

OPTIMIZATION OF PID CONTROLLER FOR INVERTED PENDULUM SYSTEM USING FUZZY LOGIC CONTROLLER

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
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CERTIFICATION OF APPROVAL

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Approved:



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Project Supervisor

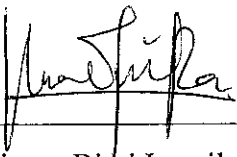
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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

A handwritten signature in black ink, appearing to read 'Maizura Binti Ismail', is written over a horizontal line.

Maizura Binti Ismail

ABSTRACT

This project is mainly about the optimization of PID controller for inverted pendulum system using fuzzy logic controller (FLC). The first part includes the background of study, the problem statement, the scope and the objective of the project. This part will briefly discuss the limitation of the current system. Basically, when perturbation is applied to the pendulum, the system will take some time to be stable. Thus, the main objective of this project is to find the optimum stable point of the system in order to reduce the oscillations of the pendulum and to minimize the time taken to stabilize the system. The literature review and theory part will discuss the journals and books regarding the inverted pendulum as well as their supported theories. The next part of this report is the methodology part. This part will briefly explain the work flow of the project in order to achieve the aim of this project. The steps taken are literature review and research, experimental stage, the design stage, and finally the analysis and comparison between the controllers. This project will deal with the inverted pendulum itself and softwares such as MATLAB and fuzzyTECH. Thus, full understandings of those softwares are needed for this project. The discussion part will discuss the findings and the understanding of the inverted pendulum, PID controller and FLC. Finally, chapter five gives the conclusion and some recommendations for future work regarding the project. In conclusion, the simulation part of this project has been successfully completed although the testing on the physical system still in progress.

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LIST OF ABBREVIATIONS

AI	-	Artificial Intelligent
EE	-	Electrical and Electronics
FLC	-	Fuzzy Logic Controller
GA	-	Genetic Algorithm
MF	-	Membership Function
PID	-	Proportional, Integral and Derivative

CHAPTER 1

INTRODUCTION

Currently, the existing system in the lab is controlled using the Proportional Integral-Derivative (PID) controller. However, in this project the fuzzy-base controller will be designed in order to obtain the optimum stable point of the inverted pendulum. The PID controller is widely used because no detailed knowledge on the controller itself is required to apply the method. However, the simplicity of the concept often limits the performance. On the other hand, fuzzy logic is more robust where it can handle inexact data and can easily adapt to systems that change in time. Fuzzy theory holds that all things are matters of degree and reduces black-white (1-0) logic to cases of grey (membership function) relationship [1]. This technique is conceptually simpler since the FLC acts by weighing alternatives in the manner of a human expert.

Statistic has shown that more than 90% controllers used in industries today are PID-type of controllers. PID controller is simple, reliable, consume lower cost and easy to operate. For lower order linear systems, the PID controller works very well and effective. This controller is the combination of the proportional (P), integral (I) and derivative (D) control algorithm.

1.1 Background of study

In general, the project underlines the analysis and comparison study of using the FLC as an intelligent controller versus the conventional controller that is commonly used in the control system.

The project involves two major phases; experimentation and computer simulation. Experiments are done in order to identify the model parameters and to observe the control performance of the conventional PID controller. FLC implementation is done

entirely via computer simulation, where the result is then compared with the conventional control performance result. Both controllers will then be tested on the inverted pendulum trainer in the laboratory.

Theoretical knowledge learnt on EE engineering subjects such as Control Systems, MATLAB coding and some other basic courses will be applied actively throughout the project. Besides, the student also need to learn and utilized a lot of new knowledge in order to complete this project. The ability to use programming and simulation software such as MATLAB and fuzzyTECH will also be emphasized.

1.2 Problem statement

The problem statement is firstly identified in order to point out the significance of the project.

The first one is to define the type of system model that is currently used for the inverted pendulum system. With the available facilities, the stability of the inverted pendulum system will be investigated using the PID controller. Thus, the system identification experiment has been performed using the pendulum to obtain the process model for the design. As a conclusion using the PID controller, longer time is needed to reach the stable position of the pendulum. Besides, by using the PID controller the stable system can only being maintain for a short duration before it become unstable again. In a worse case, the pendulum system become uncontrollable and no stable region can be achieved at all.

The second problem is to investigate whether FLC is capable to perform on the system. The capability of the FLC to overcome the problem will be emphasized. Due to that, the FLC will be used to obtain the optimum stable point of the system in order to minimize the settling time of the system.

1.3 Objectives

The project is aimed to meet the following objectives:

1. to obtain the optimum stable point of the inverted pendulum system.
2. to simulate the function of an intelligent controller, based on the system model obtained.
3. to perform control performance comparison between the FLC and the conventional controller, and
4. to simulate the FLC-based controller using MATLAB and test it in the laboratory.

1.4 Scope of project

The scope of the project is defined in order to ensure feasibility of the project. Currently, many control system methods can be used for controlling purpose depending on their usage and controllability.

Conventional control system used PID controller in controlling the inverted pendulum system. Double inverted pendulum trainer will be utilized in order to learn how the PID controller performs in order to stabilize the system. Recently artificial intelligence (AI) is widely used as the new approach for the control system. For this project, the FLC is chosen as the intelligent controller for the system. The study will be done base on the PID controller as the reference. The comparison will be made between the system with the conventional PID controller and the fuzzy-based controller. The main objective is to design the fuzzy-based controller that can optimize the inverted pendulum systems which is available in the control system laboratory.

In addition, the optimum number of MFs of the FLC is crucial in this project as it will directly affect the performance of the inverted pendulum system.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Literature Review

According to a book written by Hung T. Nguyen, *A First Course in Fuzzy and Neural Control*, the inverted pendulum system is one of the nonlinear control problems [1]. Thus, the aim of this project is to design a linear controller for the nonlinear system of the inverted pendulum system. The book explained how the FLC can be used in order to improve the controllability of the inverted pendulum system.

Currently, the inverted pendulum that will be used for this project uses the PID controller as its control system. The PID controller has been widely used in the industrial world nowadays. However, by using the PID controller for this system, longer time is needed to reach the steady state. This statement has been proved by a website on “*Fuzzy Logic*”; by using the example of water level control [14]. The website has shown and proved that the settling time for the FLC is faster than the conventional PID controller. According to *Control Systems Engineering* book by Norman S. Nise, the step response of the PID controller which is an underdamped system (please refer **Figure 1**) has lower value of damping ratio, ζ compared to the FLC step response. The lower the value of ζ , the higher the settling time, T_s of the system is [3]. This means that when the perturbation is applied to the inverted pendulum, FLC will permit less oscillations of the pendulum in order to be stable.

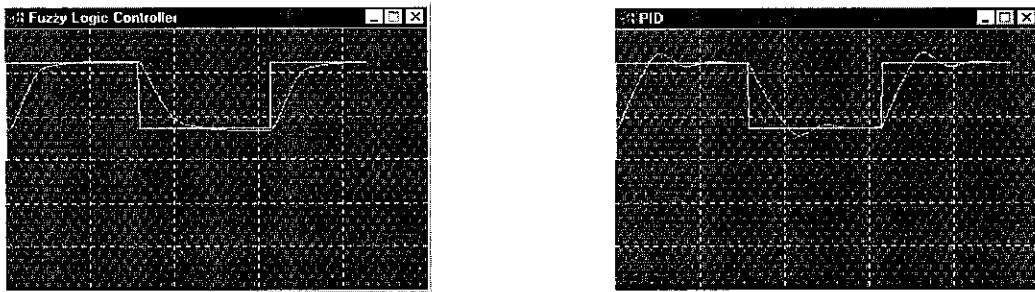


Figure 1 Comparison on the responses of FLC and PID controller

For this project, the performance of the conventional PID, fuzzy-based and fuzzy PID controller will be compared. According to a book written by Guanrong Chen titled “*Introduction to Fuzzy Sets, Fuzzy Logic and Fuzzy Control Systems*”, for lower order linear systems, both conventional and fuzzy PID controllers work equally well. However, the fuzzy PID controllers are generally used for high-order, time-delayed and nonlinear system although the design method for this combined controller are more advanced and their mathematical model are more complicated [4].

According to Jan Jantzen in the journal of “*Tuning of Fuzzy PID Controllers*”, the controller gains for the fuzzy controller are more difficult to set compared to the conventional PID controller. In fuzzy PID controller, it is difficult to tell the effect of each gain on the step response i.e overshoot, settling time. Due to that, the student has proposed some methods in tuning the fuzzy PID controller [6].

Referring to the journal titled “*Controlling of Real Inverted pendulum by Fuzzy Logic*” by Nenad Muskinja and Boris Tovornic, the full FLC is not the optimal controller for the inverted pendulum system. In this paper, full FLC is suitable for controlling the swinging of the pendulum (from initial condition) but not for the balance algorithm [7]. Thus, in order to optimize the performance of the controller, the combination of the FLC with other controller would be the best solution for the system.

2.2 Theory

2.2.1 Inverted Pendulum System

Basically, the main concerns of this project are the double inverted pendulum system and the FLC. Double inverted pendulum system consists of inverted pendulum, cart, track and motor. The system begins at rest with the pendulum pointing downward. Disturbance forced will be applied to the cart, which puts the system out of balanced. The controller will control the inverted pendulum in upright position on the cart by moving the cart in the track. The motor will provide the power to move the cart. The system is shown as below:

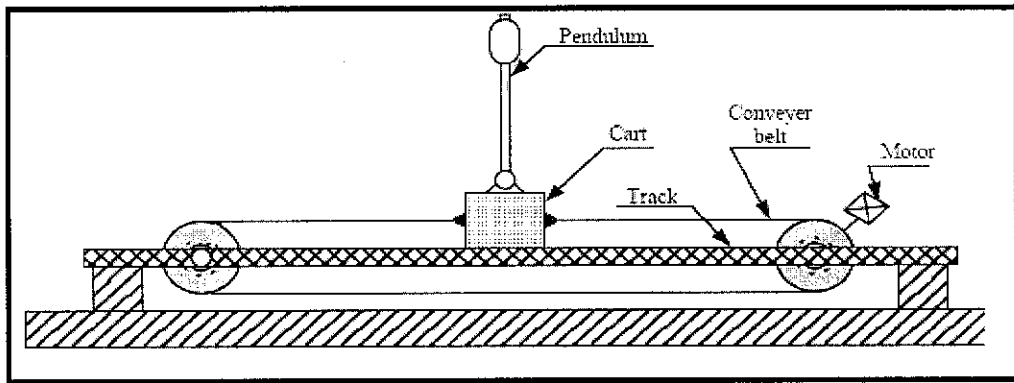


Figure 2 The real inverted pendulum system.

2.2.2 PID Controller

PID controller is the combination of the proportional gain (K_C), integral time (T_I) and derivative time (T_D) of the system. Each parameter has its own effect on the step response of the system. The internal diagram and the general equation of the PID controller are shown in the figure below:

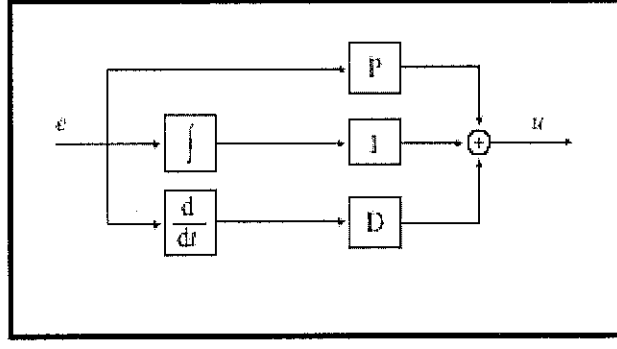


Figure 3 Basic diagram of the PID controller

The general equation for the given diagram is as below:

$$u(t) = Pe(t) + I \int_0^t e(\tau) d\tau + D \frac{de(t)}{dt} \quad (2.1)$$

2.2.3 Fuzzy Logic

2.2.3.1 Fuzzy Theory

Fuzzy theory holds that all things are matters of degree. Basically, it reduces black-white and mathematics to special limiting cases of grey relationships. Mathematically, fuzziness means multivalence so that multivalued fuzziness corresponds to degrees of indeterminacy or ambiguity, which is the possibility of partial occurrence of events or relationship [10]. Fuzzy theory has extended the bivalent indicator function I_A of nonfuzzy subset A of X ,

$$I_A(x) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases} \quad (2.2)$$

to a multivalued membership function,

$$m_A : X \rightarrow [0,1] \quad (2.3)$$

Here the value of $m_A(x)$ for the fuzzy set A is called the membership value or the grade of membership of $x \in X$. The membership value represents the degree of x belonging to the fuzzy set A [12].

2.2.3.2 Fuzzy Logic Controller

FLC uses fuzzy logic as process of mapping from a given input (crisp numerical value e) to an output (signal control u). The general structure of fuzzy logic controller consists of three basic portions: the *fuzzification* unit at the input terminal, the inference engine built on the *fuzzy logic control rule base* in the core and the *defuzzification* unit at the output terminal, which transforms fuzzy sets into real numbers to provide control signals as shown in figure below:

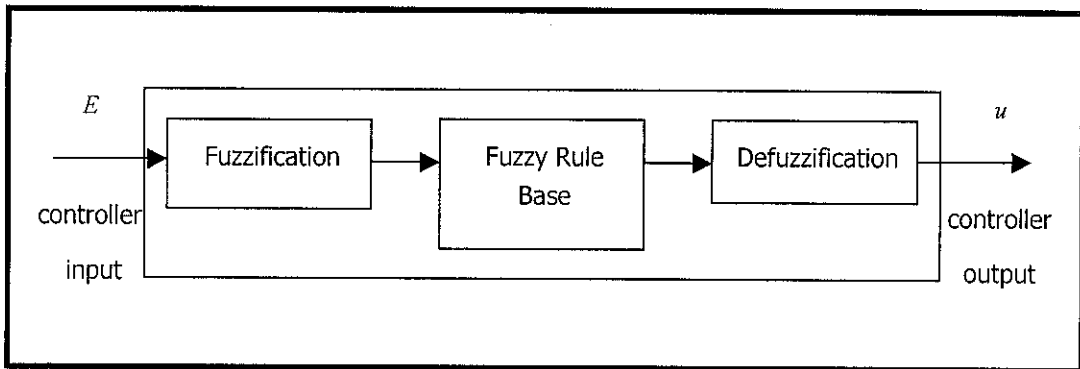


Figure 4 General structure of a fuzzy logic controller.

Fuzzification is the process of generating membership values for the antecedents and the consequent using membership functions. This is done to make the input physical signal compatible with the fuzzy control rule base in the core of the controller. Fuzzification module transforms the physical values of the systems which is the input to the FLC into a normalized fuzzy subset for the range of the input values and the associate membership function. This will describe the degrees of the confidence of the input belong to this range.

The fuzzy rule base is generally used to create the control actions, in fuzzy terms, according to the information provided by the fuzzification module. Specifically, the

rule base is a set of IF-THEN rules. The defuzzification module is the connection between the control rule base and the physical system to be controlled. It is the inverse of the fuzzification module. Many methods of defuzzification can be used. The most common method is the Centre of Gravity (COG) method with the general formula is given as

$$COG = \frac{\sum_{i=1}^m \mu_i R_i}{\sum_{i=1}^m \mu_i} \quad (2.4)$$

where m = number of fuzzy set
 μ = degree of membership
 R = centre of the output fuzzy set

Nevertheless, for systems that have a restricted number of controller action levels, the typical method of defuzzification used is known as Middle of Maxima (MOM) method. In this method, the rule with the highest firing strength is taken as the single most likely control rule. The general formula for MOM is given as

$$MOM = \{MAX\{\mu_i\}, R_i\} \quad (2.5)$$

where m = number of fuzzy set
 μ = degree of membership
 R = centre of the output fuzzy set

2.2.4 Fuzzy PID Controller

Two approaches are available in order to combine the PID and Fuzzy Logic controller which are using simple modification and natural extension of the PID controller. The former one includes modification of the conventional PID controller by inserting some meaningful fuzzy logic IF-THEN rules into the PID control system (e.g self-tune the PID control gains). Generally, this approach is complicating the overall system and do not come up with the new fuzzy PID controllers that capture the essential characteristics of the conventional PID controller. No analytic formulas will

be used for control specification and stability analysis.

The later approach is done by giving natural extensions of the conventional PID controller. This method will preserve the linear structure of the PID controller with simple and conventional analytical formula as the final results of the design. This Fuzzy PID controller is designed by employing fuzzy logic control principles and techniques to obtain a new controller that have analytical formula very similar to the conventional PID controllers.

In fact, Fuzzy PID controller is more complicated than the conventional PID controller where it has variable control gain in the linear structures. The main contribution of the variable gains in improving the control performance is that they are self-tunes gains and can adapt to the rapid changes of the errors and changing rates for the nonlinearities of the systems. Following are the basic diagram and general equation of the Fuzzy PID controller:

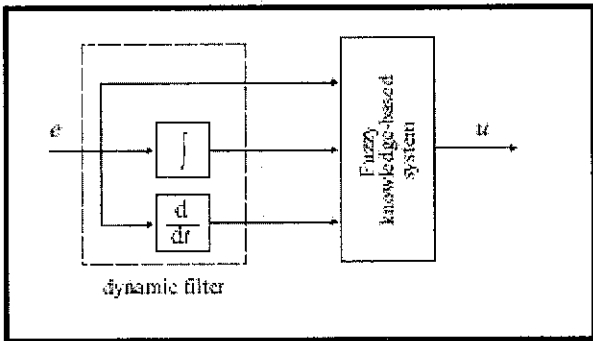


Figure 5 Basic diagram of the fuzzy PID controller

The general equation for the fuzzy PID controller is as follow:

$$u(t) = f\left(e(t), \int_0^t e(\tau) d\tau, \frac{de(t)}{dt}\right) \quad (2.6)$$

CHAPTER 3

METHODOLOGY

3.1 Overall procedure

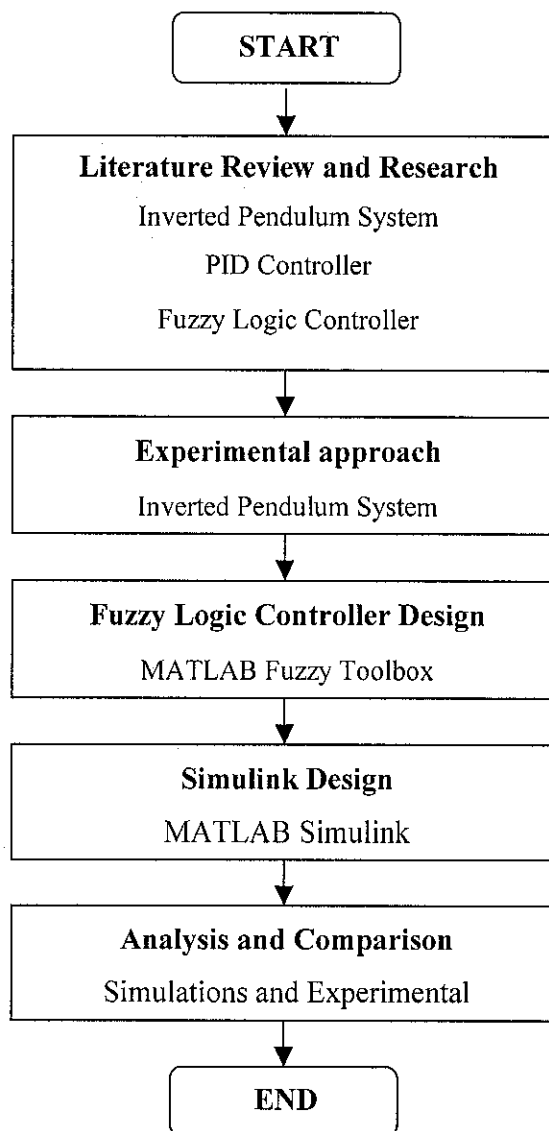


Figure 6 The methodology flowchart

3.1.1 Literature Review and Research

The aim of this stage is to ensure that the student can understand how the inverted pendulum works. The journals on the inverted pendulum system with different control methods have been analyzed. The research has been diverged to many different approaches that have been applied to the inverted pendulum system such as the PID, FLC, Neural Network, GA, state space controller etc. The comparisons of the system performances using different approaches have been made. At this point, the student can identify the consequences of different control system to the inverted pendulum system.

To be more focus, the research has been converged into the PID and FLC control systems only. The general researches regarding the existing systems that use PID and FLC have been done. The aim of this stage is to ensure that the student understand the concept of PID and FLC controller well. At this stage, deeper understandings on the PID and FLC design method have been gained. In order to proceed with the design stage, the theories behind these two controllers have been mastered.

3.1.2 Experimental Approach

The most important knowledge on using the inverted pendulum system is to understand the mechanism and be familiarized with the system. Thus, the identification experiment has been done to identify the problem of the current system. The ways how the pendulum react with the perturbation given has been analyzed. The experiment is conducted by using the PID controller as the control system. The important observations have been made and are used as the fundamental for the design stage. On the other hand, the parameters (constants and variables) of the system are also being identified during this experiment which is the main key for the design stage.

3.1.3 Fuzzy Logic Controller Design

The detailed procedures in designing the FLC are shown in Section 3.2.

3.1.4 Simulink Design

For this project, the MATLAB software is used as the interface between the physical InTeCo inverted pendulum system and the controller. The simulation block diagram for the inverted pendulum system can be obtained from the “Simulation Model and Controllers” of the manufacturer’s interface. Default model for the inverted pendulum system that uses the rule-based and PID controller is shown on **Figure 7**. Some modification on the Simulink model has been done in order to obtain optimum Simulink design for the system. The Simulink block diagram of the system has been designed in order to ensure the FLC can be applied to the system. The simulations of the system have also been done to check the functionality of the controller.

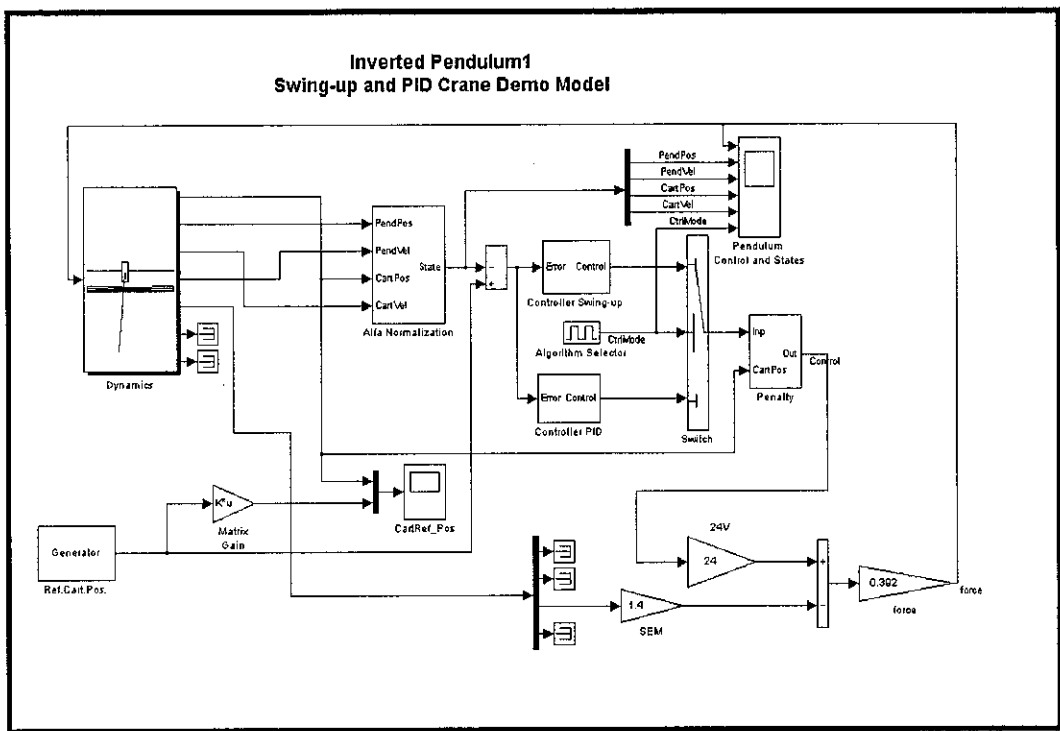


Figure 7 Default Simulink model for inverted pendulum system

3.1.5 Analysis and Comparison

The final stage of the project is the performance analysis of the controllers. The performance comparison between the PID controller and the FLC is done at the end of this project. The returns and drawbacks of each controller are analyzed and some recommendations are made for future research.

3.2 Fuzzy Logic Design Procedure

The overall methodology of designing the FLC can be simplified into the following flowchart.

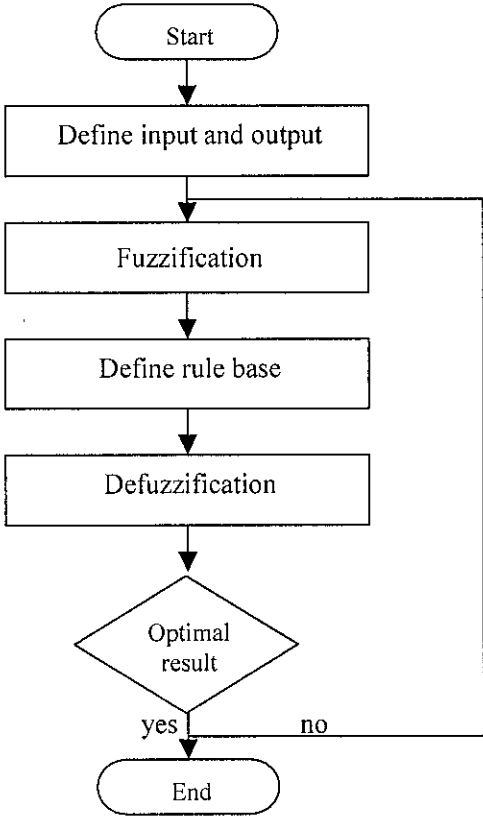


Figure 8 FLC design methodology flowchart.

3.2.1 Define input and output

This is the first step that must be conducted to ensure the optimum design of the fuzzy logic controller can be achieved. For InTeCo inverted pendulum system, there are three (3) inputs and one (1) output that have been recognized. The inputs of this system are stated as the error (angle position), derror (angle velocity) and cart velocity, while the output is the position of the cart.

3.2.2 Fuzzification

Fuzzification is the process of generating membership values for the antecedents (IF) and the consequent (THEN) using membership functions. This is done to make the input physical signal compatible with the fuzzy control rule base and can be understood by the controller. Hence, the fuzzification is basically the process of creating the membership functions (MF) of the FLC by using the given parameters. For optimal result, the fuzzification process is done heuristically by investigating the physical behavior of the inverted pendulum system. The output window of the fuzzification process is as shown in **Figure 9** below:

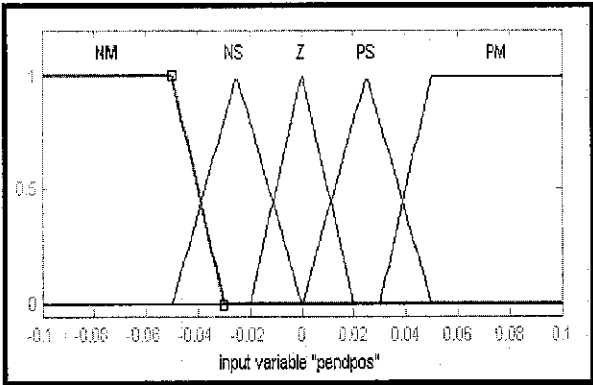


Figure 9 MF of the input

The optimum numbers of MFs is crucial in order to get the optimum stable point for the inverted pendulum system. This is for the reason that ample MFs will result in over sensitive and unstable system.

3.2.3 Define rule base

The fuzzy rule base is generally used to create the control actions of the FLC according to the information provided by the fuzzification module. Specifically, the rule base is a set of IF-THEN rules.

Table 1 Matrix of the rule base

		Derror (pendulum velocity)				
		NM	NS	Z	PS	PM
error (pendulum angle)	NM			PM		
	NS			PS		
	Z	PM	PS	Z	NS	NM
	PS			NS		
	PM			NM		

3.2.4 Defuzzification

The defuzzification module is the connection between the control rule base and the physical system to be controlled. It is the inverse of the fuzzification module. Many methods of defuzzification can be used. For this FLC, the method used is the Centre of Gravity (COG) method with the general formula is given as:

$$COG = \frac{\sum_{i=1}^m \mu_i R_i}{\sum_{i=1}^m \mu_i} \quad (3.1)$$

where m = number of fuzzy set
 μ = degree of membership
 R = centre of the output fuzzy set

3.3 Parameter Tuning

Parameter tuning is done to tune the parameters of the membership functions that define the fuzzy sets. For this project, triangular and trapezoidal fuzzy sets are used. The tuning method can be roughly divided into three (3) types which are:

3.3.1 Tuning of three (3) parameters of each fuzzy set

Triangular fuzzy sets can be generally described by three (3) parameters. By varying these three (3) parameters, the shape of the fuzzy sets can be change in detail. Referring to the **Figure 10**, the parameters to be tuned are 12 (P1-P12) in total.

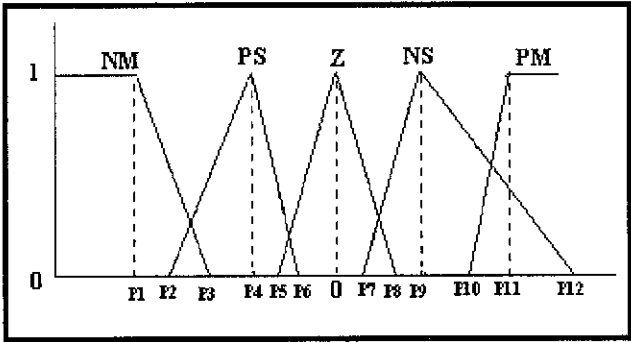


Figure 10 Tuning of three parameters

3.3.2 Tuning of one (1) parameter of each fuzzy set

In this method, there is a constraint between the adjacent fuzzy sets. Therefore, the fuzzy sets can be tuned by the parameter defining their peak values. As a result, the number of parameters to be tuned declines to four (P1-P4).

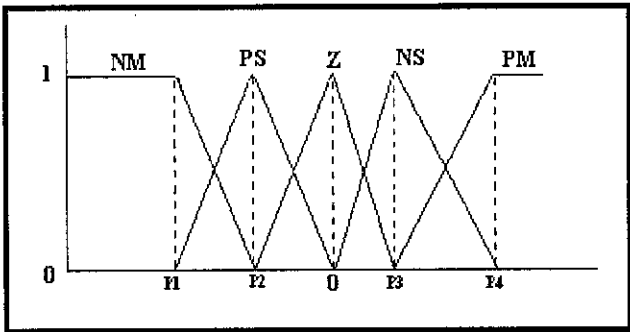


Figure 11 Tuning of one parameter

3.3.3 Tuning the scaling factor of the total set

This method is called the scaling factor method because it tuned the parameter that determines the scaling factor of fuzzy sets. The method reduces the number of parameters. This type assumes that the bases of the triangular fuzzy sets are all the same. Therefore, the only one parameter is to be tuned. The fewer the parameters to be tuned, the simpler the tuning process. This method is quite effective when there are a large number of variables to be tuned. Throughout this project, the student mostly used this method in tuning the FLC.

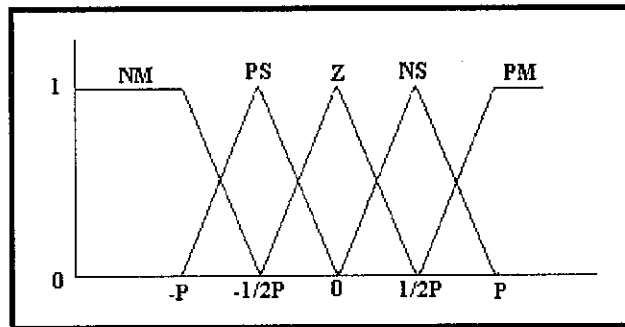


Figure 12 Tuning the scaling factor

3.4 Tools

As this project is dealing with the experimental approach and computer simulation, both the real equipment and software will be used. The tools are listed below;

1. Inverted pendulum system trainer
2. MATLAB software
3. fuzzyTECH software

CHAPTER 4

RESULTS AND DISCUSSION

4.1 System Description

The main key of this project is the understanding of the self-erecting inverted pendulum system. The basic step is to design a linear controller for the nonlinear system of the inverted pendulum. The mechanism of the system is simplified in the flow diagram as in **Figure 13** below:

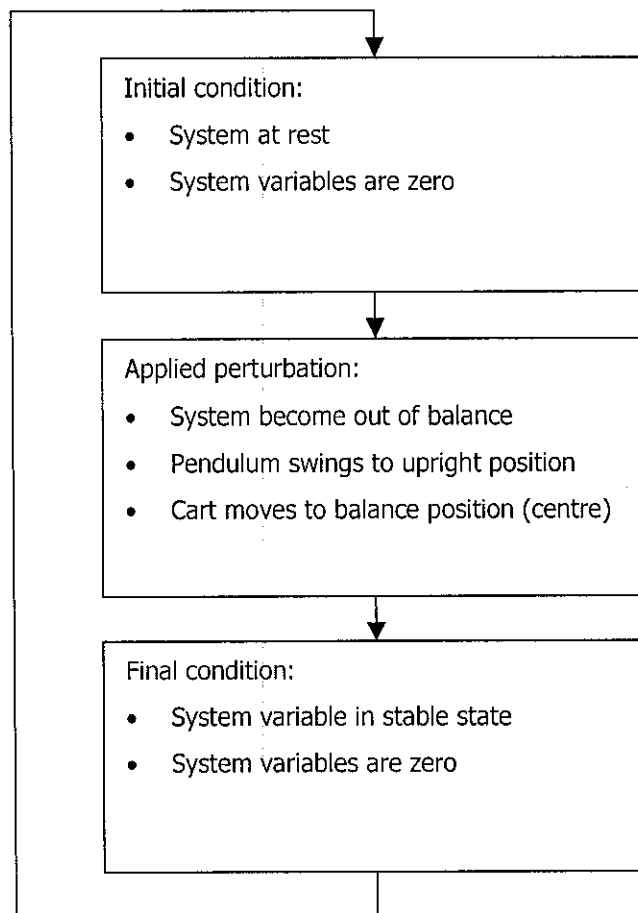


Figure 13 Flow diagram of the inverted pendulum mechanism

The parameters of the system are divided into 2 categories. The diagram below shows the parameters of the inverted pendulum system:

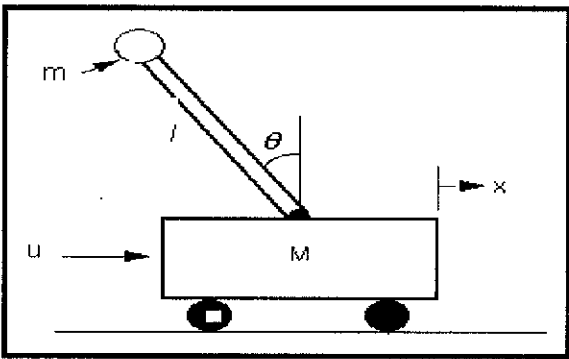


Figure 14 The diagram of the inverted pendulum system.

The state parameters of the systems are;

- x = cart position
- \dot{x} = cart velocity
- θ = angle position
- $\dot{\theta}$ = angle velocity

Referring to **Figure 13**, the system variables are said to be zero when $x = 0$, $\dot{x} = 0$ and $\dot{\theta} = 0$. Table 2 shows the main parameters for the system while **Appendix A.3** shows the detail parameters.

Table 2 The parameters of the inverted pendulum system

No.	Parameter	Name	Symbol	Unit
1	System constant	Cart mass	M	0.768 kg
		Pendulum mass	m	0.104 kg
		Pendulum length	l	0.5 m
		Gravity	g	9.8 ms^{-2}
2	System variable	Horizontal force applied	u	N
		Cart position	x	m
		Pendulum angle (from vertical)	θ	rad

The experiment is conducted based on the default SIMULINK file of the inverted pendulum system. **Figure 15** shows the driver which serves to control and measure the signals. The driver has two inputs: PWM-DC motor control and reset encoders. There are 4 outputs of the driver: cart position, cart velocity, pendulum position and pendulum velocity. The sensors block calculates velocities of the pendulum and cart while the alfa normalization normalizes the pendulum angle.

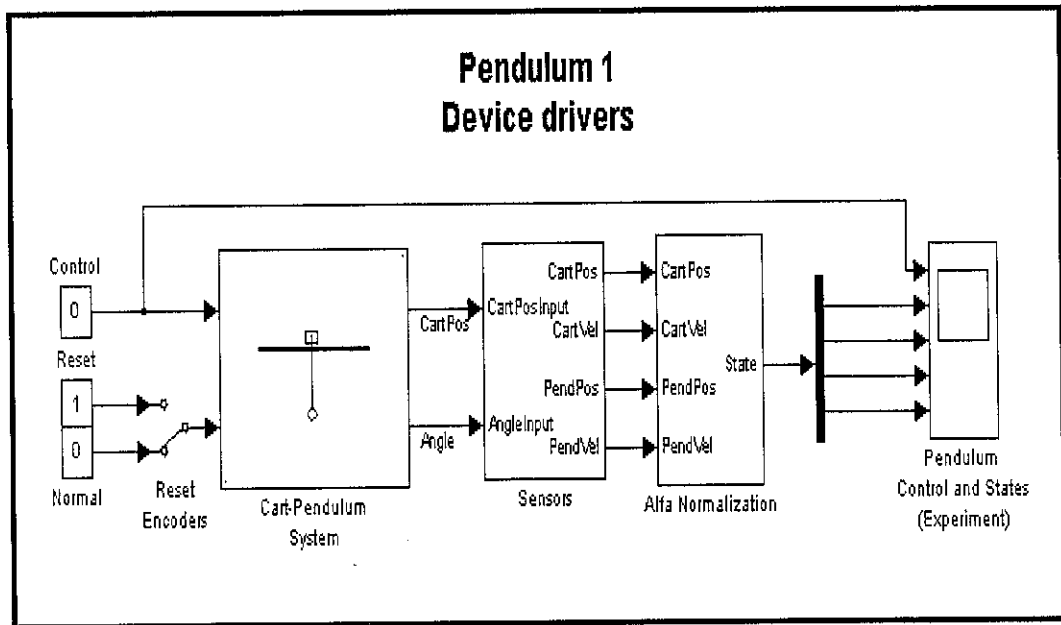


Figure 15 Pendulum system driver

The experiment done is based on the default PID controller for the system. The pendulum is located at its default position which is at the left side. Once the program is running, the cart will start to move and the pendulum will start to swing to achieve its stable position. For this experiment, the stable point is reached when the cart is located at the middle (position 0) and the pendulum is in upright position. The system will try to maintain its stable region for certain period of time depending on the disturbance given. Then, the flowchart as in **Figure 13** will be repeated.

One major observation that has been achieved from the experiment is that the time taken to stabilize the inverted pendulum system using PID controller is not reasonable. The PID controller is not performing well in stabilizing the system. Another obvious observation is that, at certain time the system will become uncontrollable. At this point, the cart will move continuously without reaching the

stable point of the system. This kind of response is shown in the graph as in the figure below. The system can only be controlled back after the encoder has been reset.

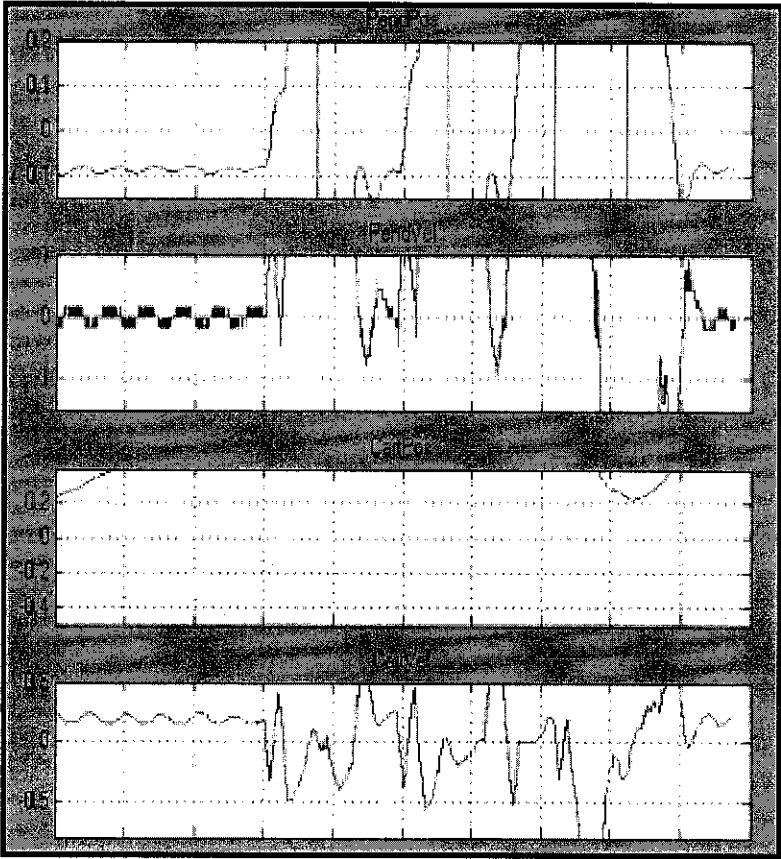


Figure 16 The graph of uncontrollable inverted pendulum system.

4.2 PID Controller Design

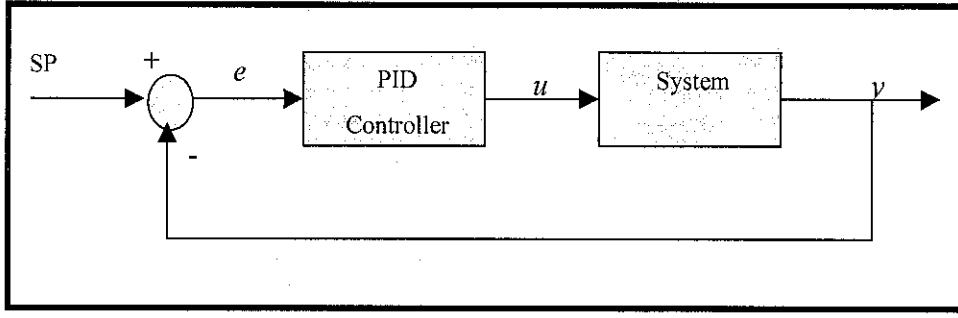


Figure 17 The general PID controller (feedback) system.

Figure 17 shows the block diagram of the PID controller. The PID controller will detect the error, e from the output, y and corrected it before it entering the system again. The setpoint, SP of the system must be specified independently to the controller. For this inverted pendulum system, the SP is set as the position of the cart. While the error, e is the difference between the SP and measured output, y . Generally, the PID controller has the form:

$$y = K_p \varepsilon_1(k) + K_i \sum_{k=0}^n \varepsilon_1(k) + K_d [\varepsilon_1(k) - \varepsilon_1(k-1)] \quad (4.1)$$

where: ε_1 = desired position of the cart – measured position of the cart

K_p = gain coefficient

K_i = integration gain

K_d = derivative gain

For this project, the theory behinds the PID controller has been mastered in order to ensure that the student deeply understand the current mechanism and problems that occurred in virtue of this controller. No further modification is done on this PID controller as it has been fully replaced with the FLC in the inverted pendulum system.

4.3 Rule-based Controller Design

Basically, the rule-base controller is an algorithm of control that combines a number of rules that taken into account the behavior of the systems. The performance of this controller depends on the time, frequency, potential energy, kinetic energy, friction etc. Thus, this controller is a must for the system to perform and it is provided by the manufacturer. The rule-based controller does not correspond to any quality criteria such as time-optimal. On the other hand, it is basically a policy that achieves the control goal. Since this controller is based on the physical characteristics of the system, it is robust and insensitive to parameters changes and disturbances.

In the inverted pendulum system, the rule-based is used as “swing-up and upright stabilization” where it controls the movement of the pendulum when the perturbation is applied. This controller is responsible for the stabilization of the pendulum which means that it will control the position of the pendulum and cart to be at the centre of the track. There are generally three (3) control policies:

- i) Swinging-up the pendulum and centering the cart to the middle of the rail.
- ii) Stabilizing the pendulum in its upright position and stabilizing the cart in the middle of the rail.
- iii) Limiting the cart position.

4.4 Fuzzy Logic Controller Design

The FLC is designed using the procedure defined previously in Chapter 3. For the purpose of accuracy and verification, the FLC for this project is designed using two different tools which are the fuzzyTECH software and the MATLAB Fuzzy Tool. Each tool has its own advantages and disadvantages. **Figure 18** below shows the example of membership function plot for the pendulum position using MATLAB Fuzzy Toolbox.

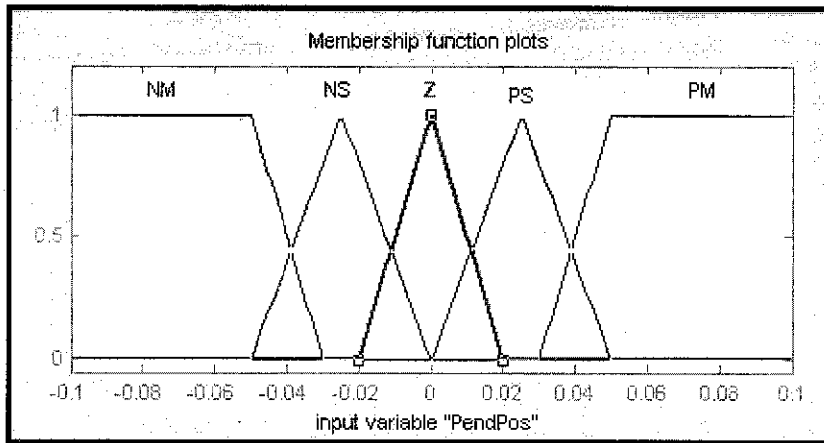


Figure 18 Initial MF assignment for pendulum position.

For this inverted pendulum system, 3 input variables have been chosen which are α = angle position (error), $\dot{\alpha}$ = Angle velocity (derror) and $\dot{\theta}$ = angle velocity. The sample of the fuzzy rule matrix is as below:

Table 3 Matrix of fuzzy rule base

		Derror (pendulum velocity)				
		NM	NS	Z	PS	PM
error (pendulum angle)	NM			PM		
	NS			PS		
	Z	PM	PS	Z	NS	NM
	PS			NS		
	PM			NM		

The matrix above is basically the basic form of the IF-THEN rules. For example, the grey box indicates that:

If Pendulum Angle is Z and Pendulum Velocity is NM then the Cart Position is PM.

For easier understanding, the control rules can be represented in the graphical form as shown below:

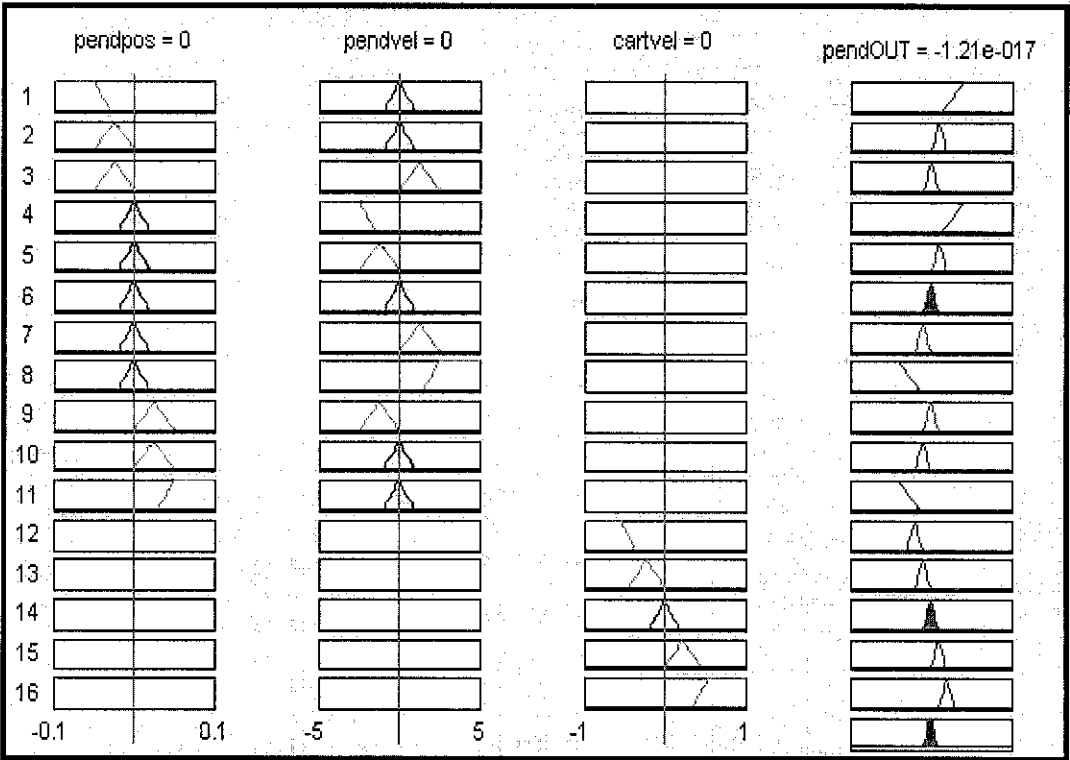


Figure 19 Graphic Representation of the control rules

For this project, the FLC is used as the replacement of the PID controller which means that the FLC is combined with the rule-based controller for the control purpose.

4.5 Results

As the inverted pendulum system is a nonlinear system, the PID controller itself is insufficient to control the movement of the cart and pendulum. Thus, the current inverted pendulum system uses the rule-based controller alternately with the PID controller in order to improve the control of the system. However, this combine-controller still need to be upgraded as the system still used ample time to achieve the stable point. Up to this point, the student has tried several methods of controller design in order to improve this existing controller. Each of the method, although will not contribute much to the project, has been a good based in designing the real controller for the inverted pendulum system. The methods used are:

- i) Improving the rule-based controller
- ii) Improving the current FLC controller
- iii) Improving the block diagram of the InTeCo system.

For the entire methods taken, the response of the input/output parameters has been observed. The behaviors of the system that can be monitored by using the scope are very important as it can be used as the base for further system improvement. Generally, the relationship between the responses of the system and the output of the scope is shown in Table 2 below:

Table 4 The interpretation of the scopes' output

NO.	PARAMETER	RESPONSE OF THE SYSTEM	OUTPUT OF THE SCOPE
1.	Angle	Clockwise	Up
		Counter clockwise	Down
2.	Angle velocity	Fast	Up
		Slow	Down
3.	Cart position	Right	Up (positive value)
		Left	Down (negative value)
4.	Cart velocity	Fast	Up
		Slow	Down

4.5.1 Improving the rule-based controller

The rule-based controller algorithm uses if...then...else form. Generally, it is used to further control the pendulum when the PID controller is insufficient for controlling the system. Referring to **Appendix B**, the switch is used to alternately choose whether to utilize the PID controller or the rule-based controller in order to optimize the performance of the system. The controller consists of several subsystems that are used to control the action of swinging-up and maintaining the pendulum in upright position. The details on the block diagrams of the rule-based controller are shown in **Appendix B**.

After studying the rule-based controller, the student has conclude that this controller can only be improved by either changing the parameters and remodeled the controller. However, as stated previously most of the parameters used in designing this controller are the taken from the physical InTeCo inverted pendulum system. Thus, the changes in the parameters are unacceptable.

Remodeling the controller can be done by modifying each subcontroller in the Simulink blocks (please see Appendix B). However after gathering all the related data, the improvement of the rule-based controller seemed to be impractical due to the reason stated at the beginning of his discussion. This is due to the unknown equations and variables that can only be alter heuristically. These equations are unavailable and are not provided by the manufacturer.

4.5.2 Improving the current FLC controller

The modification of current FLC controller is basically done by tuning the parameters. The parameters here refer to the parameters of membership functions that define the fuzzy sets. The tuning method can be roughly divided into three (3) types:

- i) Type 1 - three (3) parameters of each fuzzy set are to be tuned
- ii) Type 2 - one (1) parameter of each fuzzy set are to be tuned
- iii) Type 3 - the scaling factor of the total set is to be tuned

Type 3 is the simplest method among all and type 1 is the messiest one. However, with type 1 method the shape of the fuzzy sets can be change in detail. For this project, type 1 tuning method has been used. This is due to the nonlinearity of the system. Thus, in order to obtain optimum result, the parameters need to be tune individually. **Figure 20** shows the general diagram for the type 1 tuning method.

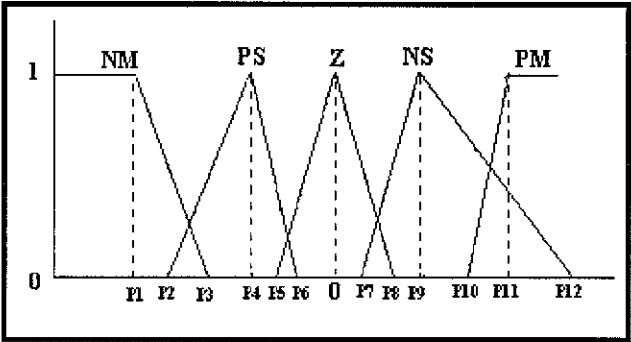


Figure 20 Tuning the scaling factor of the total set

However, by tuning the parameters of the fuzzy sets, almost no obvious effect can be observed. Thus, the improvement can be done by adding and deleting rules that are adversely affecting the control performance. Since the main objective of the improvement is to reduce the rules by improving the performance, the latter method is applied. Currently, the existing FLC uses 20 rules with the gain of -1. After revising the rules heuristically, the final rule of 16 has been achieved.

Nevertheless, number of rules is not the only factors that affect the performance of FLC. The study done has validated that the gain of the controller can also observably affect the responses of the system. For example, if the controller with 16 rules is better than 20 rules for the gain of -1, the 16-rule controller will be better with the controller gain of -0.7. Hence, the performance of the FLC is unique by virtue of the rules and the gain.

4.5.3 Improving the block diagram of the InTeCo system

InTeCo inverted pendulum system is controlled using the Simulink block diagram that are compatible with MATLAB version 6. There are 4 main parts of the system that are available at the main interface of the system which are stated below:

- i) Tools
- ii) RTWT device driver
- iii) Simulation model and controllers
- iv) First control experiment

For simulation purposes, the dynamics of the InTeCo inverted pendulum system is obtained from the “Simulation Model and Controllers” interface. This dynamics block can easily being modified for simulation purposes. The whole system is shown in **Appendix A.4**. As stated, the existing system is using the rule-based controller in addition with the PID controller. However, for this project the rule-based controller will be replaced with the FLC. The design process consists of four (4) stages which are:

- i) simulation using the actual InTeCo controllers (PID + rule-based)
- ii) simulation using the PID controller only
- iii) simulation using the FLC only
- iv) simulation using the FLC + rule based controller

4.5.3.1 *Simulation using the actual InTeCo controllers*

This simulation is done to monitor and verify the current performance of the inverted pendulum system. The responses from the simulation are kept as the fundamental point to further improve the controller. Figure 21 shows that the time taken to stabilize the system is about 20 seconds.

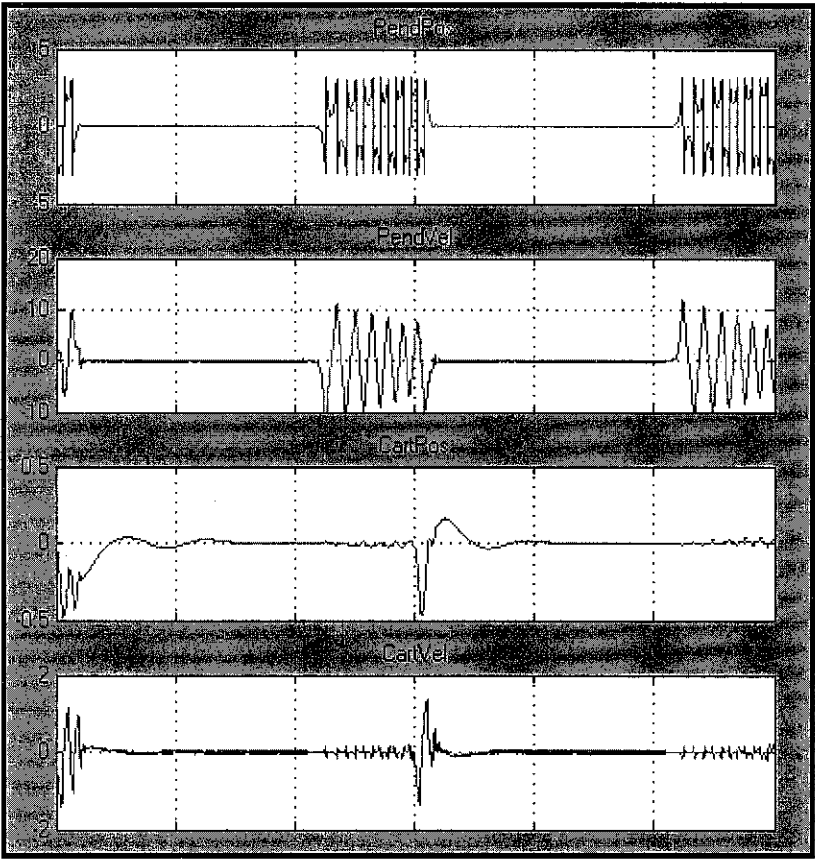


Figure 21 Result of simulation using actual InTeCo controllers

4.5.3.2 *Simulation using PID controller only*

From this simulation, the student has concluded that the PID controller alone are failed to control the inverted pendulum system. The system becomes uncontrollable and no reasonable movement has been observed from the response. Thus, another controller must be combined with the PID controller in order to make the control purpose possible.

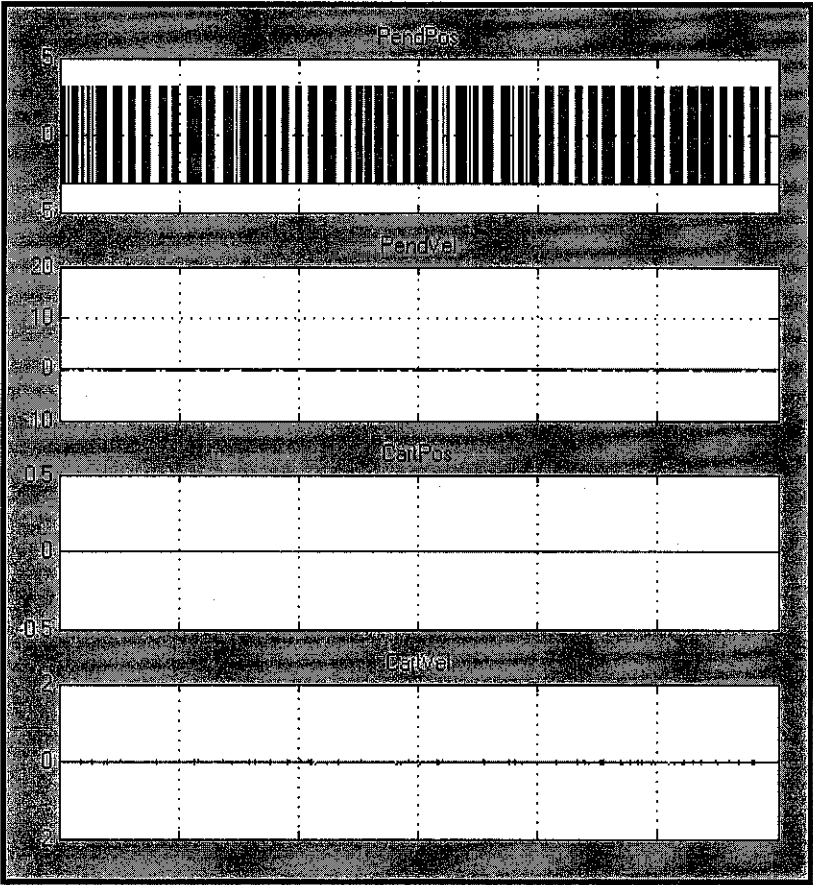


Figure 22 Result of simulation using PID controller only

4.5.3.3 *Simulation using FLC controller only*

The simulation is done to investigate the possibility of the FLC to control the system on its own without combining with another controller. Both the PID and rule-based controller for the system are discarded and have been replaced with the FLC controller. However, the FLC alone are not capable of controlling the pendulum system, the same result as in 4.5.3.2. Therefore, the rule-base controller is a necessity for InTeCo inverted pendulum system.

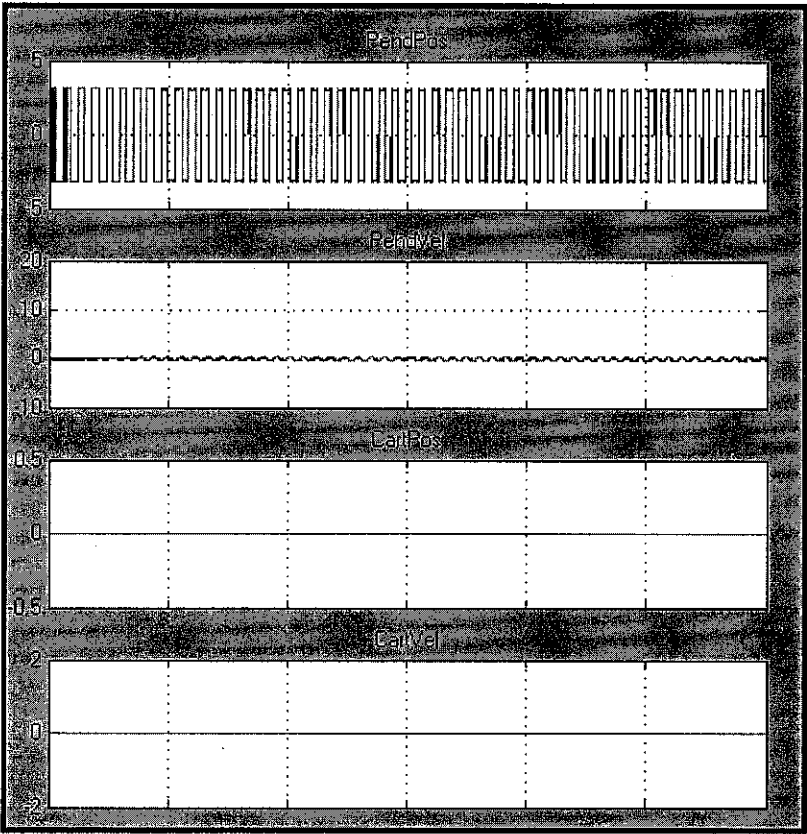


Figure 23 Result of simulation using FLC controller only

4.5.3.4 *Simulation using the FLC and rule-based controller*

This final combination of controller is resulting from the investigations that have been done through 4.5.3.1 - 4.5.3.3. For this stage, the FLC that has been improved previously is imported into the block diagram as in **Figure 24**. Some modification has been done on the rule-based controller to ensure the smoothness of the system. Hence, the subsequent simulations in improving the system are done base on this combination.

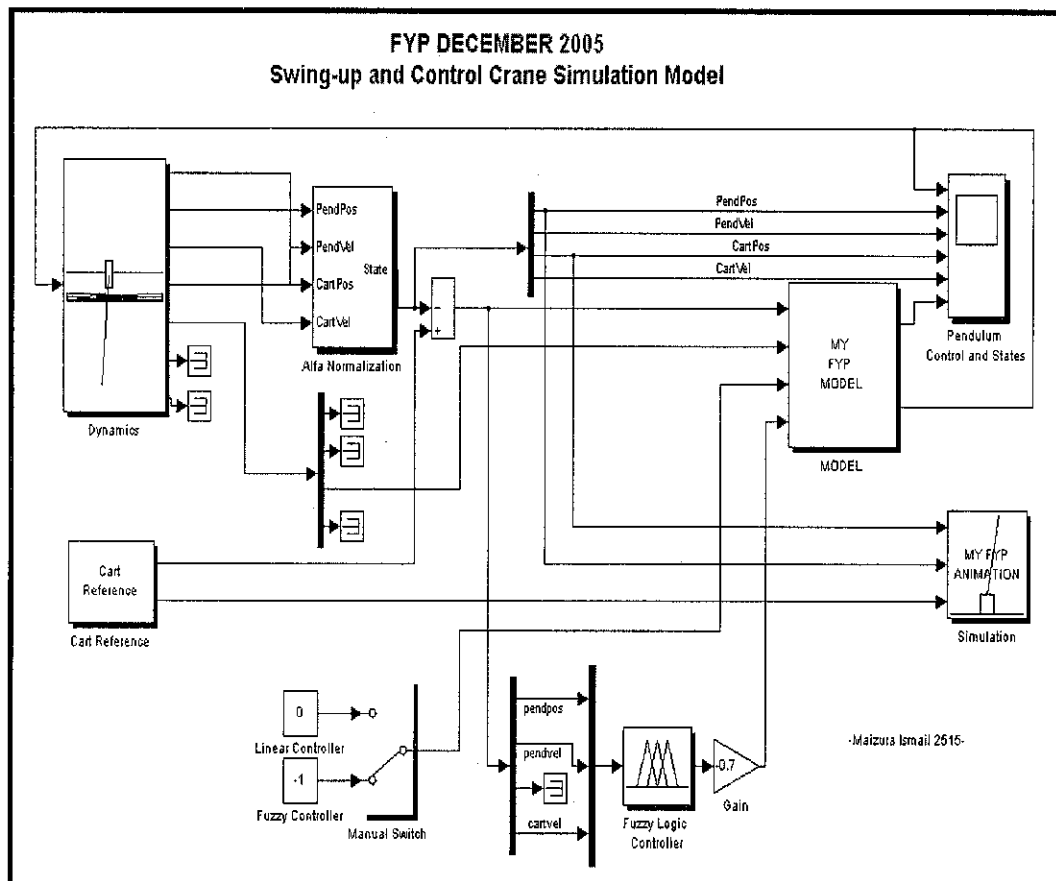


Figure 24 Simulink Block Diagram for the Inverted Pendulum System

4.5.4 Output of the final simulation model

The final simulation model is as shown in **Figure 24** where both the FLC and rule-based controller are utilized in the block diagram. The simulations are done in order to find the optimum FLC that can control the inverted pendulum system. The optimum controller is achieved by varying the parameters of the FLC such as:

- i) reducing the number of rules
- ii) changing the input of the membership function
- iii) varying the gain of the FLC

By applying the heuristic method, the optimum FLC controller has been designed. With this controller, 20 rules has being created and the optimum gain for the controller is -0.7. With this gain, the behavior of the cart can be controlled easier with the shorter ample time taken to stabilize the system. **Figure 25** below shows the result form the simulation of the final simulation model using the designated FLC.

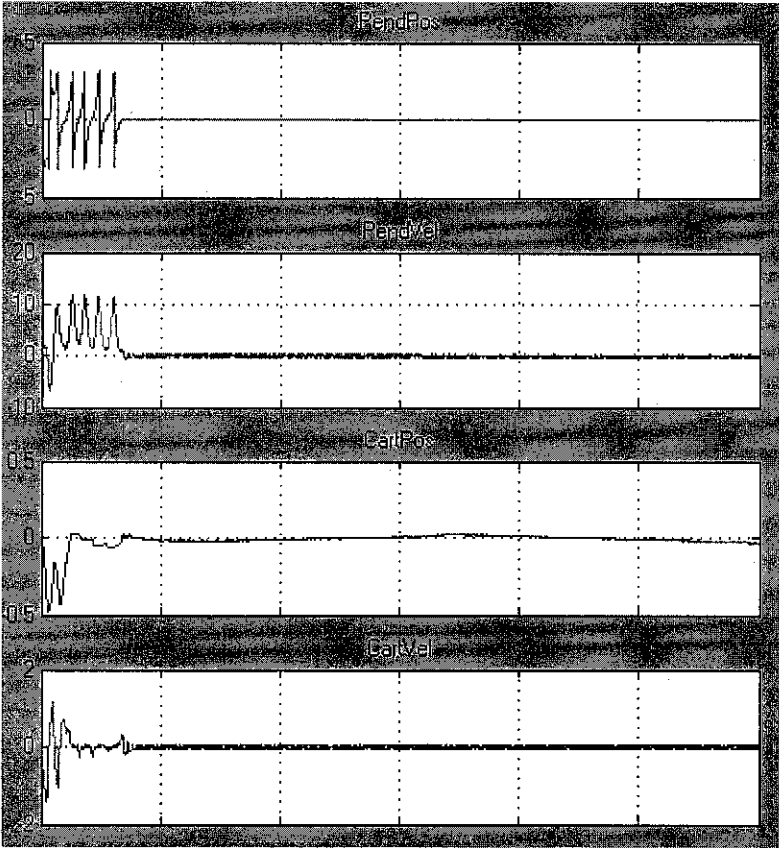


Figure 25 Result of simulation using FLC and rule-based controller

With this controller, the time taken to stabilize the system has been reduced to about 8 seconds rather than 20 seconds by using current PID controller. Once the system has been stabilize, no unstable behavior can be detected. Thus, the effectiveness of FLC in controlling the inverted pendulum system has been proved by this new design FLC. This has proved that the performance of FLC is better than PID controller in controlling the inverted pendulum system and it can be used as an alternative controller for the system.

4.6 Discussion

Inverted pendulum systems are classical control test rigs for verification and practice of different control methods with wide ranging applications of control system engineering. The project investigated the control of a double pendulum system to its inverted position by splitting the control into two different algorithms. These were the swing up algorithm and the balance (upright stabilization) algorithm at which modern control theory techniques were applied.

Throughout the project timeframe, researches have been widely done in order to find the best method in controlling the inverted pendulum system. The chosen method must be able to improve the performance of the conventional PID controller that is currently used to control the inverted pendulum system. Generally, there are two essential components of virtually any controller: a mechanism for knowledge representation and a mechanism for decision-making. With conventional PID controllers knowledge is represented by a mathematical model and decision-making is based on optimization.

When the system is complex or have only vague mathematical model, it becomes difficult to characterize the knowledge adequately with conventional means. One must find alternative ways to encode the available knowledge about the system. This will result in the development of intelligent controllers. Based on this problem, the FLC has been chosen as the intelligent controller which will eliminate the problem encountered using the conventional PID controller.

The FLC has been chose for this project due to its ability to encode the complex system. As the inverted pendulum system is one of the nonlinear systems, the FLC can be most suited for this system. By using the IF-THEN rules, no analytic formulas have to be derived from the system. The aim of this project is to design the FLC-based controller in order to improve the PID controller. This controller will then be tested on the inverted pendulum system for further investigation.

The study done has verified that the FLC alone is failed to control the inverted pendulum system. Hence, the FLC is combined with the rule-based controller for further improvement. This hypothesis has been made as according to Nenad Muskinja and Boris Tovornic in their journal titled "*Controlling of Real Inverted pendulum by Fuzzy Logic*", the full FLC is not the optimal controller for the inverted pendulum system. The full PLC is only suitable for controlling the swinging algorithm but not the balance algorithm [7]. On the other hand, the rule-based controller does not correspond to any of quality criteria as time-optimal, quadratic etc. The rule-based controller is robust and insensitive to parameter changes and disturbances [10]. Thus, FLC and rule-based controller have their own pros and cons that can be manipulated to develop better control algorithm. Both controllers nullify each other's limitations and promising better performance of the inverted pendulum system.

Continuous study has been done to guarantee the optimum stable point of the inverted pendulum system can be achieved by using this FLC-based controller. The main approaches performed to improve the current FLC system are as listed below:

- i) parameter tuning of the fuzzy sets
- ii) revision of the control rules
- iii) alteration of the controller gain

By implementing these three approaches, further improvement of the FLC can be performed for future research.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This dissertation is basically concerning on the optimization of the PID controller for inverted pendulum system by using the fuzzy logic controller. As stated, the fuzzy-based controller is investigated and designed for this project.

Basically, there are two types of pendulum that are available in the laboratory: double inverted pendulum system by InTeCo and self-erecting inverted pendulum by QUANSER (please see Appendix A). The former has been used for this project due to its stability and the ease of its software. Double inverted pendulum can be completely control using MATLAB functions. On the other hand, the self erecting pendulum can only be controlled using its special-design software: QUANSER software. This experimental procedure for this latter pendulum is tedious where the cart itself is positioned in unstable condition.

Throughout the time frame of the project, comprehensive researches have been done continuously to ensure the effectiveness of the project. The scope of this project is to utilize the FLC-based controller for improving the control algorithm of the inverted pendulum system. All the methods and theories behind this type of controller have been understood well. For investigation purpose, a number of experiments have been done on the inverted pendulum that currently uses the conventional PID controller. Several evaluations obtained from the results of the experiment have shown that the PID controller needs ample time in stabilizing the pendulum and the cart. In addition, when the controller is not well-tuned before performing the experiment, the system

will become uncontrollable. Therefore, the optimization of the PID controller is crucial for this inverted pendulum system.

Hence, an intelligent controller can be the best alternative in improving the conventional controller. While other intelligent controllers are complicated to design, the FLC has been chosen for this project due to its simplicity and its effectiveness. The main contribution of fuzzy control theory is its ability to handle many practical problems that cannot be adequately managed by conventional control techniques. By using the FLC, the optimum stable point of the inverted pendulum system has been achieved successfully.

After all, the FLC + rule-based controller has been chosen as the alternative controller that can be used to optimize the PID controller. The simulation part of this project is successfully accomplished. The response of the inverted pendulum system to the FLC-based controller can be observed using the MATLAB software by assistance of the animation diagram. From the result, the comparison between the performance of PID controller and FLC has been done and it has been proved that FLC is better than PID controller in controlling the inverted pendulum system. Thus, FLC can be used to replace PID controller for the InTeCo inverted pendulum system.

Nevertheless, the experimental part still delayed due to the internal problem. Due to time constraint and technical problem of the inverted pendulum system, the FLC-based controller not yet be tested on the physical system. As a conclusion, the student has successfully completed this project and has come out with the intelligent controller approach in optimizing the performance of the inverted pendulum system.

5.2 Recommendations for Future Work

The simulation part of the project is completely done throughout these 2 semesters. Thus, a few recommendations for the continuity of the project will be stated. This is to make sure that the FLC-based controller can be fully utilized on the inverted pendulum system and better control algorithm can be designed in the future.

Since the main objective of this project is to optimize the PID controller for the inverted pendulum system, the testing phase can be a good verification on the functionality of the FLC. Thus, the controller should be tested using the inverted pendulum trainer in the laboratory. This is to further verify that the controller will be performed well to the external hardware. At this stage, if the controllers are not well-functioning with the system, some small modification can be made (if possible) to make sure the main objective of the project will be fully achieved. Hence, the testing phase of the controller should be carried out in the future for further improvement of the controller.

Researches on the FLC-based controller have sparked the idea of designing the fuzzy-PID controller as the extended controller for the PID in order to get the optimum stable point of the system. However due to time limitation, fuzzy-PID controller has not yet being designed during this project implementation. The basic idea of the fuzzy PID controller is the combination of both the PID and the fuzzy logic controller. Generally, this controller is designed in order to improve the control performance of the PID controller. An example of the fuzzy PID controller is shown in **Figure 26**.

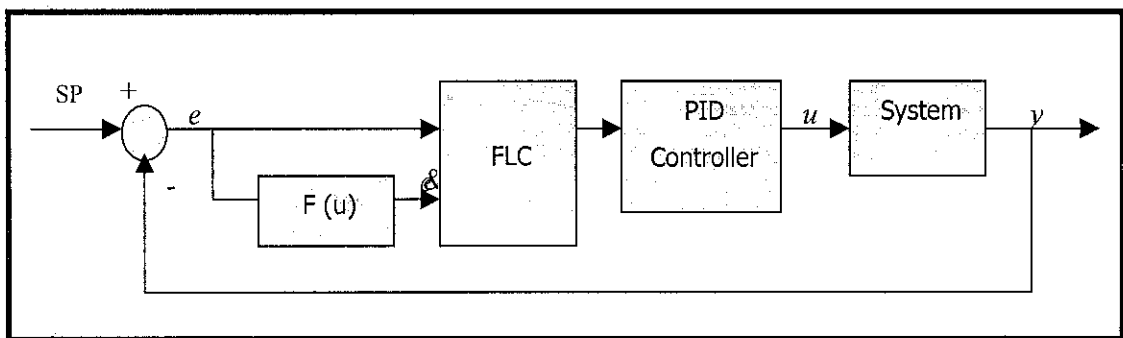


Figure 26 The general fuzzy PID controller system.

The design process of the FLC and the PID controller can be done individually. However, the gain for the controller must be redefine to ensure the optimum stable point will be obtained by this combination controller.

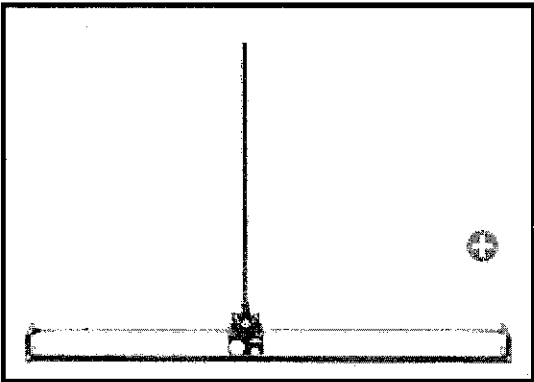
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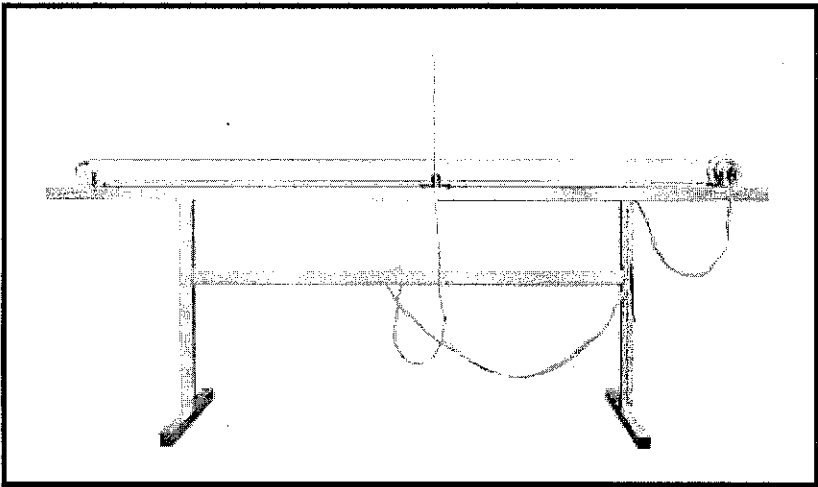
APPENDICES

- Appendix A : Inverted Pendulum
- Appendix B : Fuzzy Logic Controller
- Appendix C : Rule-based Controller

APPENDIX A
INVERTED PENDULUM SYSTEM



Appendix A.1 Quanser inverted pendulum

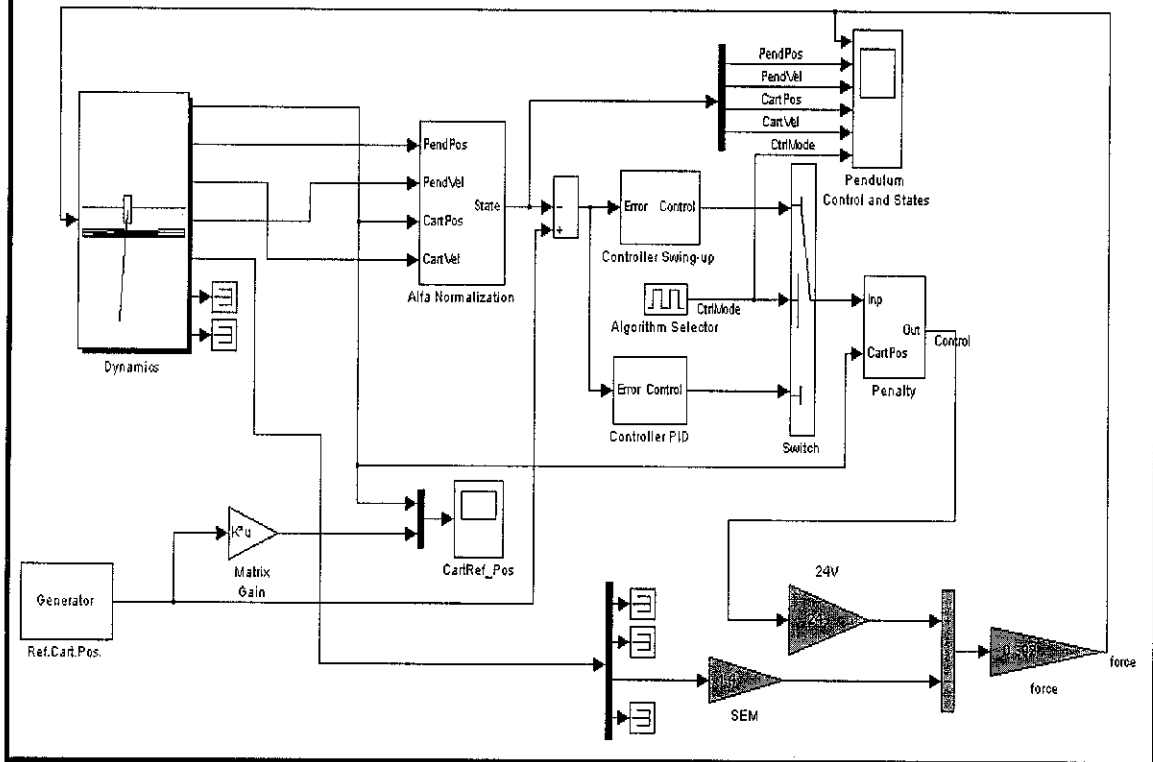


Appendix A.2 Inteco inverted pendulum

Appendix A.3 Parameters of the original model

Name	Description	Unit
m	Equivalent mass of cart and pendulum	0.872 [kg]
l	Distance from axis of rotation to centre of mass of system	0.111 [m]
f_c	Dynamic cart friction coefficient	0.5 [Ns/m]
f_s	Static friction of the cart	1.203 [N]
f_p	Rotational friction coefficient	6.65×10^{-5} [Nms/rad]
J_p	Moment of inertia of pendulum with respect to axis of rotation	0.00292 [kgm ²]
g	Gravity	9.81 [m/s ²]
p_1	Control force to PWM signal ratio	9.4 [N]
p_2	Control force to cart velocity ratio	-0.548 [Ns/m]
u_{max}	Maximum value of PWM signal	0.5
m_c	Equivalent cart mass	0.768 [kg]
m_{ps}	Pole mass	0.038 [kg]
m_{pw}	Load mass	0.014 [kg]
R_l	Rail length	1.8 [m]
l_p	Length of pole	0.5[m]
l_{po}	Distance between centre of pole mass and rotation axis	0.107 [m]
l_c	Length of load	0.03 [m]
l_{pwo}	Distance between centre of load mass and rotation axis	0.354 [m]
T	Pendulum period	1.17 [s]
J	Moment of inertia related to the mass centre	0.00282 [kg.m ²]

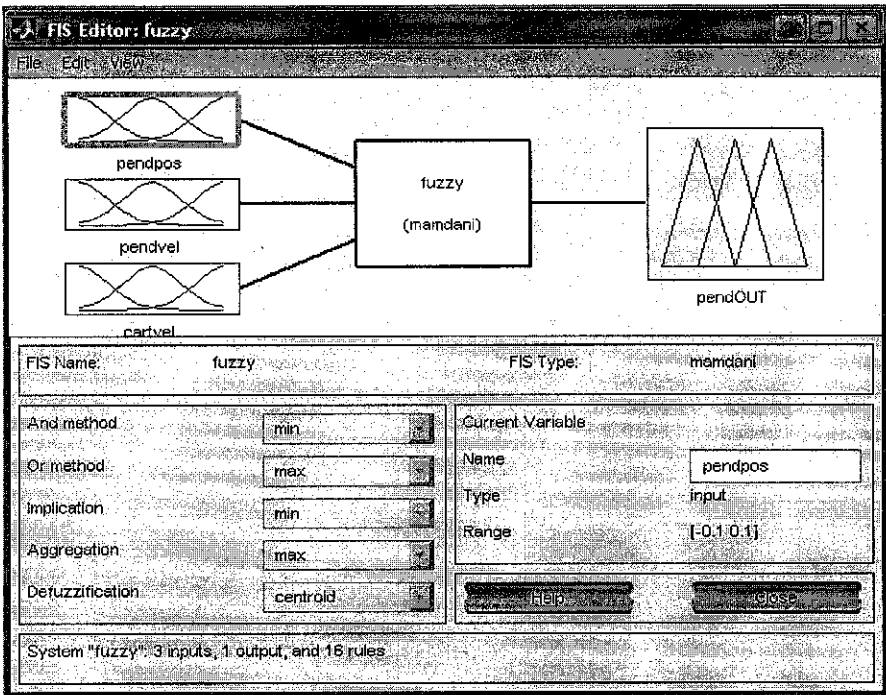
Inverted Pendulum1 **Swing-up and PID Crane Demo Model**



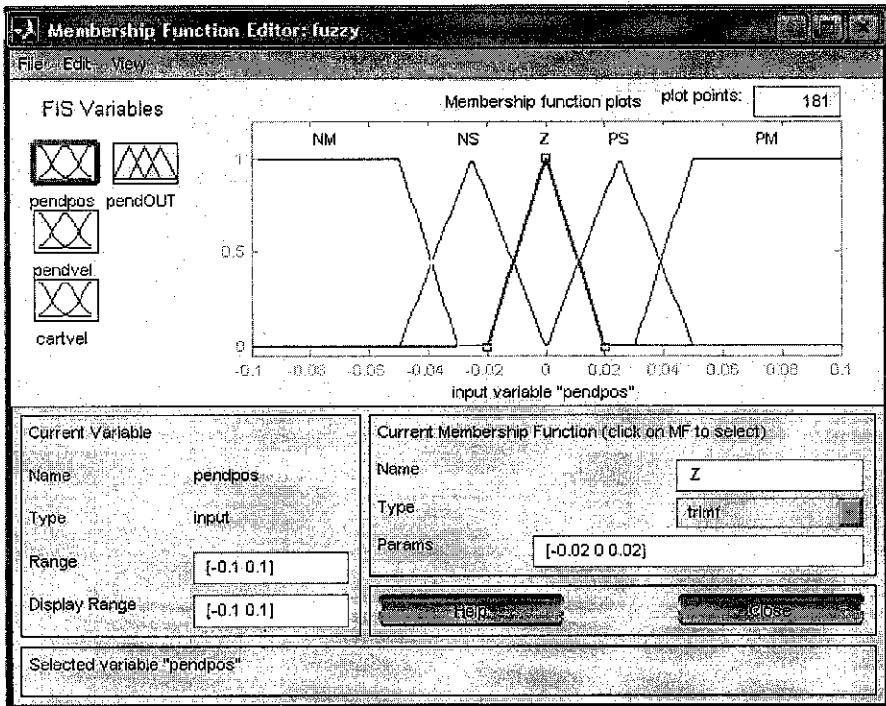
Appendix A.4 Simulink model of the InTeCo inverted pendulum system

APPENDIX B

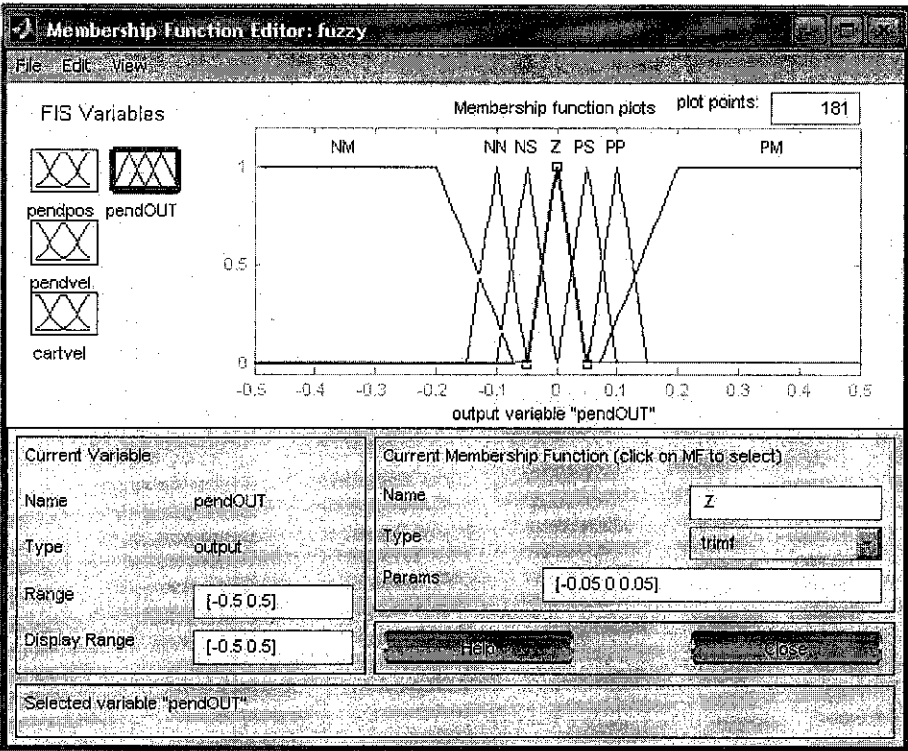
FUZZY LOGIC CONTROLLER DESIGN



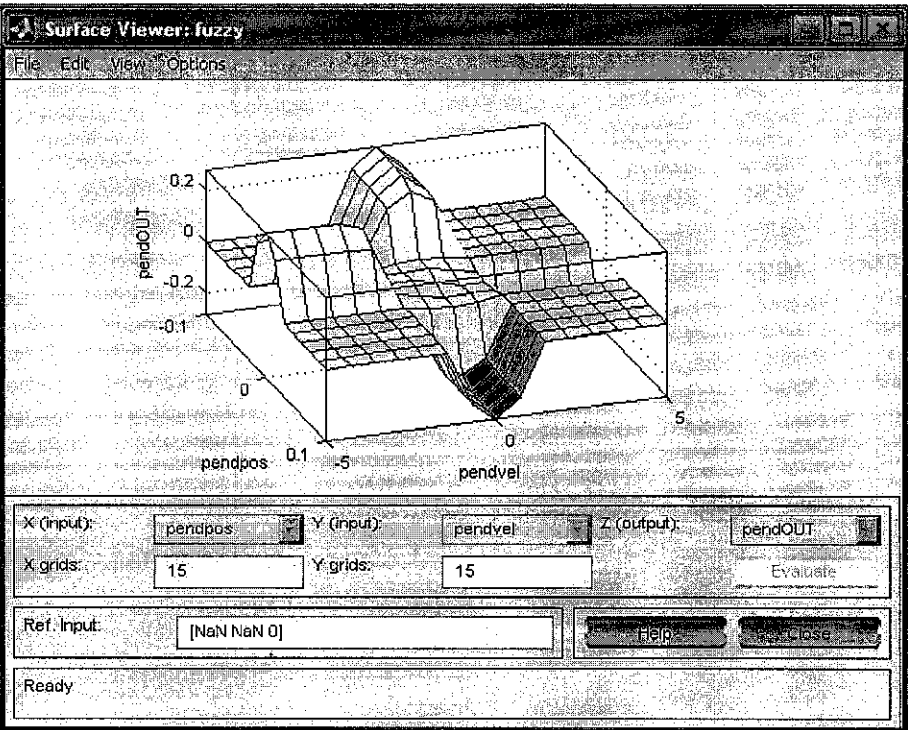
Appendix B.1 FIS editor main window for inverted pendulum system



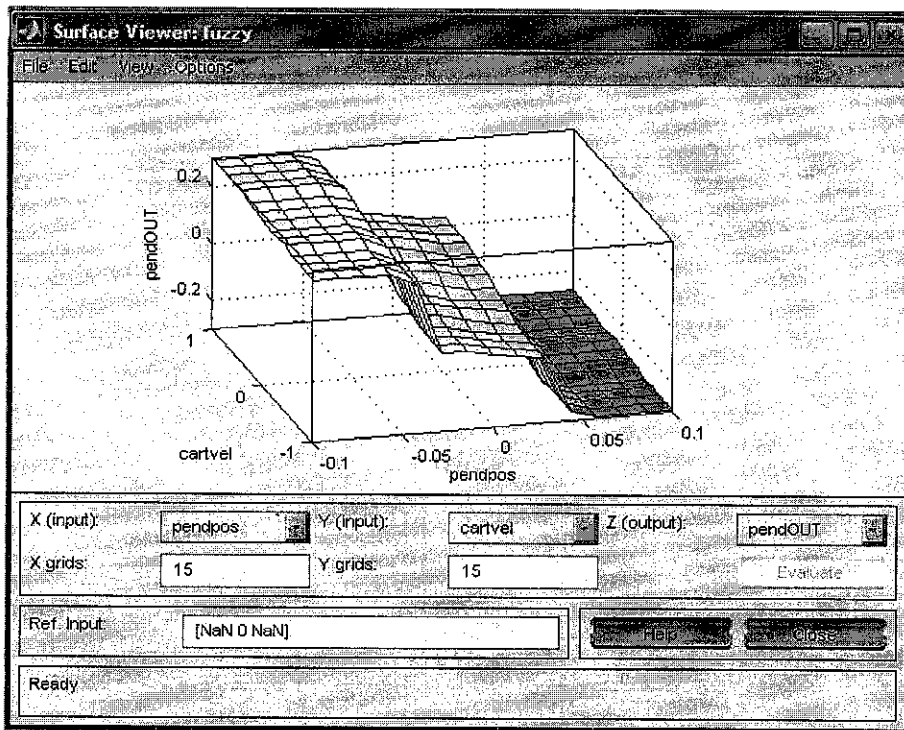
Appendix B.2 Membership function editor for the system’s input



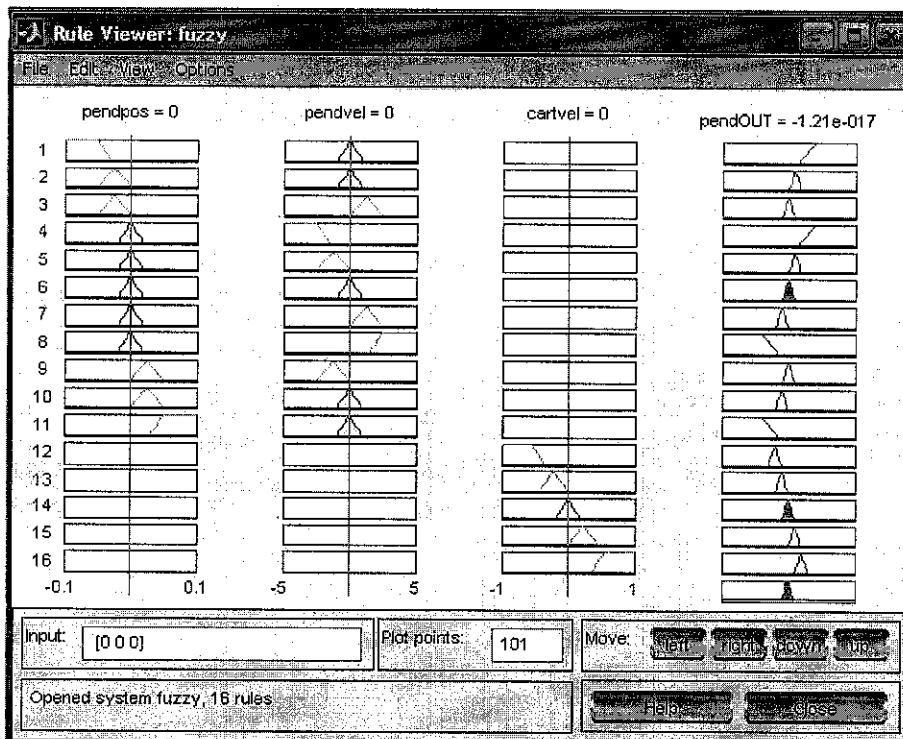
Appendix B.3 Membership function editor for the system’s output



Appendix B.4 Surface viewer for the inverted pendulum system
(input: pendulum position and pendulum velocity)



Appendix B.5 Surface viewer for the inverted pendulum system
(input: pendulum position and cart velocity)



Appendix B.5 Rule viewer for the inverted pendulum system

Appendix B.6 FLC properties

[System]

Name='fuzzy'

Type='mamdani'

Version=2.0

NumInputs=3

NumOutputs=1

NumRules=16

AndMethod='min'

OrMethod='max'

ImpMethod='min'

AggMethod='max'

DefuzzMethod='centroid'

[Input1]

Name='pendpos'

Range=[-0.1 0.1]

NumMFs=5

MF1='NM': 'trapmf', [-0.3386 -0.3216 -0.05 -0.03]

MF2='NS': 'trimf', [-0.05 -0.025 0]

MF3='Z': 'trimf', [-0.02 0 0.02]

MF4='PS': 'trimf', [0 0.025 0.05]

MF5='PM': 'trapmf', [0.03 0.05 0.3444 0.3444]

[Input2]

Name='pendvel'

Range=[-5 5]

NumMFs=5

MF1='NM': 'trapmf', [-16.92 -16.07 -2.5 -1.5]

MF2='NS': 'trimf', [-2.5 -1.25 0]

MF3='Z': 'trimf', [-1 0 1]

MF4='PS': 'trimf', [0 1.25 2.5]

MF5='PM': 'trapmf', [1.5 2.5 17.23 17.23]

```

[Input3]
Name='cartvel'
Range=[-1 1]
NumMFs=5
MF1='NM': 'trapmf',[-3.134 -2.983 -0.5405 -0.3605]
MF2='NS': 'trimf',[-0.45 -0.225 0]
MF3='Z': 'trimf',[-0.18 0 0.18]
MF4='PS': 'trimf',[0 0.225 0.45]
MF5='PM': 'trapmf',[0.3605 0.5405 2.983 3.134]

```

```

[Output1]
Name='pendOUT'
Range=[-0.5 0.5]
NumMFs=7
MF1='NM': 'trapmf',[-1.42 -1.39 -0.2 -0.07]
MF2='NS': 'trimf',[-0.1 -0.05 0]
MF3='Z': 'trimf',[-0.05 0 0.05]
MF4='PS': 'trimf',[0 0.05 0.1]
MF5='PM': 'trapmf',[0.07 0.2 1.597 1.597]
MF6='NN': 'trimf',[-0.15 -0.1 -0.05]
MF7='PP': 'trimf',[0.05 0.1 0.15]

```

```

[Rules]
1 3 0, 5 (1) : 1
2 3 0, 4 (1) : 1
2 4 0, 3 (1) : 1
3 1 0, 5 (1) : 1
3 2 0, 4 (1) : 1
3 3 0, 3 (1) : 1
3 4 0, 2 (1) : 1
3 5 0, 1 (1) : 1
4 2 0, 3 (1) : 1
4 3 0, 2 (1) : 1
5 3 0, 1 (1) : 1
0 0 1, 6 (1) : 1
0 0 2, 2 (1) : 1
0 0 3, 3 (1) : 1
0 0 4, 4 (1) : 1
0 0 5, 7 (1) : 1

```

APPENDIX C

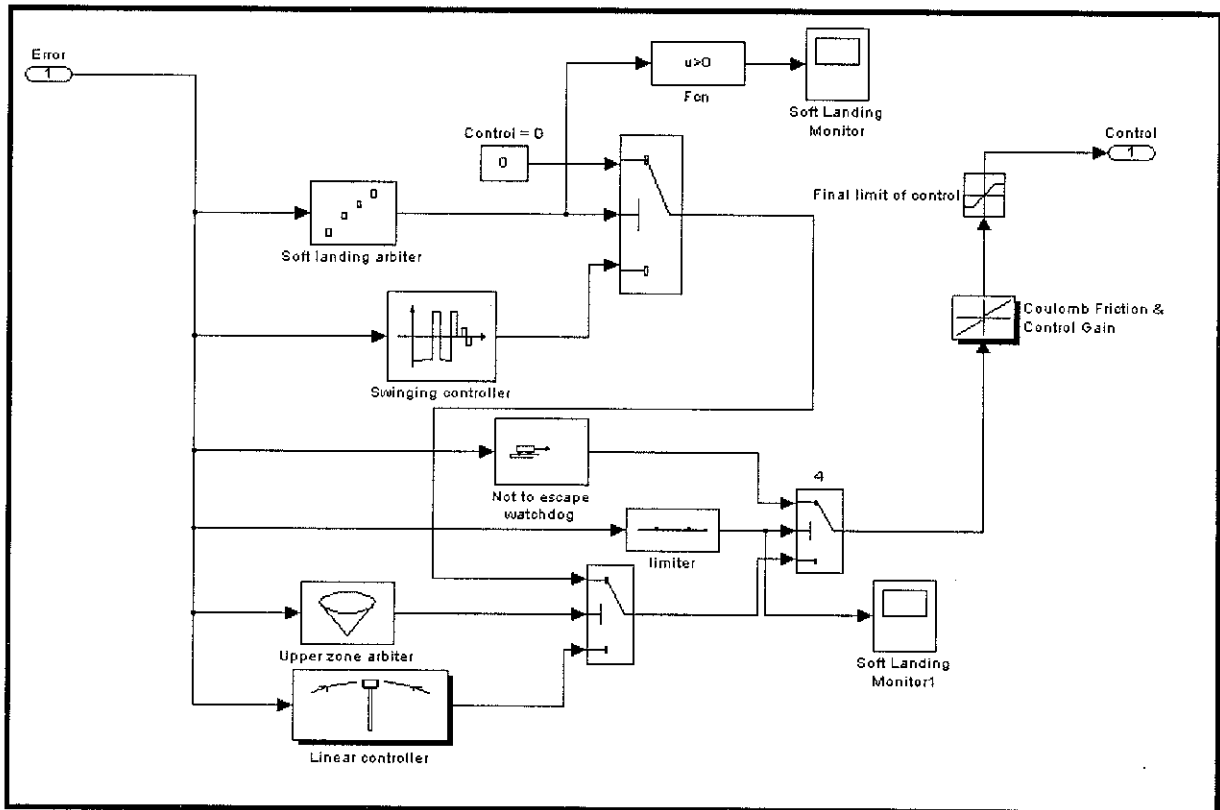
RULE-BASED CONTROLLER

```

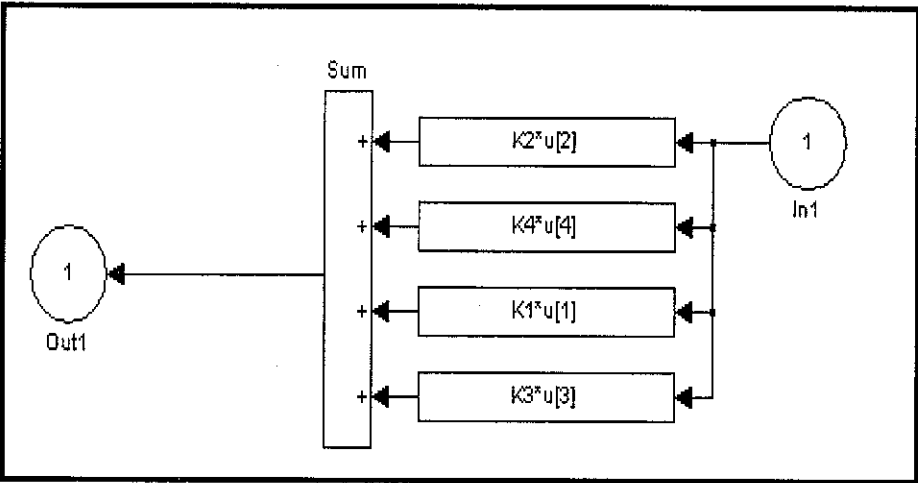
If  $|x_2| - \text{Stab.zone} < 0$ 
then  $u =: K_1 x_1 + K_2 x_2 + K_3 x_3 + K_4 x_4$ 
else if  $\{0.5 \cdot (x_4)^2 + 9.81 \cdot k \cdot R [\cos(x_2) - 1]\} > 0$ 
then  $u =: 0$ 
then  $u =: \text{sign}[x_4 \cdot (|x_2| - \pi/2)]$ 
if  $u > 0$ 
then  $u =: U \cdot u + \text{Friction}$ 
else  $u =: U \cdot u - \text{Friction}$ 
if  $|u| > 1$ 
then  $u =: \text{sign}(u)$ 
if  $|x_1| - R/2 < 0$ 
then  $u =: \text{sign}(x_1)$ 

```

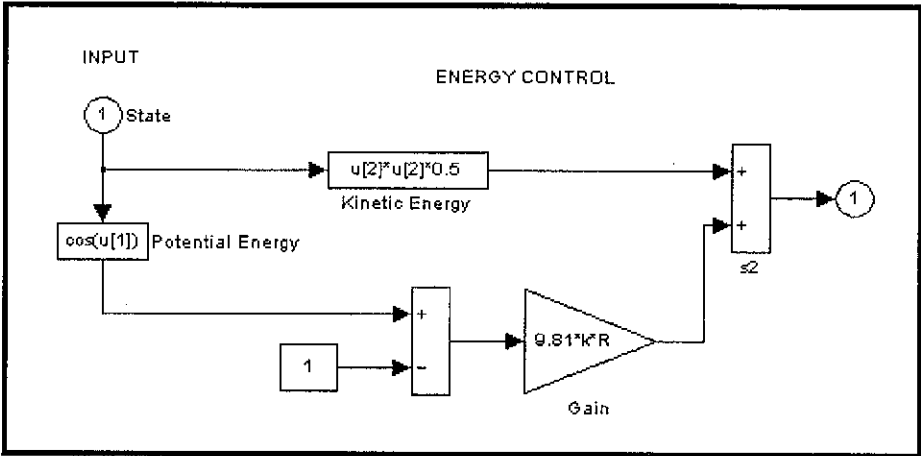
Appendix C.1 Swing-up controller algorithm



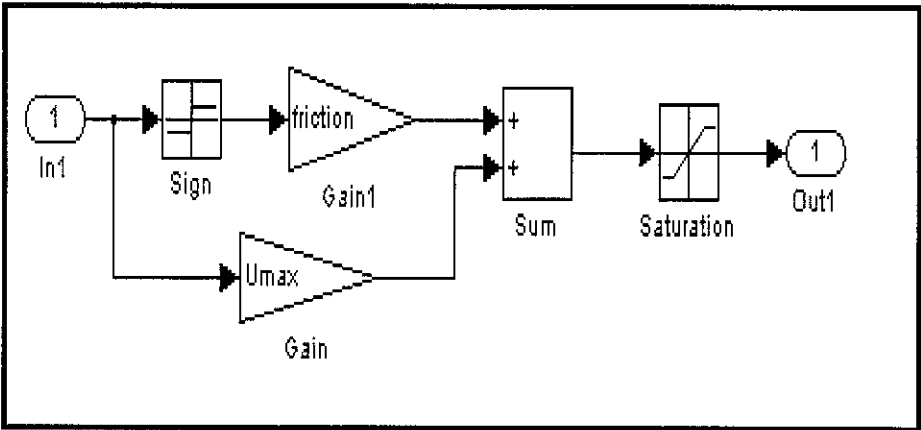
Appendix C.2 Block diagram of the swing-up controller



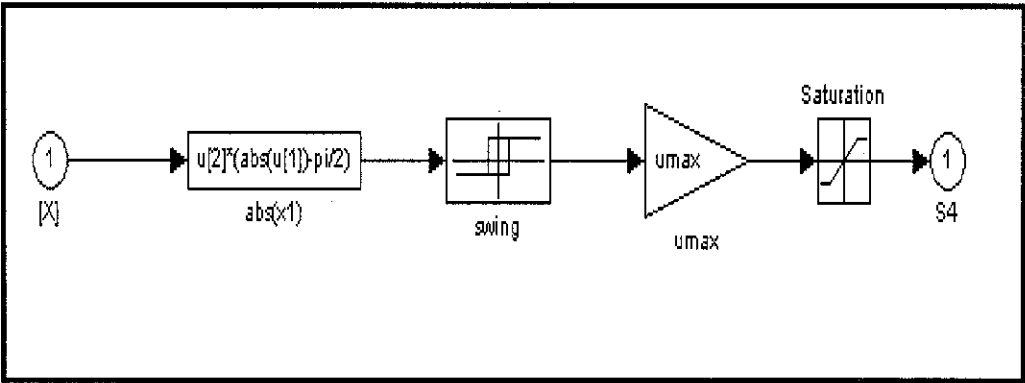
Appendix C.3 Linear controller



Appendix C.4 Soft landing arbiter



Appendix C.5 Coulomb friction and control gain



Appendix C.6 Swinging controller