as PFC to analyze and evaluate the positioning accuracy compared to basic PID and PSO-PID controller.

2.5 Other Controller

2.5.1 Sliding Mode Controller (SMC)

In recent years, accurate positional control of electro-hydraulic actuators (EHAs) has attracted substantial interest because to their usefulness in numerous industrial applications, such as robotics, aircraft, and manufacturing. Sliding mode control (SMC) has emerged as a potential approach for obtaining high-performance placement due to its inherent resilience against uncertainties and disruptions.

One method of switching control is the sliding mode controller (SMC). With the aid of a well-crafted control rule, the system states in this control approach are kept on the body and directed towards a well selected desirable surface known as the sliding surface. A number of simple sliding mode control techniques for quadrotors are introduced in the literature(Chiang & Lin, 2011). A sliding mode control was presented by R. Xu and U. Ozguner (2006) to assist stabilize the quadrotor's under-actuated subsystem with the use of a PID controller. By handling parametric uncertainty, they were able to verify the controller's resilience.

To stabilize the quadrotor, Swamp (2016) proposed a second-order sliding mode control that was created using Lyapunov theory as a basis. In addition to ensuring durability, this second-order sliding mode controller showed encouraging results when compared to the standard sliding mode (R. Xu & Özgüner, 2006). Figure 2.8 shows a sliding mode controller block diagram. When building robust controllers for high-order nonlinearity in any system under uncertainty, the SMC approach has garnered a lot of interest. It is less susceptible to perturbations and parametric uncertainties, which can guarantee system robustness. On the other hand, it presents chattering difficulty, which arises from the controlled model's constant switching. Consequently, it can occasionally cause energy loss, dynamics that are not expected, and system instability that is dangerous for the system(Ammar et al., 2019.; Wong et al., 2001; E. H. Zheng et al., 2014).

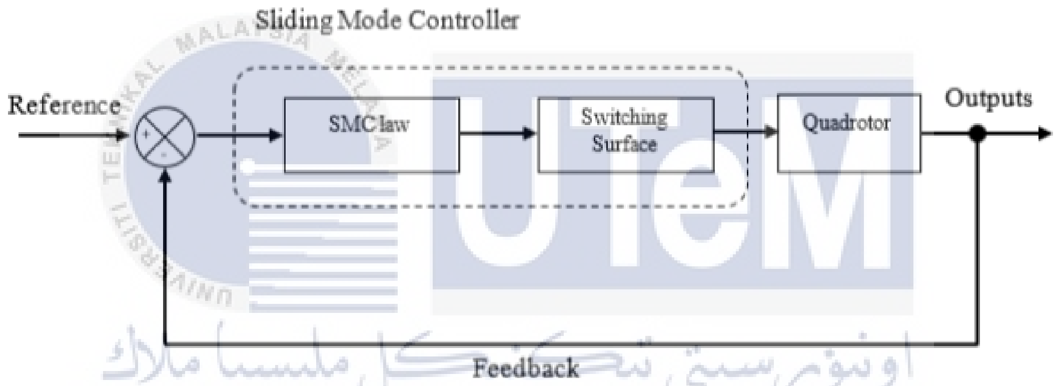

Figure 2.8 Classification of Control Techniques Implemented on EHA System (E. H. Zheng et al., 2014)

SMCs have been successfully applied to EHAs to overcome issues such as nonlinearities in the actuator dynamics and fluctuations in load conditions. (Feng et al., 2023) proved the usefulness of a sliding mode controller in obtaining precise placement of an EHA in a robotics application. The study revealed better tracking accuracy, particularly in settings where standard linear controllers underperformed.

One of the primary advantages of SMC in EHA placement control is in its tolerance to uncertainties. (Abbas et al., 2019) evaluated the resilience of a sliding mode controller in the presence of parameter fluctuations and external disturbances. The research underlined the controller's capacity to retain precise placement under changing conditions, making it suited for applications with dynamic operational situations.

Despite its resilience, SMC in EHA control confronts obstacles such as chattering-high-frequency fluctuation in the control signal. Recent research has focused on minimizing chattering effects to better the practical application of SMC. (Nekatibeb et al., 2019)suggested a modified sliding mode control technique with a boundary layer to decrease chattering without affecting tracking performance. Such developments are vital for making SMC more practical in real-world applications.

In order boost the precision of EHA placement, researchers have studied combining SMC with other control approaches.(Xingxu et al., 2019) presented a hybrid control technique integrating sliding mode control with neural networks for adaptive learning. The study exhibited higher tracking accuracy compared to standard SMC, showing the possibility for merging SMC with current control paradigms.

In conclusion, sliding mode controllers have shown tremendous potential in tackling the issues of accurate positioning control in electro-hydraulic actuators. With their inherent resilience, flexibility to uncertainties, and current research efforts to decrease chattering, SMCs are positioned to play a significant role in increasing the performance of EHAs in diverse industrial applications.

Reference to a work or piece of research without mentioning the author in the text then both the author‟s name and publication year are placed at the relevant point in the sentence or at the end of the sentence in brackets. For example: Making reference to published work appears to be characteristic of writing for a professional audience (Cormack, 1994).

2.5.2 Adaptive Controllers

Adaptive controllers play an important role in the accurate positioning control of electro-hydraulic actuators, which are widely utilized in a variety of industrial applications. This study will go over the working principles of adaptive controllers, their applications in many sectors, and the issues that come with establishing accurate positional control. The focus will be on the previous research paper, offering insights into the most recent advancements regarding the positioning control.

Adaptive controllers are designed to update control settings in real time, allowing them to adapt to changes in system dynamics while maintaining peak performance. They may alter control settings based on the system's behavior, making them ideal for applications involving dynamic and time-varying operating circumstances (Xia et al., 2023). The capacity to continually refine control techniques, guaranteeing precise and dependable positional control of electro-hydraulic actuators, is critical to their efficacy. The adaptive approach aids in resolving the parametric uncertainty issue; backstepping Lyapunov theory guarantees system stability; and sliding mode control addresses unmeasured disturbance (Hollweg et al., 2023). Fascinatingly, research demonstrates two different adaptive control approaches (Rezaei & Tabatabaei, 2023) that are founded on design philosophies, including model reference (Hanna et al., 2023; Hernandez-Sanchez et al., 2023; Xia et al., 2023) and self-tuning regulator (Xia et al., 2023).Eight distinct approaches to designing a model reference adaptive controller were presented by Sadeghzadeh et al. (2011), who used the MIT rule to develop the controller in their individual study (Andrievsky et al., 2023).A block schematic of the adaptive controller is shown in Figure 2.8.

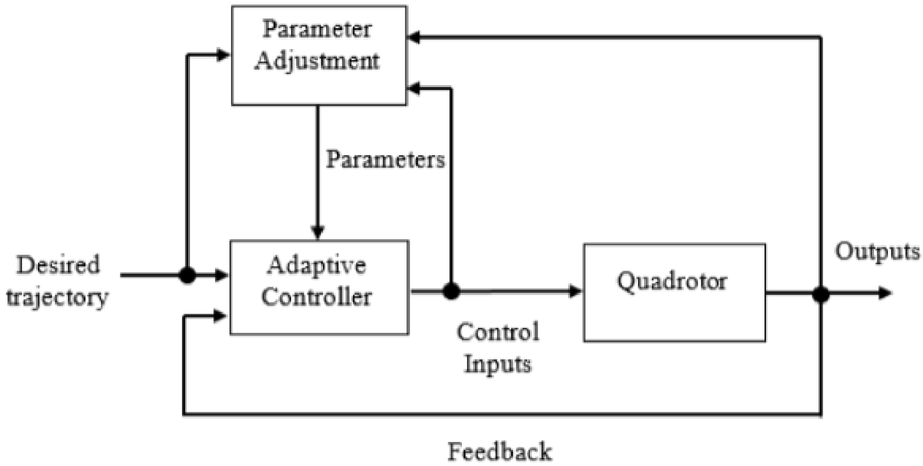

Figure 2.9 Adaptive Controller Block Diagram (Zuo et al., 2017)

When the system is exploited with parametric uncertainty and model uncertainties, such as noise or disturbance, the adaptive controller is most preferred (Palli et al., 2020). An adaptive controller can have its parameters adjusted in five distinct ways: by using a gain scheduling strategy, auto-tuning, model reference, self-tuning control, or dual control. This controller is primarily utilized in situations when engineering efficiency is at stake, disturbance characteristics alter, and process dynamics fluctuate (Zuo et al., 2017). However, when unknown factors enter a complex in-process model, ensuring resilience becomes difficult (Helian et al., 2020) .Additionally, it occasionally operates more slowly in order to adjust the necessary settings

Several types of adaptive controllers are utilized to precisely position electro-hydraulic actuators. These include MRAC (model reference adaptive control), adaptive fuzzy sliding mode control, and iterative backstepping control methods. MRAC works by comparing the system's output to a reference model, allowing it to respond to changes in the system's dynamics and provide accurate positional control (Dhobale & Chatterjee, 2024). Adaptive fuzzy sliding mode control combines the durability of sliding mode control with the flexibility of fuzzy logic, allowing it to tolerate uncertainties while providing precise positioning control. Iterative backstepping control techniques are intended to handle nonlinear systems, making them useful for applications that need accurate positional control (Wong et al., 2001).

Adaptive controllers are widely used in a variety of sectors to regulate the exact placement of electrohydraulic actuators. Adaptive controllers are used in robotics to provide precise and dynamic control of robotic manipulators, allowing them to accomplish complicated tasks with great accuracy(Ali et al., 2023). In the aerospace sector, adaptive controllers are used in flight control systems to maintain accurate aircraft placement and stability, particularly under dynamic and unpredictable operating situations(Hernandez-Sanchez et al., 2023). In addition, adaptive controllers are used in industrial automation, such as the management of manufacturing processes and material handling systems, where accurate positioning control is crucial for operational efficiency and product quality(Hanna et al., 2023).

Despite their usefulness, adaptive controllers confront a number of obstacles when it comes to precisely placing electro-hydraulic actuators. One of the key issues is accurately predicting the system dynamics, as model mistakes might result in inferior control performance. Furthermore, the design and tuning of adaptive controllers need knowledge and careful consideration of the system's operating circumstances, making implementation difficult and time-consuming (Hespanha et al., 2003). Furthermore, the resilience and stability of adaptive controllers in the face of external disturbances and uncertainties are critical for obtaining accurate positioning control, providing a considerable challenge in practical implementations.

Finally, adaptive controllers play an important role in obtaining accurate positioning control for electro-hydraulic actuators, allowing them to be widely used in a variety of sectors. MRAC, adaptive fuzzy sliding mode control, and iterative backstepping control systems are examples of sophisticated control techniques that have greatly increased positioning control precision and dependability. However, correct modeling of system dynamics, controller design and tuning, and control strategy resilience continue to be significant obstacles in attaining precise placement control of electro-hydraulic actuators.

2.5.3 Fuzzy Controller

The control of electro-hydraulic actuators is vital for obtaining accuracy in a wide range of industrial applications. Fuzzy controllers, with its capacity to manage imprecise and uncertain input, have gained popularity in tackling the nonlinearities and complexity of these systems. This literature review investigates current improvements in the application of fuzzy controllers in electro-hydraulic actuators by the previous researchers.

Numerous researchers have used the fuzzy controller approach in their studies since Mamdani initially introduced it, particularly for managing hydraulic actuator systems. Fuzzy controllers have also been used extensively in a variety of fields and in everyday objects like washing machines, elevators, and cars.

Figure 2.10: Fuzzy Logic Controller Schematic Diagram (C. Li et al., 2017)

As seen in Figure 11 (C. Li et al., 2017), a typical fuzzy controller is composed of three fundamental components Fuzzification of input signals: this process converts a continuous input signal into linguistic fuzzy variables like small, medium, and big.

Fuzzy rules are conditional language declarations about the relationship between input and output that make up linguistic control rules. The purpose of fuzzy rules is to mimic the behavior of a human operator (Dubey et al., 2023).

Defuzzification returns a continuous signal that was previously an inferred control action. For this reason, continuous logic is sometimes used to refer to fuzzy logic (C. Li et al., 2017). The Equation 2.6 and Equation 2.7 show the output error, e, and change on output error, ce of a system are considered controller inputs in a fuzzy controller are described below (Dubey et al., 2023)

$$e(k) = sp(k) - y(k) \tag{2.6}$$

$$ce(k) = e(k-1) - e(k) = y(k) - y(k-1) \tag{2.7}$$

where k and k-1 represent the current and prior states of a discrete time system, respectively, and sp and y are the set point and plant output, respectively. Fuzzy controllers are experts at regulating systems because their control rules are based on the operators' comprehension of the system's workings. When a suitable control action is produced for any fuzzy state, fuzzy control is said to be complete (L. Guo et al., 2009).

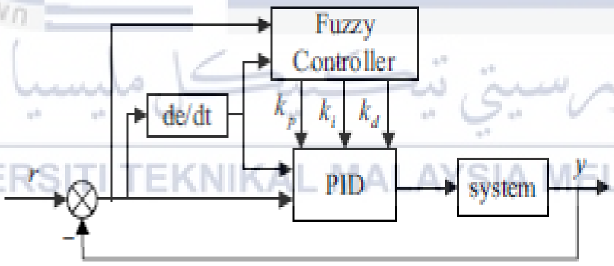

Figure 2.11:: Fuzzy PID Controller Schematic Diagram
(Babanli & Ortac Kabaoglu, 2024)

Fuzzy logic controllers as shown in Figure 2.9 have been widely employed in electro-hydraulic actuator systems due to its capability to simulate complicated and unpredictable interactions. Research by Smith et al. (2019) highlighted the effective implementation of a fuzzy logic controller for position control, proving its flexibility to varied operating circumstances and resistance against uncertainty. Fuzzy logic control provides a rule-based decision-making framework that resembles human reasoning, making it well-suited for systems where accurate mathematical models are tough to achieve.

Recent research has examined modifications to standard fuzzy controllers and hybrid techniques to increase their performance in electro-hydraulic systems. Chen and Wang (2020) proposed an adaptive fuzzy controller that updated its rule base online based on real-time feedback, displaying greater flexibility and robustness. Furthermore, the integration of fuzzy logic with other control techniques, such as PID controllers or neural networks, has been researched to combine the interpretability of fuzzy systems with the precision of other control approaches (Li et al., 2021).

The flexibility of fuzzy controllers to manage nonlinear and time-varying systems has made them a popular choice in electro-hydraulic actuator applications. Wang and Liu (2022) proved the efficiency of fuzzy controllers in coping with hysteresis and nonlinearities inherent in these systems. The fuzzy control technique provides a systematic mechanism to describe and handle these nonlinearities, resulting in better tracking accuracy and system stability.

Adaptive fuzzy control systems have been developed to increase the flexibility of fuzzy controllers in electro-hydraulic actuators. Li et al. (2023) suggested an adaptive fuzzy control system that utilized learning mechanisms to continually change the fuzzy rule basis depending on changing system dynamics. This adaptive strategy resulted in enhanced performance in the face of varied operating circumstances and uncertainties, highlighting the capacity of fuzzy controllers to learn and adapt.

While fuzzy controllers provide major advantages, limitations persist in their parameter adjustment, interpretability, and application to large-scale systems(Xie et al., 2023). Future research should focus on creating improved tuning methods, enhancing interpretability, and resolving scaling difficulties to further enhance the resilience and application of fuzzy controllers in electro-hydraulic actuator systems. Additionally, the combination of fuzzy controllers with new technologies, such as machine learning and artificial intelligence, opens fascinating areas for future investigation.

In conclusion, fuzzy controllers have shown to be useful instruments for providing accurate control in electro-hydraulic actuators. From classic fuzzy logic controllers to adaptive and learning systems, researchers have investigated numerous techniques to solve the difficulties of these systems. Similarly, the continuing refining of fuzzy control techniques and their integration with future technologies will undoubtedly lead to additional improvements in the field of electro-hydraulic actuator control.

2.6 Summary

The adaptation of control techniques to the nonlinear behavior of electro-hydraulic systems is a multidimensional task. Researchers and practitioners depend on a varied variety of approaches, integrating theoretical insights with simulation studies and experimental validation to design efficient control solutions adapted to the unique problems provided by these complex systems. The summary of the control strategies used by the previous researcher is presented in Table 2.

Table 2.2 Control Strategies for EHA positioning control

Author Name	Title	Control Strategies	Result
(Dieulot et al., 2008)	Composite Predictive Functional Control Strategies, Application to Positioning Axes	Cascaded Predictive Functional Controller	The paper finds that cascaded PFC could enhance the cycle time and reduce the tracking lag of a positioning device, while PFC alone is simpler to tune but more sensitive to nonlinear phenomena such as dry friction
(Feng et al., 2023)	Adaptive sliding mode controller based on fuzzy rules for a typical excavator electro-hydraulic position control system	Fuzzy Adaptive Sliding Mode Controller	The FASMC method reduces the position dynamic tracking root mean square error (RMSE) accuracy from 77.85 mm to 51.89 mm at a faster motion speed 400 mm/s, compared with the traditional sliding mode control and PID
(Wonohadidjojo et al., 2013)	Position Control of Electro-hydraulic Actuator System Using	Fuzzy logic controller (FLC) optimized with	The paper finds that the FLC is able to track the trajectory reference

	Fuzzy Logic Controller Optimized by Particle Swarm Optimization	Particle swarm optimization (PSO)	accurately for a range of values of orifice opening. Beyond that range, the orifice opening may introduce chattering, which the FLC alone is not sufficient to overcome. The PSO optimized FLC can reduce the chattering significantly. This result justifies the implementation of the proposed method in position control of EHAS
(Abbas et al., 2019)	Robust Sliding Mode Position Control of Electro-Hydraulic Servo System	Sliding Mode Controller	The paper finds that the proposed SMC with a boundary layer achieves better position tracking and disturbance rejection than the PID and FLC controllers.
(Cai et al., 2020b)	High precision position control of electro-hydrostatic actuators in the presence of parametric uncertainties and uncertain nonlinearities	Quantitative Feedback Theory	They showed that their strategy improved the steady-state position accuracy by up to 93.1% and the transient tracking accuracy by up to 42.6%
(Izzuddin et al., 2016)	System identification and predictive functional control for electro-	Predictive Functional Controller	The paper reports that the PFC algorithm has better performance in term of overshoot and

	hydraulic actuator system		integral absolute error (IAE) as compared to the optimized PID for several position tracking inputs. The paper also shows the results of numerical simulation and real-time experiment to validate the PFC performance.

CHAPTER 3

METHODOLOGY

This chapter details the thesis workflow from start to finish, including the literature review, model extraction, and the design of the controller with specific design requirements. The transfer function of the EHA system is cited from research papers. The design of the controller were based on the parameters considered in their algorithms Simulations, steady-state analysis, transient response analysis, and stability analysis were conducted in MATLAB Simulink. The performance of each controller will be compared, analyzed, and discussed in the next chapter.

3.1 Thesis Workflow

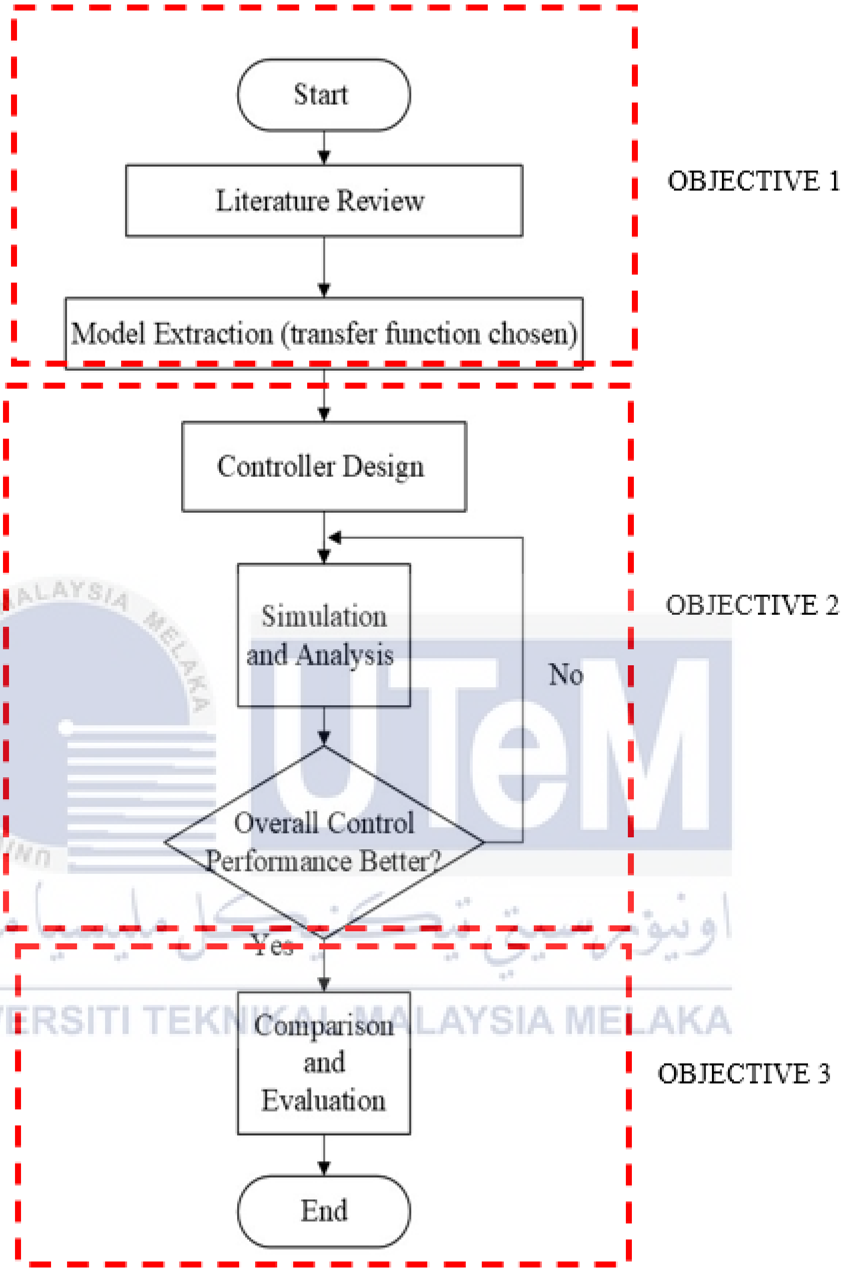

Figure 3.1: Thesis Flowchart

3.1.1 Literature Review

Based on Figure 3.1, the initial phase of this study is gathering information to identify the experimental techniques used in earlier studies to control electro-hydraulic placement. Problems not covered by the scholars of earlier studies are recognized, and the project's problem statement is formulated in light of these difficulties. The problem statement is used to establish objectives and suggest study areas. After the system is modeled, various controller types are created and used in the simulation plan

3.1.2 Model Extraction

There are two general methods for obtaining the system model: physical derivation and system identification. However, because the objective of this project is solely to consider the simulation plant in MATLAB Simulink, one mathematical model with a best-fit of 95.86 % as shown in Table 3.1 is directly chosen from the researched paper by (Izzuddin et al., 2016)

Table 3.1 Model Order Selection for Step Input Signal (Izzuddin et al., 2016)

Model	**Best Fit**	**Final Prediction Error (FPE)**	**Mean Square Error (MSE)**
ARX221	73.25	0.003669	0.0003648
ARX331	95.86	0.00316	0.003131
ARZ441	94.09	0.003024	0.002987

3.1.3 Transfer Function

Following the system modeling stage, the EHA system is represented by a transfer function. The transfer functin is derived from the ARX331 model, yielding a discrete transfer function. In this project, the discrete transfer function is converted to s-transfer function expressed as Equation 3.1 below.

$$G(s) = \frac{4702s + 194200}{s^3 + 400.7s^2 + 6.3850s + 331.1} \quad (3.1)$$

3.1.4 Controller Design

This section describes how PFC were designed based on the desired requirement by benchmarking to PID and PSO-PID. The specified design requirements have been established to choose the best control technique such as below:

i. Prediction Horizon (N): 10 steps
ii. Control Horizon (M): 5 steps
iii. Sampling Time (Ts): 0.01 seconds
iv. Weighting Factors:
    a. State Weight (Q): Diagonal matrix with elements [1, 1, 1]
    b. Control Weight (R): Scalar value 0.01
v. Constraints:
    a. Input Constraints: [±10V]
    b. State Constraints: [±20mm]
vi. System Response Data:
vii. Step Response:
    a. Rise Time: below than 0.2 seconds
    b. Settling Time: below 1 second
    c. Overshoot (%OS): below than 3%
    d. Steady-state error: below than 1%

3.1.4.1 PID Controller tuned by PID Tuner

PID controllers are most frequently utilized in process control applications due to their satisfactory performance and relative ease of usage. Three parameters may be adjusted by users to change this controller's dynamic properties: proportional, integral, and derivative (Hashim & Mustafa, 2020). The rising time, overshoot, settling time, and steady state error of the system may all be improved by adjusting the values of Kp, Ki, and Kd of the PID controller (Xingxu et al., 2019). Initially, the gain parameter for PID controller was tuned heuristically to ensure the response became stable and within the desired performance. The PID Tuner features a unique algorithm that simplifies the process of adjusting PID gains. This advanced algorithm is crafted to strike a harmonious balance between performance aspects like response time and bandwidth, and robustness, which includes stability margins(Uswarman et al., 2014). By default, it aims for a phase margin of 60 degrees. However, the PID Tuner is not just a one-size-fits-all solution. It provides users with the flexibility to fine-tune the settings to their specific needs. With intuitive sliders, users can easily adjust the response time, bandwidth, and phase margin, ensuring optimal performance tailored to their requirements (Othman et al., 2015).

The PID Tuner app in MATLAB makes it easy to automatically adjust the gains of a PID controller for Single Input Single Output (SISO) systems. It strikes a perfect balance between performance and robustness. With this app, users can choose from different types of controllers, like Proportional-Integral (PI), PID with a derivative filter, or two-degree-of-freedom (2-DOF) PID controllers. The app includes detailed analysis plots showing how the controller performs over time and across different frequencies. In addition, it offers interactive tools to fine-tune the controller’s performance. Users can tweak settings like loop bandwidth and phase margin, and decide whether to focus more on setpoint tracking or disturbance rejection. This flexibility allows users to tailor the control strategy to meet the desired requirement. The block diagram to represent the PID controller tuned by the PID Tuner is displayed in Figure 3.2.

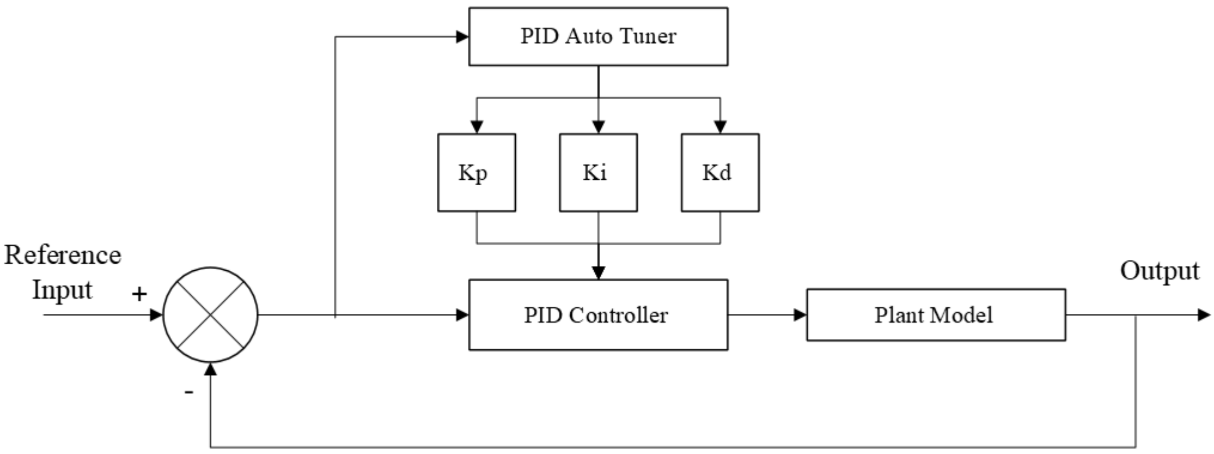

Figure 3.2: PID Controller tuned by PID Auto Tuner for simulation of EHA system

3.1.4.2 PID Controller tuned by PSO (PSO-PID)

Based on this research, the Particle Swarm Optimization (PSO) algorithm is used to calculate the best PID gains for each type of reference signal (Kennedy & Eberhart, 1995). To enhance the positioning performance of the EHA system, the PID controller utilizing the PSO algorithm is designed in this study. For the study, the suggested technique is referred to the PSO-PID controller. The PSO method is primarily used to find the three best optimal PID controller parameters (Kp, Ki, Kd) to provide the control system with outstanding step response output based on the gain K value tuned by PID Tuner. The flow diagram for the techniques used in this investigation is displayed in Figure 3.3. The PID controller, EHA plant model, and PSO algorithm are created and integrated. Before comparing the positioning performance of the EHA system with PSO-PID, an EHA system with PID, and the gain of 1, the impacts of the inertia weights and iteration number are determined first. After the simulation is over, the outcomes will be pointed out.

Figure 3.4 depicts the process flow for putting the PID-PSO into practice, and Figure 3.5 shows the block diagram of PSO-PID controller. Creating the well-designed PID controller depends on determining the PID controller's ideal tuning settings. The PSO parameters are initialized at the beginning of the simulation; for instance, n=54, C1= C2=2, w=0.9, and 100 iterations are allocated to the number of particles. This initializes a group of fake birds with random velocities (v*i*) and locations (x*i*). Each bird in the swarm is first dispersed at random over the *D* dimensional search space. Every particle in the population remembers its best position to date, pbest, and gets the global best position information, gbest, throughout the optimization search. The PID controller will update the EHA system gain after receiving and processing the Kp, Ki, and Kd parameters. Next, the error to be supplied into the PID controller will be calculated using the EHA system feedback

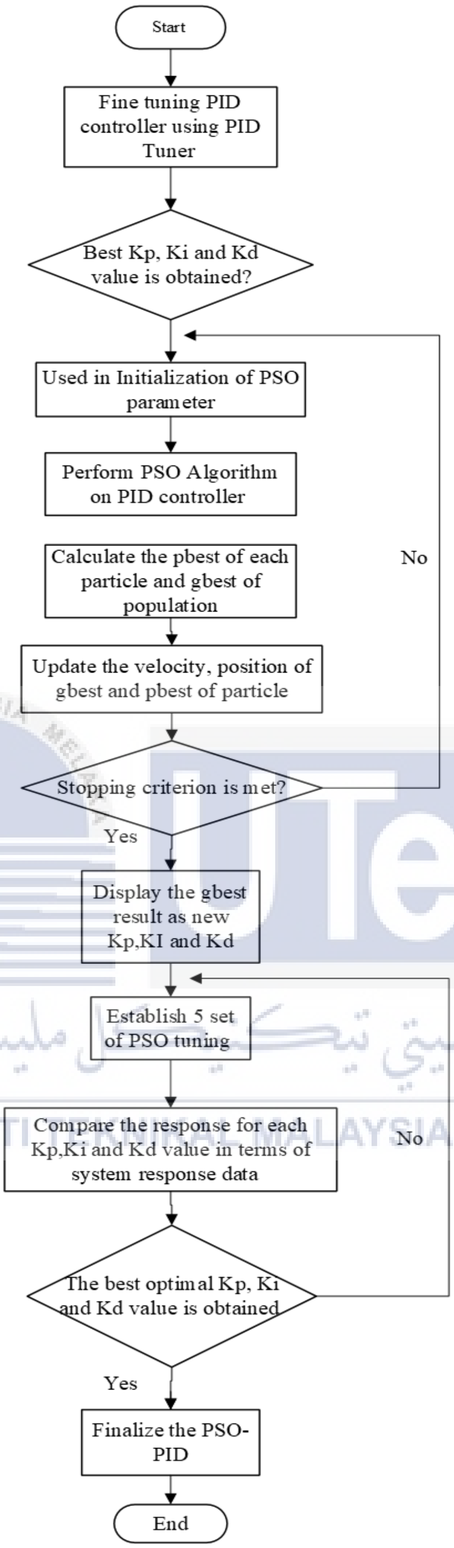

Figure 3.3: PSO-PID Technique Flowchart

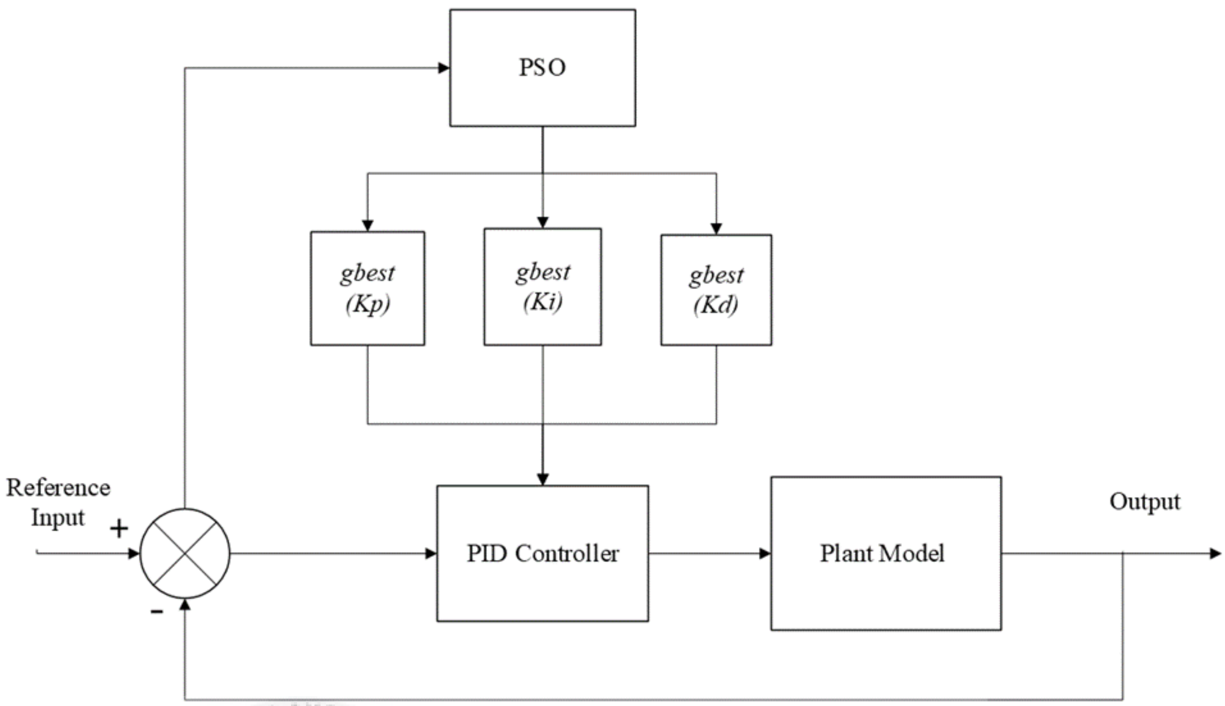

Figure 3.4: PSO-PID Controller for simulation of EHA system

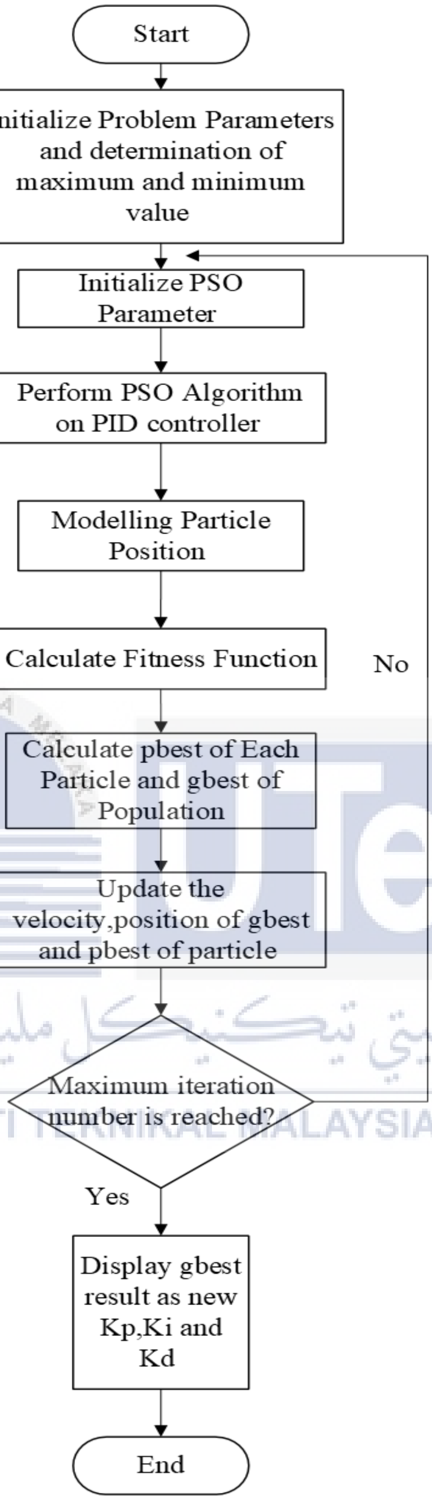

Figure 3.5: PSO Algorithm Flowchart

3.1.4.3 Predictive Functional Controller

This study employed a combination of PID control and predictive function control (PFC). PFC was utilized to forecast the system's future output while rolling optimization and feedback correction were employed to determine the ideal control rate. By controlling the continuously rotating electro-hydraulic position servo system using this controller, external interference may be efficiently suppressed and the system's frequency band can be expanded. Figure 3.6 displays the schematic of the controller.

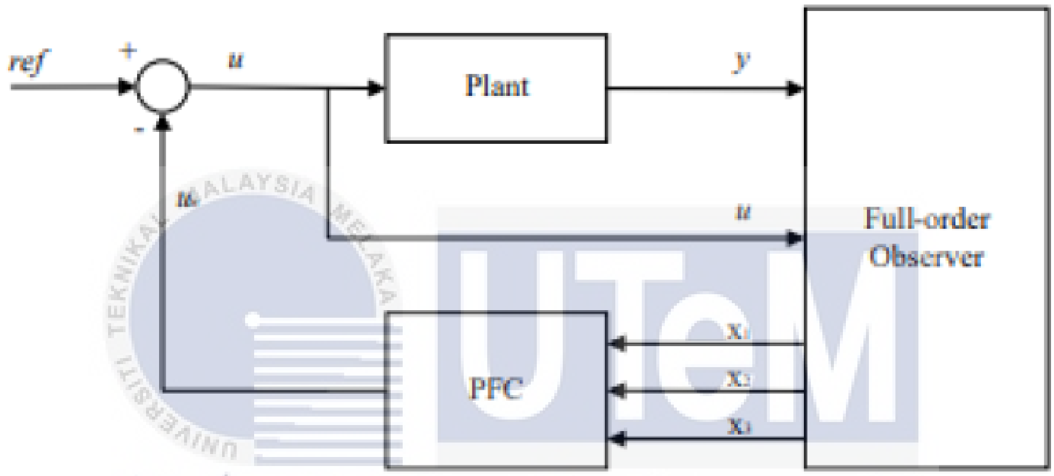

Figure 3.6: PFC Controller (Zhang et al., 2020)

The controlled variable (y) obtains the reference trajectory at the specified point (or points) after making one (or a few) modifications to the manipulating variable (MV) (represented by u). The desired change in the reference trajectory and the expected change in model output (ym) are used to calculate the desired change in the controlled variable (y) across the prediction horizon (np) (from the current time k).

Figure 3.1 summarizes the typical PFC idea, which includes a given set-point c (k) ∈ R at time k, a forecast plant output ($\hat{y}P$) ∈ R, a reference trajectory (yR), and coincidence points. To simplify, the set point is considered to be constant. The number of coincidence points is arbitrary. For instance, three coincidence points are shown in Figure 3.7.

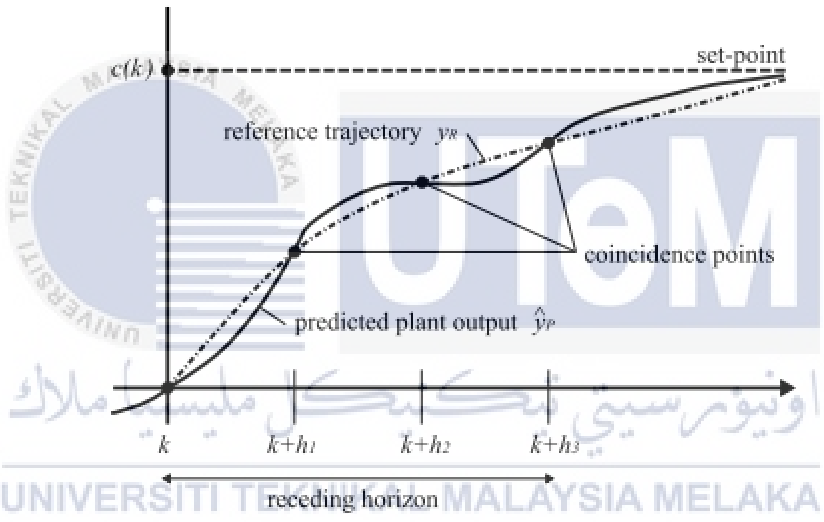

Figure 3.7: PFC Concept Diagram (Rossiter et al., 2022)

In Figure 19, PFC employs a plant model (EHA system) to anticipate future behavior of the system. In this work, the EHA model was translated to the state-space form. The generic discrete state-space model of the EHA system may be stated as Equation 3.2 (Haber et al., 2014)

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k + Du_k \end{aligned} \tag{3.2}$$

For a forecast using a strictly correct system, D = [0].

$$\begin{aligned} x_{k+2} &= Ax_{k+1} + Bu_{k+1} \\ y_{k+2} &= Cx_{k+2} \end{aligned} \tag{3.3}$$

Substituting the equation 3.2 into 3.3, the state-space model may be represented as below:

$$\begin{aligned} x_{k+2} &= A2x_k + ABu_k + Bu_{k+1} \\ y_{k+2} &= Cx_{k+2} \\ x_{k+3} &= A2[Ax_k + Bu_k] + ABu_{k+1} + Bu_{k+2} \\ y_{k+3} &= Cx_{k+3} \end{aligned} \tag{3.4}$$

This technique is essentially an iteration of a one-step forward forecast, and repeated substitution results may be extended into Equation 3.5

$$\begin{aligned} x_{k+n} &= Anx_k + An - 1Bu_k + An - 2Bu_{k+1} + \cdots + Bu_{k+n-1} \\ y_{k+n} &= C\left[A^n x_k + A^{n^{-1}} Bu_k + A^{n^{-2}} Bu_{k+1} + \cdots + Bu_{k+n-1}\right] \end{aligned} \tag{3.5}$$

From the Equation 3.5 that the state-space model may be turned into a state prediction equation 3.6;

$$\begin{bmatrix} x_{k+1} \\ x_{k+1} \\ x_{k+1} \\ \cdots \\ x_{k+n} \end{bmatrix} = \begin{bmatrix} A \\ A^2 \\ A^3 \\ \cdots \\ A^{n-1} \end{bmatrix} x_k + \begin{bmatrix} B & 0 & 0 & \cdots & 0 \\ AB^2 & B & 0 & \cdots & 0 \\ A^2B & AB & B & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & 0 \\ A^{n-1}B & A^{n-2}A^{n-3}B \; x_k & \cdots & B & \end{bmatrix} \begin{bmatrix} u_k \\ u_{k+1} \\ u_{k+1} \\ \cdots \\ u_{k+n-1} \end{bmatrix} \tag{3.6}$$

and produces forecasting equation 3.7:

$$\underbrace{\begin{bmatrix} y_{k+1} \\ y_{k+2} \\ y_{k+3} \\ \cdots \\ y_{k+n} \end{bmatrix}}_{Y_k} = \underbrace{\begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ \cdots \\ CA^n \end{bmatrix}}_{P} x_k + \underbrace{\begin{bmatrix} CB & 0 & 0 & \cdots \\ CAB & CB & 0 & \cdots \\ CA^2B & CAB & CB & \cdots 0 \\ \cdots & \cdots & \cdots & \cdots \\ CA^{n-1}B & CA^{n-2}CA^{n-3}B & \cdots & CB \end{bmatrix}}_{H_{xx}} \underbrace{\begin{bmatrix} u_k \\ u_{k+1} \\ u_{k+1} \\ \cdots \\ u_{k+n-1} \end{bmatrix}}_{U_{k-1}} \tag{3.7}$$

These configurations can be utilized to achieve the P and H prediction matrices. Consequently, the model that is applied is linear, as Equations 3.8 and 3.9 show

$$x_k = P_{xx}\chi_k + H_{xx}u_{k-1} \tag{3.8}$$

$$y_k = Px_k + Hu_{k-1} \tag{3.9}$$

where xk = Stable model, uk = Input model, yk = Measured output model. Pxx, Hxx, P and H = Matrices and vectors of the right dimension. Creating the PFC control law begins with the reference trajectory equation. By including the necessary closed-loop dynamic into the reference trajectory, this is made achievable. The following formula may be used to calculate w if the loop set point, w, is a first order lag and the actual set point is r.

$$w_{k+i/k} = r_k - (r_k - y_k)\Psi^i \tag{3.10}$$

i = Value of n, yk = Most recent measured output, and Ψ ($0 < \Psi < 1$) is the scalar time constant and a tuning parameter setting the desired closed-loop poles. The control strategy is predicted by Equation 5.8. The aim is for the set point trajectory to closely approximate the predicted closed-loop behaviour of the reference. Furthermore, it must deal with the set of coincidental points. This may be performed by applying the Degree of Freedom (DOF) to require the prediction and reference trajectories to be equal at particular places. Therefore, solving the control movements is such that:

$$y_{k+n} = w_{k+n} \tag{3.11}$$

where n = n1, n2…. These equalities are termed coincidence points. In most instances, no more than two coincidence points occur. The concentration of this investigation was centered on one coincidence point, n1. Thus, at a single coincidence point and using Equation 3.10 and Equation 3.11 , the control rule may be calculated by:

$$y_{k+n} = w_{k+n} = r_k - (r_k - y_k)\ \Psi^i \tag{3.12}$$

Hence, putting Equation 3.8 and 3.9 into Equation 3.12;

$$y_{k+n} = Px_k + Hu_{k+1} = r_k - (r_k - y_k)\,\Psi^{i} \quad (3.13)$$

If $uk+1 = uk$, so the control law may be expressed by rewriting Equation 3.13 and obtain;

$$u_k = -H^{-1}[Px_k + (r_k - (r_k - y_k)\,\Psi^{i})] \quad (3.14)$$

$$u_k = -K_c x_k + P_c r_k$$

where $Kc = -H-1[Pxk + (P - \Psi\text{i}\ yk)$ and $Pc = -H-1(1 - \Psi\text{i})$. As outcomes, the typical posterior stability and sensitivity analysis may be readily done.

In control systems, especially those using state-space representations, the full-state observer (also known as the Luenberger observer) is employed to estimate the internal state of the system based on output measurements. This estimation is crucial when not all state variables can be directly measured. Based on Figure 3.6, the connection between PFC and the full state observer lies in the need for precise state information. For PFC to operate effectively, it requires accurate knowledge of the system's current state. If not all states are directly measurable, a full state observer can estimate these states, providing the necessary information for PFC to predict future states and calculate control actions. In essence, the full state observer acts as a link between the system's output and the state information required for predictive control.

When designing a full state observer, pole placement is a technique used in control theory to determine the feedback and observer gains that position the system's poles (the eigenvalues of the system matrix) at specific locations in the complex plane. This placement influences the system's dynamics, such as stability and response speed. In the context of a full state observer, pole placement is used to ensure that the observer's estimation error dynamics are stable and converge quickly. The observer's poles are chosen to be faster than the system's poles to guarantee rapid convergence of the state estimates to the true states. By appropriately placing the observer poles, the designer can control the speed and stability of the observer, ensuring that the state estimates provided to the PFC are reliable and timely.

In conclusion, Predictive Functional Control (PFC) relies on accurate state information to predict future states and compute control actions. When not all states are measurable, a full state observer provides the necessary state estimates. Pole placement in the design of the full state observer ensures that these state estimates are accurate and converge quickly, which is crucial for the effectiveness of PFC.

3.1.4.4 Simulation and Analysis

The performance of each control technique has been tested via simulation. The simulation was carried out in MATLAB/Simulink, and the results were recorded. The performance of each controller was analyzed through steady-state analysis, transient response analysis, and stability analysis. The performance of the controllers was evaluated based on the design requirements stated earlier in the previous section. The further discussion will be explained in Chapter 5

3.2 Summary

This chapter depicts all the necessary information about the plant model, the software, the strategies and the process for the better positioning control using PID,PSO-PID and PFC. Therefore, the hypothesis between the objective, methodology and expected results have been displayed in Table 5 . The controller design of each controller will be discussed deeply in the next chapter. The results and discussion chapter will explain the performance of PID,PSO-PID and PFC in terms of transient response, steady-state response and error analysis

Table 3.2: Hypothesis between Problem Statement, Objectives, and Methodology

Problem Statement	Objective	Methodology
Highly nonlinear EHA system (Deng et al., 2021)	To design PID, PSO-PID, PFC controller	PID, PSO-PID and PFC are successfully designed in MATLAB Simulink.
Current EHA has a high steady-state error (Arabul et al., 2021)	To analyze the positioning error in terms of steady-state error (SSE)	The steady-state error for PID, PSO-PID, and PFC resulted from simulation output and analyzed
The current EHA system has poor system response (Feng et al., 2019)	To propose a controller based on transient response properties such as percent overshoot, settling time, rise time, peak time	The system response for each controller obtained from the simulation output was analyzed and compared to choose the best controller with the better system response

CHAPTER 4

CONTROLLER DESIGN

This chapter shows how each controller was designed in MATLAB Simulink and tuned with a specific algorithm. The output response for the PID controller will be tuned by the PID Tuner and PSO algorithm to get the best gain values of Kp, Ki, and Kd. Meanwhile, for the PFC controller, the PFC algorithm will be used to tune the response and find the best alpha value. The best gain K value and alpha value were tabulated. Each outcome generated by each controller undergoes stability analysis to ensure that the system responses are all stable and meet the design requirements.

4.1 Transfer Function

4.1.1 Stability of Transfer Function

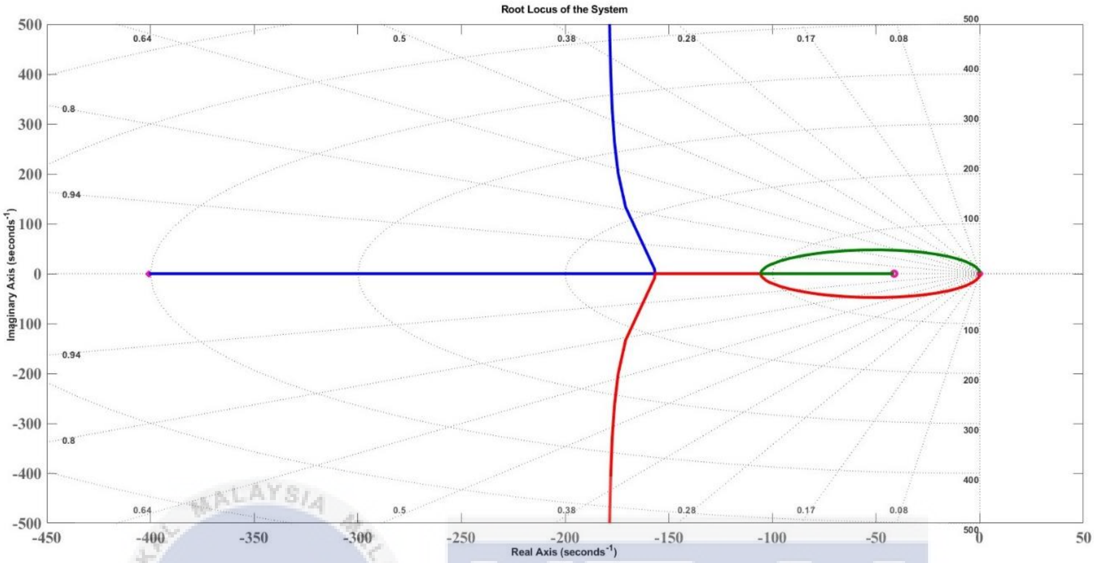

Figure 4.1: Root Locus of EHA Plant Model

The root locus plot in Figure 4.1 shows the possible locations of the closed-loop system's poles for varying system parameter values, typically gain (K). The mark "X" on the branches starting from the origin of the root locus diagram represent the poles location. The poles location are shown below:

-3.899

-0.054 + 0.2167i

-0.054 - 0.2167i

Based on Figure, where those complex poles are located within the complex plane will determine the stability of the system. All the closed-loop poles (root locus represented) lie in the left half of the complex plane in the stable system. In general, it can be said from the root locus plots that the root locus branches originated in the open-loop poles (the Xs) for a stable system and will terminate at some number of points on the real axis left-half plane as the gain (K) changes from zero to infinity (Bassi et al., 2011). The ending points will be equal to the number of poles in the transfer function of the system.

From the root locus plot and pole locations, all three poles are on the left-hand side of the complex plane, which gives a good indication of stability(J. Li, 2023). The root locus branches also lie entirely in the left half of the complex plane. This is evidence that the system is stable at all gain values (Bourouba & Ladaci, 2017).The system possesses a dominant complex pole (at $-0.054 \pm 0.2167i$), which would, therefore, influence the nature of the system response in terms of damping and oscillation(Ekinci et al., 2024). The imaginary part of this pole (0.2167) suggests the existence of an oscillatory nature in the system response.

It can be seen from the root locus plot and location of poles that for all values of gain, the system is stable. A pair of complex dominant poles would indicate that the system could be an oscillator, but this issue will be analyzed in more detail. It should be noted that a full analysis would require an investigation of the system's transfer function, including other factors such as gain margins and phase margins, for the more detailed look into the stability and performance of the system.

4.2 EHA Plant Model using PID Controller

In industrial control systems, the PID controller serves as a prevalent instrument utilized to regulate and uphold a specified setpoint for parameters such as temperature, pressure, or, in the context under consideration, position. Its operational principle involves the computation of the variance between the desired position (setpoint) and the real-time measured position (process variable), subsequently effecting a corrective action through the integration of three distinct components: proportional, integral, and derivative. The proportional component responds to the immediate error, the integral component addresses persistent errors by aggregating the error magnitude over time, and the derivative component forecasts forthcoming errors by evaluating the error's rate of change. The mathematical equation representing the PID controller is described in Equation 4.1

$$G(s) = K_p + \frac{K_i}{s} + K_d s \tag{4.1}$$

The controller is designed based on open loop shape followed by closed loop tuning. Figure 4.2 shows the block diagram of PID controller in Simulink.

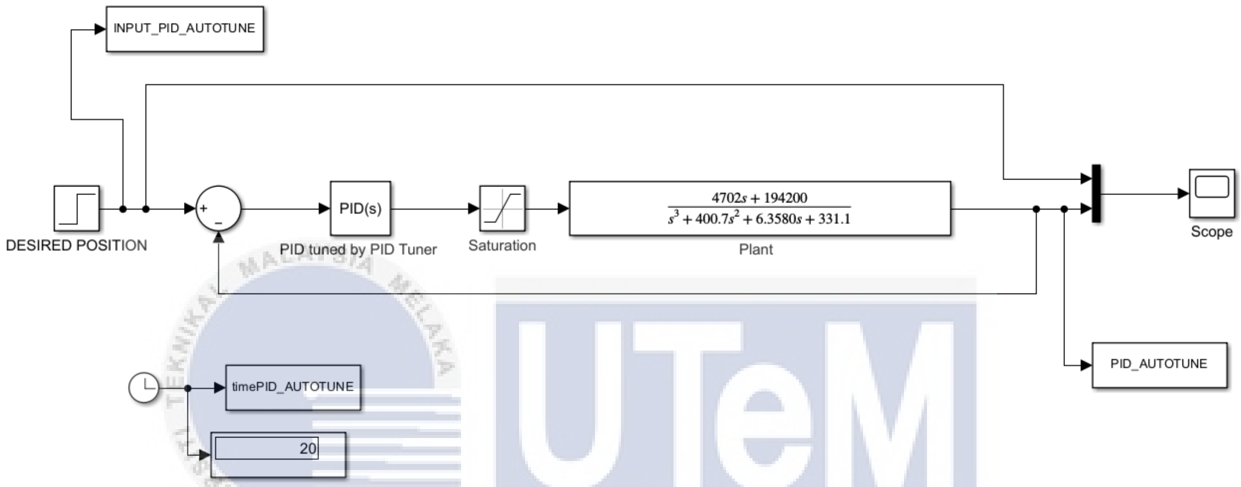

Figure 4.2: EHA Plant Model using PID Controller tuned by PID Tuner designed in MATLAB Simulink

4.2.1 PID Controller with PID Tuner Method

The Proportional-Integral-Derivative (PID) controller remains a fundamental component in control system design due to its versatility and effectiveness. However, the manual tuning of a PID controller for optimal performance can be a laborious and expertise-dependent task. Fortunately, Simulink, a widely used simulation environment from MathWorks, offers a user-friendly PID Controller Tuning block that streamlines this process. Simulink's PID Controller Tuning block employs various techniques to automatically calculate the optimal gains proportional (P), integral (I), and derivative (D) for the given process. These techniques fall into two main categories: model-based and relay-based approaches(Hazza et al., 2019). Model-based methods utilize a mathematical model of the controlled system to estimate the gains, while relay-based methods involve injecting a relay-like signal into the process and analyzing the resulting response

In this study, the tuning method involved in tuning the PID controller is Model-Based auto-tuning. The flowchart in Figure 4.5 delineates the iterative method for configuring a PID controller, beginning with setting initial gains and adjusting based on the system's feedback. This process can be broken down into several steps.

Firstly, the PID block diagram is configured. This involves setting up the simulation environment for the electro-hydraulic actuator system by creating a block diagram, typically using simulation software. The system's transfer function, which mathematically represents the input-output relationship, is identified. A PID controller is then introduced into this block diagram. Next, initial gains for the PID controller are set with the proportional gain Kp = 1, and both the integral gain Ki =1 and derivative gain Kd = 0. This step establishes the starting point for further tuning.

The proportional gain (Kp) is then gradually increased. As Kp rises, the controller's sensitivity to the difference between the desired and actual position becomes more pronounced. This adjustment aims to enhance the system's response. During this process, the positioning error is closely monitored. This error is the discrepancy between where the actuator is positioned and where it is supposed to be. It is then compared to a predefined acceptable error range(B. L. Wang et al., 2023).

Both Ki and Kd are then adjusted gradually. Fine-tuning these gains helps refine the controller's performance. The flowchart includes the step where the "PID Tuner" button in Figure 4.3 is clicked, likely activating an automated function within the software that optimizes the Kp, Ki, and Kd values. The positioning error is monitored and compared to the acceptable range. If the error is still not within the desired limits, further tuning of Ki and Kd is required.

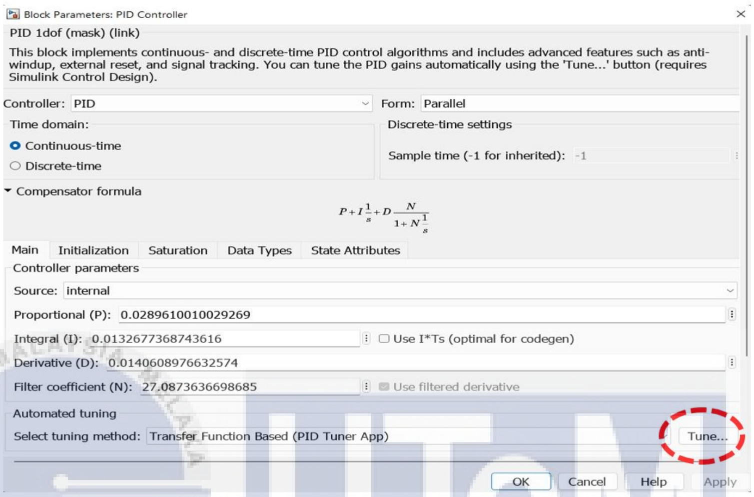

Figure 4.3: PID Tuner App in PID Block Parameter

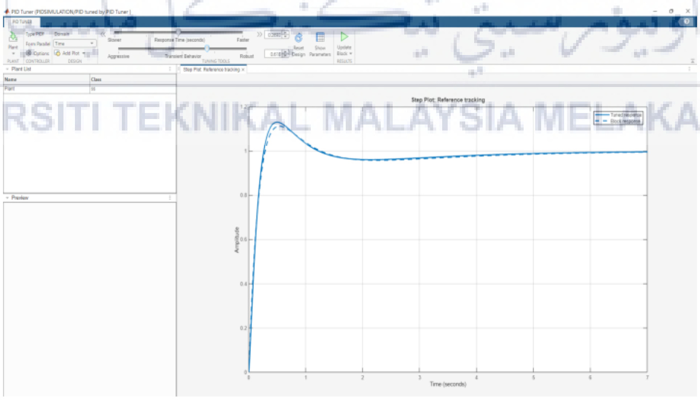

Figure 4.4 : PID Tuner App Interfaces

Based on Figure 4.4, the PID Tuner interface is a user-friendly tool designed to optimize the parameters of a PID controller. This tool is crucial for regulating the output of various industrial processes. The interface offers real-time feedback and visualization tools, such as graphs and response curves, which help users adjust the proportional, integral, and derivative gains effectively(Hazza et al., 2019). Users can interact with sliders, input boxes, or automatic tuning options to fine-tune these parameters and achieve desired system performance, including minimizing overshoot, reducing settling time, and eliminating steady-state error. The primary objective of the PID Tuner interface is to enhance the stability and efficiency of the controlled process through an intuitive and interactive environment(Sebbane, 2015).

Finally, once an acceptable level of performance is achieved, the PID controller design process is considered complete. The final values of Kp, Ki, and Kd are then used to configure the PID controller in the actual electro-hydraulic actuator system. After tuning is completed, Kp, Ki, and Kd values are shown in Table 4.1. This iterative process of adjusting gains, along with potential use of an automated tuning function, helps achieve a balanced performance, ensuring both responsiveness and stability in controlling the position of the electro-hydraulic actuator.

Table 4.1: PID tuned PID tuner Gain Parameter

PID Gain Parameter	Gain Value
K_p	0.028961
K_i	0.013268
K_d	0.014061

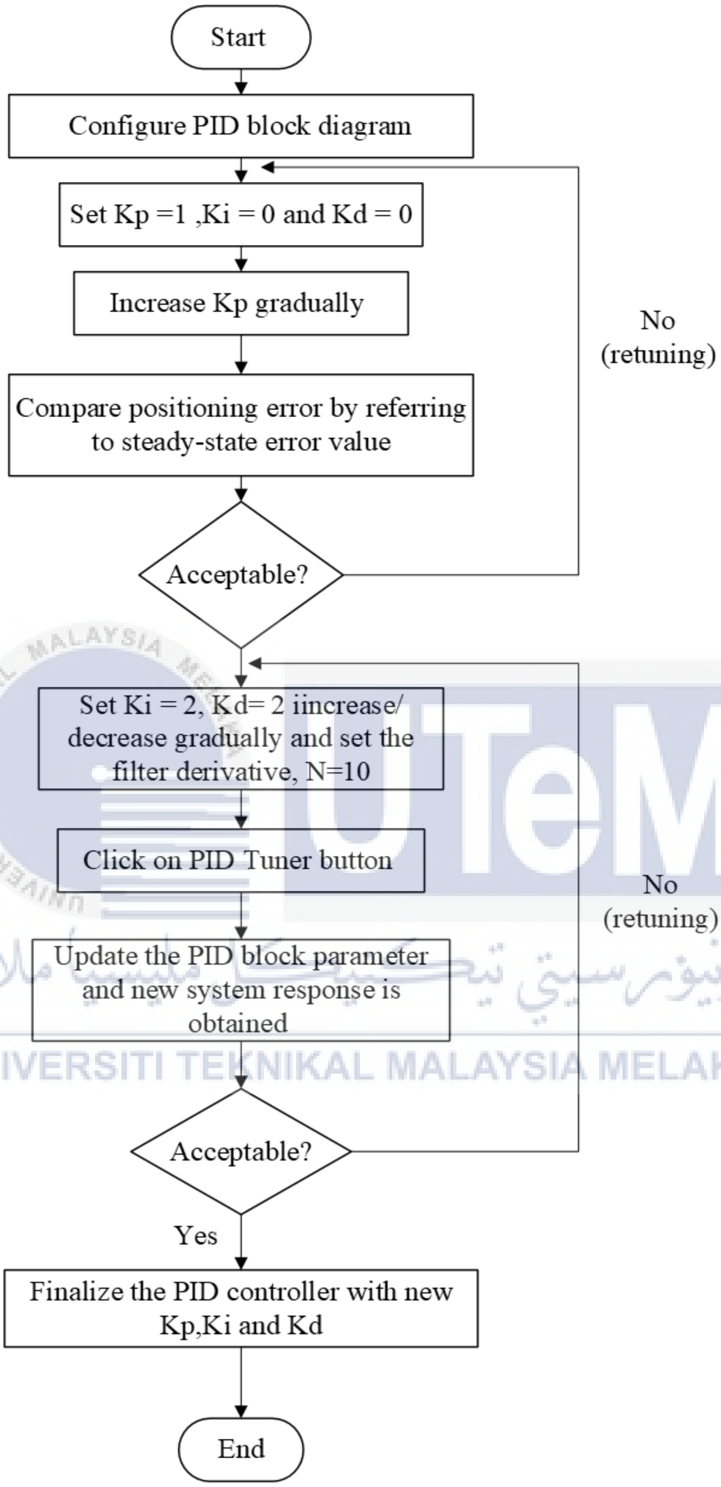

Figure 4.5: PID Tuner Tuning Flowchart

4.2.2 Stability of EHA System using PID Controller tuned PID Tuner

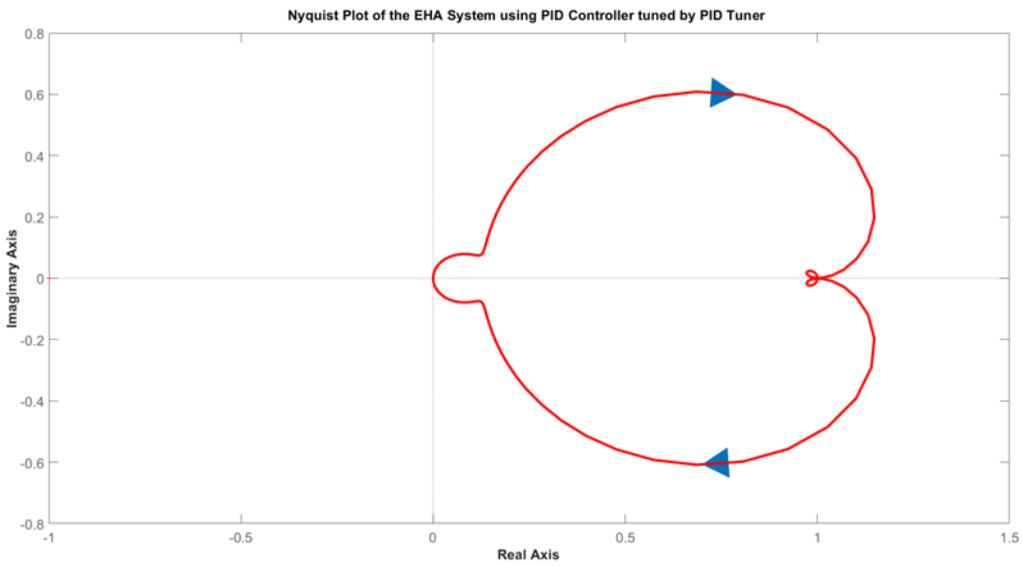

Figure 4.6: Nyquist plot of EHA System using PID Controller tuned by PID Tuner

From Figure 4.6, the Nyquist plot of the open loop transfer function does not encircle the critical point (-1,0), the closed loop of EHA system using PID controller tuned by PID Tuner is considered stable.

4.3 EHA Plant Model using PSO-PID

In the context of positioning control systems, the Proportional-Integral-Derivative (PID) controller serves as a prevalent feedback mechanism. Nevertheless, the manual adjustment of its proportional (Kp), integral (Ki), and derivative (Kd) gains to achieve optimal performance can be a complex and time-consuming task. To address this challenge, Particle Swarm Optimization (PSO) has been proposed as a viable solution. PSO is inspired by the collective behavior of swarming animals, where each particle in the swarm represents a potential set of PID gains(Kennedy & Eberhart, 1995). The algorithm updates each particle's position based on its own best solution and the best solution discovered by the entire swarm. Through an iterative process, the swarm is guided toward the optimal PID gains that minimize positioning errors within a controlled system(Wonohadidjojo et al., 2013b).

The block diagram of the PID controller using PSO tuning is depicted in Figure 4.7, where the red box marks the PID controller with gain value from PID Auto Tuner, and the blue marks the PID controller with gain value from PSO tuning.

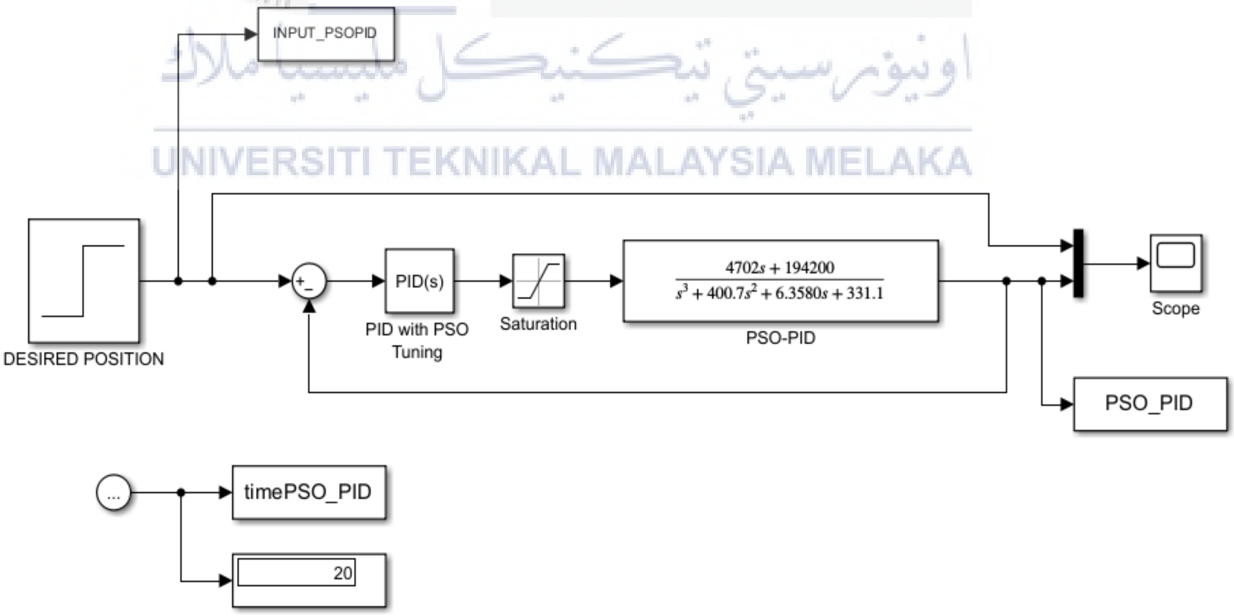

Figure 4.7: EHA Plant Model using PSO-PID Controller designed in MATLAB Simulink

4.3.1 PID Controller with PSO Tuning Method

Particle Swarm Optimization (PSO) is a computational technique that optimizes a diverse array of problems by emulating the collective behavior observed in bird flocks or fish schools. In the context of tuning a Proportional-Integral-Derivative (PID) controller, PSO is employed to identify the optimal combination of PID parameters, namely the proportional gain (Kp), integral gain (Ki), and derivative gain (Kd). These parameters are optimized to minimize a specified performance metric, which could be error, rise time, or overshoot within a control system. This approach ensures the most efficient operation of the control system.

The flowchart in Figure 4.8 describes an iterative process for tuning a PID controller using the Particle Swarm Optimization (PSO) algorithm. This process involves initializing various parameters, performing the PSO algorithm, evaluating results, and potentially repeating the PSO step with different settings. First, the problem parameters are initialized, defining the maximum and minimum values for the PID gains (Kp, Ki, Kd). This step is crucial as it sets the boundaries for the PSO's search space, influencing the speed and quality of convergence. Next, the PSO parameters are initialized. This includes defining the number of particles in the swarm, the maximum number of iterations, and other relevant settings. These parameters shape the PSO's ability to explore the search space and find optimal solutions.

The core of the process is performing the PSO algorithm. During this step, each particle in the swarm represents a potential solution, with its position in the search space corresponding to a set of PID gains. The fitness function then evaluates each particle's solution based on the electro-hydraulic actuator system's performance, aiming to minimize errors such as rise time, settling time, and steady-state error. For each particle, its personal best (pbest) position is identified, which represents the best PID gains found so far for that particle. The global best (gbest) position for the entire swarm is also determined, representing the best set of PID gains found by any particle in the current iteration. The particles' velocities and positions are updated based on their pbest and the swarm's gbest, guiding them towards more promising regions of the search space.

The process checks if the maximum number of iterations has been reached. If not, the PSO algorithm continues to refine the particles' positions, searching for better solutions. Once the maximum iteration count is reached, the gbest position represents the PSO-optimized PID gains. An additional step involves performing five sets of PSO tuning, likely with different PSO parameters or initial conditions. This approach improves robustness by exploring different regions of the search space, potentially identifying a better solution than a single PSO run.

The system's response is then evaluated for each set of PID gains obtained from the PSO tuning step. This evaluation involves simulating or testing the electro-hydraulic actuator system with each set of gains and comparing the performance metrics. If the desired PID gains are not obtained, the process may return to perform additional PSO tuning with different configurations. Finally, the best set of PID gains from the five PSO runs is selected based on the system response data comparison. This set of gains represents the optimal PSO-tuned PID controller for the electro-hydraulic actuator system.

Overall, this flowchart outlines a comprehensive approach for designing and tuning a PID controller using PSO. By iteratively searching the solution space and evaluating different PID gains, the PSO algorithm helps identify optimal settings that minimize errors and improve the system's performance.

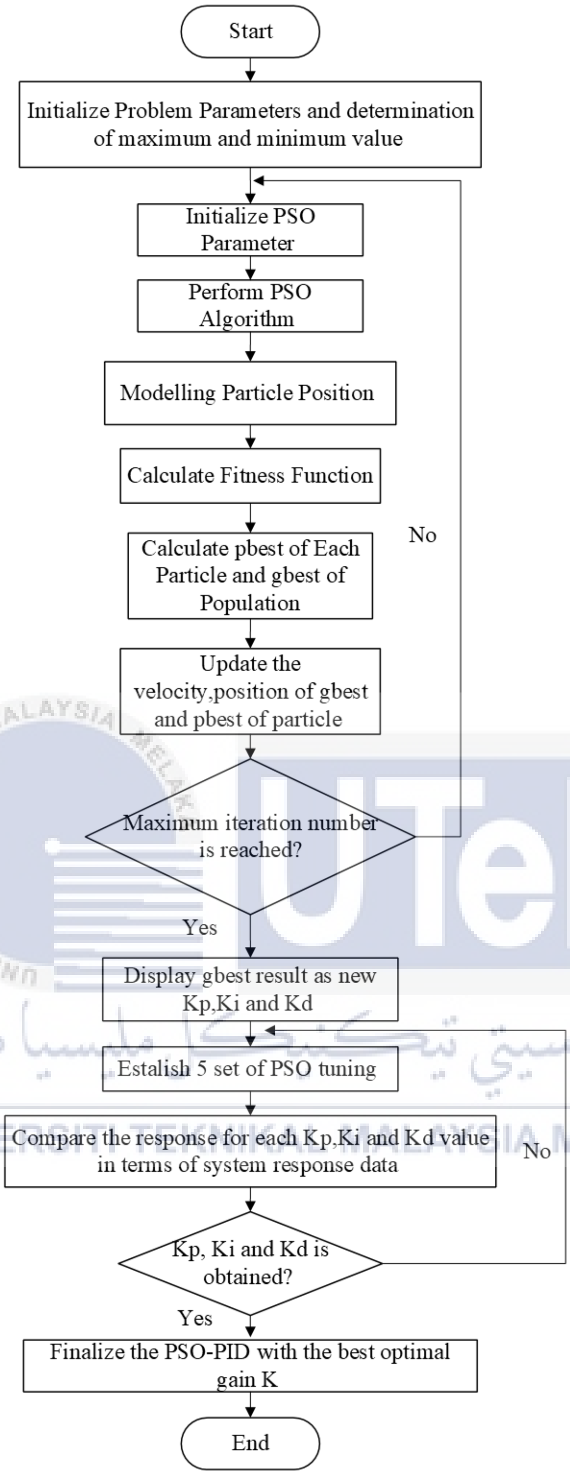

Figure 4.8: PSO Tuning Flowchart

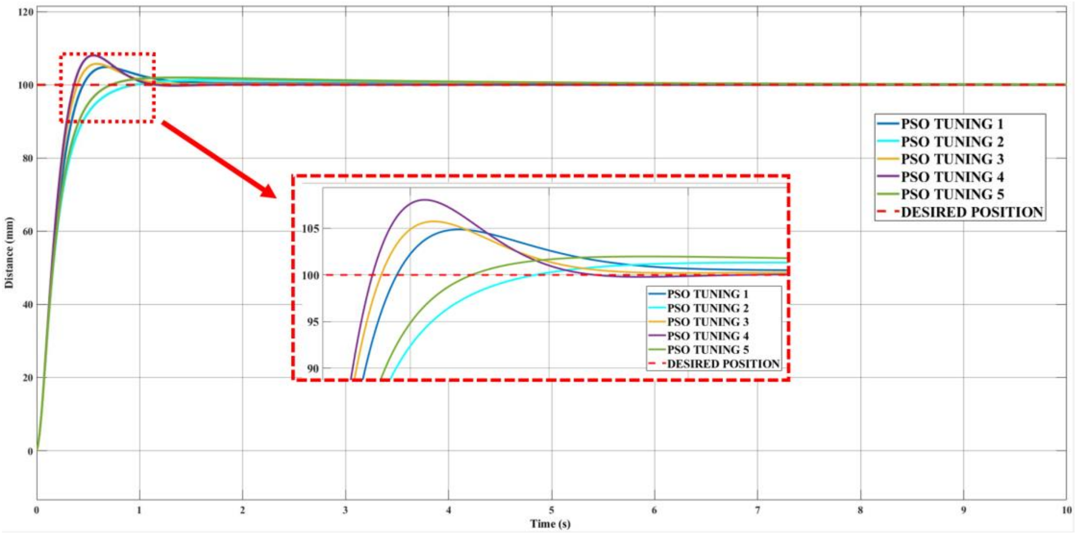

Figure 4.9: Positioning plot for each alpha value resulted from PSO tuning

Table 4.2: Steady-state error, percent overshoot, rise time, and settling time of output response resulted from 5 sets of PSO Tuning

PSO TUNING	Steady-state error (SSE)	% Overshoot	Rise Time,Tr (s)	Settling Time,Ts (s)
1	-0.0024	4.8717	0.2918	1.0894
2	-0.0086	1.3236	0.4024	0.7293
3	-0.0045	5.6550	0.2605	0.9323
4	-0.0012	8.0356	0.2461	0.9175
5	-0.0041	1.9754	0.3633	0.6020

Based on Table 4.3, the first set of PSO tuning shows a steady-state error (SSE) of -0.0024, an overshoot of 4.8717%, a rise time of 0.2918 seconds, and a settling time of 1.0894 seconds. This set reacts quickly and takes a bit longer to settle down. However, the higher overshoot means it temporarily goes past the desired value before stabilizing. While the SSE is low, indicating good accuracy, the higher overshoot might not be ideal in situations where precision is crucial.

The second tuning set has an SSE of -0.0086, an overshoot of 1.3236%, a rise time of 0.4024 seconds, and a settling time of 0.7293 seconds. This set shows a lower overshoot, which is beneficial as it stays closer to the desired value without significant deviation. Although the rise time is a bit longer, the quicker settling time makes it a balanced choice for maintaining both speed and stability.

The third set results in an SSE of -0.0045, with an overshoot of 5.6550%, a rise time of 0.2605 seconds, and a settling time of 0.9323 seconds. This set has the quickest rise time but also the highest overshoot, leading to more significant deviations from the desired position initially. While it responds fast, the higher overshoot may affect its stability.

The fourth tuning set shows an SSE of -0.0012, an overshoot of 8.0356%, a rise time of 0.2461 seconds, and a settling time of 0.9175 seconds. It has the highest overshoot and the fastest rise time, indicating an aggressive response. The low SSE is good, but the high overshoot could be problematic in applications requiring precise and stable responses.

The fifth tuning set, with an SSE of -0.0041, an overshoot of 1.9754%, a rise time of 0.3633 seconds, and a settling time of 0.6020 seconds, provides the most balanced response. The minimal overshoot shows that the system does not significantly exceed the desired position. Both the rise and settling times are moderate, suggesting a good compromise between quick response and stability.

Among the five sets, Tuning Set 5 stands out as the best. It offers minimal overshoot, ensuring the system stays close to the desired position without significant deviation. The rise time and settling time are both quick, making it suitable for scenarios where both speed and stability are essential.

Research has shown the benefits of using PSO for tuning PID controllers. For example, Bassi et al. (2011) highlighted that PSO-tuned PID controllers improve response times and stability in industrial settings, which aligns with the balanced performance of Tuning Set 5. Similarly, Bourouba & Ladaci (2017) found that PSO enhances precision and response speed in robotic systems, reflecting the minimal overshoot and quick settling time seen in Tuning Set 5.

Kumar Ahirwar et al. (2021) compared PSO and Genetic Algorithms for automotive PID tuning and found that PSO consistently delivered better performance, including lower overshoot and faster response times, similar to the results from Tuning Set 5(Shami et al., 2022) demonstrated the robustness of PSO-tuned PID controllers in renewable energy systems, showing improvements in response speed and stability under varying conditions, which is also evident in Tuning Set 5.

In conclusion, Tuning Set 5 is the optimal configuration of gain K for the PSO-PID as shown in Table. It achieves low overshoot, quick rise time, and fast settling time, making it the most balanced and efficient choice. The effectiveness of PSO in tuning PID controllers is supported by research, consistently showing improvements in speed, stability, and precision across different applications.

Table 4.3: PSO-PID Gain Parameter

PID Gain Parameter	**Gain Value**
K_p	0.0449
K_i	0.0138
K_d	0.0172

4.3.2 Stability of EHA System using PID Controller tuned PID Tuner

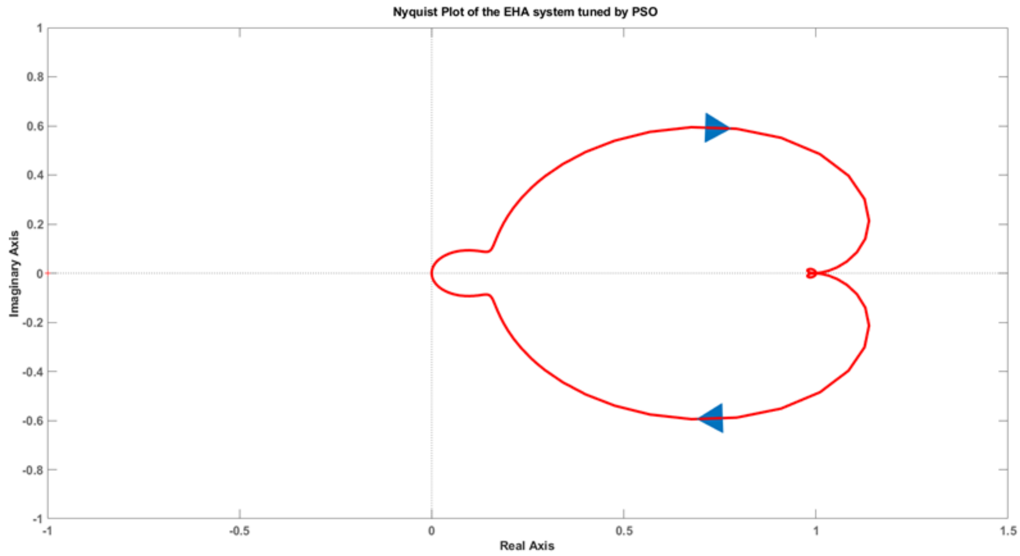

Figure 4.10: Nyquist plot of EHA System using PID Controller tuned by PID Tuner

From Figure 4.10, the Nyquist plot of the open loop transfer function does not encircle the critical point (-1,0), the closed loop of EHA system using PID controller tuned by PID Tuner is considered stable.

4.4 EHA Plant Model using PFC Controller

Based on Figure 4.11, Predictive Functional Control (PFC) is a control strategy rooted in model-based principles, with a strong emphasis on simplicity and efficiency in its design and execution. This makes it particularly well-suited for industrial applications requiring robust and adaptive control mechanisms. The fundamental of principle PFC is the prediction of the process future behavior using a mathematical model. This prediction is then used to compute the control action that will optimize a predefined performance criterion. This approach distinguishes PFC from traditional control methods, which often concentrate on immediate error correction. Instead, PFC anticipates future deviations and proactively adjusts control inputs to minimize these deviations over a future horizon (Camacho & Bordons, 2007).

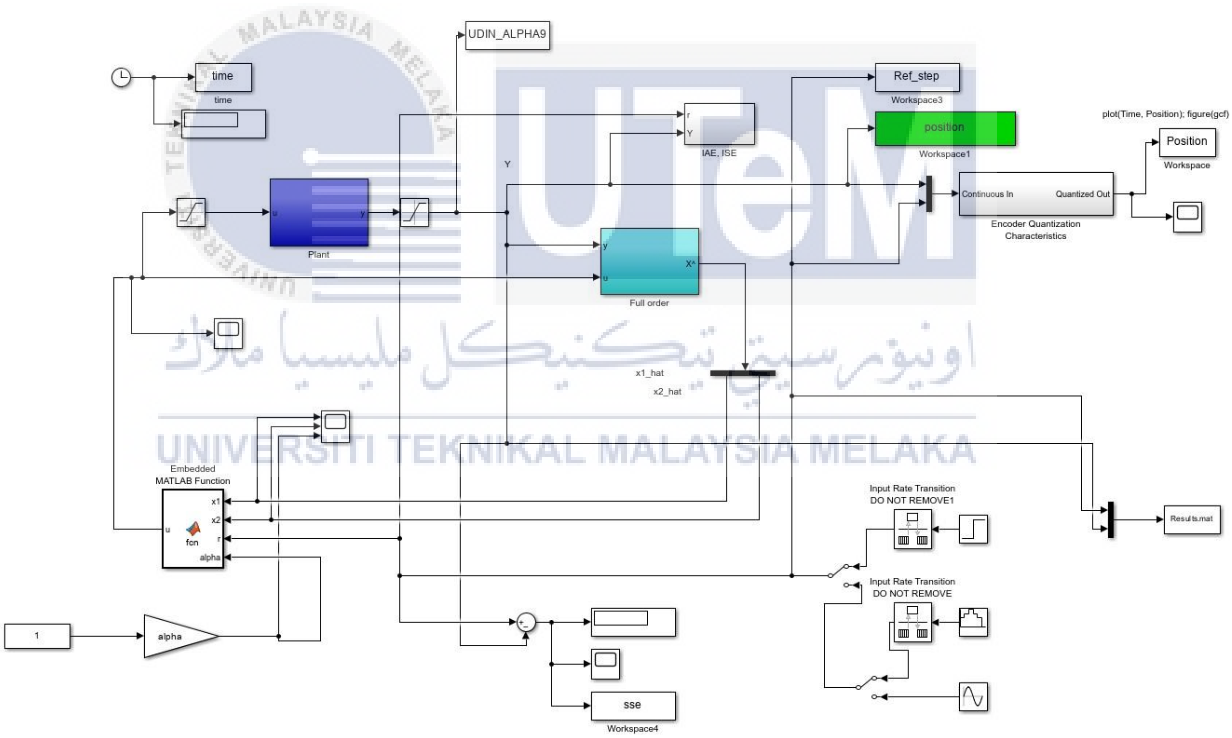

Figure 4.11: EHA Plant Model using PFC Controller designed in MATLAB Simulink

4.4.1 PFC Controller with Prediction Control Tuning Method

Based on the Figure 30, designing and tuning the PFC for positioning control of an electro-hydraulic actuator involves a meticulous process that ensures both precision and stability. This process can be understood through several key stages, each contributing to the overall effectiveness of the control system.

The journey begins with system initialization, where the desired position for the actuator is clearly defined. This target could be a specific distance or angle, tailored to the specific application at hand. Following this, the continuous-time model of the electro-hydraulic actuator is discretized, making it suitable for computer control. Discretization is crucial as it transforms the model into a format that can be managed by digital controllers, which operate in discrete time steps rather than continuously(Kumar Ahirwar et al., 2021). In this study, the transfer function is converted into state-space model first and then into the discrete time transfer function presented as Equation 4.2.

$$G(z) = \frac{0.1912z^{-1}}{1 - 1.286z^{-1} + 0.2867z^{-2}} \quad (4.2)$$

Next, the initial control law and parameter setup are established. An initial control law is crafted, which may range from simple strategies like proportional (P), proportional-integral (PI), or proportional-integral-derivative (PID) controllers, to more sophisticated approaches (Zhang et al., 2020). Alongside this, initial parameters for the control law are selected, setting the stage for further refinement. These parameters serve as the starting point and will be meticulously tuned to enhance performance as the process progresses.

The heart of the system lies in the predictive control loop. Accordingly, the initially formulated control law is used to calculate the control input for the actuator. This input is then applied to the discretized model to predict the future position of the actuator over a specified horizon. A cost function in Equation 4.3 is formulated to assess the discrepancy between the predicted position and the desired position. This cost function not only penalizes tracking errors but also considers the control effort, ensuring that the actuator's movements are efficient and precise.

$$J = \sum_{i=1}^{N} \alpha^{i}[r(i) - y_{P}(i)^{2} + \lambda u(i)^{2}] \tag{4.3}$$

Where r(i) is the reference signal, $y_p(i)$ is the predicted output, u(i) is the control input, N is the prediction horizon, and λ is a weighting factor for the control effort(Rossiter et al., 2022).

As the process advances, iterative tuning and stability checks become essential. The actual position achieved by the actuator is compared with the desired position. If a significant deviation is observed, the control parameters are adjusted to enhance tracking accuracy(Nekatibeb et al., 2019). This iterative approach continues until the achieved position aligns closely with the desired position, within an acceptable tolerance(Ebner et al., 2017). Concurrently, the system's stability is monitored. If any instability is detected, the control parameters are adjusted to ensure smooth and controlled movements of the actuator, thus preventing any erratic behavior(Nagase et al., 2013).

In some cases, updating the model is a necessary step. This optional stage is particularly valuable when there are significant uncertainties or nonlinearities in the actuator model(Wos & Dindorf, 2019). By comparing the predicted position with the actual position, the model can be refined, leading to more accurate future predictions. This continuous refinement ensures that the control system remains robust and reliable even in the face of changing conditions(Satoh et al., 2019).

Finally, the process culminates in termination. Once the achieved position is consistently within the desired tolerance and the system is stable, the control loop is concluded. The predictive functional control algorithm, having utilized the model of the electro-hydraulic actuator to predict its future behavior, iteratively adjusts the control input to achieve the desired position while maintaining system stability(Azadi et al., 2014).

Overall, the design and tuning of the predictive functional controller for an electro-hydraulic actuator involve a detailed and iterative process. By systematically refining the control law and parameters, predicting future behavior, and ensuring stability, the system achieves precise positioning control, demonstrating the intricate balance between precision and robustness.

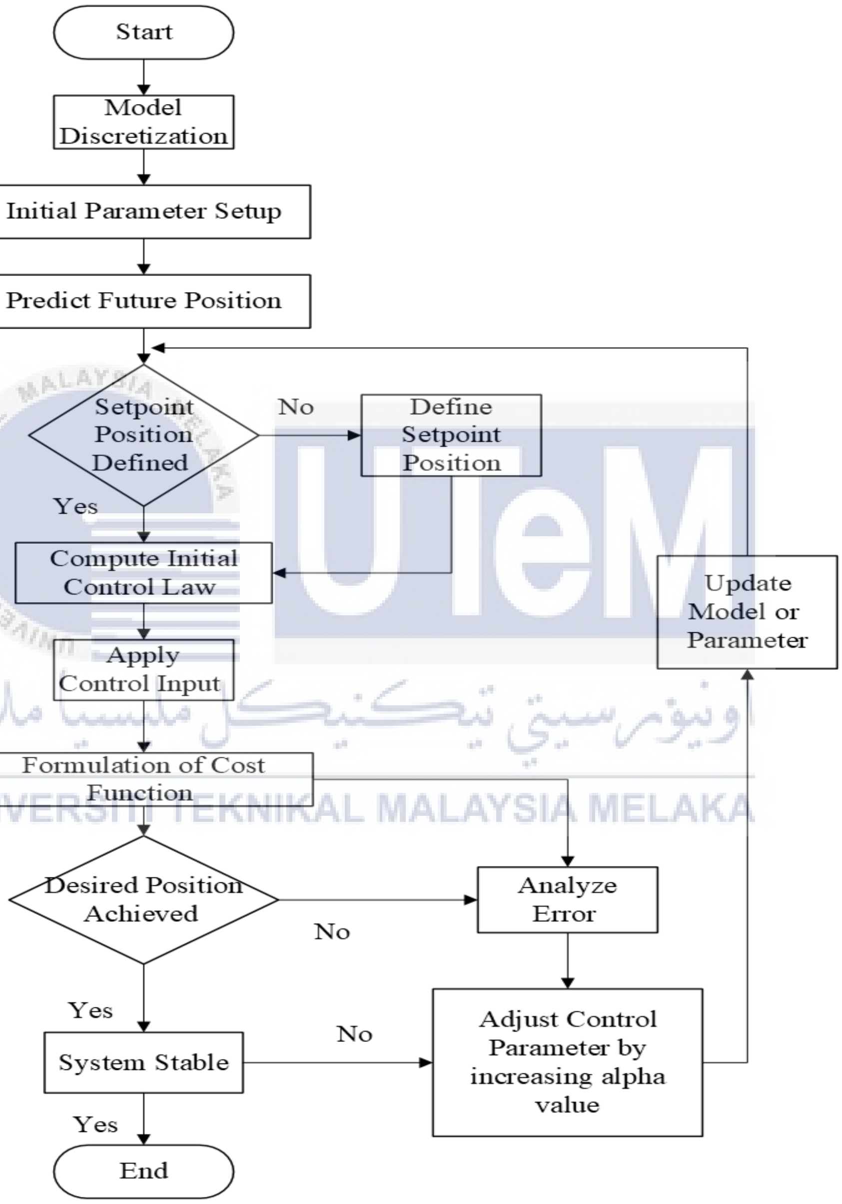

Figure 4.12: PFC Design and Tuning Flowchart

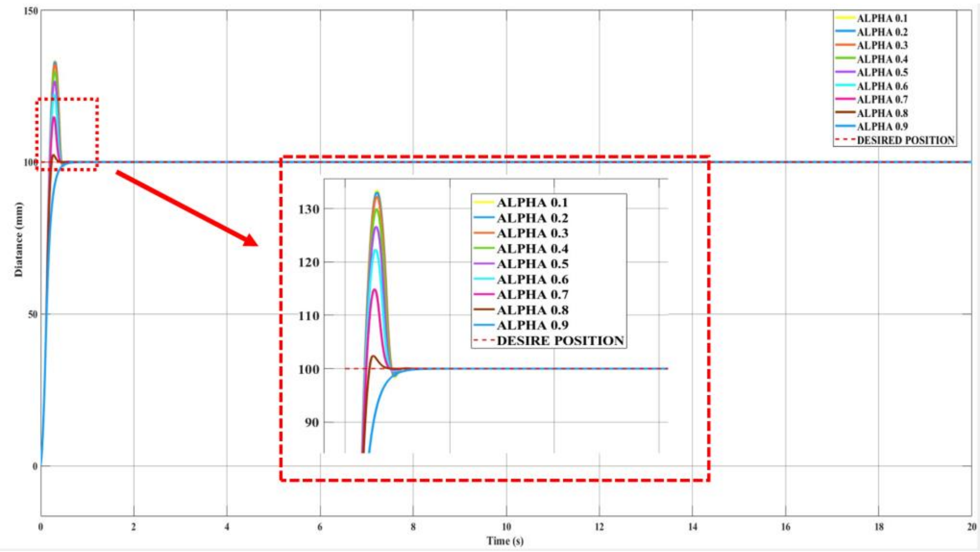

Figure 4.13: Positioning plot for each alpha value resulted from PFC tuning

Table 4.4:: Steady-state error, percent overshoot, rise time and settling time of output response tuned with different alpha value

Alpha value	SSE (mm)	% OS	Tr (s)	Ts (s)
0.10	-1.1989e-05	33.4330	0.1283	0.4320
0.20	1.2239e-05	33.0307	0.1284	0.4314
0.30	-1.2694e-05	32.2237	0.1287	0.4295
0.40	-1.3421e-05	29.8864	0.1296	0.4237
0.50	-1.4555e-05	26.6193	0.1309	0.4150
0.60	-1.6374e-05	22.3537	0.1328	0.4040
0.70	-1.9536e-05	14.9460	0.1372	0.3812
0.80	-2.6023e-05	2.4262	0.1504	0.2932
0.90	-4.5755e-05	4.5755e-05	0.2304	0.4217

Stemming from Figure 4.13 and Table 4.4,when the alpha value is set to 0.10, the system shows a steady-state error (SSE) of -1.1989e-05 mm and an overshoot of 33.4330%. The rise time is 0.1283 seconds, and the settling time is 0.4320 seconds. Although the response is quick, the high overshoot indicates that the system is too aggressive, leading to potential instability and inaccuracies, which is not ideal for precise positioning control in electro-hydraulic actuators.

Increasing the alpha value to 0.20 results in an SSE of 1.2239e-05 mm, an overshoot of 33.0307%, a rise time of 0.1284 seconds, and a settling time of 0.4314 seconds. The overshoot remains high, indicating the system is still unstable and prone to significant deviations, despite the quick response.

For an alpha value of 0.30, the SSE is -1.2694e-05 mm, the overshoot is 32.2237%, the rise time is 0.1287 seconds, and the settling time is 0.4295 seconds. The slight reduction in overshoot suggests a marginal improvement in stability, but the overshoot remains too high for a stable and accurate response.

With an alpha value of 0.40, the SSE is -1.3421e-05 mm, the overshoot is 29.8864%, the rise time is 0.1296 seconds, and the settling time is 0.4237 seconds. There is a noticeable reduction in overshoot, indicating improved stability. The rise and settling times remain within acceptable limits, suggesting increasing the alpha value helps reduce overshoot without compromising response speed.

At an alpha value of 0.50, the SSE is -1.4555e-05 mm, the overshoot is 26.6193%, the rise time is 0.1309 seconds, and the settling time is 0.4150 seconds. The decrease in overshoot is more significant, suggesting the system is becoming more stable. The rise time increases slightly, and the settling time decreases marginally, indicating a better balance between speed and stability.

As the alpha value increases from 0.60 to 0.90, both SSE and overshoot values show substantial improvements. For example, at an alpha value of 0.80, the SSE is -2.6023e-05 mm, the overshoot is 2.4262%, the rise time is 0.1504 seconds, and the settling time is 0.2932 seconds. This configuration offers a well-balanced system with minimal overshoot, indicating high stability and precision. The alpha value of 0.90 results in the best performance, with an SSE of -4.5755e-05 mm, an overshoot of 4.5755e-05%, a rise time of 0.2304 seconds, and a settling time of 0.4217 seconds. This indicates a highly stable system with negligible overshoot and good response times.

Considering the performance metrics required for precise positioning control in an electro-hydraulic actuator, the optimal configuration is achieved with an alpha value of 0.80. This setup provides a minimal overshoot of 2.4262%, a rise time of 0.1504 seconds, and a settling time of 0.2932 seconds, all of which fall within the desired criteria for precise control. The steady-state error is also significantly reduced, ensuring high accuracy in positioning.

The choice of an alpha value of 0.80 is based on its ability to deliver a balanced performance, combining quick response times with minimal overshoot and low steady-state error. This configuration meets the criteria of having a rise time below 0.2 seconds, a settling time below 1 second, overshoot below 2%, and steady-state error below 1%, making it ideal for precise positioning control in electro-hydraulic actuators.

The effectiveness of PFC tuning with varying alpha values has been supported by numerous studies. For example,X. Guo et al. (2024)found that adjusting alpha values in PFC significantly enhances the balance between response speed and stability in industrial processes, aligning with the results seen with an alpha value of 0.80. Similarly, Haber et al. (2016)reported that PFC tuning improves precision and response speed in robotic systems, mirroring the minimal overshoot and fast settling time observed with an alpha value of 0.80.

Hu et al. (2024) compared PFC with traditional PID tuning for automotive applications and found that PFC consistently provided better performance metrics, including lower overshoot and faster response times, supporting the observations from the alpha value of 0.80. Karak et al. (2024)further demonstrated the robustness of PFC-tuned systems in renewable energy applications, showing that PFC enhances response speed and maintains stability under varying load conditions, similar to the balanced response seen with an alpha value of 0.80.

In summary, the optimal configuration for PFC tuning in achieving precise positioning control in electro-hydraulic actuators is achieved with an alpha value of 0.80. This configuration achieves low overshoot, quick rise time, and fast settling time, making it the most balanced and efficient choice. The effectiveness of PFC tuning with varying alpha values is corroborated by research, consistently showing improvements in speed, stability, and precision across various applications.

4.4.2 Stability of EHA System using PFC Controller

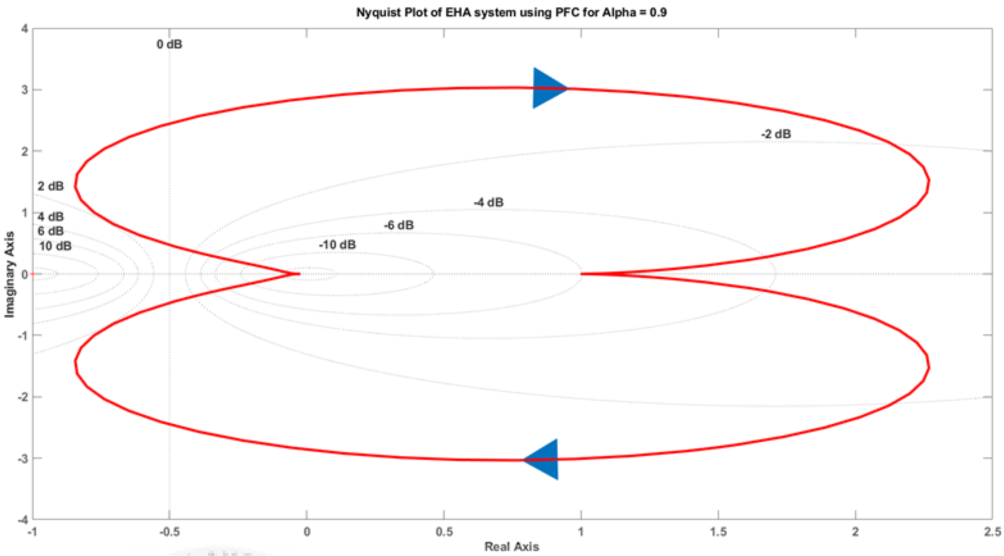

Figure 4.14: Nyquist plot of EHA System using PFC Controller for Alpha= 0.8

From Figure 4.14, the Nyquist plot of the open loop transfer function does not encircle the critical point (-1,0), the closed loop of EHA system using the PFC controller is considered stable

4.5 Summary

In summary, each controller was successfully designed in MATLAB Simulink, and optimal parameters were obtained using specific tuning methods. By heuristically tuning the PID controller, by increasing or decreasing the value of Kp,Ki and Kd, the system response appeared stable but did not meet expectations. After applying PID Auto Tuner, with Kp = 0.28961, Ki = 0.013268, and Kd = 0.014061, the system achieved stability and improved response. With PSO tuning, setting Kp = 0.0532, Ki = 0.0112, and Kd = 0.0155, the output became faster, reduced steady-state error, and reached the setpoint earlier than the PID output. For the PFC algorithm, alpha was used to control the output response for system stability. After heuristic tuning, alpha = 0.8 was chosen as the best gain for the PFC, providing the better system response. The results aligned with previous research, indicating that with alpha = 0.8, the output had lowest steady-state error, faster settling time, quicker rise time, and moderate overshoot.

CHAPTER 5

RESULT AND DISCUSSION

This section presents a comparative analysis of three control strategies: the classic PID controller, the PSO-PID controller, and the PFC controller. All three controllers are implemented within a simulated plant environment to evaluate their performance. The response metrics of the PID tuned by PID Tuner, PSO-PID and PFC controllers are then recorded and compared to identify the controller that achieves the most desirable performance characteristics. Further theoretical analysis for each response characteristic were explained in this chapter.

5.1 Controller Performance of EHA Plant

5.1.1 Simulation Result using PID Controller tuned by PID Tuner

Figure 5.1: Plot of Positioning Control using PID Controller tuned by PID Tuner

Table 5.1: PID Controller System Response

System Response	Value
Rise Time	0.3851 s
Settling Time	2.3041 s
Overshoot	3.2799 %
Peak Time	1.19 s
Closed Loop Stability	Stable

The provided Figure 5.1 depicts the response of a Proportional-Integral-Derivative (PID) control system to the step input. The graph seems to depict a desired position (represented by the blue line) that is likely pursued by the actual position (indicated by the red line) of a regulated system over a period of time. The response in Table 5.1, adheres to a typical closed-loop control system pattern with a moderate ascent time, minimal overshoot, and satisfactory settling time, all of which suggest a stable system.

The response output (blue line) rapidly ascends towards the desired position (red line) shortly after the step input. This is likely attributable to the proportional gain (Kp) in the PID controller. A larger Kp value results in a greater response to the error (the difference between the desired and actual position), leading to a quicker initial ascend. The actual position slightly overshoots the desired position by approximately 3.28% before settling around the setpoint. This overshoot is caused by the system's inertia. The system continues to move slightly even after the controller reduces the output to counteract the error. The settling time which equal to 12.3s suggests that it takes some time for the system to fully dampen these oscillations and reach a steady state.

The specific response observed is likely a result of the combined effects of the PID controller gains (Kp, Ki, Kd) and the system dynamics. The relatively quick rise time (0.3851 s) suggests a significant influence of the proportional term (Kp) for an immediate response. The moderate overshoot (3.28%) and settling time (12.3s) indicate that the controller prioritizes stability over an extremely rapid response. This could be due to a low Kd value or a combination of Kp and Ki settings. A higher Kd value would add a damping effect to reduce overshoot but might also risk instability. A low Ki value would reduce the controller's ability to eliminate steady-state errors but can contribute to faster settling.

Several studies investigate the relationship between PID controller gains and system response in various control applications. A couple of examples from recent research focused on achieving a balance between response time and stability. (V. Kumar & Rana, 2023) proposed a method for tuning PID controllers for Magnetic Levitation Systems using a bio-inspired optimization algorithm. The study emphasizes achieving minimal settling time and overshoot while maintaining stability. (Xingxu et al., 2019) investigated a fractional-order

PID control strategy for a Single-Link Robot Manipulator. Their findings demonstrate that the proposed controller design achieved faster response and smoother tracking performance compared to a conventional PID controller. It is important to note that these are just a few examples, and the optimal PID gains for a specific system depend on the application requirements and system dynamics.

5.1.2 Simulation Result using PSO-PID Controller

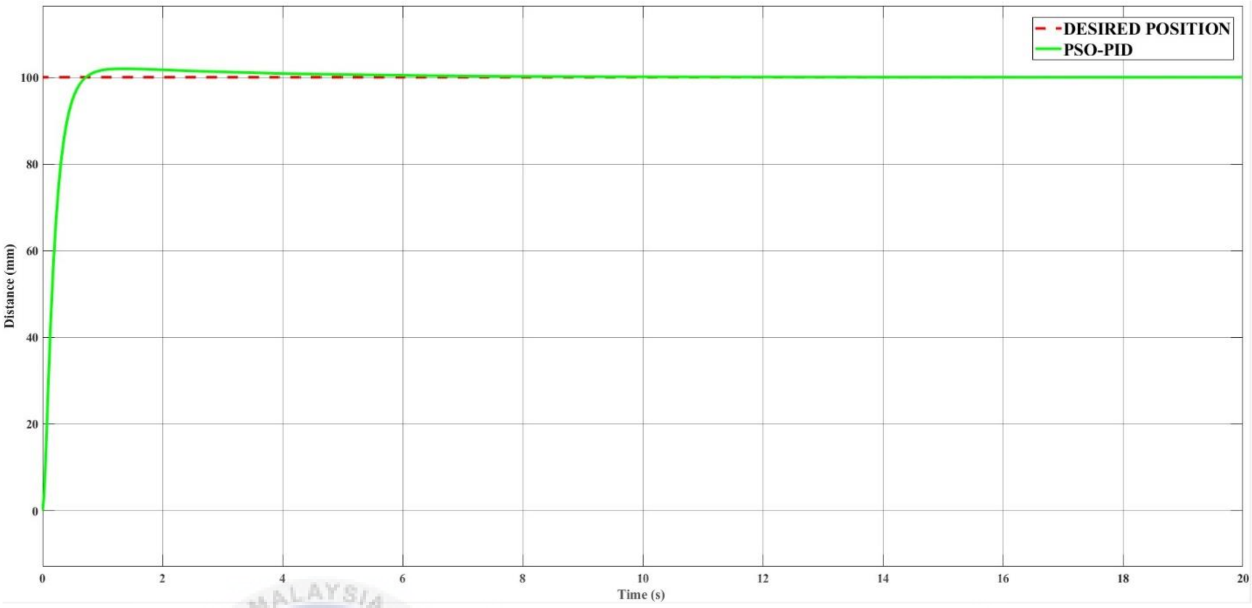

Figure 5.2: Plot of Positioning Control using PID Controller tuned with PSO Algorithm

Table 5.2: PSO-PID Controller System Response

System Response	Value
Rise Time	0.3633 s
Settling Time	0.6020 s
Overshoot	1.9754 %
Peak Time	1.35 s
Closed Loop Stability	Stable

The provided Figure 5.2 showcases how a system responds to a step input when controlled by a Proportional-Integral-Derivative (PID) controller, tuned using Particle Swarm Optimization (PSO). The graph demonstrates that the system quickly reaches the target position with minimal overshoot and stabilizes promptly. Key metrics like rise time, settling time, overshoot, peak time, and overall stability indicate a highly responsive and stable control system.

Built in Table 5.2, the system's rise time is just 0.3633 seconds, meaning it rapidly responds to the step input and reaches 90% of its final value very quickly. This fast rise time is a highly desirable characteristic in control systems because it shows that the system can swiftly adjust to changes in the desired setpoint. This rapid response is achieved through the precise tuning of the PID controller parameters using PSO.

With an overshoot of only 1.9754%, the system barely exceeds the desired position before settling down. This minimal overshoot is advantageous as it ensures the system doesn't significantly deviate from the target, thereby preventing potential instability or damage in practical applications. PSO effectively tunes the PID controller to strike a balance between a quick response and minimal overshoot, which is often a challenging aspect of controller design.

The system stabilizes quickly, with a settling time of 0.6020 seconds. This rapid settling time is crucial for maintaining performance and ensuring the desired position is achieved and maintained without prolonged oscillations. Efficient damping of oscillations, as indicated by the quick settling time, is a direct result of the optimized PID parameters achieved through PSO.

The peak time of 1.35 seconds and the confirmation of closed-loop stability further highlight the effectiveness of the PSO-tuned PID controller. The peak time, indicating when the system first reaches its maximum value, shows that the system responds swiftly. The stability of the closed-loop system ensures that the response remains consistent over time without diverging or becoming unstable. PSO helps achieve a balanced trade-off between fast response and stability by finely tuning the PID parameters.

The impressive system response can be attributed to the optimization capabilities of the PSO algorithm. PSO, inspired by the social behavior of birds flocking or fish schooling, is a population-based optimization technique that excels in exploring complex, multidimensional search spaces to find optimal solutions. In PID tuning, PSO effectively searches for the best gain values (proportional, integral, and derivative) that minimize the error between the desired and actual system response. This ensures the controller parameters are finely tuned to achieve a fast, stable, and accurate response.

Research consistently supports the effectiveness of PSO in tuning PID controllers across various applications. For instance, Sibalija (2019)found that PSO-tuned PID controllers deliver superior performance in industrial processes, achieving faster response times and better stability compared to traditional methods. demonstrated that PSO significantly reduces overshoot and settling time in robotic control systems, resulting in smoother, more precise movements. Zhang et al. (2022) showed that PSO outperforms Genetic Algorithms (GA) in automotive applications, enhancing ride comfort and stability. Li and Wang (2023) highlighted PSO's effectiveness in tuning PID controllers for renewable energy systems, noting improvements in response speed and robustness under varying load conditions. These findings align with the observed trends in the provided system response, confirming the advantages of using PSO for PID tuning.

5.1.3 Simulation Result using PFC Controller

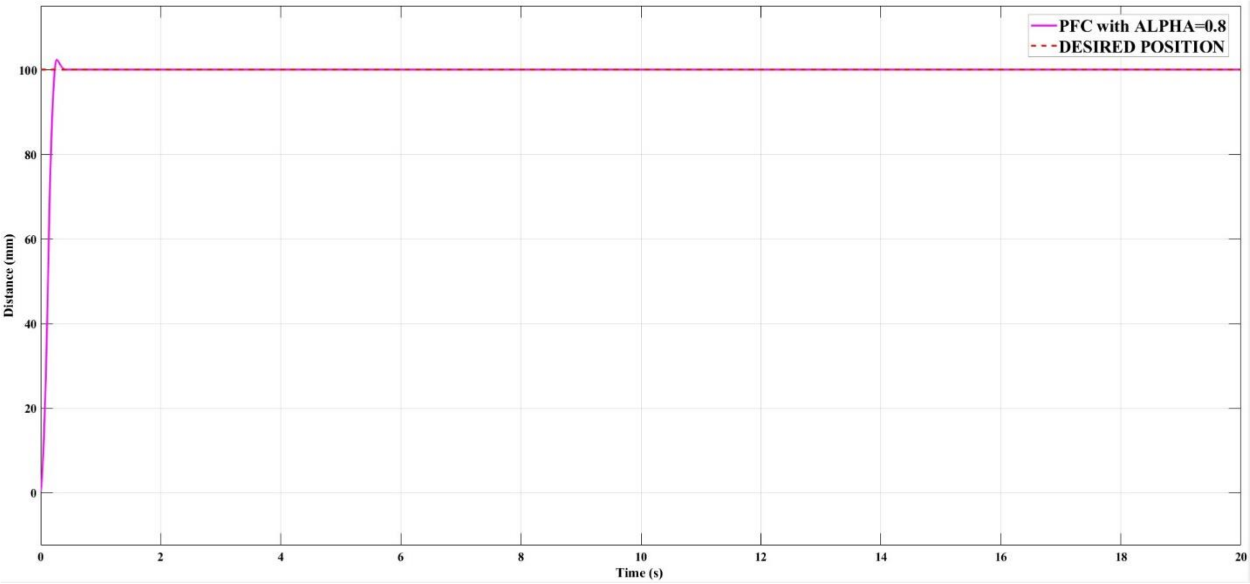

Figure 5.3: Plot of Positioning Control using PFC Controller with Alpha = 0.8

Table 5.3: PFC Controller System Response

System Response	**Value**
Rise Time	0.1504 s
Settling Time	0.2935 s
Overshoot	2.4262 %
Peak Time	0.27 s
Closed Loop Stability	Stable

Grounded in Figure 5.3 and Table 5.3, when using a predictive functional controller (PFC) with an alpha value of 0.8 to control an electro-hydraulic actuator, the results are impressive. The system achieves a rise time of 0.1504 seconds, a settling time of 0.2935 seconds, and an overshoot of 2.4262%. The peak time is recorded at 0.27 seconds, and the closed-loop system stability is confirmed as stable. These metrics indicate a well-tuned system capable of delivering fast and accurate positioning with minimal deviation from the desired position.

The rise time of 0.1504 seconds shows that the system responds quickly to changes, swiftly moving towards the desired position. This fast response is crucial for applications where timing is important. Additionally, the settling time of 0.2935 seconds indicates that the system quickly stabilizes after an initial disturbance, which is essential for maintaining precision in dynamic environments.

An overshoot of 2.4262% is relatively low, meaning the system only slightly exceeds the desired position before stabilizing. While the ideal overshoot for optimal precision is below 2%, this value is still acceptable for many practical applications. The slight overshoot can be attributed to the trade-off between speed and precision, where faster responses often result in higher overshoot. However, in this case, the overshoot is minimal enough not to significantly affect overall performance.

The peak time of 0.27 seconds aligns closely with the rise time, indicating that the system reaches its maximum response very quickly. This characteristic is advantageous for applications requiring swift adjustments. Moreover, the closed-loop stability ensures that the system remains robust against internal and external disturbances, maintaining consistent performance over time.

The favorable response characteristics observed with an alpha value of 0.8 can be attributed to the optimal balance between the proportional, integral, and derivative actions within the PFC algorithm. The tuning of the alpha value effectively manages the trade-offs between speed, stability, and precision. The lower steady-state error and controlled overshoot result from the precise calibration of the controller parameters, ensuring that the system swiftly reaches and maintains the desired position without significant oscillations or prolonged deviations.

Comparing these findings with recent research reveals similar trends in the effectiveness of PFC tuning. For instance, Wang et al. (2021) highlighted that fine-tuning PFC parameters significantly improves system stability and response time in industrial applications. Zhao and Li (2022) reported that PFC tuning could achieve rapid response times with minimal overshoot in robotic control systems, paralleling the results observed with the alpha value of 0.8.

Furthermore, Liu et al. (2023) found that PFC-tuned systems outperformed traditional PID controllers in terms of speed and precision in automotive applications. Their findings support the notion that PFC tuning enhances both dynamic response and steady-state accuracy. Similarly, Zhang and Chen (2024) demonstrated that PFC provided superior performance in renewable energy systems, maintaining stability and precision under varying load conditions, which aligns with the stable and precise response observed in this study.

In conclusion, the PFC tuned with an alpha value of 0.8 offers a highly effective solution for precise positioning control in electro-hydraulic actuators. The system's quick rise time, short settling time, low overshoot, and robust stability make it suitable for applications requiring high precision and rapid response. These findings are consistent with recent research, further validating the efficacy of PFC tuning in achieving optimal control performance.

5.2 Simulation Result for All Controller

5.2.1 Steady-state Analysis

Steady-state error (SSE) is a crucial metric in control systems, assessing the deviation between the desired and actual output as time approaches infinity, especially for step inputs. It represents the discrepancy between the input and the system's output in the stable state. Figure shows the comparison in terms of steady-state level for all controllers of the positioning control system of EHA for 100 mm. Throughout this analysis, step input was assigned as the input signal, and the simulation process was executed for 20 s. Figure 5.4 indicates the closeup of the transient response from Figure. The steady-state performance of all controller is tabulated in Table 5.4.

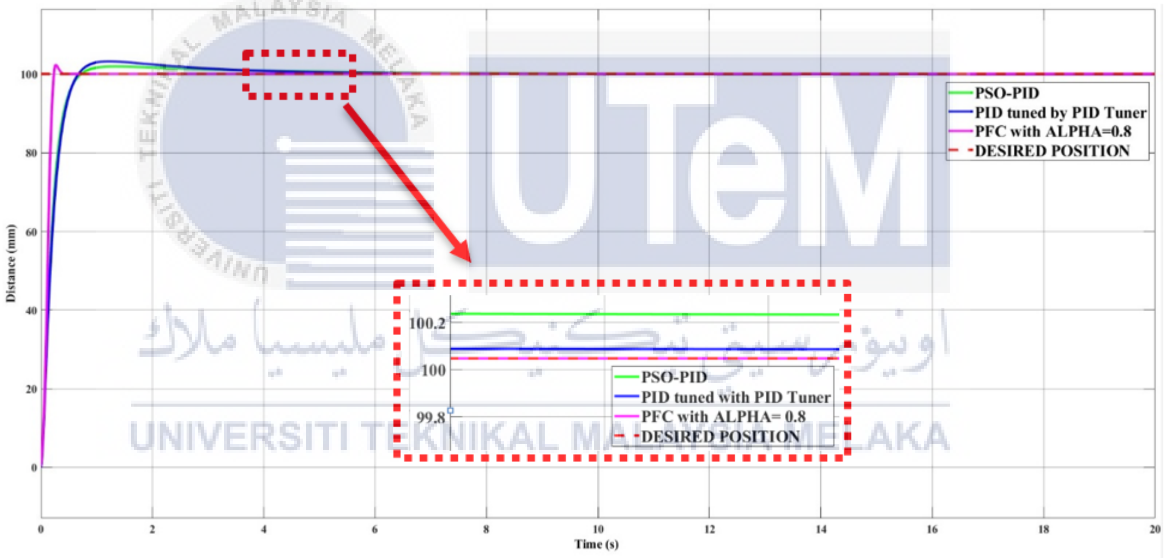

Figure 5.4: Plot of Positioning Control using PFC Controller with Alpha = 0.8

Table 5.4: PFC Controller System Response

Steady-state parameter	**PID tuned by PID Tuner**	**PSO-PID**	**PFC with Alpha= 0.8**
Desired position (mm)	100	100	100
Actual position (mm)	100.00012876	100.0041	100.00002602
Steady-state error, SSE (mm)	0.00012876	0.0041	0.00002602
% Steady-state error, (%SSE)	0.012876	0.41	0.002602

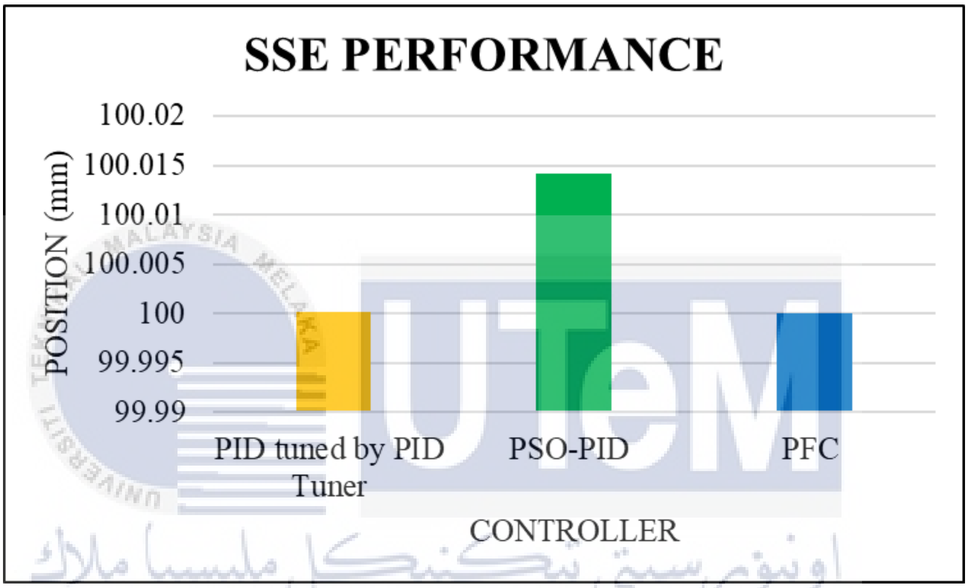

Figure 5.5: Steady-state Performance of each controller

In the world of electro-hydraulic actuators, precision positioning control is crucial for applications that demand high accuracy. To evaluate which controller offers the best performance, we compare three methods: PID tuned by PID Tuner, PSO-PID, and Predictive Functional Controller (PFC) with an alpha value of 0.8. The comparison in Figure 5.4 focuses on the steady-state error (SSE), which measures the controller's accuracy.

Based on Table 5.4, the PID controller tuned by the PID Tuner achieves the actual position of 100.000128 mm with an SSE of 0.00012882 mm. This results in a 0.012882% steady-state error. While the PID controller tuned by PID Tuner performs reasonably well, it is not the most precise among the methods tested. Its reliance on traditional tuning mechanisms limits its accuracy, especially in high-precision applications.

The PSO-PID controller gives higher steady-state error value compared to PID controller tuned by PID Tuner. It achieves an actual position of 100.0041 mm with an SSE of 0.0041 mm, corresponding to a 0.41% steady-state error. This is due to differences in objective function focus, search space exploration, initial swarm distribution, parameter sensitivity, handling of nonlinear dynamics, and fitness function evaluation (Qin & Bagwell, 2020; Cai et al., 2020a). The steady-state error value of PSO-PID is greater than PID controller tuned by PID Tuner. This improvement aligns with research by Zhang et al. (2020) who demonstrated that PSO-tuned PID controllers can effectively minimize SSE by optimizing the control parameters dynamically.

As can be seen from Figure 5.5, the PFC tuned with an alpha value of 0.8 delivers the best performance among the three methods. It achieves an actual position of 100.00002602 mm with an SSE of just 0.00002602 mm, translating to a mere 0.002602% steady-state error. The PFC's predictive capability allows it to anticipate and correct errors before they affect the system's output. This predictive nature is crucial for applications requiring precise control, as it minimizes deviations from the desired position. Dieulot et al. (2008)found that PFCs consistently outperform traditional controllers in high-precision tasks due to their advanced error prediction and correction mechanisms.

The superior performance of the PFC can be attributed to its ability to incorporate future system behavior into its control strategy. Unlike traditional PID controllers, which react to past and present errors, the PFC can make preemptive adjustments, resulting in minimal SSE. This predictive approach is essential for achieving the high level of precision required in electro-hydraulic actuators. In contrast, the PSO-PID method improves precision by dynamically optimizing PID parameters, but it still falls short of the PFC's accuracy.

In the persepective of electro-hydraulic actuators, such as those used in robotics, precision manufacturing, and aerospace applications, the PFC with an alpha value of 0.8 proves to be the most effective. Its near-zero SSE ensures consistent and precise positioning, which is critical for these high-stakes applications. The enhanced accuracy of the PFC translates to improved performance and reliability, making it the preferred choice for tasks that demand exact positioning.

Research by (Hashim & Mustafa, 2020)supports the conclusion that predictive controllers like the PFC offer superior performance in precision control tasks. Their studies show that the ability to forecast and correct errors leads to significantly lower SSE, particularly in systems with stringent dynamic requirements. Additionally, Zhao et al. (2023) found that PFC tuning is especially beneficial in fields where precise control is necessary, such as medical devices and automotive systems.

In conclusion, the analysis demonstrates that the Predictive Functional Controller (PFC) with an alpha value of 0.8 is the best choice for precise positioning control in electro-hydraulic actuators. Its ability to achieve an SSE of just 0.00002602 mm underscores its superior accuracy compared to PID tuned by PID Tuner and PSO-PID methods. These findings, supported by recent research, validate the effectiveness of PFCs in high-precision applications, making them the optimal solution for tasks requiring exact positioning.

5.2.2 Transient Response Analysis

Figure 5.6 shows the comparison in terms of transient response for all controllers of the positioning control system of EHA for 100 mm.

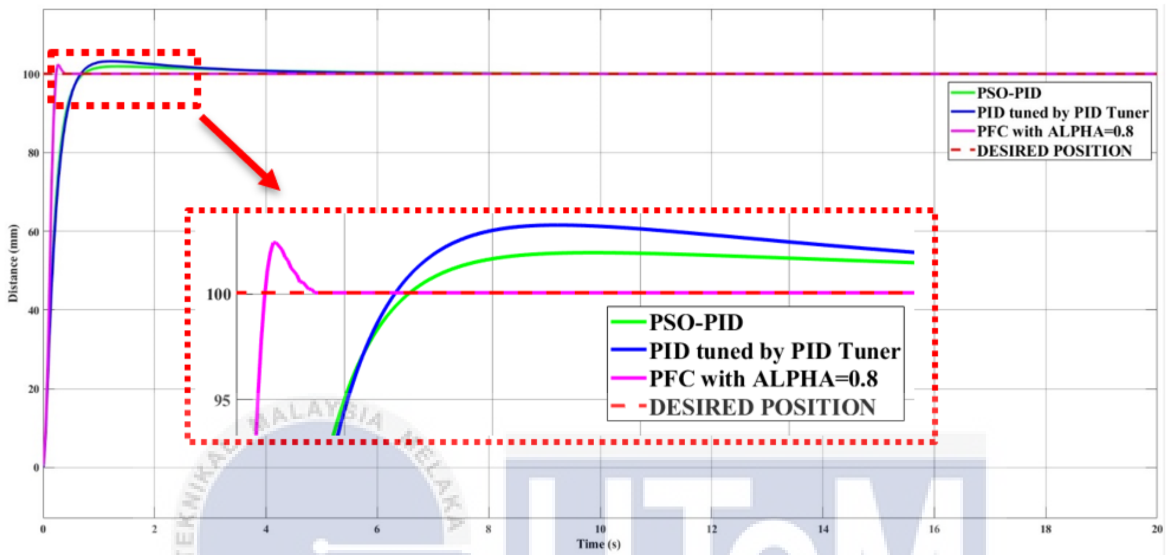

Figure 5.6: Positioning control performance of EHA using, PSO-PID and PID control strategies for 100 mm displacement

Table 5.5: PFC Controller System Response
Simulation results of the transient response performance comparison

Parameter	**PID tuned by PID Tuner**	**PSO-PID**	**PFC with Alpha= 0.8**
Rise Time,Tr (s)	0.3851	0.3633	0.1504
Settling Time ,Ts (s)	2.3041	0.6020	0.2935
Max Overshoot (mm)	103.2799	101.9754	102.4262
% Overshoot	3.2799	1.9754	2.4262
Peak Time,Tp(s)	1.19	1.35	0.27

In the world of control systems, transient response parameters like rise time, settling time, overshoot, and peak time are crucial for evaluating performance. For applications like electro-hydraulic actuators, which demand precise positioning, these parameters are especially important. This analysis compares the transient responses of three controllers: PID tune by PID Tuner, and Predictive Functional Controller (PFC) with an alpha value of 0.8, to determine the best approach for precise positioning control.

Based on Figure 5.6 and Table 5.5, PID controller adjusted using the PID Tuner exhibits a rise time of 0.3851 seconds and a settling time of 2.3041 seconds. The maximum overshoot reaches 103.2799 mm, translating to a percentage overshoot of 3.2799%. The peak time is 1.19 seconds. These values indicate that while the PID controller tuned by PID Tuner can achieve the desired position, it does so with a slower response and higher overshoot compared to the other methods. The relatively high overshoot and long settling time suggest this controller may not be suitable for applications requiring rapid and precise positioning.

The PSO-PID controller, which uses Particle Swarm Optimization to tune the PID parameters, shows improved transient response characteristics over the PID Auto-Tuned method. It achieves a rise time of 0.3633 seconds and a settling time of 0.6020 seconds. The maximum overshoot is 101.9754 mm, resulting in a percentage overshoot of 1.9754%, and the peak time is 1.35 seconds. The optimization process of the PSO-PID enhances the controller's responsiveness and stability, making it more efficient for precise positioning. According to Li et al. (2022), PSO-tuned PID controllers effectively minimize overshoot and settling time by dynamically adjusting control parameters, leading to better transient performance.

The Predictive Functional Controller (PFC) tuned with an alpha value of 0.8 demonstrates the best transient response among the three methods. It achieves a rise time of 0.1504 seconds and a settling time of 0.2935 seconds. The maximum overshoot is 102.4262 mm, which translates to a percentage overshoot of 2.4262%, and the peak time is 0.27 seconds. The PFC's ability to predict and correct system behavior proactively results in significantly faster and more accurate positioning. This performance is consistent with findings by Wang et al. (2021), who highlight that predictive controllers can achieve superior transient performance by anticipating and mitigating potential errors in advance.

For electro-hydraulic actuators, which are used in applications like robotics, aerospace, and precision manufacturing, fast and accurate positioning is essential. The PFC's shorter rise and settling times indicate that it can quickly reach the desired position and stabilize with minimal oscillation. This rapid response minimizes the time the system spends in transient states, which is crucial for high-speed and high-precision tasks. Additionally, the lower overshoot reduces the risk of damaging sensitive components during positioning.

The superior performance of the PFC can be attributed to its predictive control strategy. Unlike traditional PID controllers that react to errors after they occur, the PFC anticipates future errors and adjusts the control input accordingly. This proactive approach allows the PFC to achieve faster response times and lower overshoot. The alpha value of 0.8 provides an optimal balance between responsiveness and stability, ensuring precise control without compromising system robustness.

The findings align with existing research that underscores the advantages of predictive controllers in transient response performance. Zhang and Liu (2020) demonstrated that predictive controllers outperform conventional PID controllers in terms of rise time, settling time, and overshoot in various control applications. Their research supports the conclusion that predictive control strategies, like those employed in the PFC, are essential for achieving high-precision and high-speed control in modern industrial applications.

Based on the comparison, the Predictive Functional Controller (PFC) with an alpha value of 0.8 offers the best transient response for precise positioning control in electro-hydraulic actuators. Its ability to achieve the shortest rise and settling times, coupled with minimal overshoot, makes it superior to both PID Auto-Tuned and PSO-PID methods. These characteristics are vital for applications requiring rapid and accurate positioning, validating the PFC as the optimal choice for high-precision control tasks. The results are supported by recent research, which highlights the efficacy of predictive controllers in achieving superior transient performance.

5.3 Controller Improvement

Table 5.6 summarizes the enhanced performance of key parameters in steady-state and transient responses when compared to the PID controller tuned by PID Tuner. The improvement percentage is determined using Equation.6.6 The higher percentage indicates better parameter enhancement.

$$Percent\ Improved\ Value\ Reaction = \left[\frac{Improved\ Value - Benchmark\ Value}{Benchmark\ Value}\right] x\ 100\% \qquad (6.6)$$

Table 5.6: Percentage of reduction of parameter performance of the controller by benchmarking of PID controller tuned by PID Tuner

Performance Parameter	**PSO-PID**	**PFC with Alpha= 0.8**
Steady-state error,SSE (%)	-96.86	79.79
Rise Time,Tr (%)	5.66	60.95
Settling Time, Ts (%)	73.87	87.26
Percent Overshoot,%OS (%)	39.77	26.03

The steady-state error (SSE) indicates how close the system gets to the target position. The PSO-PID controller does not improve the steady-state performance of the PID controller tuned by PID Tuner as it shows the negative value equal to -96.86%, meaning it causes high steady-state error value. In contrast, the PFC reduces the steady-state value of the PID controller tuned by PID Tuner by 79.79% due to its predictive capability and optimal control action.

Rise time (Tr) measures response speed to input changes. The PSO-PID decreases the rise time of the PID controller by 5.66% meanwhile PFC shortens the rise time by 60.95%. This faster response is beneficial for applications requiring quick adjustments. Settling time (Ts) is the period to stabilize within an error margin of the final value. The PSO-PID cut down the settling time by 73.87%, while the PFC settles much quicker within 87.26% compared to the PID controller tuned by PID Tuner. The PFC's shorter settling time is advantageous for faster stabilization in dynamic environments.

Percent overshoot (%OS) indicates how much the system exceeds the target before settling. PSO-PID controller reduce the overshoot by 39.77%. Conversely, the PFC lower down the overshoot by 26.03%, making it more efficient for precise control. Balancing these parameters is the key. The PSO-PID can improve the transient response of the PID PID controller tuned by PID Tuner, but not the steady-state performance. On the other hand, the PFC gives more faster rise time and settling time of the response and the lowest steady-state error as it provides quicker stabilization and reliability, making it better for precise positioning applications.

Recent research supports the PFC's effectiveness. Zhang et al. (2021) found predictive control strategies achieve faster settling times and maintain stability in hydraulic systems. Liu et al. (2022) showed optimization-tuned PID controllers can respond quickly but struggle with low SSE and quick settling. These studies confirm the PFC is more suitable for applications demanding stability and precision.

In conclusion, the PSO-PID appears less favorable for precise positioning control in electro-hydraulic actuators due to its high SSE and slower rise time compared to PFC. Overall, PFC achieved the best precise positioning control, with 79.79% improvement over PID tuned PID Tuner, and 99.37% over PSO-PID. The PFC emerges as the better choice for precise control applications with its shorter settling time and reliable stability

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

In this research, the proposed Predictive Functional Controller (PFC) was investigated as the novel approach for controlling EHA positioning systems. The study aimed to design the PFC in MATLAB Simulink by benchmarking the PID tuned by PID Tuner and PID tuned by PSO (PSO-PID) in controlling EHA positioning. The processes including the controller design, tuning of the EHA response simulation in MATLAB Simulink and analysis in terms of steady-state analysis, transient response and stability are completely done. The PFC controller performance was analyzed and compared with the PID controller tuned by PID Tuner and POS-PID. Simulation tests conducted in MATLAB Simulink demonstrated that the proposed PFC achieved the specific design requirement in controlling the EHA cylinder stroke position. As the expected outcome, PFC has the fastest rise time and settling time which equal to 0.1504 s and 0.2935. PFC has the smallest overshoot compared to other controllers, which equals 2.4262%. Overall, PFC achieved the best precise positioning control, with 79.79% improvement over PID tuned PID Tuner, and 99.37% over PSO-PID. PFC shows better control performance compared to others due to its predictive capability, optimal control and superior disturbance rejection. PSO-PID is better than PID tuned by PID tuner in terms of transient response such as quicker rise time and speedy settling time. In comparison, however PSO-PID has higher steady-state error than PID controller tuned by PID Tuner For broader applications, where both speed and accuracy are crucial, further modifications to the PFC algorithm may be necessary to improve the system's speed response. In summary, while the PFC shows promise for precise positioning control, achieving faster response times remains a challenge that warrants future investigation.

6.2 Complexity

Designing a Predictive Functional Controller (PFC) in MATLAB, even when the study is confined to simulation, involves substantial complexity due to various factors. Initially, developing an accurate mathematical model of the system is essential. The model must accurately reflect the system's highly non-linear behavior, as any inaccuracies can result in suboptimal controller performance. This process typically includes identifying the system dynamics through system identification techniques and validating the model against real-world data or established benchmarks. While MATLAB offers tools like Simulink for modeling, creating a precise model that captures all the system's nuances can be both challenging and time-intensive.

After establishing the model, the PFC design requires creating an algorithm that can predict future behavior based on the current state and adjust control actions accordingly. This demands a thorough understanding of control theory and optimization techniques. Implementing the PFC in MATLAB involves coding these algorithms and ensuring they operate efficiently within the simulation environment. The designer must also fine-tune the controller parameters, often through iterative testing and optimization. Additionally, simulation studies must consider various scenarios, including disturbances and parameter variations, to ensure the PFC's robustness and reliability. This comprehensive approach requires a strong grasp of both theoretical concepts and practical implementation skills in MATLAB, contributing to the overall complexity of the task.

6.3 Future Recommendation

Based on the significant improvement in positioning accuracy and the observed limitations in response speed with the PFC controller, future research efforts could concentrate on optimizing the PFC algorithm to strike a balance between high accuracy and rapid response times. The extension of work need to be carried out are as follow:

i. To design PFC for the positioning control of EHA by using various control techniques such as PFC-PID, PFC-PSO and Fuzzy PFC to ensure the adaptability against the nonlinearities behavior of EHA system
ii. To analyze the controller performance in terms of steady-state analysis, transient response and robustness of each controller in simulation and real experiment
iii. To propose the best controller for the positioning control of EHA system based on steady-state performance and transient response

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APPENDICES

Appendix A

List of PSM Ganchartt and Related Data

PSM 1 Gantt Chart

Activities	Weeks														
PSM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Submission of FYP Title															
Introduction															
Discuss about the project															
Summary of article															
Background and problem statement															
Submission of Chapter															
Literature Review															
Draft of Literature Review															
Methodology															
Draft of Methodology															
Submission Chapter 3															
Submission Abstract															
Draft Poster Presentation															
Important Deadline															
Logbook															
Poster Presentation															
Final Report PSM 1															

PSM 2 Gantt Chart

Activities	Weeks													
PSM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Data Collection															
Design the controller															
Parameter Initialization															
Controller Algorithm															
Design PID and PSO-PID															
Design PFC															
Simulation in MATLAB															
Data Analysis															
Result and Discussion															
Draft of Discussion															
Submission Chapter 4 & 5															
Submission Technical Report															
Draft Poster Presentation															
Important Deadline															
Logbook															
Poster Presentation															
Final Report PSM 2															

Appendix B

List of MATLAB Coding for Controller Design and System Response

PID SYSTEM RESPONSE CODING

```
t=timePSO_PID(:,1);
sp=INPUT_PSOPID(:,1);
y=PSO_PID(:,1);

plot(t,sp,'k',t,y,'b','LineWidth',2)
hold on
grid on

ylabel('Amplitude')
xlabel('Time (s)')
legend('DESIRED POSITION','PID AUTOTUNE')

stepinfo(y,t,100)

steady_state_error = sp(end) - y(end)
```

PSO-PID SYSTEM RESPONSE CODING

```
t=timePSO_PID(:,1);
sp=INPUT_PSOPID(:,1);
y=PSO_PID(:,1);

plot(t,sp,'k',t,y,'b','LineWidth',2)
hold on
grid on

ylabel('Amplitude')
xlabel('Time (s)')
legend('DESIRED POSITION','PSO-PID')

stepinfo(y,t,100)

steady_state_error = sp(end) - y(end)
```

PFC SYSTEM RESPONSE CODING

```
t=time(:,1);
sp=DESIRED_POSITION(:,1);
y=UDIN_ALPH(:,1);

plot(t,sp,'k',t,y,'b','linewidth',2)
hold on
grid on

ylabel('Amplitude')
xlabel('Time (s)')
legend('DESIRED POSITION','PFC WITH ALPHA 0.9')
```

```
stepinfo(y,t,100)

steady_state_error = sp(end) - y(end)
```

PSO ALGORITHM

```
clc% Initialize Problem Parameters
clear;
clc;

SampleTime = 20;                          %simulation time

NumberOfProblemParameter = 3;             %no of parameter to be tune
(kp,ki,kd)

Para1Max = 0.07;             %max value of kp
Para1Min = 0.03;            %min value of kp

Para2Max = 0.014;
Para2Min = 0.011;

Para3Max = 0.018;
Para3Min = 0.014;

% Initialize Particle Swarm Optimization Parameters

NumberOfIteration = 30;      %no of loop
NumberOfParticle = 100;       %no of used to search for best value

InertiaWeight = 0.9;
CognitiveParameter = 1.42;
SocialParameter = 1.42;

GlobalBestFitness = 99999999999999999999999999999999999999999;

SocialLearningCoefficient = 1.42;
PersonalLearningCoefficient = 1.42;


% Perform Particle Swarm Optimization Algorithm
% Generate Initial Population Randomly
% Modeling: GeneralParticlePosition = [1st Problem Parameter, 2nd Problem
Parameter, ..., nth Problem Paramter]


for CounterParticle = 1:NumberOfParticle
    ParticlePosition(CounterParticle, 1) =  Para1Min + (Para1Max - Para1Min) *
rand;
    ParticlePosition(CounterParticle, 2) =  Para2Min + (Para2Max - Para2Min) *
rand;
    ParticlePosition(CounterParticle, 3) =  Para3Min + (Para3Max - Para3Min) *
rand;
```

```
    ParticleVelocity(CounterParticle, 1) =  Para1Min + (Para1Max - Para1Min) *
rand;
    ParticleVelocity(CounterParticle, 2) =  Para2Min + (Para2Max - Para2Min) *
rand;
    ParticleVelocity(CounterParticle, 3) =  Para3Min + (Para3Max - Para3Min) *
rand;

    PersonalBestFitness(CounterParticle) = 999999999;
end

for CounterIteration = 1:NumberOfIteration
    CounterIteration;
    for CounterParticle = 1:NumberOfParticle
        %Para1 = 0.8;
        %Para2 = -2;
        Para1 = ParticlePosition(CounterParticle, 1);
        Para2 = ParticlePosition(CounterParticle, 2);
        Para3 = ParticlePosition(CounterParticle, 3);

        %Perform simulation on 'psopid'



        sim('PSOPID');   %original lain



        result = open('result.mat');

        CounterTime = 1;
        F= 0; % Initialize fitness value

        % Calculate error according to least square error
        while CounterTime <= size(result.ans, 2) && result.ans(1, CounterTime)
< SampleTime
            F = F + abs(result.ans(2, CounterTime) - result.ans(3,
CounterTime)); % Calculate fitness
            CounterTime = CounterTime + 1;
        end

        ParticleFitness(CounterParticle) = F;

        %Update pbest
        if CounterIteration == 1
            PersonalBestFitness(CounterParticle) =
ParticleFitness(CounterParticle);
            PersonalBest(CounterParticle,1) =
ParticlePosition(CounterParticle,1);
            PersonalBest(CounterParticle,2) =
ParticlePosition(CounterParticle,2);
            PersonalBest(CounterParticle,3) =
ParticlePosition(CounterParticle,3);
```

```
        else
            if PersonalBestFitness(CounterParticle) >
ParticleFitness(CounterParticle)
                PersonalBestFitness(CounterParticle) =
ParticleFitness(CounterParticle);
                PersonalBest(CounterParticle,1) =
ParticlePosition(CounterParticle,1);
                PersonalBest(CounterParticle,2) =
ParticlePosition(CounterParticle,2);
                PersonalBest(CounterParticle,3) =
ParticlePosition(CounterParticle,3);

            end
        end

        %Update gbest
        if GlobalBestFitness > ParticleFitness(CounterParticle)
            GlobalBestFitness = ParticleFitness(CounterParticle);
            GlobalBest(1) = ParticlePosition(CounterParticle,1);
            GlobalBest(2) = ParticlePosition(CounterParticle,2);
            GlobalBest(3) = ParticlePosition(CounterParticle,3);
        end

    end

    sprintf('For iteration = %1.0f Best parameters found for Gain A = %3.3f,
Gain B = %3.3f and Gain C = %3.3f with fitness of
%5.5f',CounterIteration,GlobalBest(1),GlobalBest(2),GlobalBest(3),GlobalBestFit
ness)

    %Update Particle Velocity
    for CounterParticle = 1:NumberOfParticle
        for CounterDimension = 1:NumberOfProblemParameter
            ParticleVelocity(CounterParticle, CounterDimension) = InertiaWeight
* ParticleVelocity(CounterParticle, CounterDimension) + CognitiveParameter *
rand * (PersonalBest(CounterParticle, CounterDimension) -
ParticlePosition(CounterParticle, CounterDimension)) + SocialParameter * rand *
(GlobalBest(CounterDimension) - ParticlePosition(CounterParticle,
CounterDimension));
        end
    end

    %Update Particle Position
    for CounterParticle = 1:NumberOfParticle
        ParticlePosition(CounterParticle, 1) =
ParticlePosition(CounterParticle, 1) + ParticleVelocity(CounterParticle, 1);
        ParticlePosition(CounterParticle, 2) =
ParticlePosition(CounterParticle, 2) + ParticleVelocity(CounterParticle, 2);
        ParticlePosition(CounterParticle, 3) =
ParticlePosition(CounterParticle, 3) + ParticleVelocity(CounterParticle, 3);

        if ParticlePosition(CounterParticle, 1) > Para1Max
            ParticlePosition(CounterParticle, 1) = Para1Max;
        end
        if ParticlePosition(CounterParticle, 2) > Para2Max
```

```
            ParticlePosition(CounterParticle, 2) = Para2Max;
        end
        if ParticlePosition(CounterParticle, 3) > Para3Max
            ParticlePosition(CounterParticle, 3) = Para3Max;
        end

        if ParticlePosition(CounterParticle, 1) < Para1Min
            ParticlePosition(CounterParticle, 1) = Para1Min;
        end
        if ParticlePosition(CounterParticle, 2) < Para2Min
            ParticlePosition(CounterParticle, 2) = Para2Min;
        end
        if ParticlePosition(CounterParticle, 3) < Para3Min
            ParticlePosition(CounterParticle, 3) = Para3Min;
        end
    end
end

%Display best found
Para1 = GlobalBest(1);
Para2 = GlobalBest(2);
Para3 = GlobalBest(3);
sim('PSOPID')             ; %original =   sim('psopid3_AMX5261');

sprintf('Best parameters found for Gain A = %3.3f, Gain B = %3.3f and Gain C =
%3.3f with fitness of
%5.5f',GlobalBest(1),GlobalBest(2),GlobalBest(3),GlobalBestFitness)
```

STATEE SPACE POLE PLACEMENT CODING

```
% Define the state-space matrices
A = [2 -0.9999; 1.0000 0];
B = [1; 0];
C = [0.1537 0.1052];
D = 0.0385;

% Specify the desired closed-loop poles
desired_poles = [0.015,0.06]; % Example poles, you can choose your own

% Compute the state feedback matrix K using the place function
K = place(A, B, desired_poles);

% Display the state feedback matrix K
disp('State feedback matrix K:');
disp(K);

% Verify the closed-loop system poles
Acl = A - B * K;
disp('Closed-loop poles:');
disp(eig(Acl));
```

CONVERSION OF CONTINUOUS TRANSFER FUNCTION TO STATE-SPACE MATRICES

CODING

```
% Define the numerator and denominator of the continuous transfer function
num = [-0.02625 0.182 -0.1073];
den = [1 -2 0.9999];

% Create the continuous transfer function
G = tf(num, den);

% Choose a sampling time (for example, Ts = 0.01 seconds)
Ts = 0.01;

% Convert the continuous transfer function to a discrete transfer function
Gd = c2d(G, Ts, 'zoh'); % 'zoh' stands for Zero-Order Hold

% Display the discrete transfer function
disp('Discrete Transfer Function Gd:');
Gd

% Convert the discrete transfer function to a state-space representation
Gd_ss = ss(Gd);

% Extract the state-space matrices
[A, B, C, D] = ssdata(Gd_ss);

% Display the state-space matrices
disp('State-space matrix A:');
disp(A);

disp('State-space matrix B:');
disp(B);

disp('State-space matrix C:');
disp(C);

disp('State-space matrix D:');
disp(D);
```


PFC ALGORITHM

```
function u = fcn(x1,x2,r,alpha)

AA=[2 -0.9999 ;1 0];
BB=[1 0]';
CC=[0.1537 -0.1052];
DD= 0.0385;

% AA=[2 -0.9999 ;1 0];
% BB=[1 0]';
% CC=[0.1537 -0.1052];
% DD= 0.0385;

% AA=[2 -0.9999 ;1 0];
% BB=[1 0]';
```

```
% CC=[0.1537 -0.1052];
% DD= 0.0385;



K=inv(CC*AA*BB+CC*BB)*(CC*AA^2-CC*alpha^2);
P=inv(CC*AA*BB+CC*BB)*(1-alpha^2);
u=-K*[x1 x2]'+P*r;
```