DEVELOPMENT OF PID-TYPE FUZZY LOGIC CONTROLLER WITH ADAPTIVE INVASIVE WEED ALGORITHM TO CONTROL OF FLEXIBLE ARM SYSTEM

ADRIAN LEONG WAI CHEN

Bachelor of Mechatronics Engineering
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DEVELOPMENT OF PID-TYPE FUZZY LOGIC CONTROLLER WITH ADAPTIVE INVASIVE WEED ALGORITHM TO CONTROL OF FLEXIBLE ARM SYSTEM

ADRIAN LEONG WAI CHEN

A report submitted
in partial fulfillment of the requirements for the degree of
Mechatronics Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled “DEVELOPMENT OF PID-TYPE FUZZY LOGIC CONTROLLER WITH ADAPTIVE INVASIVE WEED ALGORITHM TO CONTROL OF FLEXIBLE ARM SYSTEM is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : ....

Date : ....

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPROVAL

I hereby declare that I have checked this report entitled “DEVELOPMENT OF ADAPTIVE INVASIVE WEED ALGORITHM WITH PID-TYPE FUZZY LOGIC CONTROLLER TO CONTROL OF FLEXIBLE ARM SYSTEM” and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEDICATIONS

To my beloved mother and father

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ACKNOWLEDGEMENTS

Through this section, I would like to use this opportunity to express my deepest gratitude and special thanks to my supervisor, Dr. Hyreil Anuar who in spite of being busy with his duties but still took time out to hear, guide and keep me on the correct path for my final year project.

I also expressed my thankfulness to my panels, Pn Nurdiana bt Nordin and Dr. Hairol Nizam bin Md Shah for evaluating my project and also listen carefully to my presentation. Then, I would like to thank to my friends, especially to my course mate for giving necessary advices and guidance to my project. Their valuable comments help me a lot in improving the quality of the project.

Next, I would like to express my gratitude to my family. Due to the endless support and care, I able to complete my project with confidence.

Finally, I perceive this project as a big milestone in my study. I will strive to use gained skills and knowledge in the best possible way.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ABSTRACT

Flexible robot arm is widely used in the industry nowadays. This is because it is able to handle tasks that are difficult, dangerous or repetitive and variety manufacturing work. Therefore, the flexible robot arm is required to be highly accurate and repeatable in controlling to work like a human's hand. This project attempts to improve accuracy and repeatability using a PID-type fuzzy logic controller (PID-FLC) and optimize by an invasive weed optimization (IWO) algorithm for a flexible robot arm. The algorithm will be validated with the design of fuzzy logic controller for a single-link flexible arm system. To simulate such system, a PID-type fuzzy logic controller will be designed in the Simulink. The proportional-integral- derivative (PID) acts as scaling gain for the fuzzy logic controller in order to normalize inputs and output and to damp oscilations of the system. Next, the IWO algorithm will be optimised the performance of PID-type fuzzy logic controller by discovering the best value of membership function for fuzzy logic controller. Last but not least, the result of PID-FLC with IWO will be evaluated and validated by inserting different value of iterations for IWO. The performance of PID-FLC is evaluated by comparing and analysing with Ziegler-Nichols tuned PID controller, PD-FLC with IWO and PID-FLC without IWO in term of rise time, overshoot and undershoot, settling time and steady state error. As a result, the most suitable iterations to get the ideal result of PID-FLC with IWO is analysed and obtained. 30 number of iterations able to generate the optimum performance of PID-FLC with less time-consuming and low cost function. Other than that, PID-FLC with IWO has better settling time and overshoot and undershoot compared to Ziegler-Nichols tuned PID controller. PID-FLC shows better performance by improving 11% of lower overshoot at first signal, 27.9% of smaller undershoot at second signal and 0.8% lower overshoot at third signal compared to PD-FLC with IWO. PID-FLC also achieved better overall performance than PID-FLC without IWO in term of rise time, settling time, overshoot and undershoot and teady-state error. However, there are some future works to be done which are comparing the performance of IWO with other biological-based algorithm and apply this optimized control system to the real model of robot arm.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ABSTRAK

Lengan robot fleksibel digunakan secara meluas dalam industri pada masa kini. Ini kerana ia dapat mengendalikan tugas-tugas yang sukar, berbahaya atau berulang dan pelbagai jenis pembuatan. Oleh itu, lengan robot fleksibel dikehendaki menjadi sangat tepat dan boleh mengawal untuk bekerja yang megulangi seperti tangan manusia. Projek ini cuba meningkatkan ketepatan dan pengulangan dengan menggunakan PID-FLC dan mengoptimumkan dengan Invasive Weed Optimization (IWO) algoritma untuk lengan robot fleksibel. Algoritma ini akan digunakan dengan reka bentuk pengawal logik fuzzy untuk sistem lengan fleksibel. Untuk mendapatkan sistem sedemikian, PID-FLC akan direka di dalam Simulink. PID bertindak sebagai penambahan skala untuk FLC untuk mengimbangkan input dan output dan juga untuk mengimbangi sistem. Seterusnya, algoritma IWO akan dioptimumkan prestasi PID-FLC dengan menemui nilai terbaik *membership function* untuk *fuzzy logic controller*. Akhir sekali, keputusan PID-FLC dengan IWO akan dinilai dan disahkan dengan memasukkan nilai *"iteration"* yang berbeza untuk IWO. Prestasi PID-FLC dievaluasi dengan membandingkan dan menganalisis dengan PD-FLC dengan IWO dan PID-FLC tanpa IWO dari segi *rise time, overshoot* dan *undershoot, settling time* dan *steady state error*. Akibatnya, *"iteration"* yang paling sesuai untuk mendapatkan hasil ideal PID-FLC dengan IWO dianalisis dan diperolehi. 30 bilangan *"iteration"* yang dapat menghasilkan prestasi optimum PID-FLC dengan masa yang lebih singkat dan "*cost function*" yang rendah. Di samping itu, PID-FLC dengan IWO menunjukkan *rise time*, *overshoot* dan *undershoot* yang lebih baik daripada *Ziegler-Nichols PID controller*. PID-FLC menunjukkan prestasi yang lebih baik dengan meningkatkan 11% daripada *overshoot* yang lebih rendah pada isyarat pertama, 27.9% daripada *undershoot* yang lebih kecil pada isyarat kedua dan 0.8% *overshoot* yang lebih rendah pada isyarat ketiga berbanding PD-FLC dengan IWO. PID-FLC juga mencapai prestasi keseluruhan yang lebih baik daripada PID-FLC tanpa IWO dari segi *rise time, overshoot* dan *undershoot, settling time* dan *steady state error*. Walau bagaimanapun, terdapat beberapa kerja masa depan yang akan dilakukan seperti membandingkan prestasi IWO dengan algoritma berasaskan biologi yang lain dan menggunakan sistem kawalan optimum ini kepada model robot lengan sebenar.

TABLE OF CONTENTS

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

اونيونرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF TABLES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF FIGURES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF SYMBOLS AND ABBREVIATIONS

PID-FLC	-	PID fuzzy logic controller
PD-FLC	-	PD fuzzy logic controller
FLC	-	Fuzzy Logic Controller
IWO	-	Invasive weed optimization
PID	-	Proportional- Integral- Derivative
PD	-	Proportional- Derivative
PI	-	Proportional- Integral- Derivative
P	-	Proportional
I	-	Integral
D	-	Derivative
PSO	-	Particle Swarm Optimization
SMES	-	Simple Multimembered Evolution Strategy
ICMOA	-	Multi-objective optimization immune algorithm
HIWO	-	Hybrid Invasive Weed Optimization
CCIWO	-	Cooperative co-evolutionary Invasive Weed Algorithm
nFOA	-	Novel Fruit Fly Optimizationa Algorithm
HEDA	-	Hybrid Estimation of Distribution Algorithm
KMEA	-	Knowledge-based Multi-agent Evolutionary Algorithm
ANN	-	Artificial Neural Network
Kd	-	Derivative Gain
Kp	-	Proportional Gain
Ki	-	Integral Gain

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF APPENDICES

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 1

INTRODUCTION

1.1 Project Background

Traditionally, industrial robot arms are designed based on human's arm which needed to control the location and velocity of the robot's end-effector repeatedly and accurately. Nowadays, robot arms are often used to perform complex tasks which cannot be finished by human which required a robust force control strategies. Position and velocity control in some Degree-Of-Freedom (DOF) are also essential for certain task. Therefore, the method of implementation of stable and accurate force control is an important area of robotics research in order to fulfil those extra demands. Although there are a lot of researches have been worked on enhancing on the controller, however, technological limitations of current controller causes the difficulty to achieve in practice [1]. Yet, current knowledge is applied on the controller to minimize its error as much as possible.

Because of the simple structure and robust performance of proportional- integral-derivative (PID) control in a wide range of operating conditions, PID control which act as a well-known control strategy has been widely used in the industry [6]. According to the thesis that was presented by Sena TEMEL, Semih YAĞLI and Semih GÖREN [7], there are different transient performances of P, P-D, P-I and P-I-D controller.

P controller is mainly used to decrease the steady-state error of the system. However, it cannot eliminate the steady-state error of the system and it probably will causes oscillation and amplifies process noise. P-I controller manage to eliminate the steady-state error but it will be prone to overshooting in the event of large change. P-D controller able to increase the stability of the system as it handles large changes well with minimal overshoot but have poor performance on tracking small changes or errors. For PID controller, it has the optimum control dynamics since it has 3 parameter that including zero steady-state error, fast response, no oscillations and higher stability [7].

In recent decades, a lot of researchers found that nonlinearities in a control system have causes specific phenomena where it had to be taken into account to study. It could be a useful tool to solve the delicate problem of modelling and control of the complex systems

[2]. Fuzzy logic controller (FLC) is one of the tools that able to solve the unknown nonlinearities, time delays, disturbances as well as change in system parameters and reach the desired control performance [3]. FLC a set of linguistic control rules that combine the dual concepts of fuzzy implication is and the compositional rule of inference [4]. Thus, it able to convert the linguistic control strategy according expert knowledge into an automatic control strategy by providing an algorithm.

However, at present, there is no systematic steps to design an FLC or tune the fuzzy logic for best performance. Therefore, biological-based algorithms such as an invasive weed optimization (IWO) are used for benchmark functions and tuning FLC. The design of IWO algorithm is inspired from the phenomenon of colonization of invasive weed in the nature. The colonization of invasive weed means each invading weed will take the unused resources in the field and start to grow. As it grows to a flowering weed, it will start to produces new weeds. The weeds with better adoption to the environment will take more resources and produces more seeds until it spreads over the field. In the end, only the weeds that have better fitness can survive [5]. Therefore, by using its properties, the system will become well adapted and improved over time.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1.2 Motivation

In 1960s, a robotic arm which is developed by Joseph Engelberger [8] is mass produced for factory automation. Robotics manipulators and robotics arms are used in the industry since 1960s. Although the robotics arms were first designed for manufacturing and production process, however, there are a lot of robotics arms have been developed for other purpose nowadays. For example, robot arm that are used for defusing bombs by military and the assistive robotics arm by JACO [9] that able to help individuals with disabilities. Other than that, there are other robotic arms that are used in daily life or help to work in project such as Care-O-bot [10] and also mobile manipulator robot PR2 by Willow Garage [11].

Robotic arms can be found in every field such as manufacturing, military, medical field and so on. This is because it has the ability to work in environments that are inhospitable to human, freedom form human limitation, high accuracy and precision and also high production rate [12]. In this recent years, the rise of China automation demand has push the market into a growth super-cycle of robotics due to China is the largest purchaser of robotic arms. According to the research that done by IDTechEx [13], the rise of the automation demand will emerged a new class of robots that are collaborative, mobile and increasingly intelligent. This new robots will then causes the overall market grow by a factor of nearly 3 and 7 in next 10 and 20 years [13].

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

In order to let robotic arm performs and complete tasks more precisely, accurately and efficiently, thus, a good quality of system is needed. First of all, more researches of the controller of robotic arm system are done to obtain more knowledge and information that enhance the quality of the system as well as the performance of robotic arm.

The main purpose of this project is to design a PID-type fuzzy controller (PID-FLC) with invasive weed optimization (IWO) to enhance the quality of robotic arm system in term of accuracy and its performance will be compared. MATLAB is used for simulation of the controller.

1.3 Problem Statement

Proportional- integral- derivative (PID) controller is the one of the most common type of controller that can be found in the industry. PID controller is used to control dynamic processes with variable at wide limits parameters and uncontrolled violations in the process control systems.

However, PID controller required a calibration procedure, level of knowledge of dynamics of the controlled process in order to choose the correct parameters of the regulator. It becomes a main problem to the most of regulators that have been used in the industry due to lack of knowledge of finding correct parameters for the regulator [14]. It also causes each regulator only capable to do one task because of unable to adjust the parameters of the regulator.

Although fuzzy logic controller (FLC) is getting popular to replace PID controller, but it also faced with a problem of the tuning. Due to it implies the handling of a great quantity of variables such as the shape, number and range of the membership function, the percentage of overlap among them need to be determined and rule base need to be designed as well. The problem will become more complicated when it need to control multivariable systems [15].

Therefore, the main efforts of this project is focused on design the FLC for automatic adjustment of regulators. The problem of tuning of the fuzzy logic also need to be solved throughout this project. Finally, the controller will be analysed and compared to show its improvement.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1.4 Objective

1. To design PID type fuzzy logic controller for flexible arm system

2. To validate the performance of PID type fuzzy logic controller with IWO for flexible arm system.

3. To compare the performance of the designed PID-type fuzzy logic controller with IWO with Ziegler-Nichols tuned PID Controller, PD-type fuzzy logic controller with IWO and PID-type fuzzy logic controller without IWO.

1.5 Scope of the Project

There are few scopes of this project. First and foremost, the construction of the flexible arm system is only focused on one-link flexible robot arm. Besides, the rotation of flexible arm system is limited in between -90 degree to 90 degree. This project will cover the comparison of the result of PID-FLC with IWO with Ziegler-Nichols tuned PID controller, PD-FLC with IWO and PID-FLC without IWO. All the result from simulation will be done by using Matlab and Simulink. Therefore, there is no hardware configuration for this project.

اونيؤرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

After discovering the problem of control system to control flexible robot arm and motivation on developing better solution for flexible robot arm, a review of previous related works will be discussed and compared each other to find a better method to optimize the controller. In this chapter, the background of controller will be briefly explained for a better understanding. Besides, researches that have been done also can obtain useful information by synthesizing their works to make this project successful.

2.2 Control System for the Manipulator

A control system for the manipulator is necessary in order to move the robot with planned trajectory or maintain a robot in a desired dynamic behaviour. The forming of the controlled variable will causes the different of accuracy of motion along on the output of the system required. Therefore, there are different methods are used to overcome the control problem of manipulators as well as increase its accuracy. Generally, proportional- integral-derivative (PID) controller is used in most of the manipulators due to its effectiveness on the torque calculation. However, this method required a time-consuming process and level of knowledge of dynamics of the controlled process to derive the model of the manipulator system.

Hence, artificial intelligence technique such as fuzzy logic and neural network are applied on the controller to replace the PID controller. Fuzzy logic allows the system to make definite decisions based on imprecise or ambiguous data but it is difficult to define the fuzzy parameter. For artificial neural network (ANN), there are some factors has to be considered which are the complexity models of the system which will make the learning process harder and choosing the suitability of learning algorithm to the models [16].

2.2.1 Conventional Controller

During the 1930, PID controller become popular and gained widespread in industrial acceptance due to the benefits of this controller such as simplicity, robustness and wide applicability. After that, there are many various tuning methods for this controller have been proposed. The purpose of tuning a PID controller is to gain a better control system response based on desirable control objectives such as percent of overshoot, rise time, settling time, manipulated variable behaviour and steady state error. Table 2.1 is tabulated to show different tuning methods a PID controller and compare their performances.

Table 2.1 Tuning method of a PID controller

<table>
<tr><th>Tuning Method</th><th>Explanation</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Closed-loop Ziegler-Nichols Method [20]</td><td>is a trial and error tuning method based on sustained oscillations
Obtain the ultimate gain, Ku and frequency, Pu
Apply gain to the controller setting, the controller parameters can be obtained.
controller setting:
<table><tr><th>Controller</th><th>k_c</th><th>τ_I</th><th>τ_D</th></tr><tr><td>P</td><td>$0.5k_{cu}$</td><td>-</td><td>-</td></tr><tr><td>PI</td><td>$0.45k_{cu}$</td><td>$P_u/1.2$</td><td>-</td></tr><tr><td>PID</td><td>$0.6k_{cu}$</td><td>$P_u/2$</td><td>$P_u/8$</td></tr></table></td><td>do not require the process model</td><td>time – consuming, force the system to margin if instability, not applicable for unstable open loop processes</td></tr>
<tr><td>Tyreus – Luyben Method [20]</td><td>similar steps as Ziegler- Nichols method but different controller parameter setting
Only for PI and PID controller
controller setting:
<table><tr><th>Controller</th><th>k_c</th><th>τ_I</th><th>τ_D</th></tr><tr><td>PI</td><td>$k_{cu}/3.2$</td><td>$2.2P_u$</td><td>-</td></tr><tr><td>PID</td><td>$k_{cu}/3.2$</td><td>$2.2P_u$</td><td>$P_u/6.3$</td></tr></table></td><td>lesser settling time, overshoot and wildness than Z-N method</td><td>time-consuming and force the system to margin if instability</td></tr>
</table>

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Table 2.2 Methods of tuning a PID controller (cont.)

<table>
<tr><th>Tuning Method</th><th>Explanation</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Damped Oscillation Method [20]</td><td>obtain the parameters of Gd and Pd.
Gd = Proportional gain at decay ratio of ¼
Pd= Period of oscillation
Apply gain to controller setting and obtain the controller parameter
controller setting:
<table>
<tr><th>Controller</th><th>k_c</th><th>τ_I</th><th>τ_I</th></tr>
<tr><td>P</td><td>$1.1G_d$</td><td>-</td><td>-</td></tr>
<tr><td>PI</td><td>$1.1G_d$</td><td>$P_d/2.6$</td><td>-</td></tr>
<tr><td>PID</td><td>$1.1G_d$</td><td>$P_d/3.6$</td><td>$P_d/9$</td></tr>
</table>
</td><td>solve the problem of marginal stability</td><td>more suitable for first order system</td></tr>
<tr><td>Cohen- Coon Method [21]</td><td>process reaction curve by first order plus dead time model
determining of three parameters of km , τm and d
Apply to the Cohen –Coon controller setting to get the controller parameter
Cohen –Coon controller setting:
<table>
<tr><th>Controller Type</th><th>k_c</th><th>τ_I</th><th>τ_D</th></tr>
<tr><td>P</td><td>$\frac{1}{K_m}\frac{\tau_m}{d}(1+\frac{d}{3\tau_m})$</td><td>-</td><td>-</td></tr>
<tr><td>PI</td><td>$\frac{1}{K_m}\frac{\tau_m}{d}(\frac{9}{10}+\frac{d}{12\tau_m})$</td><td>$d\frac{30+3d_m/\tau_m}{9+20d_m/\tau_m}$</td><td>-</td></tr>
<tr><td>PD</td><td>$\frac{1}{K_m}\frac{\tau_m}{d}(\frac{5}{4}+\frac{d}{6\tau_m})$</td><td>-</td><td>$d\frac{6-2d/\tau_m}{22+3d/\tau_m}$</td></tr>
<tr><td>PID</td><td>$\frac{1}{K_m}\frac{\tau_m}{d}(\frac{4}{3}+\frac{d}{4\tau_m})$</td><td>$d\frac{32+6d/\tau_m}{13+8d/\tau_m}$</td><td>$d\frac{4}{11+2d/\tau_m}$</td></tr>
</table>
</td><td>provides a good approximation to process reaction curve and fast ast response</td><td>less robust than Z-N method</td></tr>
</table>

As mentioned before, P controller is mainly used to decrease the steady-state error of the system but unable to eliminate the steady-state error of the system. P-I controller manage to eliminate the steady-state error and tracking small change error but lead to high overshoot of the system. P-D controller able to increase the stability of the system as it handles large changes well with minimal overshoot but have poor performance on tracking small changes or errors. For PID controller, it has the optimum control dynamics since it has 3 parameter that including zero steady-state error, fast response, no oscillations and higher stability.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2.2.2 Fuzzy Logic Controller

The blocks of a FLC is shown in Figure 2.1. Each of the block has its own characteristic.

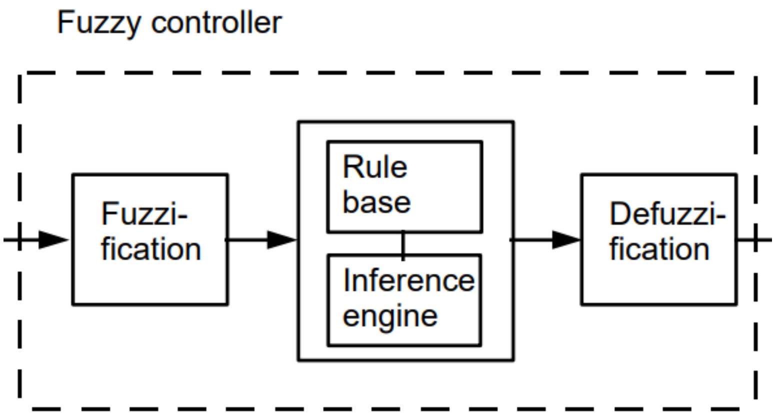


Figure 2.1Blocks of a Fuzzy Controller

The first block inside the controller is fuzzification which used to converts every input data to degrees of membership by a lookup in one or more membership functions [19]. The fuzzification block will then compare the input data with the conditions of the rules to determine the fitness of each rule into the particular input instance [19]. However, there are several typical shapes of membership functions which is shown in Figure 2.2. The suitable form of membership function need to be selected for certain problem in order to achieve the best performance.

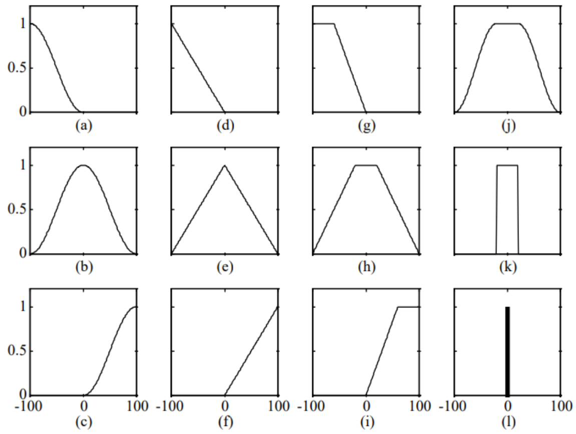


Figure 2.2Examples of membership functions.

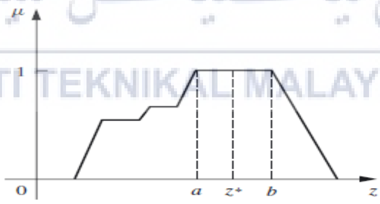
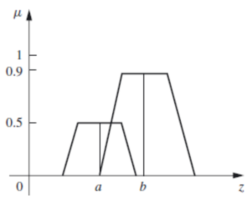
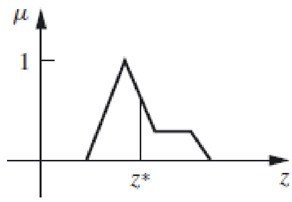
The Figure 2.2 shows (a) s-function, (b) π-function, (c) z-function, (d-f) triangular versions, (g-i) trapezoidal versions, (j) flat π-function, (k) rectangle, (l) singleton.

In rule-based fuzzy systems, the relationships between variables are represented by means of fuzzy if–then rules of the following general form.

- If ⟨ input variable is A ⟩ then ⟨ output variable is B ⟩

Defuzzification is the last step of fuzzy control. Defuzzification is the process of converting a fuzzified output into a single crisp value with respect to a fuzzy set [22]. There are 4 different defuzzification methods which is shown in Table 2.2.

Table 2.3 The methods of defuzzification [23]

Defuzzification method	Graphical representation	Algebraic expression
Max membership principle		$\mu_C(z^*) \geq \mu_C(z)$
Mean max membership		$z^* = \frac{a+b}{2}$
Weighted average method		$z^* = \frac{\sum \mu_{C'}(z) * z}{\sum \mu_{C'}(z)}$
Centre of gravity (COG) or centroid method		$z^* = \frac{\int \mu_{C'}(z) * z dz}{\int \mu_{C'}(z) dz}$

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Finally, there are two types of important fuzzy inference method which are Mamdani and Sugeno fuzzy inference methods. Mamdani fuzzy inference was first introduced by Mamdani and Assilian (1975). This method is the most common inference method that has been used for FLC. Another inference method is Sugeno or Takagi-Sugeno-Kang fuzzy inference method which is introduced by Sugeno at 1985. Both of the methods work well with control issues for nonlinear system. However, the main difference between the both methods lies in the consequent of fuzzy rules.

For Mamdani fuzzy models, the rule base is constructed as the fuzzy rules that are written above. The fuzzy rules of Sugeno models is presented as follows [24]:

- If Input 1 is *x* and Input 2 is *y*, then Output is $z = ax + by + c$ (2.1)

f(x,y) is a crisp function and it is very often a polynomial function. If Sugeno fuzzy rules is developed in first-order and it will presented as:

R1: If $e_0(t)$ is ‘NB’ and $e1(t)$is ‘NB’ Then t is $z_1 = a_1 e(t) + b_1 e1(t)$ (2.2)

R2: If $e(t)$ is ‘NB’and $e1(t)$is ‘NS’ Then t is $z_2 = a_2 e(t) + b_2 e1(t)$ (2.3)

Besides, the method of defuzzification of both inference method are different. Mamdani uses centre of gravity (COG) method for defuzzification and Takagi-Sugeno implements a weighted average approach to derive the crisp output. The complete process of the two inference method is shown in Figure 2.3.

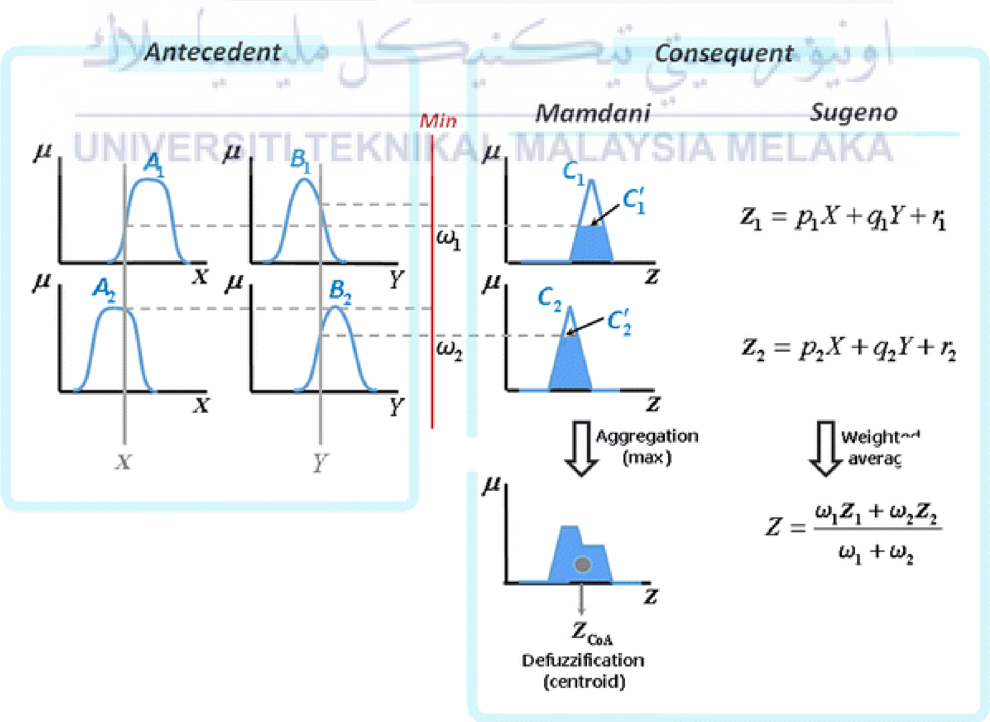


Figure 2.3 The example of whole process of Mamdani and Sugeno inference method [25]

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

There are few researches are about the comparison of Sugeno and Mamdani inference method for certain applications. With the equal conditions and parameters, all of the researches show that Sugeno inference method has slightly better performance than Mamdani inference method. From the paper of Topaloglu, F et al [26], the result shows that Sugeno FIS model has higher value of suitability factor and it allows the system to operate full capacity. Besides, Hamam, A et al [27] concluded that Sugeno FIS demonstrates higher accuracy and more dynamical values. Last but not least, in the paper of Alexandra, E [28] found that Sugeno- type FIS tend to allow the evaluation of risk to work at its full capacity with smooth.

2.2.3 Comparison of Different Types of Controller

PD-, PI-, and PID- type fuzzy logic controller (FLC) are the technique that always used in terms of transient process. PI-FLC is the most common and practical technique that has been used then followed by the PD-FLC. This is because the PI- type controller has the advantage of the inherent stability of proportional controllers and the offset elimination ability of integral controller but it has large overshoot and excessive oscillation for higher order systems, systems with integrating elements or large dead time, and also for nonlinear systems. In spite of that, PD-FLC able to solve the problem of large overshoot and excessive oscillation. However, PD- FLC is faced with the problem of measurement noise and sudden load disturbances [3].PID- FLC has the best performance among them but it is not suitable for the generation of an efficient rule base and tuning of its large number of parameters [17]

A lot of researchers are attracted by the capability of these intelligent controller to improve the performance of the system and the researches are presented below.

In a paper from Asim. A.K et al (2006) have proposed a fuzzy PID controller that is tuned by Zeigler Nichols Method. This controller is compared with the conventional PID controller, Linear PID controller and nonlinear fuzzy PID controller without tuning. The results show that the fuzzy PID controller that is tuned by using Zeigler Nichols Method has better performance in term of overshoot, settling time, rise time and integral absolute error than the others [6].

Other than that, a robust self-tuning scheme for PI- and PD- type Fuzzy Logic Controllers (FLC) is proposed by Rajani K. Mudi et al. The fuzzy rule-base for tuning the output scaling factor (SF) is defined on the error and change of error of the controlled variable using the membership functions. This proposed self- tuning technique is then apply to the both PI- and PD-FLC for the analysis. The results show that the performance of self-tuning PI- and PD-FLC is improved over the Ziegler-Nichols tuned conventional PI- and PD controller. The improvement include smaller peak overshoot, settling time, smaller integral absolute error (IAE) and smaller integral-of-time-multiplied absolute error (ITAE) [17].

Oguzhan K. et al [18] are proposed a PD-Fuzzy Controller tuned with particle swarm algorithm (PSO) for robot trajectory Control. In this paper, the PD-Fuzzy Controller is tuned by using genetic algorithm which is PSO. A 2 DOF planar robot is used. The result shows that PSO algorithm able to control the robot trajectory with minimum error which is occurred in between 0.1331 and -1.8455e-4. Besides, PSO algorithm is a more convenient and easier method for tuning due to there is need not required derivative knowledge or complex mathematical equation.

There are another self- tuning method of PID- type fuzzy logic controller (PID-FLC) coefficients which is proposed by M. Guzelkaya et al [19]. The method that has been used for this paper is relative rate observer. It uses to adjust the scaling factors that correspond to the derivative and integral coefficients of the PID-FLC using a fuzzy inference mechanism in an online manner [19]. The result is compared with conventional PID-FLC (CM) and the two other PID-FLCs with tuning mechanisms which are the peak observer method (POM) and the function tuner method (FTM). It shows that the new method is more efficient compared to other related method due to lesser number of parameters is to be tuned and more robust to the system parameter or structural changes.

In a conclusion, the self- tuning method of PID-FLC brought a lot of improvements to the output system. Besides, controller that tuned by using biological-based algorithm able to brings convenience to technicians since it does not required derivative knowledge or complex mathematical equation to tune the PID controller. Therefore, a PID-FLC with a biological-based algorithm is chosen to improve the manipulator system.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2.3 Biological-based Algorithm

Biological-based algorithm is a metaheuristic which reflects the process of natural selection. Biological-based algorithm are usually used to generate high-quality solution in order to optimize a system or search problem by relying on bio-inspired operators. There are a lot of different biological-based algorithm is used for different application. Recently, there are many researchers start to apply invasive weed algorithm that was first introduced by Mehrabian and Lucus in 2006 on different application and compare with other biological-based algorithm due to its outstanding performance.

Table 2.4 The comparison of IWO and different algorithm in term of performance

Type of IWO	Other algorithms that used to compare	Method that used for comparison	Result
IWO [5]	PSO	Test with different boundary such as invisible and restricted boundary condition Apply different standard deviation to evaluate performance Compare the average number of fitness evaluations required per successful run	IWO has better performance and more stable on different boundary and standard deviation, faster reach the optimization goal and better convergence as well as final error level
HIWO [29]	RY, KM, SAFF, SMES and ICMOA	All equality constraint $h_q(x) = 0$ has been replaced by $\lvert h_q(x)\rvert - \delta \leq$, using the degree of violation $\delta = 1e - 4$. Run the 12 test functions with different setting of f_n and inf_n.	IWO has better performance in term of standard deviation, higher robustness, efficiency and searching quality.
CCIWO [30]	nFOA, HEDA and KMEA	Hypothesis test with 10000,20000 and 50000 function evaluations Elapsed CPU time with 10000, 20000 and 50000 function evaluations	CCIWO shows better result in all of the test. CCIWO overall converge much faster to reach lower levels of convergence rate trend lines.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

From the comparison above, the result shows that IWO able to improve the performance and increase the stability of the system in overall compared to other types of biological-based algorithm. This might be suitable to control the flexible robot arm. Therefore, IWO is chosen as the biological-based optimization to optimize the fuzzy logic controller for the flexible robot arm.

2.4 Summary

In this chapter, a lot of researches had been done for improving the performance of controller. However, the performance of the controller able to be improved by continuously implementing new technology such as artificial intelligent. Fuzzy logic controller allows the system to make definite decisions based on imprecise or ambiguous data which able to replace conventional PID controller. Besides, the research shows that the performance of fuzzy logic controller (FLC) can be improved by adding PI or PD. In addition, the biological-based algorithm which is invasive weed optimization (IWO) algorithm showing a outperform result compared to the other biological-based algorithm. This method is applied in tuning the FLC. Therefore, this project will be mainly discussed about PID-FLC with invasive weed optimization (IWO) and examine its performance by comparing with other types of FLC and performance of FLC without IWO.

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 3

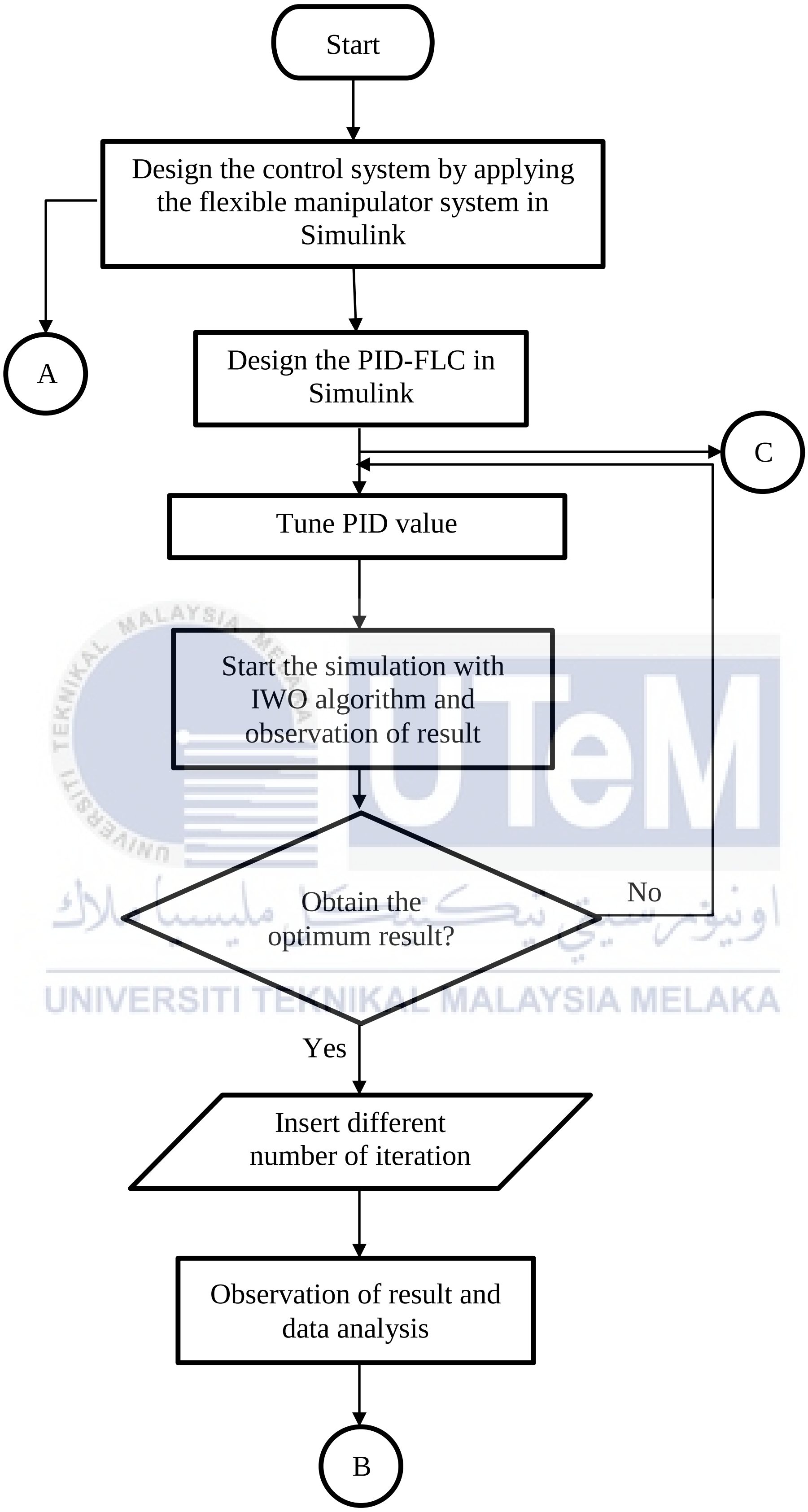
METHODOLOGY

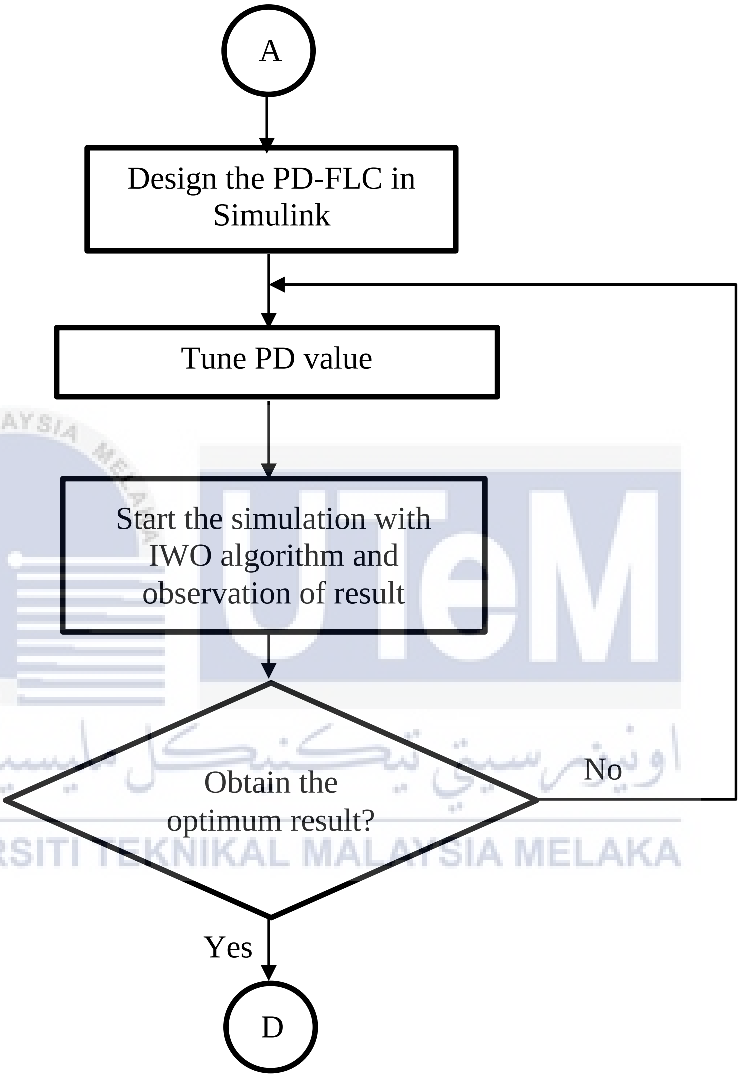
3.1 Introduction

In the first two chapters, the background and global issues of robotic arm as well as its controller had been discussed. Other that than, different researches are considered to overcome the problem that faced by the recent controller. As a result, this project is focused on optimizing the controller for robotic arm by designing PID fuzzy logic controller (PID-FLC) with IWO algorithm.

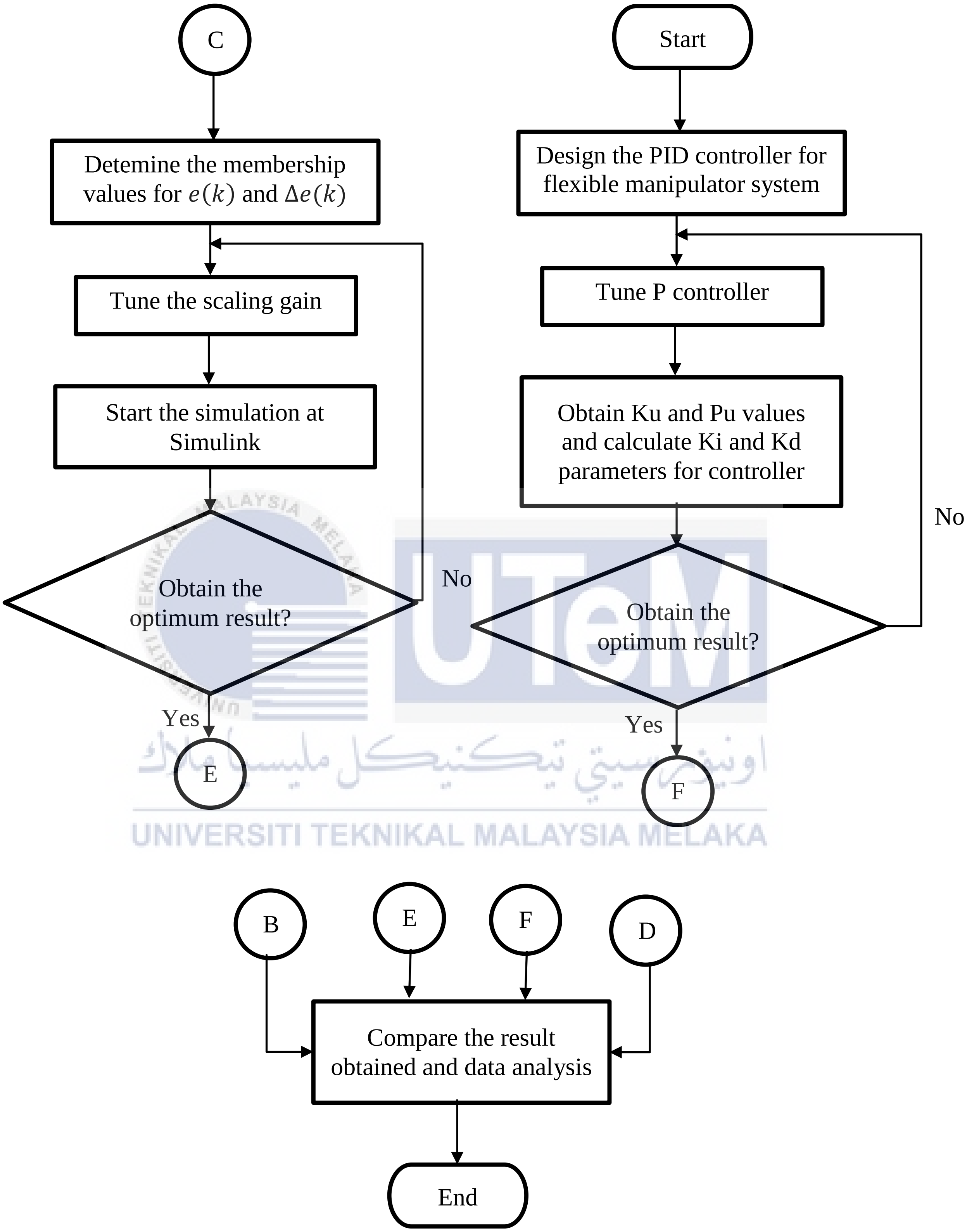
In this chapter, the method of design the PID-FLC with IWO algorithm and comparison with other types of FLC with IWO algorithm will be discussed. First and foremost, the control system will be designed in the Simulink. Then, the initial condition of fuzzy logic will be set in the IWO algorithm. Finally, the initial conditions of IWO and the gains of PID are also set before run the simulation. The steps of designing control system and obtaining result is shown in Figure 3.1.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA


Start
Design the control system by applying the flexible manipulator system in Simulink
A
Design the PID-FLC in Simulink
C
Tune PID value
Start the simulation with IWO algorithm and observation of result
Obtain the optimum result?
No
Yes
Insert different number of iteration
Observation of result and data analysis
B



UNIVERSITI TEKNIKAL MALAYSIA MELAKA



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 3.1The flowchart of controller design

3.2 Simulation Tool

The simulation tool that has been used throughout this project is MATLAB. By using the Simulink block library in MATLAB software, the control system can be designed and modelled in block diagram according to the scheme of control system in Figure 3.1. MATLAB also able to run the simulation by inserting the inputs and coding. Finally, the result will be shown in graphical form.

3.3 Design of Control System

The control system is designed based on the scheme of control system which is shown in Figure 3.2. From the scheme of control system, IWO is used to evaluate the performance of the fuzzy logic controller by randomly inserting different values of input into it. Then. IWO will keeps the value of input with better performance.

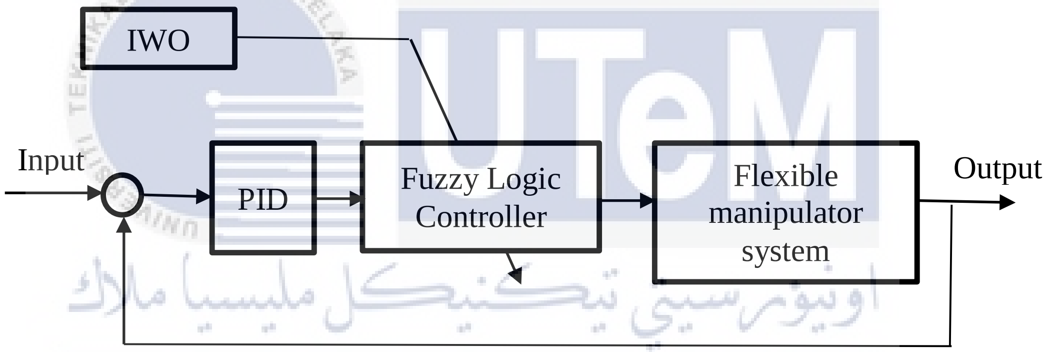


Figure 3.2Scheme of control system

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Besides, the flexible manipulator system which is the plant of the control system plays an important role to get the result due to it provides movement of the output link. It also fixed manipulated object with the specified orientation and along a predetermined path. Thus, a simple manipulator with lower links is used to get the optimization result of the controller which is designed by Azad (1994) and Poerwanto (1998). The design of single-link flexible manipulator system is considered as below.

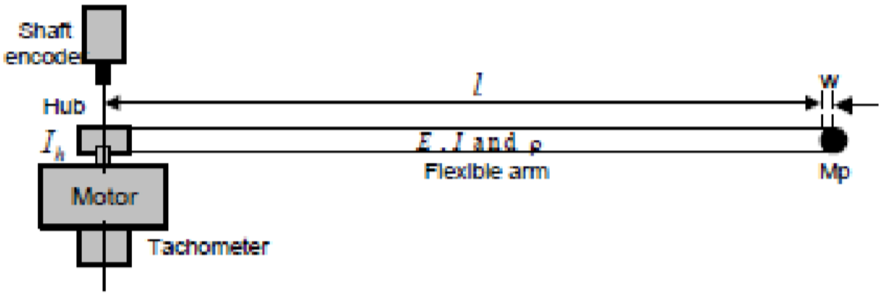


Figure 3.3 Schematic diagram of flexible manipulator system

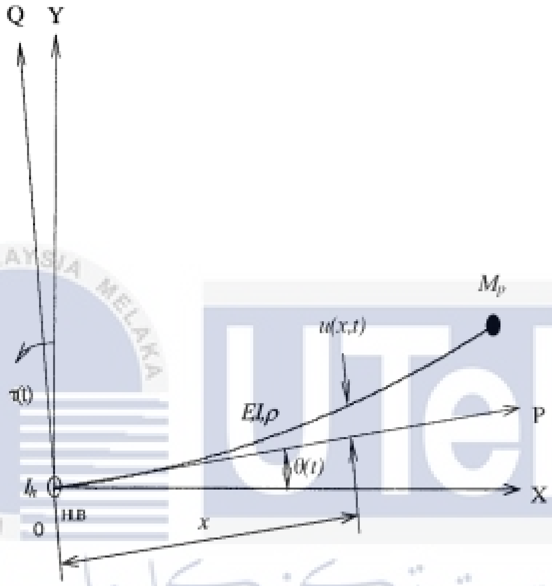


Figure 3.4 Free body diagram of flexible manipulator system [31]

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

From the Figure 3.3, motor is the main part of the flexible manipulator system which is used to rotate the flexible arm. Tachometer and shaft encoder are the measuring device of the system. The shaft encoder is used to determine the hub-angular position. Then, the tachometer is used to detect the hub- angular velocity. At the end effector of the flexible arm, there is a payload with mass, Mp in order to simulate an object is held during the operation. The flexible manipulator system also can be represented in free body diagram which is shown in Figure 3.4. I_h that is shown in the free body diagram represents the hub inertia of the flexible manipulator. The payload mass, Mp that attached to the endpoint is moved in the POQ plane with an angular displacement, $\theta(\mathrm{t})$. Furthermore, the actuator motor is applied a control torque, τ(t) at the hub. According to the free body diagram, the net displacement, $y(x, t)$ of an endpoint at a distance x can be formulated as the sum of rigid body motion $\theta(\mathrm{t})$ and elastic deflection, $u(x, t)$.

$$y(x,t) = x\theta(t) + u(x,t) \tag{3.1}$$

Although this report will only focused on the angular displacement, but the consideration on different condition for manipulator system able to increase the accuracy on obtaining the result of the control system. The model of flexible manipulator system is designed in the Simulink which is shown in Figure 3.5 (Assemgul, 2014) based on the free body diagram of flexible manipulator system in Figure 3.4. The parameter of the flexible manipulator is set as in Table 3.1. Therefore, the model of flexible manipulator system able to simulates the real-time motion of the flexible robot arm. Throughout the simulation, the accuracy of hub-angular position is examined.

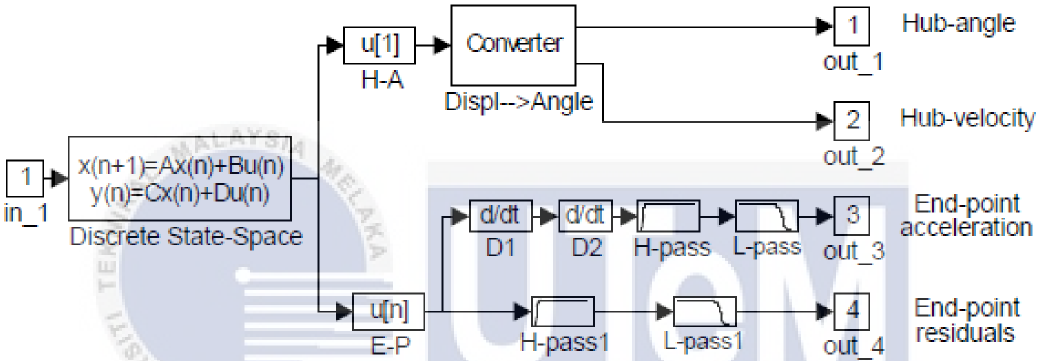


Figure 3.5 Simulink designed block diagram of single-link flexible system

Table 3.1 Parameter of flexible manipulator

Parameter	Symbol	Value
Length	l	960 mm
Width	w	19.008 mm
Thickness	h	3.2004 mm
Mass Density per unit volume	ρ	$2710\ K_g m^{-3}$
The second moment of inertia	I	$5.1924 * 10^{-11} m^4$
The young modulus	E	$71 * 10^9\ Nm^{-2}$
Moment of inertia	I_b	$0.04862\ K_g m^2$
The hub inertia	I_h	$5.86 * 10^{-4} K_g m^2$

The reference signal for the input of control system is set in Figure 3.6. The positive and negative pulses that included in the signal simulates the real moving character of the flexible robot arm. The flexible robot arm is moved from 0 degree to 80 degree and turned into another side to -50 degree from the rest point.

3.4 Design of Fuzzy Logic Controller

Fuzzy logic is chosen as the controller for the flexible manipulator system due to it able to control complex continuously varying systems and cover a wider range of operating condition. For fuzzy inference system, zero-order Takagi-Sugeno type of inference system is used to increase accuracy and dynamical values.

For membership functions, 2 inputs which are error, $e(k)$ and change-in-error, $\Delta e(k)$ are represented in the form of linguistic variables. Each input has five linguistic variables. Those five linguistic variables are negative big (NB), negative small (NS), zero (ZO), positive small (PS) and positive big (PB). The terms such as NB, NS, PS, PB and ZO are characterized via triangular-shaped membership functions which is shown in Figure 3.5. Figure 3.5 also shows that 10 parameters of membership values will be estimated for each input. Each input will be inserted with any value in a range. Since the value of each parameter will be decided by using the genetic algorithm (IWO), thus, the parameter for error, $e(k)$ and change-in-error, $\Delta e(k)$ is represented in a_i and b_i.

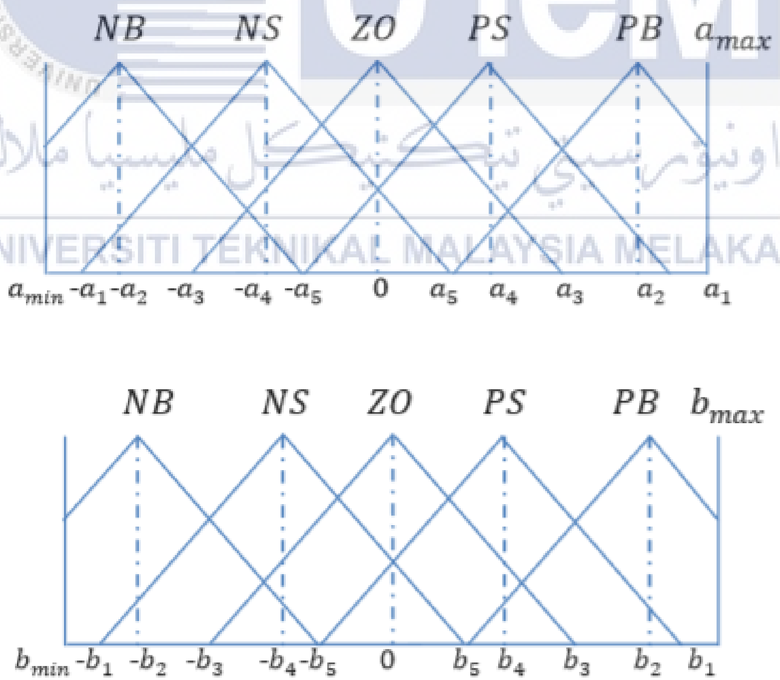


Figure 3.6The membership function of error, $e(k)$ and change-in-error, $\Delta e(k)$

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The output Sugeno FIS is in zero order. Thus, it has constant value for the each term of output of Sugeno FIS

Table 3.2 The output of zero order Sugeno FIS

Torque	Constant value
NB	x_1
NS	x_2
ZO	x_3
PS	x_4
PB	x_5

For rule-base, it is act as a knowledge-based for FLC to order to obtain the desired output. The rule-base is presented in a table form which is shown in Table 3.3. However, it is same as the rule-base that presented in If-Then form. There are total of 25 control rules for the FLC.

Table 3.3 rule-base for flexible manipulator system

		Change-in-error				
		NB	NS	ZO	PS	PB
Error	NB	PB	PB	PB	PS	ZO
	NS	PB	PS	PS	ZO	NS
	ZO	PS	ZO	ZO	ZO	NS
	PS	PS	ZO	NS	NS	NB
	PB	ZO	NS	NB	NB	NB

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

3.5 PID Tuning Method

Although FLC has advantage over PID controller, but PID able increase the stability and overall performance of the flexible manipulator system. In this system, the three gains which are Kp, Ki and Kd will act as scaling gains of the manipulator system to execute the rule-base efficiently. The PID parameter values for FLC will be tuned by trial and error. Besides, the traditional PID controller which is Ziegler-Nichols method will be used and designed to compare the performance of PID-FLC with IWO. Thus, the PID parameters will be tuned by using Ziegler- Nichols Method. It is a heuristic tuning method based on sustained oscillations.

3.6 Invasive Weed Optimization (IWO) Algorithm

IWO algorithm is designed to tune the membership functions of the fuzzy control. IWO algorithm will find the most suitable value for input terms of fuzzy control. Few steps is considered to simulate the colonizing behaviour of weeds. The design steps of the basic IWO algorithm is concluded as below:

Table 3.4 The design steps of the basic IWO algorithm [31]

• Initialization
Repeat • Reproduction • Spatial dispersal • Competitive exclusion
• Meet the termination criterion

Step 1 is to initialize a population. Size of the initial population need to be determined to form a population of initial weeds. Then, a population of initial solutions is being dispread over the D-dimensional search space randomly.

Step 2 is reproduction. Each of the weeds will generates seeds in the reproduction process. As the phenomenon that happened by the colonization of weeds, the higher weed's fitness will produces more seeds. The formula of weeds that producing seeds is [32]:

$$weed = \frac{f - f_{\min}}{f_{max} - f_{min}}(s_{max} - s_{min}) + s_{\min} \tag{3.2}$$

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

where:

- f : The current weed's fitness

- f_{min} and f_{max} : The minimum and maximum fitness of current population

- s_{max} and s_{min} : The maximum and minimum number of seeds that current population can produce

Step 3 is about spatial dispersal. The generated seeds are spreading around their parent weeds in a normal distribution. However, the standard derivation, σ of the normal distribution should be reduced from a specified initial value, σ_0 to a final value, σ_f to ensure the that the probability of dropping a seed in a distant area decreases nonlinearly at each iteration. As a result, filter plant will be grouped and inappropriate plants will be eliminated. The formula is summarized as follow:

$$\sigma_{iter} = \frac{(iter_{max} - iter)^a}{(iter_{max})^a} * \left(\sigma_0 - \sigma_f\right) + \sigma_f \tag{3.3}$$

where:

- σ_{iter} : standard deviation at current iteration

- $iter_{max}$: maximum number of iterations

- σ_0 and σ_f : initial and final standard deviations

- a : Nonlinear modulation index. Generally, a =3

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Step 4 is competitive exclusion. After some iteration is passed, the number of weeds in a colony will reach its maximum (P_MAX) by fast reproduction [30]. In this time, each weed will start to produce seeds. The produced seeds are spread over the search area. When all the seeds have located in their position over the search area, they will ranked with their parents. If the weed has lower fitness, it will be eliminated to maintain the maximum allowable population. Hence, weeds and seeds are ranked together. Lastly, only the seeds or weeds with better fitness will be survive and allow to replicate. The ones with lower fitness will be eliminated. The reproduction and competitive mechanism give a chance for less fit weeds to reproduce. This process is repeated until the maximum number of iteration or maximum elapsed CPU time is met.

The flowchart of Invasive Weed Optimization (IWO) is shown below:

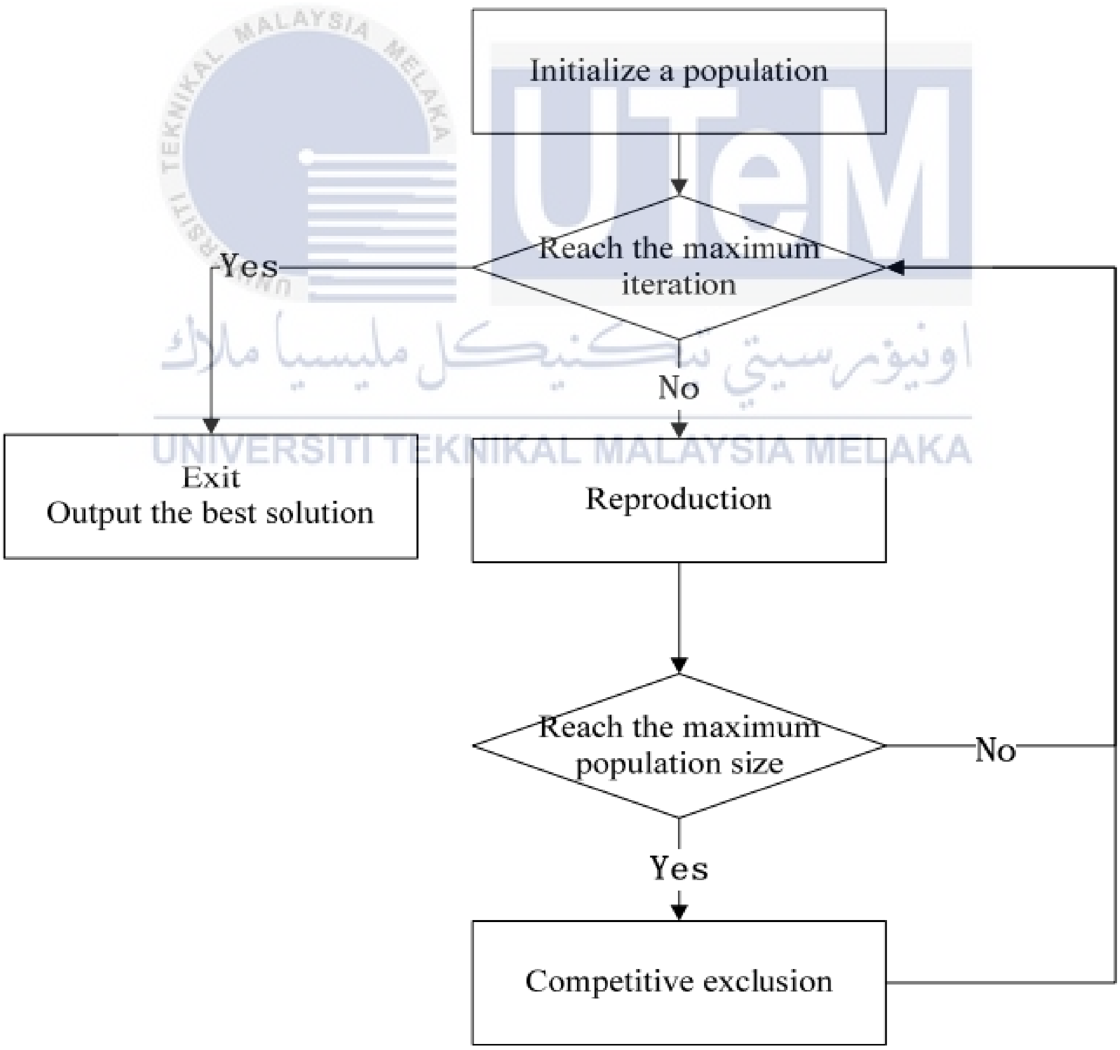


Figure 3.7 Flowchart of IWO [31]

The initial condition for IWO is set as follows:

Table 3.5 Initial Condition of IWO

Parameter of IWO	Value
Number of initial plant	10
Number of variables	10
Maximum number of plant	30
Minimum number of seed	0
Maximum number of seed	5
Iterations	x

In order to determine the best performance of IWO for designed controller, cost function of different iteration that obtained from the feedback value of the manipulator system is compared. Cost function that obtained for this system is the value of ITAE. ITAE which is time-weighted absolute error act as a performance index in designing controller. The lower cost function obtained will provide a more accurate and precise controller for robot arm. Theoretically, the higher the iterations of IWO, the lower the cost function will be obtained. However, high iterations of IWO consume a lot of time on the simulation and cost function value will become constant at certain number of iterations. Hence, it is necessary to find a suitable number of iterations to obtain the optimal performance of PID-FLC for flexible manipulator system.

3.7 Summary

In a conclusion, the PID-type fuzzy logic controller (PID-FLC) will be developed and designed by using MATLAB and Simulink software. The result is obtained by running the simulation in the Simulink. Sugeno-type fuzzy logic is used as the controller of the system to control the hub-angular displacement and its speed. In addition, PID which act as scaling of gains is tuned and connected to FLC to optimize the performance of FLC. Besides, the development of IWO algorithm will help to tune the parameters of fuzzy membership function intelligently for PID-FLC with IWO and PD-FLC with IWO. For PID-FLC without IWO, the value of membership function for FLC will be set initially. Next, the performance of FLC will be improved by tuning the scaling gain. The scaling gain is tuned by using trial and error method. Lastly, the different type of controllers will be designed and the performance of each controller will be discussed and analysed in the next chapter.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

Before run the simulation, different types of fuzzy logic controller such as PD-FLC and PID-FLC for flexible arm system have designed by using Simulink. After that, the simulation will be started by running the Invasive Weed Optimization Algorithm. IWO will evaluate the performance of the fuzzy logic controller by randomly inserting different values of membership function. Then. IWO keeps the value of membership function with better performance and eliminate those with lower performance. In order to get the best performance, new values of membership function will be determined and replicated from the values with better performance. This process is repeated until the maximum number of iteration is met.

The performance of different iterations for PID-FLC with IWO is then evaluated and analysed to obtain the best and most suitable iterations for PID-FLC. Finally, the performance of PID-FLC with IWO is compared with PD-FLC with IWO and PID-FLC without IWO in term of cost function, rise time, overshoot and undershoot, settling time and steady-state error.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

4.2 Simulation Results of PID-type Fuzzy Logic Controller with IWO

Figure 4.1 shows the design of control system of PID-type fuzzy logic controller in the Simulink.

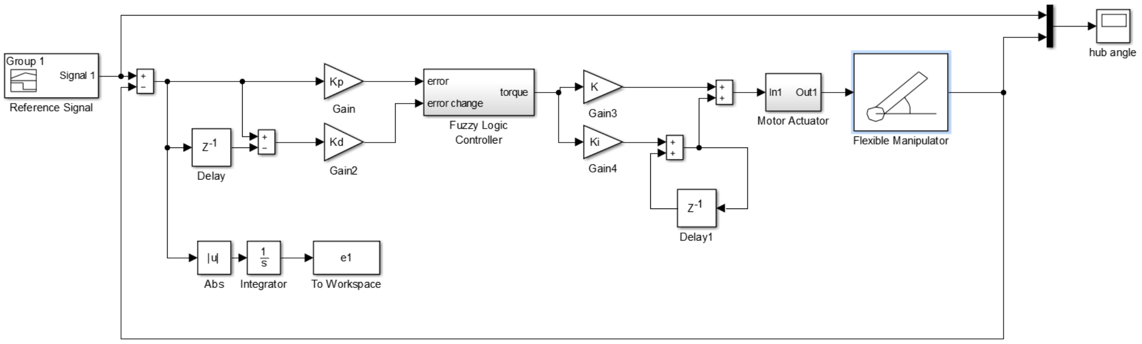


Figure 4.1 The design of control system for PID-FLC

The gains of PID-type fuzzy logic controller are scaled as shown in Table 4.1 to normalize inputs, output and to damp oscillations in the system.

Table 4.1 The scaling gain value of PID-FLC

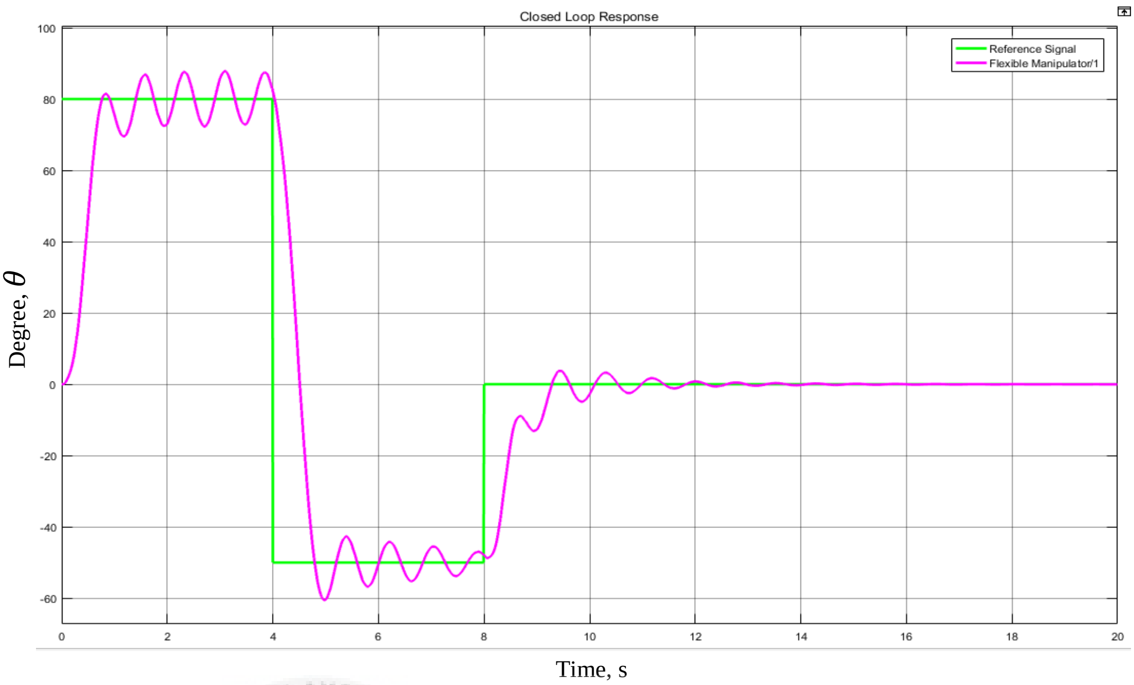
Kp	Kd	Ki	K
0.0068	0.032	0.006	-500

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

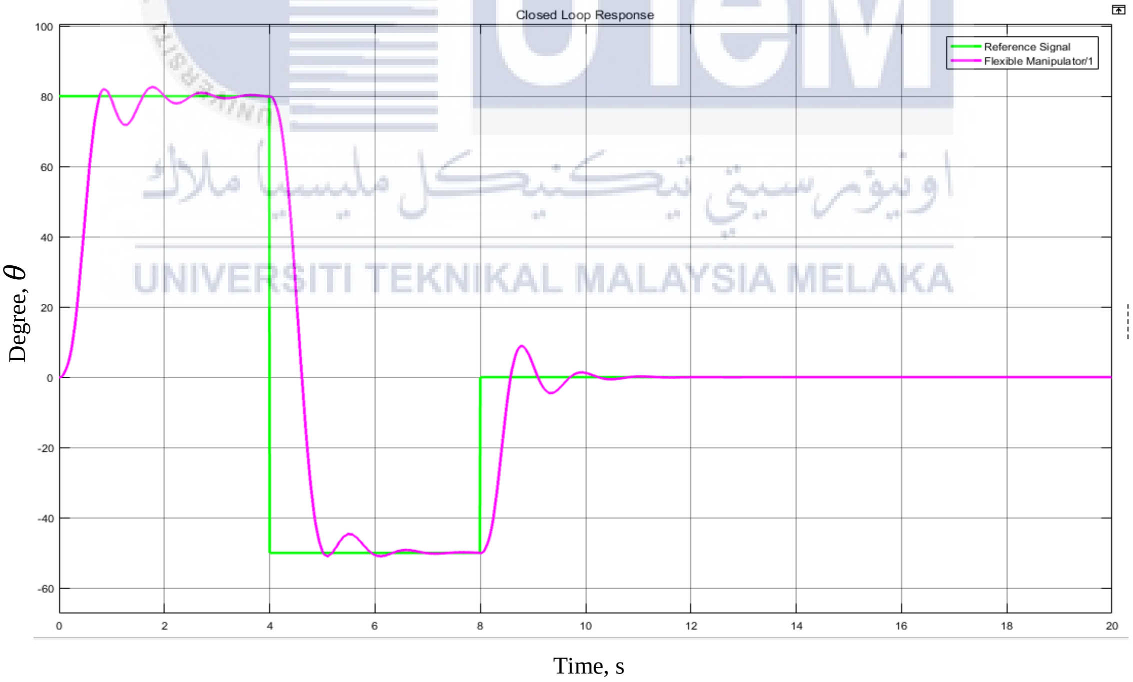
Table 4.2 shows the fitness function of PID-type fuzzy logic controller (PID-FLC) with different iteration as well as time taken for IWO to finish all the iteration in order to get the best performance of PID-FLC.

Table 4.2 Result of PID-type fuzzy logic controller with different iteration

No. of iteration	Time Taken (s/seconds)	Cost Function
10	5227s	5.966e+06
20	11352s	5.510e+06
30	14558s	5.485e+06
100	54163s	5.420e+06

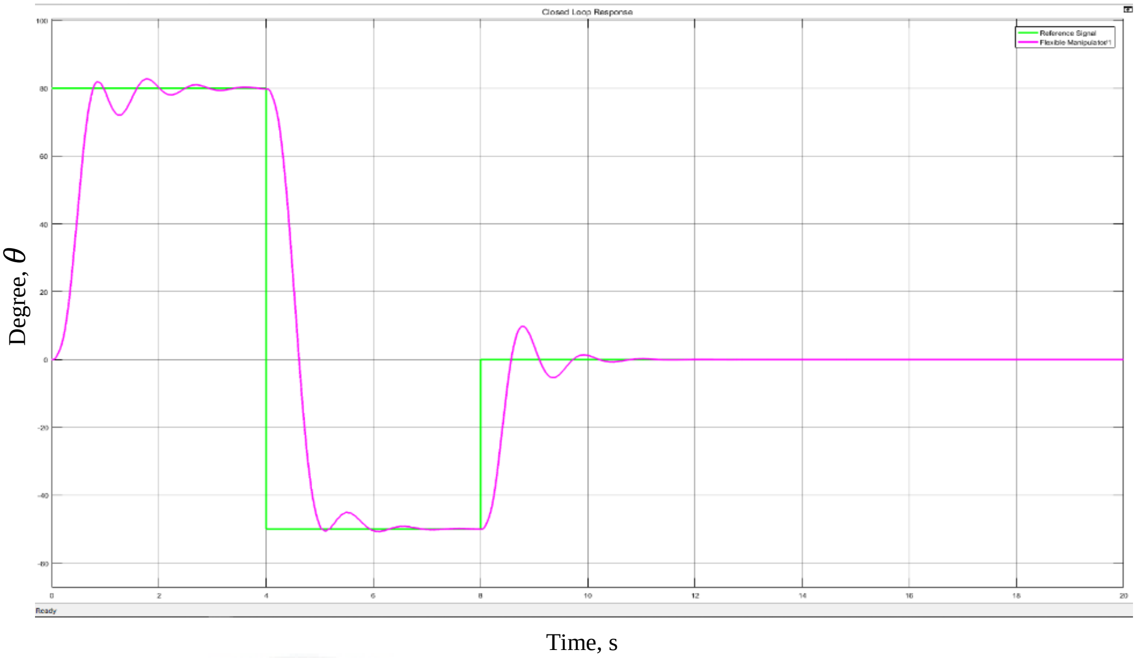


(a)

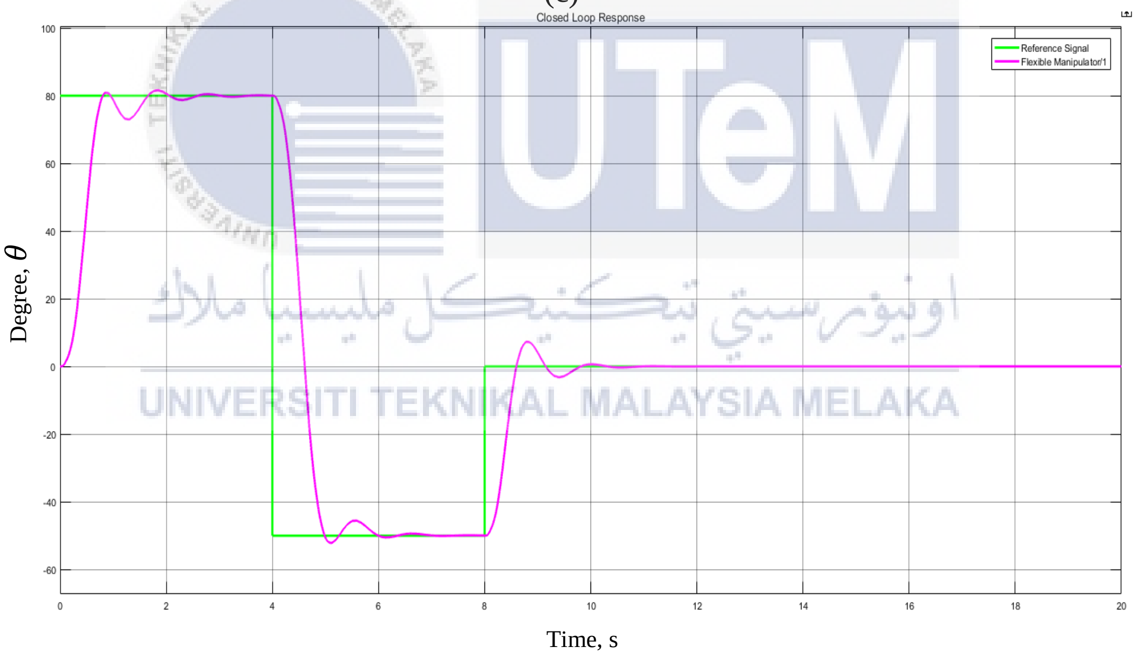


(b)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA



(c)



(d)

Figure 4.2 (a) Hub-angular transient response of PID-FLC (IWO) with 10 iterations, (b) Hub-angular transient response of PID-FLC (IWO) with 20 iterations, (c) Hub-angular transient response of PID-FLC (IWO) with 30 iterations, (d) Hub-angular transient response of PID-FLC (IWO) with 100 iterations

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

From the Figure 4.2, the numerical results of time domain parameters of PID-FLC for each iterations is obtained and plotted as follows:

Table 4.3 Numerical results of time domain parameters of PID-FLC with IWO

Iteration	t_{r1}, s	t_{s1}, s	PO_1	t_{r2}, s	t_{s2}, s	PU_1	t_{r3}, s	t_{s3}, s	PO_3	e_{ss3}
10	**0.764**	**-**	8.094	**0.809**	**-**	10.61	1.290	6.827	**-8.813**	0
20	0.777	**3.420**	2.698	1.024	3.021	1.097	0.582	**2.819**	**9.173**	0
30	0.768	3.492	**2.432**	1.051	**2.977**	**0.811**	**0.575**	2.843	9.728	0
100	0.807	3.461	**1.799**	1.001	3.004	2.158	0.601	2.841	**7.554**	0

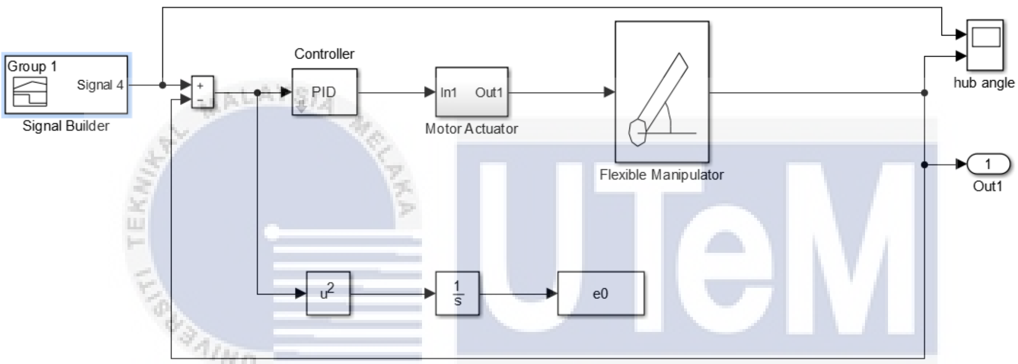
Based on Table 4.2, optimization of FLC is a time consuming process. Besides, the value of cost function is decreasing as the increasing of number of iteration. However, the cost function value reduces with less significant gap after 20 iterations. This is due to IWO has reached the minimal cost function at 20 iterations. Despite of 100 iterations have lower cost function value, it spent more time on simulation but obtained the similar result as 20 iterations and 30 iterations which is shown in Figure 4.2.

By observing the numerical results of time domain parameters of PID-FLC with IWO, there are high similarity of the results obtained by means of IWO with 30 iterations and IWO with 20 iterations. This is because IWO attained the best membership function values of fuzzy logic controller for this nonlinearity system and obtain required time-domain response with the best quality control at 20 iterations. Yet, IWO with 30 iterations shows better in overall numerical result. IWO with 30 iterations achieved faster rise time and smaller overshoot at first signal which is from 0° to 80° than IWO with 20 iterations. IWO with 30 iterations also achieved faster settling time and smaller undershoot at second signal which is from 80° to -50° than IWO with 20 iterations. For IWO with 100 iterations, it reached the similar rise time and settling time for the 3 three different signal as IWO with 30 and 20 iterations. However, it achieved lower and smaller overshoot at the first and third signal compared with IWO with 20 and 30 iterations.

After the comparison, IWO with 30 iterations is the best option to obtain the best performance for flexible manipulator system. Next, the performance of the PID-FLC with IWO will be compared with PD-FLC with IWO.

4.3 Comparison of Performance of PID-FLC (IWO) and Ziegler-Nichols tuned PID Controller

Before the comparison of the performance between PID-FLC with IWO and Zieler-Nichols tuned PID controller. A PID controller for the flexible manipulator system is designed in the Simulink which is shown in Figure 4.3. In order to apply Ziegler-Nichols tuning method, the ultimate gain, Ku and frequency, Pu will be obtained. Ku is the value for P controller while Pu is the frequency of the output that obtained by P controller. The Ku is determined as 1.46 and Pu is obtained as 4.873. The PID gain values then are calculated as shown in Table 4.4.



اونيۈرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 4.3 The design of control system for PID controller in Simulink

Table 4.4 The gain values of PID controller

Controller	K_p	K_i	K_d
PID	$0.6 * 1.46$ $= 0.876$	$\frac{2}{4.873} = 0.4104$	$\frac{4.873}{8} = 0.6091$

The values of Kp, Ki and Kd will be inserted in the Simulink. The output transient response of the Ziegler-Nichols tuned PID controller is shown in Figure 4.4 and the performance will be compared with PID-FLC with IWO which is shown in Figure 4.5. Finally, the numerical result of both controllers are compared in Table 4.5.

Figure 4.4 Transient response of Ziegler-Nichols tuned PID Controller

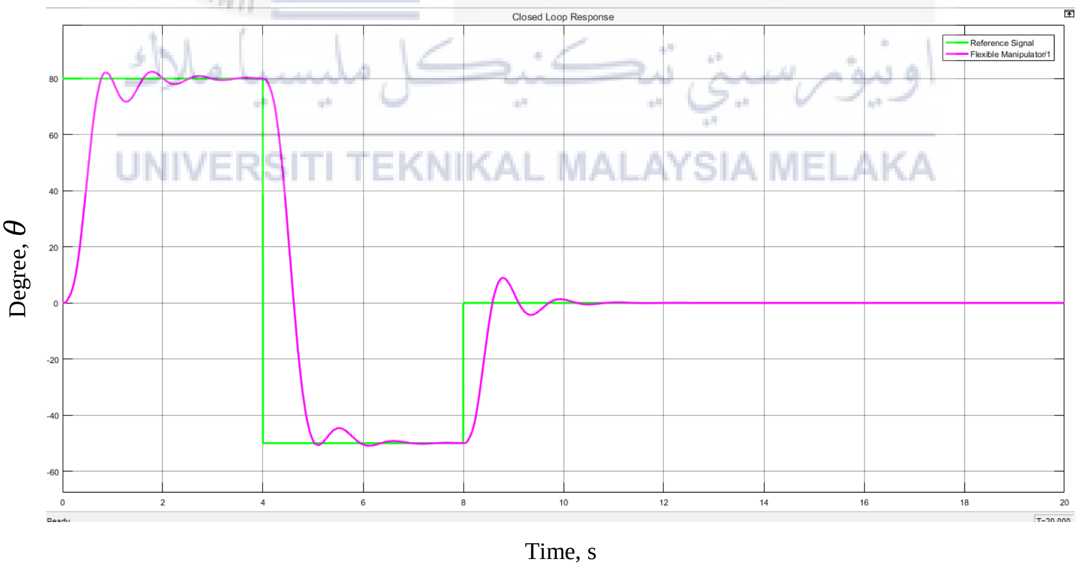


Figure 4.5 Transient response of PID-FLC with IWO

UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Table 4.5 Numerical results of time domain parameters of Ziegler-Nichols tuned PID controller and PID-FLC with IWO

Types	t_{r1}, s	t_{s1}, s	PO_1	t_{r2}, s	t_{s2}, s	PU_1	t_{r3}, s	t_{s3}, s	PO_3	e_{ss3}
PID controller	**0.696**	3.77	35.76	**0.828**	3.174	81.79	0.702	3.413	20.20	**0**
PID-FLC (IWO)	0.768	**3.492**	**2.432**	1.051	**2.977**	**0.811**	**0.575**	**2.843**	**9.728**	**0**

By visually comparing the result of both controllers that shown in Figure 4.4 and Figure 4.5, the Ziegler-Nichols tuned PID controller has the less output oscillations along the reference signals compared to PID-FLC with IWO. However, the Ziegler-Nichols tuned PID controller shows much larger overshoot and undershoot than PID-FLC with IWO.

The numerical result of Ziegler Nichols tuned PID Controller shows that it has better rise at first and second signals compared to PID-FLC with IWO. Other than that, PID-FLC with IWO shows better performance in term of settling time and overshoot and undershoot. This is because Ziegler-Nichols method is not capable for tuning the nonlinearities system. Therefore, the performance of PID controller can be improved by using different methods that able to handle nonlinearities system or adding fuzzy logic into the controller. However, both controllers able to achieved zero steady-state error.

As a result, the PID-FLC with IWO has better overall performance than Ziegler-Nichols tuned PID controller. Next, the performance of PID-FLC with IWO will be compared with PD types of controller with IWO and PID-FLC without IWO

4.4 Comparison of Performance of PD-FLC (IWO), PID-FLC (IWO) and PID-FLC without IWO

Since PD-FLC and PID-FLC have different design of control system, thus the scaling gains is tuned to the relevant value to obtain closer angular movement to the reference signal. The design of control system of PD-FLC with IWO and scaling gain is shown as follows:

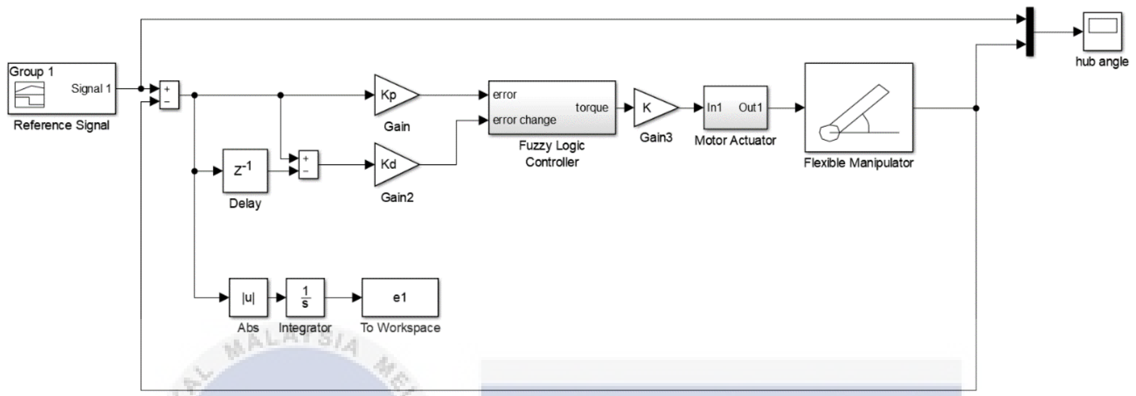


Figure 4.6 The design of control system for PID-FLC

Table 4.6 The scaling gain value of PID-FLC

Kp	Kd	K
0.0065	0.032	-500

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

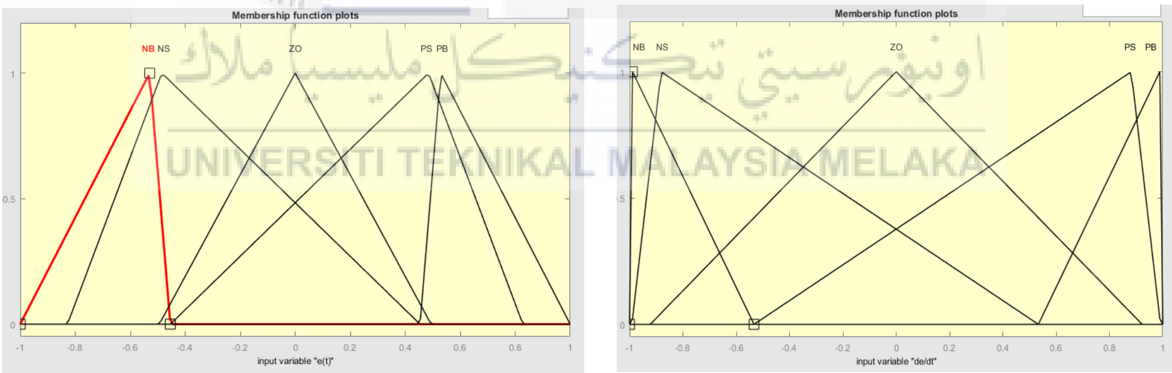
Both PD-FLC and PID-FLC ran the same IWO algorithm with 30 iterations. The performance of both control system is compared in term of cost function, time and numerical results of time domain parameters. The membership function parameters of PD-FLC and PID-FLC, their cost functions and time taken to complete the simulation is shown in Table 4.5. The membership function parameters that obtain by IWO are then presented in Figure 4.4 and Figure 4.5.

Table 4.7 Simulation Result

Types of FLC	Time Taken (s)	Cost Function	$e(t)$ parameters	$\Delta e(t)$ parameters
PD-FLC (IWO)	11480	5.513e+06	$a_1 = 0.8281$ $a_2 = 0.5291$ $a_3 = 0.4942$ $a_4 = 0.4848$ $a_5 = 0.4540$	$b_1 = 0.9914$ $b_2 = 0.9889$ $b_3 = 0.9227$ $b_4 = 0.8819$ $b_5 = 0.5333$
PID-FLC (IWO)	14558	5.485e+06	$a_1 = 0.6038$ $a_2 = 0.5163$ $a_3 = 0.4993$ $a_4 = 0.4946$ $a_5 = 0.4932$	$b_1 = 1$ $b_2 = 0.9549$ $b_3 = 0.8796$ $b_4 = 0.8604$ $b_5 = 0.5511$

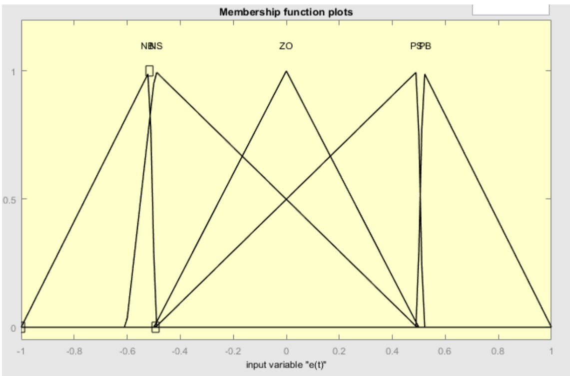
The graph of membership function for PID-FLC with IWO and PD-FLC with IWO is tabulated by using the $e(t)$ parameters and $\Delta e(t)$ parameters that obtained from IWO as shown in Figure 4.4 and Figure 4.5. For the PID-FLC without IWO, the graph of membership function is set initial before run the simulation as shown in Figure 4.6.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

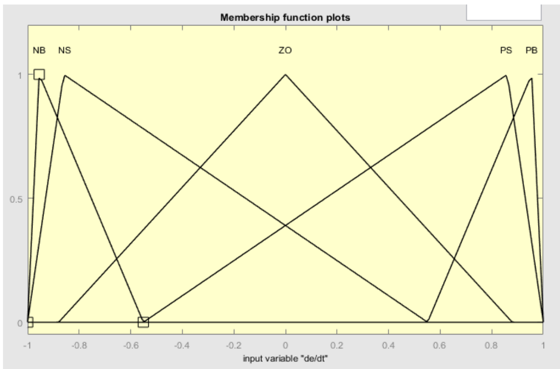


(a) (b)

Figure 4.7 (a) Error membership functions of PD-FLC with IWO(b) Change-in-error membership functions of PD-FLC with IWO

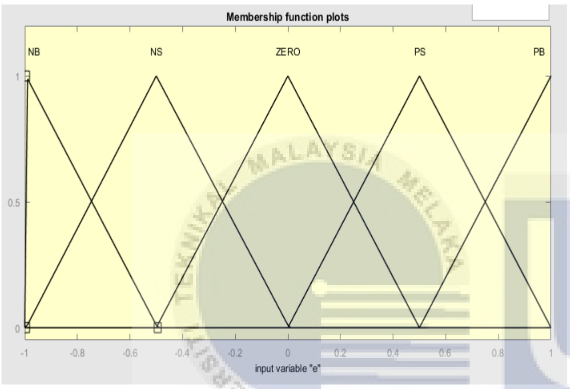


(c)

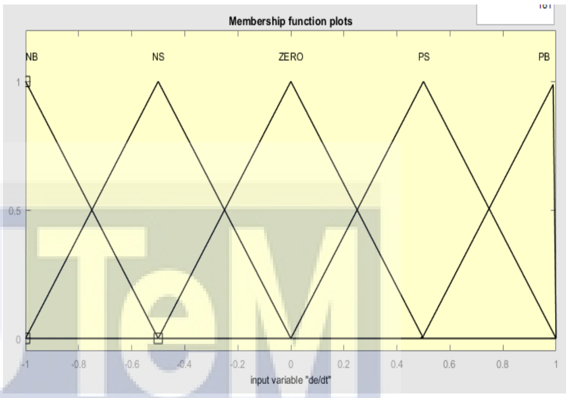


(d)

Figure 4.8 (c) Error membership functions of PID-FLC with IWO (d) Change-in-error membership function of PID-FLC with IWO



(e)



(f)

Figure 4.9 (c) Error membership functions of PID-FLC without IWO (d) Change-in-error membership function of PID-FLC without IWO

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

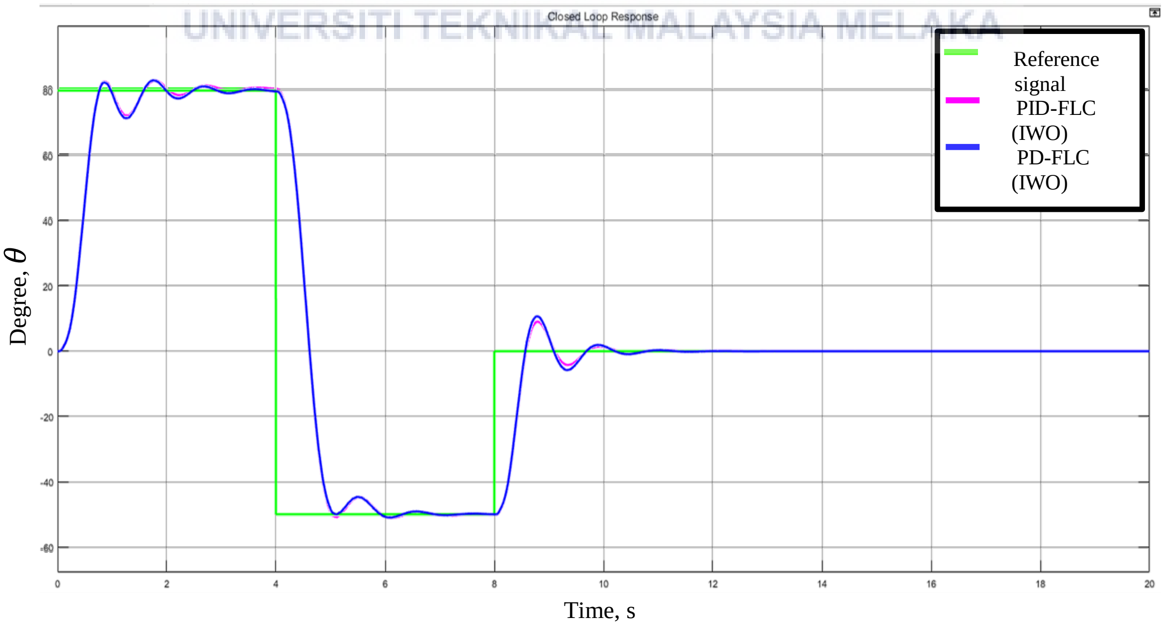


Figure 4.10 Transient response of PID-FLC with IWO and PD-FLC with IWO

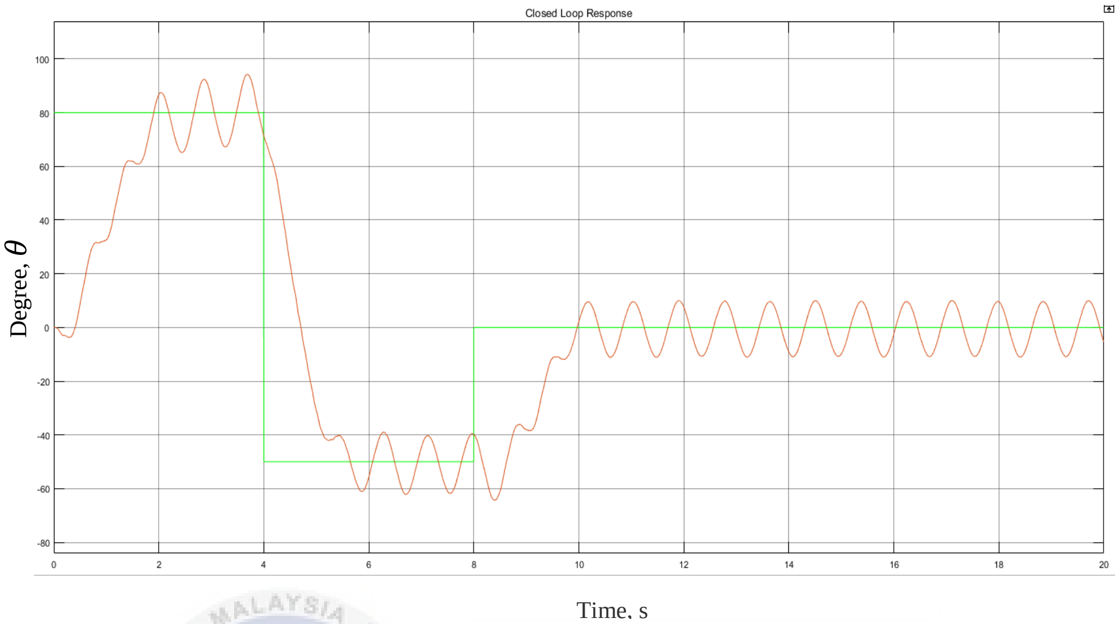


Figure 4.11 Transient response of PID-FLC without IWO

Table 4.8 Numerical results of time domain parameters of PID-FLC with IWO and PD-FLC with IWO

Types	t_{r1}, s	t_{s1}, s	PO_1	t_{r2}, s	t_{s2}, s	PU_1	t_{r3}, s	t_{s3}, s	PO_3	e_{ss3}
PD-FLC (IWO)	**0.768**	**3.417**	2.733	**1.024**	3.036	1.125	**0.575**	**2.836**	9.807	**0**
PID-FLC (IWO)	**0.768**	3.492	**2.432**	1.051	**2.977**	**0.811**	**0.575**	2.843	**9.728**	**0**
PID-FLC without IWO	1.909	-	-83.6	1.665	-	-7.86	1.965	-	-36.11	-

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

From the Figure 4.4 and Figure 4.5, IWO successfully obtained the optimum values of membership function for PID-FLC as well as PD-FLC. Since PID-FLC with IWO and PD-FLC with IWO obtained the different values of membership function, thus, the Figure 4.4 and Figure 4.5 show that fuzzy logic controller actually required different value of membership function for different types of scaling gain used and plant for the control system. It is impossible for human being to get the ideal values of membership function for FLC in a short period. Therefore, the initial value of membership function for PID-FLC without IWO is determined as in Figure 4.6. By using IWO, it able to find the ideal values of membership function for FLC with shorter time and higher accuracy.

By visually observe the Figure 4.7, both PID-FLC with IWO and PD-FLC with IWO have obtained almost the same transient response result. Both types of FLC with IWO are suitable to process and handle the nonlinearity of the system and able to provide the quality control to stabilize the system. This is due to PID controller and PD controller can handle large changes well with minimal overshoot in order to increase the stability of the nonlinear system. However, the hub-angular transient response of PID-FLC without IWO in Figure 4.8 shows high output oscillations across the reference signal over time. It is necessary to modify the value of membership functions in order to reduce the derivative action in output. Hence, the initial membership values for PID-FLC without IWO is not suitable to stabilize the nonlinear manipulator system.

Due to incompatible of membership values for PID-FLC without IWO, it shows poor performance in rise time, settling time, steady state and overshoot and undershoot in Table 4.6. It undergoes undershoot for the three different signal which means the flexible robot arm unable to reach all the required position for the PID-FLC without IWO. However, the result of PID-FLC with IWO and PD-FLC with IWO shows that both FLC able to reach the required position with minimal oscillation and successfully obtained zero steady state error.

However, the numerical results of time domain parameters in Table 4.6 shows that PID-FLC with IWO achieved smaller overshoot and undershoot for three different signal given compared to PD –FLC with IWO. For the first signal, PID-FLC with IWO achieved 11% of lower overshoot compared to PD-FLC with IWO. PID-FLC also improved 27.9% of smaller undershoot at second signal and 0.8% lower overshoot at third signal. This is due to the reason that PID controller is the optimum control dynamics since it has 3 parameters compared to PD controller which only has 2 parameters. Although PD-FLC able to minimize the overshoot but it have poor performance at tracking small changes and error of the

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

feedback system. Besides, PID-FLC with IWO also obtained smaller cost function than PD-FLC with IWO. Other than that, PID-FLC with IWO and PD-FLC with IWO have the overall similar result on rise time and settling time. There are only minor differences on the result of both rise time and settling time.

Last but not least, the nonlinear system achieved zero steady state error at the last part of the signal for the both types of FLC. Therefore, the control problem for the flexible manipulator system is considered solved by using PID-FLC with IWO.

4.5 Summary

The IWO have been successfully optimized both PID-FLC and PD-FLC and obtain a stable and better quality control of nonlinear system. Besides, the scaling gains of the FLC which have the strongly impact to the transient process are selected by trial and error. The result shows that IWO with 30 iterations is suitable and enough to obtain the best values of membership function for FLC and performance for flexible manipulator system. Although Ziegler-Nichols tuned PID controller shows lesser output oscillations along the reference signal, but PID-FLC with IWO has better overall performance in term of settling time and overshoot and undershoot compared to Ziegler-Nichols tuned PID Controller. Besides, both types of FLC with IWO achieved the acceptable result for the nonlinear system in term of time-domain characteristics but PID-FLC without IWO shows poor performance on stabilize the nonlinear manipulator system. Hence, PID-FLC with IWO is the better choice for the flexible manipulator system due to it has better performance in term of overshoot and undershoot than PD-FLC with IWO and better overall performance than PID-FLC without IWO.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In a conclusion, the development of a stable and accurate controller for robot arm is important since robotics arm is widely used in manufacturing, military, medical field and so on. A higher performance controller for a robot arm will ensure the robot arm to have more precise and accurate work that can increase the success rate during production. Therefore, an artificial intelligent which is fuzzy logic is implemented to control the nonlinear and complex system and then scaled by PID or PD gains. In addition, invasive weed optimization (IWO) is used to determine the suitable parameters of membership function for fuzzy logic controller.

By evaluating the result, PID-FLC with IWO achieved a stable transient response after 20 iteration. Finally, IWO with 30 iterations is the most suitable and optimum option for the flexible manipulator system which is the robot arm system due to it has lower cost function and greater overall performance than IWO with 20 iterations. Besides, PID-FLC with IWO shows faster settling time and much lower overshoot and undershoot compared to Ziegler-Nichols tuned PID controller although Ziegler-Nichols tuned PID controller has low output oscillations along the reference signal. Furthermore, PID-FLC with IWO has showed overall performance in term of rise time, settling time, steady state error as well as overshoot and undershoot than PID-FLC without IWO due to incompatible of membership values for PID-FLC without IWO that causing high output oscillations across the reference signal over time. PID-FLC with IWO also shows better performance in term of overshoot and undershoot than PD-FLC with IWO. Although the numerical result only shows slightly different on the overshoot and undershoot, but it will become a big issue when involving massive production or precise work. Hence, PID-FLC with IWO is a better choice for the flexible manipulator system.

As a result, the objectives have achieved. Thus, it can be concluded that PID-FLC with IWO is successfully designed and validated its performance by comparing PID-FLC with IWO with PD-FLC with IWO and PID-FLC without IWO.

5.2 Future Works

The simulation result in the chapter five shows that a lot of computational time is needed for optimization of fuzzy logic controller by using IWO. Therefore, it is necessary to continue on the increasing of number of iterations in order to obtain the minimum cost function of the flexible manipulator system. Other than that, the performance of IWO to optimize the FLC can be compared with other types of biological-based algorithm such as PSO, HEDA, RY, KM and so on. Finally, the optimized control system can be applied into the real model of robot arm and analysed its performance. Hence, there is a need of more researches on the evaluation of the performance of PID-FLC with IWO.

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

REFERENCES

[1] N. Mendes and P. Neto, "Indirect adaptive fuzzy control for industrial robots: A solution for contact applications," *Expert Syst. Appl.*, vol. 42, no. 22, pp. 8929–8935, 2015.

[2] S. Refoufi and K. Benmahammed, "Control of a manipulator robot by neuro-fuzzy subsets form approach control optimized by the genetic algorithms," *ISA Trans.*, vol. 77, pp. 133–145, 2018.

[3] M. J. E. Salami and Y. I. Bulale, "Design and implementation of fuzzy-based PID controller," *Proc. IEEE Int. Conf. Ind. Technol.*, vol. 1, pp. 220–225, 2002.

[4] C. C. Lee, "Fuzzy Logic in Control Systems : Fuzzy," *IEE Trans. Syst. man. Cybern.*, vol. 20, no. 2, pp. 419–435, 1990.

[5] S. Karimkashi and A. A. Kishk, "Invasive weed optimization and its features in electromagnetics," *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1269–1278, 2010.

[6] A. A. Khan and N. Rapal, "Fuzzy PID Controller: Design, Tuning and Comparison with Conventional PID Controller," no. 1, pp. 1–6, 2006.

[7] S. Temel, S. Yagli, and S. Gören, "P , Pd , Pi , Pid Controllers," p. 63, 2012.

[8] "Unimate - The First Industrial Robot." [Online]. Available: https://www.robotics.org/joseph-engelberger/unimate.cfm. [Accessed: 22-May-2019].

[9] "JACO Robotic Arm for People with Upper Extremity Disabilities." [Online]. Available: https://www.abilities.com/community/buzz/64b-jaco.html. [Accessed: 22-May-2019].

[10] M. Hans, B. Graf, and R. D. Schraft, "Robotic Home Assistant Care-0-bot : Past - Present - Future," *Proc. 2002 IEEE Lnt. Work. Robot Hum. lnteractive Commun.*, no. Figure 3, pp. 380–385, 2002.

[11] "Overview | Willow Garage." [Online]. Available: http://www.willowgarage.com/pages/pr2/overview. [Accessed: 22-May-2019].

[12] H. Bengtson, "Advantages of Robotics with Emphasis on Industrial Robotics Technology." [Online]. Available: https://www.brighthubengineering.com/robotics/76606-advantages-of-robotics-in-engineering/. [Accessed: 22-May-2019].

[13] Khasha Ghaffarzadeh, "New Robotics and Drones 2018-2038: Technologies, Forecasts, Players." [Online]. Available: https://www.idtechex.com/en/research-report/new-robotics-and-drones-2018-2038-technologies-forecasts-players/584. [Accessed: 22-May-2019].

[14] A. Doroshenko, "Problems of modelling Proportional–Integral–Derivative controller in automated control systems," *MATEC Web Conf.*, vol. 112, p. 05013, 2017.

[15] C. Cornelis *et al.*, *Studies in Fuzziness and Soft Computing , Volume 261*. 2010.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

[16] B. P. Gowd1, K. Jayasree2, and M. N. Hegde3, "Comparison of Artificial Neural Networks and Fuzzy Logic Approaches for Crack Detection in a Beam Like Structure," *Int. J. Artif. Intell. Appl.*, vol. 9, no. FEBRUARY, pp. 43–51, 2001.

[17] R. K. Mudi and N. R. Pal, "A robust self-tuning scheme for PI- and PD-type fuzzy controllers," *IEEE Trans. Fuzzy Syst.*, vol. 7, no. 1, pp. 2–16, 1999.

[18] O. Karahan and Z. Bingül, "PD-fuzzy controller tuned with PSO for robot trajectory control," *IFAC Proc. Vol.*, vol. 2, no. PART 1, 2009.

[19] J. Jantzen, "Design of Fuzzy Controllers," *Zhonghua Kou Qiang Ke Za Zhi*, vol. 21, no. 5, pp. 264-266,317, 1986.

[20] M. Shahrokhi and A. Zomorrodi, "Comparison of Tuning Methods of Pid Controller," *Dep. Chem. Pet. Eng. Sharif Univ. Technol.*, pp. 1–2, 2013.

[21] M. F. B. M. NORIS, "COMPARISON BETWEEN ZIEGLER-NICHOLS AND COHEN-COON METHOD FOR CONTROLLER TUNINGS MOHD FADZLI BIN MOHD NORIS A thesis submitted in fulfillment of the requirements for the award of the degree of Bachelor of Chemical Engineering Faculty of Chemical & Natural," no. November, 2006.

[22] Timothy J. Ross, *Fuzzy Logic With Engineering*. 2010.

[23] Debasis Samantha. Defuzzification Method [Online]. Available in: http://www.nid.iitkgp.ernet.in/dsamanta/courses/archive/sca/Archives/Chapter%205%20Defuzzification%20Methods.pdf

[24] B. Y. Bejarbaneh, E. Y. Bejarbaneh, M. F. M. Amin, A. Fahimifar, D. Jahed Armaghani, and M. Z. A. Majid, "Intelligent modelling of sandstone deformation behaviour using fuzzy logic and neural network systems," *Bull. Eng. Geol. Environ.*, vol. 77, no. 1, pp. 345–361, 2018.

[25] T. Sugeno, Michio. *Industrial applications of fuzzy control*, Elsevier Science Inc., 1985.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

[26] F. Topaloğlu and H. Pehlivan, "Comparison of Mamdani type and Sugeno type fuzzy inference systems in wind power plant installations," *6th Int. Symp. Digit. Forensic Secur. ISDFS 2018 - Proceeding*, vol. 2018-Janua, pp. 1–4, 2018.

[27] A. Hamam and N. D. Georganas, "A comparison of mamdani and sugeno fuzzy inference systems for evaluating the quality of experience of hapto-audio-visual applications," *HAVE 2008 - IEEE Int. Work. Haptic Audio Vis. Environ. Games Proc.*, no. October, pp. 87–92, 2008.

[28] A. A. Shleeg and I. M. Ellabib, "Comparison of Mamdani and Sugeno Fuzzy Interference Systems for the Breast Cancer Risk," *Int. J. Comput. Information, Syst. Control Eng.*, vol. 7, no. 10, pp. 695–699, 2013.

[29] H. Chen, Y. Zhou, P. Guo, X. Ouyang, S. He, and H. Zheng, "A Hybrid Invasive Weed Optimization with Feasibility-Based Rule for Constrained Optimization Problem," no. 4, pp. 160–167, 2013.

[30] H. Y. Sang, P. Y. Duan, and J. Q. Li, "An effective invasive weed optimization algorithm for scheduling semiconductor final testing problem," *Swarm Evol. Comput.*, vol. 38, pp. 42–53, 2018.

[31] M. H. Shaheed, M. O. Tokhi, A. J. Chipperfield, and A. K. M. Azad, "Modelling and Open-Loop Control of a Single-Link Flexible Manipulator with Genetic Algorithms," *J. Low Freq. Noise, Vib. Act. Control*, vol. 20, no. 1, pp. 39–55, 2002.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPENDICES

UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPENDIX A GANTT CHART

Activities	2018															
	September				October				Novemebr				December			
	Week															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14		
Title selection and scheduling project									Mid-Sem Break						Study Week	Final Examination
Objectives and problems identification																
Make researches and collect secondary data																
Design PID Controller																
Design PID -FLC without IWO																
Preparation of draft report and presentation to panel																

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Activities	2019														
	February		March				April				May				
	Week														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Design PID-FLC with IWO									Mid-Sem Break						Study Week
Design PID-FLC in Simulink															
Tune scaling gain for PID-FLC with IWO															
Run with different iteration for PID-FLC with IWO															
Design PD-FLC with IWO															
Design PD-FLC in Simulink															
Tune scaling gain for PD-FLC with IWO															
Performance analysis															
Preparation of Final report and presentation to panel															

UNIVERSITI TEKNIKAL MALAYSIA MELAKA