MODELLING AND POSITION CONTROL OF MS150 DC SERVOMOTOR USING FUZZY-PID HYBRID CONTROLLER

By

TAN YEK WHA

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2012

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.

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Tan Yek Wha

ABSTRACT

Servomotors are used in a variety of industrial applications, which required reliable and precise control of the servo motors on the mechanism's joints. The conventional feedback (FB) controller, which the Proportional-Integral-Derivative (PID) controller has good performances, while is not robust enough for non-linear system such as a motor. A feedforward (FF) compensator is added to the PID controller for the purpose of load disturbance rejection, and it had successfully increased the control performance by decreased the overshoot (O.S.) value when a load distribution is added. However, in order to obtain better control result, Proportional (P), Integral (I), and Derivative (D) parameters need to re-tune by every attempt of load changes. Thus, intelligent control algorithms (IA) are indeed to compensate the lacking of an ordinary controller. The servomotor is mathematically modelled into MATLAB/SIMULINK to obtain a virtual model of a servomotor for simulation use. The model is used for the servomotor's position control simulation, and the control performances are compared among of the relevant conventional, fuzzy, and hybrid controllers. The PD controller gives the best result when no load is applied on MS150. Meanwhile, when a load disturbance is applied on MS150, PID controller performs the best, with the Integral (I) element brings the control performance to zero steady-state error (SSE). The Mamdani FLC with 7x7 MFs results in a better control performance compared to 5x5 and 9x9 MFs' FLC that it is able to produce smallest SSE. Yet, FLC has its drawbacks too. The SSE for FLC is hardly to eliminate and gives a slower response compare to PID controller. There still a 0.001 rad of SSE for the 7x7 MFs FLC, when a load is applied on the servomotor. Consequently, the idea of the hybrid of Fuzzy-PID was present to use each other's strengths to make up for each other's weaken points, and this control architecture was robust enough to the load changes and performed better with zero O.S. and SSE compare to the conventional controller and the ordinary FLC.

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Thank you.

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LIST OF ABBREVIATIONS

AC	Alternative Current
CV	Controlled Variable
D	Derivative
DC	Direct Current
EMF	Electromagnetic Force
FB	Feedback
FF	Feedforward
FFPID	Feedforward with Proportional-Integral-Derivative controller
FIS	Fuzzy Inference System
FL	Fuzzy Logic
FLC	Fuzzy Logic Controller
FLIC	Fuzzy Logic parallel Integral Controller
FLPID-P	Fuzzy Logic parallel Proportional-Integral-Derivative controller
FLPID-S	Fuzzy Logic series Proportional-Integral-Derivative controller
FYP	Final Year Project
I	Integral
IA	Intelligent Algorithms
KVL	Kirchhoff's Voltage Law
MF	Membership Function
NNC	Neural Network Control
O.S.	Overshoot
P	Proportional
PD	Proportional-Derivative
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
P-only	Proportional only
PV	Process Variable
SP	Set Point
SSE	Steady-State Error
TF	Transfer Function
ZN	Ziegler-Nichol

NOMENCLATURES

$v_a(t)$	Input voltage
$i_a(t)$	Armature voltage
R_a	Resistance
L_a	Inductance
$\emptyset$	Magnetic flux
$K_{i,} K_o$	Gain of IP/OP Potentiometer
K_g	Gain of Tacho Generator
K_{op}	Gain of Op Amplifier
K_{au}	Gain of attenuator unit
K_{pa}	Gain of pre-amplifier
K_{sa}	Gain of Servo Amplifier
K_t	Torque constant of motor
K_b	Back EMF constant of motor
J_m	Inertia of motor rotor
J_L	Inertia of additional inertia disc
B_m	Viscous friction coefficient of motor shaft
B_L	Viscous friction coefficient of load shaft
τ_a	Electrical time constant
τ	Mechanical time constant
K_p	Proportional gain
K_I	Integral gain
K_D	Derivative gain
$e(t)$	Error signal
$y(t)$	Control signal
$K_{p\text{-}u}$	Ultimate gain
P_u	Ultimate period
e	Error
Δe	Change of error
Δu	Change of output control signal
Δe_P	Change of proportional gain
Δe_I	Change of integral gain
Δe_D	Change of derivative gain
t_r	rising time
t_s	settling time

CHAPTER 1

INTRODUCTION

According to the Robot Institute of America (1979), a robot is a programmable, multifunctional manipulator designed to move material, parts, tools or specialized devices through various programmed motions for the performance of a variety task. The advantages of a robot manipulator are: they are replacing human operators who involve hard reaching places, monotonous task and dangerous environments, such as fire, chemicals, nuclear facilities, underwater and etc. to complete a task efficiently and effectively in a higher accuracy [2]. The major problem to study with a robot control is the mathematical modelling of the robot arm and the actuators on the manipulator. These mainly involves the analysis, modelling, and control of the direct current (DC) motor that drive each joint of a robot. Therefore, modelling, analysis and control of the DC motor are the crucial parts of a servomechanism control. Henceforth, this study is focused on the modelling and control of DC motor.

1.1 Background of the study

Servomechanisms are used in most industrial applications like manufacturing, logistic, biomedical, cars, outer space and recently in the military field [21] that include precision control on the servomotor of their joints [14]. Servomotor uses FB controllers to control the operation. The basic continuous FB control, which is PID controller, has good control performance but it is not robust enough when there is disturbance. The fuzzy logic system that using the linguistic solutions is suitable for handling the non-linear dynamics such as servomechanisms. However, the control response of the FLC is slower than a PID controller and its SSE is difficult to eliminate. Thus, it is probable that the hybrid of PID and Fuzzy Logic control system can overcome the problem of FLC as well as compensate the drawback of a conventional controller.

The system identification technique is used to mathematically derive a transfer function (TF) of the system, to build a virtual control model that almost equivalent to the real MS150 system. The model is used for the position control simulation and the control performances are compared among of the relevant conventional, fuzzy, and hybrid controllers. The project is aiming to improve the controller's performance by hybridizing the Fuzzy and PID controller.

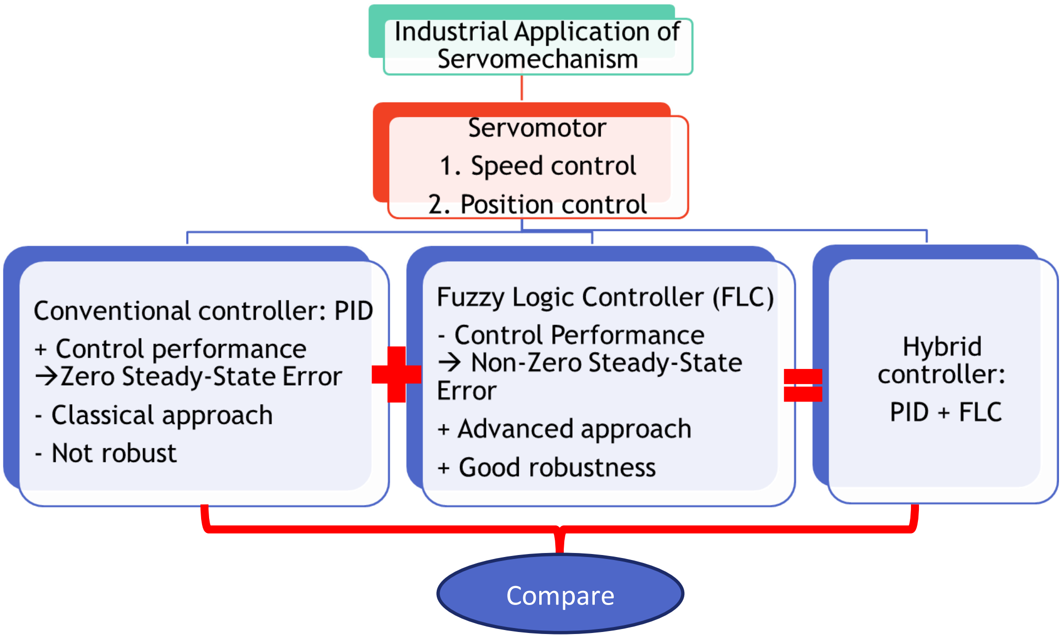


Figure 1: Overview of study background

1.2 Problem Statement

During the past few decades, servomechanisms have become important in most industrial applications. They serve as intelligent alternatives for man into many unknown and unreachable explorations. As the applications of servomechanism have been increasing in numbers, the demand imposed on their reliability and precision operation have also to be increased simultaneously with the growth of the complexity of the mechanism and the automation control area.

As mention previously, modelling, analysis and control of the DC motor that drive each joint of a robot are the very important parts of a servomechanism control. Henceforth, this study is focused on the modelling and control of DC motor.

The conventional controller (PID) was unable to provide adequate control performance for load disturbances, while FLC alone as an intelligent controller demonstrates in inadequate control performance. Thus, the advance control algorithms such as a hybrid controller are indeed to compensate the lacking of the ordinary controller.

1.3 Objective

The aims of the project are to design and develop an advanced controller, which is the hybrid PID-Fuzzy controller for servomotor application and to investigate the control performance of PID, Fuzzy and Hybrid PID-Fuzzy controllers.

1.4 Scope of study

The main scopes of this project consist of research, modelling, simulation, and analysis results. The researches in this final year project (FYP) help the student to understand about the new technology, which is the FLC in controlling the servomechanism. Then, the basic knowledge and the techniques learnt from researches will be applied to model the servomotor into MATLAB/SIMULINK to obtain a virtual model of servomotor. Lastly, again the basic knowledge of control will be applied to improve the simulation testing and analyzing project outcomes. The simulation will be done by using MATLAB/SIMULINK to present the final results.

This project required of the fundamental knowledge about the MS150 servomotor and servomechanisms such as crane and robot arms. It also required the control knowledge about the FLC and the Fuzzy-PID Hybrid Controller too.

CHAPTER 2

LITERATURE REVIEW

This chapter provides an overview of the project related research topics, followed by the basic theories starts with DC servomotor, PID controller, FLC and finally the Hybrid of Fuzzy-PID Controller. The work main related papers were summarized in a table attached in APPENDIX I.

8 main study related research topics had been studied, which from the year of 1998 to 2010. Paper number 7 will be the main reference throughout the project. The study outcome shows that both PID and FL controllers have the advantages and disadvantages. However, each of the controllers has the qualities that the other lacks. 5 out of 8 papers show that better control performance can be obtained by the hybrid of FLC and PID controller. Table 1 reviews the research summary, which had majorly compared PID controller and FLC on the control performance and robustness features.

Table 1: PID versus FLC

Controller	**Proportional- Integral-Derivative Controller (PID)**	**Fuzzy Logic Controller (FLC)**
Control Performance	Improve the transient response and steady-state error at the same time.	Slow response, The steady - state error of the controlled variable is difficult to eliminate.
Robustness	Not robust: Parameters are fixed during operation, Based on a linear system.	Better robustness: Suitable for handling uncertain, non-linear and mathematically intangible dynamics, Wider range of operating conditions and customizable (linguistic control rules).
Others	Traditional approach	Advance approach, But need experiences and skills

2.1 Servomotor

The servomotor is an electric motor that has control system components. Any motor can be used in a servo system and there are two types of motors, which are DC motors and alternative current (AC) motors [1]. DC motor is a common actuator in many mechanical systems and industrial applications such as industrial robots, educational robots, different types of cranes and etc. [11, 14, and 21]. DC motors are preferable in industrial application because they have better starting torque compare to AC motors, although they are more expensive than AC motors [3].

A DC motor has two main components, electrical component and mechanical component. Figure 2 shows the schematic of the armature controlled DC motor with a fixed field circuit.

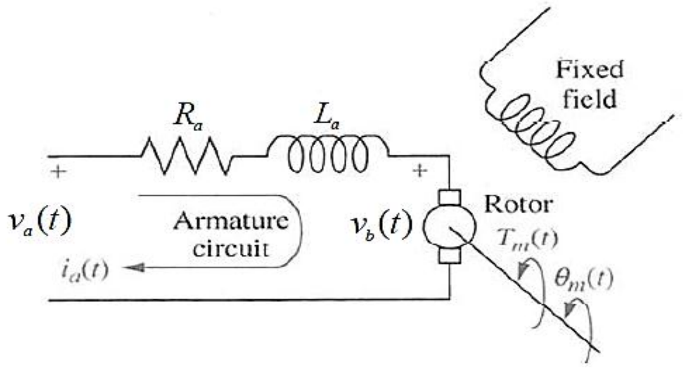


Figure 2: Schematic of DC motor system [5, 6]

In modelling of the DC motor, the motor is divided into three major components of the equation: electrical equation, mechanical equation, and electro-mechanical equation [7]. The electrical equation for a DC motor system is obtained based on Kirchhoff's Voltage Law (KVL) as follows:

$$v_a(t) - v_b(t) = L\frac{\partial i_a(t)}{\partial t} + Ri_a(t) \qquad (2.1)$$

The mechanical equation is obtained as follows, based on Newton law of motion:

$$T_m(t) = J\frac{\partial^2 \theta_m(t)}{\partial t^2} + B\frac{\partial \theta_m(t)}{\partial t} \qquad (2.2)$$

When the input voltage $v_a(t)$ is applied, the armature current $i_a(t)$ goes through resistance R_a and inductance L_a producing magnetic flux, ∅ and causing the motion of the rotor according to the motor torque as illustrated in the following equation.

$$T_m(t) = K_t i_a(t) \qquad (2.3)$$

The back electromagnetic force (EMF) was induced by the angular speed of the motor shaft as follows:

$$v_b(t) = K_b \omega_m(t) = K_b \frac{\partial \theta_m(t)}{\partial t} \qquad (2.4)$$

Substituting Eq. (2.4) into Eq. (2.1) and Eq. (2.3) into Eq. (2.2) the results are:

$$V(t) = L \frac{\partial i_a(t)}{\partial t} + R i_a(t) + K_b \frac{\partial \theta_m(t)}{\partial t} \qquad (2.5)$$

$$and$$

$$K_t i_a(t) = J \frac{\partial^2 \theta_m(t)}{\partial t^2} + B \frac{\partial \theta_m(t)}{\partial t} \qquad (2.6)$$

Transforming the above two equations using Laplace transform to obtain the two equations as follows:

$$V(s) = sLI_a(s) + RI_a(s) + sK_b\theta_m(s) \qquad (2.7)$$

$$and$$

$$K_t I_a(s) = s^2 J\theta_m(s) + sB\theta_m(s) \qquad (2.8)$$

Substituting Eq. (2.7) and Eq. (2.8) gives the motor TF,

$$G_{motor}(s) = \frac{\Omega_m(s)}{V_a(s)} = \frac{K_t}{JLs^2 + (JR + BL)s + BR + K_t K_b} \qquad (2.9)$$

In 2007, Lacevic et al. [4] performed an experiment of speed and position control in cascade mode shows that the position is the time integral of speed. Hence, the TF of the motor position is determined by multiplying the transfer function of the motor speed by the term $\frac{1}{s}$:

$$G_{position}(s) = \frac{\theta_m(s)}{V_a(s)} = \frac{K_t}{s[JLs^2 + (JR + BL)s + BR + K_t K_b]} \qquad (2.10)$$

The schematic diagram in Figure 2 is modelled as a block diagram in Figure 3. This block diagram represents an open-loop system, and the motor has built-in FB EMF, which tends to reduce the current flow. Block diagram gives a clear picture of the TF relation between each block of the system.

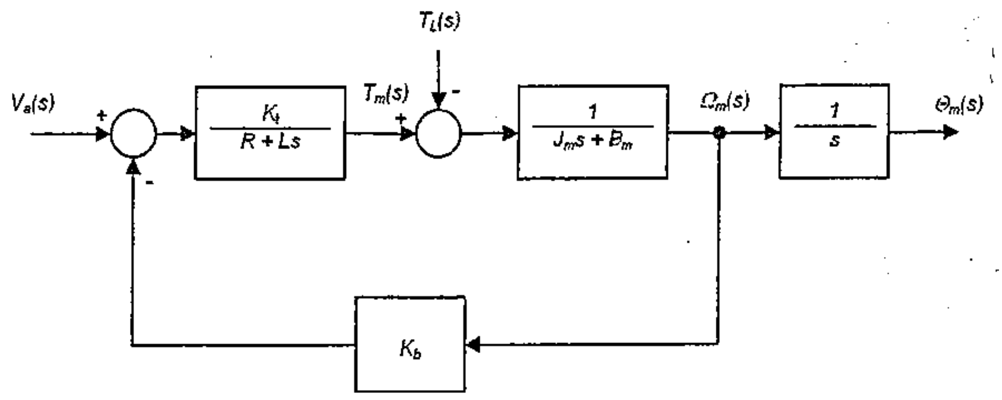


Figure 3: Reduce Block Diagram of DC motor system [6]

From the instruction manual of the MS150, the system parameters were summarized in Table 2 [8].

Table 2: The main system parameters of MS150

Parameter	Values
Gain of IP/OP Potentiometer	$K_{i/o} = 4.8\ V/rad$
Gain of Tacho Generator	$K_g = 0.025\ V/rad/s$
Gain of Op Amplifier	$K_{op} = 10$
Gain of attenuator unit	$K_{au} = 0.256$
Gain of pre-amplifier	$K_{pa} = 25$
Gain of Servo Amplifier	$K_{sa} = 2$
Resistance of armature of motor	$R = 3.2\Omega$
Inductance of armature of motor	$L = 8.6 \times 10^{-3} H$
Torque constant of motor	$K_t = 3.3 \times 10^{-3} Nt\ m/A$
Back EMF constant of motor	$K_b = 100 \times 10^{-3}\ V/rad/s$
Inertia of motor rotor	$J_m = 30 \times 10^{-6}\ kg\ m^2$
Inertia of additional inertia disc	$J_L = 412 \times 10^{-6} kg\ m^2$
Viscous friction coefficient of motor shaft	$B_m = 50 \times 10^{-6}\ Nt\ m\ s$
Viscous friction coefficient of load shaft	$B_L = 160 \times 10^{-6} Nt\ m\ s$

To study the behaviour of the DC motor when no load, substitute the parameter values of DC motor from Table 2 into equation (2.9). The open loop transfer function of the motor is:

$$G_{motor}(s) = \frac{\Omega_m(s)}{V_a(s)} = \frac{3300}{0.258s^2 + 96s + 490} \qquad (2.11)$$

The block diagram of the plant is shown in Figure below.

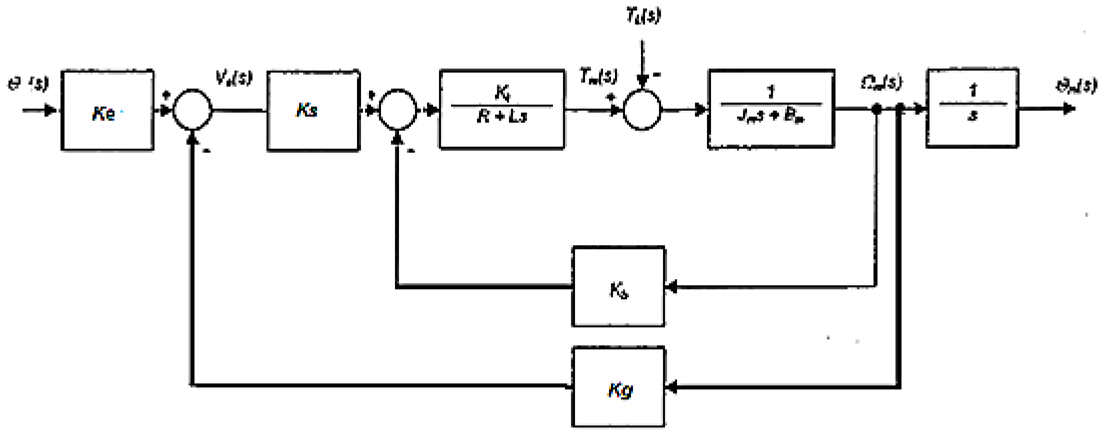


Figure 4: Block Diagram of the MS150 Modular

The system transfer function for the system can be derived from the analysis and results in [9, 10] as:

$$H(s) = \frac{\theta_0(s)}{\theta_i(s)} = \frac{K_{i/o}\,K_s K_t}{RBs(1+\tau_a s)(1+\tau s) + \left(K_t K_b + K_t K_s K_g\right)s} \qquad (2.12)$$

Where $K_s = K_{op}K_{au}K_{pa}K_{sa}$, $\tau_a = L/R$, and $\tau = J/B$. Substituting the system parameters into Eq. (2.12), the TF for no load case is,

$$H_1(s) = \frac{\theta_0(s)}{\theta_i(s)} = \frac{2027520}{0.258s^3 + 96s^2 + 11050s} \qquad (2.13)$$

However, since the electrical time constant, $\tau_a$can be negligible compares to the mechanical time constant, τ Eq. (2.12) can be simplified to

$$H(s) = \frac{\theta_0(s)}{\theta_i(s)} = \frac{K_{i/o}\,K_s K_t}{RJs^2 + \left(RB + K_t K_b + K_t K_s K_g\right)s} \qquad (2.14)$$

Substituting the system parameters into Eq. (2.14), the TF for no load case becomes,

$$H_2(s) = \frac{\theta_0(s)}{\theta_i(s)} = \frac{21120}{s^2 + 115.1s} \qquad (2.15)$$

2.2 PID controller

Traditionally, servomotors use FB controllers to control their operations. The conventional continuous FB control is PID controller has good performance for a huge number of control applications. Since the development of PID control in 1910 and Ziegler-Nichols' (ZN) tuning method in 1942, PID controllers became popular in control engineering due to their simplicity of implementation and design. The ability to be used in a variety of applications also made it to be famous [11]. Moreover, PID controller is available at low cost and it able to provide robust and reliable performance for most systems if the parameters are tuned properly. According to [11, 12], PID controllers or PID variations (P-only, PD, and PI) are widely used in more than 90% to 95% of control applications. However, it has the limitation. PID controller can gives only satisfactory performance if the requirement is reasonable linear and the process parameters change are limited.

PID is a type of FB controller output a control variable (CV), based on the error between user-defined set point (SP) and measured process variable (PV). Each element of the PID controller refers to a particular action taken on the error:

i. **Proportional gain, K_p:** It act as an adjustable amplifier that responsible for system or process stability. If K_p is set too low, the PV can drift away, while, too high of K_p will lead PV to large overshoot and oscillatory response.

ii. **Integral gain, K_I:** Integral control tends to reduce the effect of SSE that may be caused by the K_p, where a small integration time result a fast changing to the PV [12]. Hence, K_I is responsible to drive the SSE to zero. However, when K_I is set too high, it tempts oscillation or instability for the system.

iii. **Derivative gain, K_D:** A derivative term which tends to adjust the response as the process approaches the SP. Hence, K_D is responsible for system or process response. Therefore, too small of K_D will brings the PV to aggressive, while, too big of K_D leads the PV to slow response.

Table below summarized the effect of increasing a PID parameter independently.

Table 3: The effect of increase a PID parameter independently

Parameter	Steady-State Error (SSE)	Overshoot (O.S.)	Settling time, t_s	Rising time, t_r	Stability
K_p	Decrease	Increase	Small change	Decrease	Degrade
K_I	Eliminate	Increase	Increase	Decrease	Degrade
K_D	Theoretically no effect	Decrease	Decrease	Minor change	Improve if K_D is small enough

PID algorithm can be implemented in different forms depending on the process and control requirements. There are two types of system combination, which are parallel and series. The easiest form introduced is the parallel form, as shown in Figure 4, where the P, I and D elements has the same input signal, error, *e* (*t*).

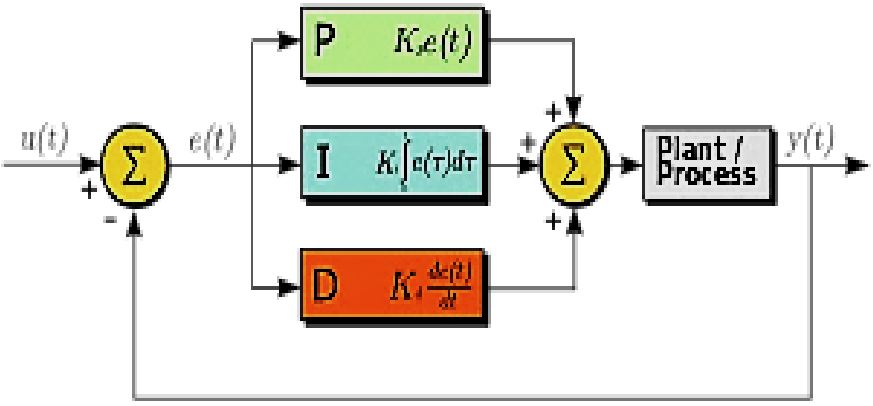


Figure 5: Parallel PID controller structure

The terms, K_p, K_I and K_D stand for the proportional, integral, and derivative gains. The terms *e*(*t*) and *y*(*t*) represent the error and the control signal respectively. The TF of the PID controller in parallel is:

$$G_{PID,Parallel}(s) = K_p + \frac{K_I}{s} + K_D s \qquad (2.16)$$

The parameters of PID controller can be set using manual tuning method, ZN tuning method, Cohen Coon tuning method (open-loop tuning) and etc. Table 4 below shows the advantages and disadvantages of these tuning methods.

Table 4: The comparisons between different types of tuning method

Method	Advantages	Disadvantages
Manual tuning	- No math required. - Online method	- Requires experienced personnel
Ziegler-Nichols tuning	- Proven method. - Online method	- Trial-and-error method, very aggressive tuning.
Cohen-Coon tuning	- Good process models	- Some math. - Offline method. - Only good for first-order processes.

Whereas, ZN tuning method can be divided into 2 types, which are ZN Process Reaction-Curve (PRC) method (ZN open-loop tuning method) and ZN ultimate cycle method (ZN closed-loop tuning method).

ZN open-loop tuning method is based on the process reaction curve (PRC) of the open-loop system or process [24]. It needs the PRC to determine the dead time, Θ, the time constant, τ, and the value when the process response reaches steady-state, X_u, for a step change of X_0, which the loop tuning constants, K_0 can be calculated as following,

$$K_0 = \frac{X_0}{X_u} \cdot \frac{\tau}{\theta} \qquad (2.17)$$

Hence, it also named as ZN PRC tuning method. The three combinations of PID controller as below:

Table 5: PID parameters by ZN open-loop tuning method

Control Type	K_p	K_I	K_D
P-only	K_0	-	-
PI	$0.9K_0$	$3.3\,\Theta$	-
PID	$1.2K_0$	$2\,\Theta$	$0.5\,\Theta$

ZN closed-loop tuning method is suitable to apply only to system or process that have a time delay or having dynamics of third or higher order [25]. For this tuning method, if K_{p-u} is the ultimate value of K_p, whereby the value of K_p which the output response is constant oscillation and P_u is the ultimate period of oscillation [11, 15].

The three combinations of PID controller are shown at Table 6 below.

Table 6: PID parameters by ZN closed-loop tuning method

Control Type	K_p	K_I	K_D
P-only	$0.50K_{p-u}$	-	-
PI	$0.45K_{p-u}$	$1.2K_p/P_u$	-
PID	$0.60K_{p-u}$	$2K_p/P_u$	$K_pP_u/8$

2.2.1 Feedforward PID Controller (FFPID)

Disturbance is the concern in most of the control systems or process. Any system may have unpredictable inputs which are the disturbances that drive the system away from its desired task [27]. The algorithm that combined FF with FB controls can significantly improve the system's performance compared to just a simple FB control. In the most ideal condition, FF control can completely eliminate the effect of the measured disturbance. Even when there are modelling errors, FF control still can reduce the disturbance effect better than FB control alone. The following table shows the comparison between FF and FB controller.

Table 7: Feedforward controller versus feedback controller

Controller	Feedforward	Feedback
Advantages	- Compensates for disturbance before system output is affected - Does not affect the system stability	- Provides zero SSE - Effective for all disturbances
Disadvantages	- Cannot eliminate SSE - Requires a sensor and model for each disturbance	- Does not compensate until the system output deviates from its SP - Affects the control system stability

Table 7 shown that the idea for the combination of FF and FB controller was to use each other's strength to make up for each other's weakening point.

As shown in the reduce block diagram of DC motor in Figure 3 load torque will be the external disturbance for a servomotor. Hence, FFPID should eliminate the load disturbance input to drive the output to response to the desired input. The load disturbance on the motor is considered as disturbance input that will be rejected by the FF compensator. The block diagram of FFPID can be drawn as Figure 5.

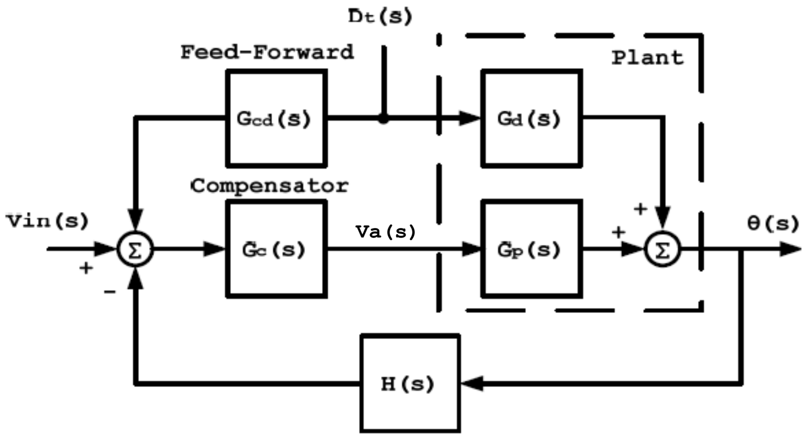


Figure 6: Feedforward compensator structure [26]

As mention before, a DC motor have 2 major components, which are electrical component and mechanical component. Assume that the $G_1(s)$, is the electrical part that contains the resistor R and the inductance L and, $G_2\ (s)$, is the mechanical part, which containing the inertia, J and the viscous friction, B elements. By using the superposition method, the total output TF will be as below.

$$\theta(s) = \frac{K_t G_1(s) G_2(s)}{1 + G_1(s) G_2(s) K_t K_b} V_a(s) + \frac{G_2(s)}{1 + G_1(s) G_2(s) K_t K_b} D_t(s) \qquad (2.18)$$

$$\theta(s) = G_p(s) V_a(s) + G_d(s) D_t(s) \qquad (2.19)$$

$G_p(s)$, is the plant that guided the input, $V_a(s)$ to the output, while, $G_d(s)$ is the TF from disturbance input, $D_t(s)$ to the output.

However, as the FB controller, $G_c(s)$ was adding to control model. The TF will be as following.

$$\theta(s) = \frac{G_c(s) G_p(s)}{1 + G_c(s) G_p(s) H(s)} V_{in}(s) + \frac{G_d(s)}{1 + G_c(s) G_p(s) H(s)} D_t(s) \qquad (2.20)$$

$$\theta(s) = T(s) V_{in}(s) + T_d(s) D_t(s) \qquad (2.21)$$

$T(s)$, is the plant from the input, $V_{in}(s)$ to the output, while, $T_d(s)$ is the plant from disturbance input, $D_t(s)$ to the output.

Since, this FFPID is designed to reject the disturbance input. Therefore, the FF controller, $G_{cd}(s)$ should reject the load disturbance input without affecting the plant, $T(s)$. The TF from the disturbance input to the output is:

$$T_d(s) = \frac{G_d(s) - G_{cd}(s)G_c(s)G_p(s)}{1 + G_c(s)G_p(s)H(s)} \qquad (2.22)$$

$T_d(s)$ have to reach zero in order to reject the load torque disturbance. Thus, the numerator of Eq. (2.20) should equal or approximately to zero. Consequently, $G_{cd}(s)$ will be good to reject the load torque disturbances, where

$$G_{cd}(s)G_c(s) = \frac{G_d(s)}{G_p(s)} \qquad (2.23)$$

The performance of the controller was depending on the $G_p(s)$ parameters and the type of the $G_c(s)$ controller. When the system controller is the conventional parallel PID controller, the final TF of the FF compensator, $G_{cd}(s)$ will be as following.

$$G_{cd}(s) = \frac{Ls^2 + Rs}{K(K_D s^2 + K_P s + K_I)} \qquad (2.24)$$

2.3 Fuzzy Logic Controller (FLC)

Fuzzy logic (FL) is based on fuzzy set theory that established by Lofti A. Zadeh in 1968. Unlike classical logic that only characterizes the results into true or false values, FL also indicates the degree of truthiness or falseness of each input. FL provides a systematic calculus to deal with incomplete information. It also performs numerical computation by using linguistic labels required by MF.

The basic principle of the FLC is to express operator's experiences into the IF-THEN rules. Every rule has two parts, condition part, which is the IF-PART of the rule, and outcome, which is the THEN-PART of the rule. The combination of such rules is called FL rule base. Generally, FLC contains of three principal components, which are fuzzifier, rule base and inference engine, and finally defuzzifier. The basic configuration of FLC can be seen in Figure 5 below:

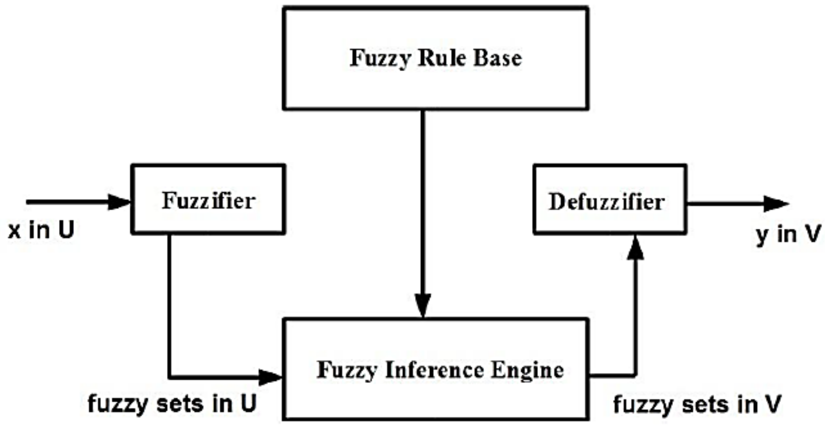


Figure 7: Basic configuration of fuzzy system [3]

Input will go through a fuzzification interface and then converted to linguistic signals. Subsequently, the rule base, which is a database that hold the decision-making logic are used to summarize the fuzzy output. Then, a defuzzification method uses to convert the fuzzy output from the interface engine to output [14].

Fuzzifier is where to define the MFs of input variables and output variables. It involves the conversion of the input and output signals into a number of fuzzy sets. Figure 6 shows an example input and output variables that are used in a MS150 system [15].

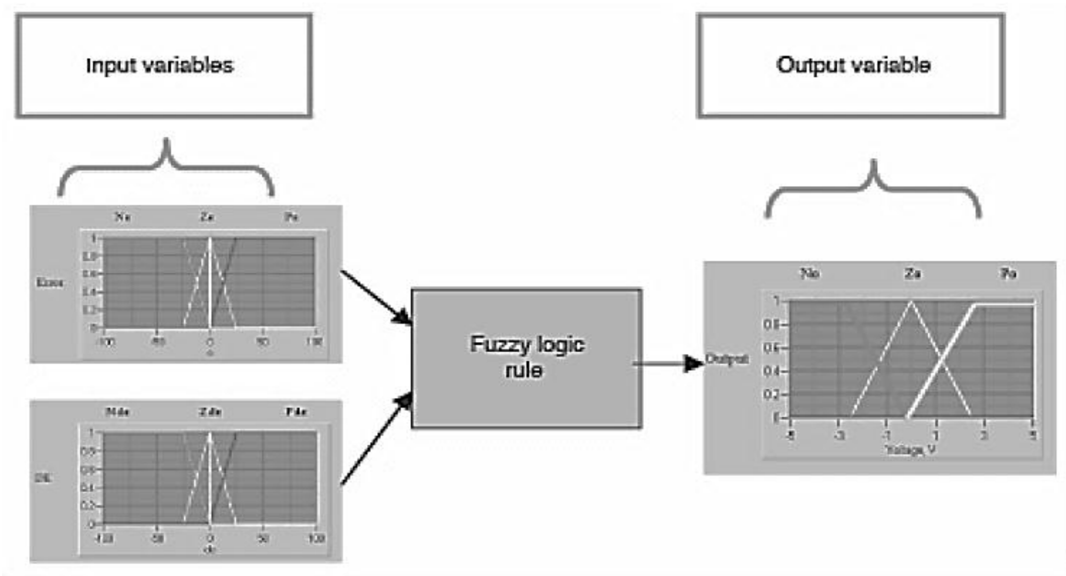


Figure 8: Fuzzification input and output variables [15]

The basic function of the rule base and inference engine is to represent the expert knowledge in a form of IF-THEN rule structure. The FL can be derived into an $n \times n$ rule which consists of n^2 rules. Figure 7 shows the examples of 3×3 fuzzy logic rules to control a MS150 servomotor [14].

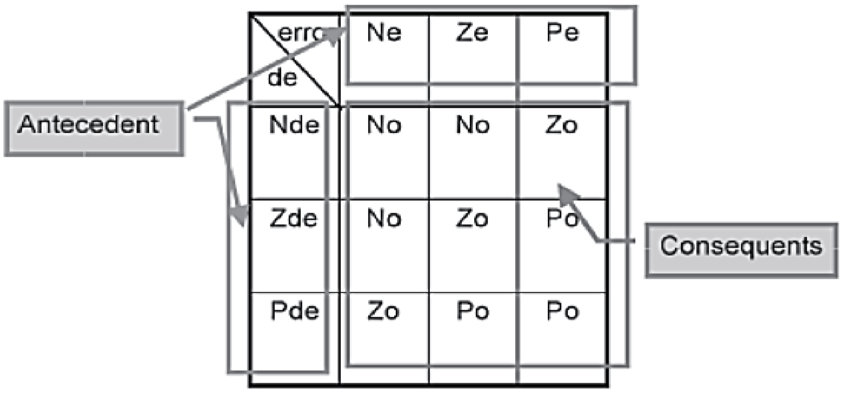


Figure 9: The Fuzzy Logic rules [15].

The fuzzy logic rules-based of example above is shown below.

1) If error is Ne AND de is Nde THEN output is No
2) If error is Ne AND de is Zde THEN output is No
3) If error is Ne AND de is Pde THEN output is Zo
4) If error is Ze AND de is Nde THEN output is No
5) If error is Ze AND de is Zde THEN output is Zo
6) If error is Ze AND de is Pde THEN output is Po
7) If error is Pe AND de is Nde THEN output is Zo
8) If error is Pe AND de is Zde THEN output is Po
9) If error is Pe AND de is Pde THEN output is Po

, where N is Negative, Z is Zero and P is Positive.

Finally, defuzzification is used to have a crisp value from the FLC. There are three types of defuzzifier, which are center of gravity defuzzifier, center average defuzzifier, and maximum defuzzifier [16]. The common defuzzifier that's been used in most research is center average defuzzifier, which it fulfills the three criteria in designing a defuzzifier: plausibility, computational simplicity, and continuity [3].

The center average defuzzifier is given by the algebraic expression:

$$s^* = \frac{\int s \cdot u_s(s)ds}{\int u_s(s)ds} \qquad (2.25)$$

The servomotor is an unpredictable non-linear system, which the ordinary PID controller was not robust enough to apply for it. Many literatures such as [3], [11], [17] and etc. shows FLC is an advance knowledge that can be well applied to the control of systems with disturbance and nonlinear dynamics to overcome the weakness of PID controllers. FLC also been investigated by which has good robustness compared to PID controller.

2.4 Hybrid controller

PID controller is the most popular control tool in many industrial applications due to the ability to improve the transient response as well as eliminate the SSE of the system at the same time. However, the parameters of PID controller are fixed during operation. This cause PID controller is inefficient to control a system, when the system is disturbed by unknown facts or have dynamic changes [3, 14].

As servomechanisms have become important in most industrial applications, the demand imposed on their reliability and precision operations have also increased simultaneously with the growth of the complexity of the mechanism and the automation control area. Consequently, classical PID controller that based on linear system theory has to simplify or linearize the non-linear systems before they can be used, yet this still without any guarantee to provide good performance [18].

The main difficulty in designing a nonlinear controller is the lack of a general structure [19]. In addition, most control solutions developed during the last few decades have been based on precise mathematical models of the systems. However, most of nonlinear systems are difficult to describe by mathematical relations precisely [14]. For this reason, these model-based design approaches may not provide satisfactory solutions. Consequently, this motivates the interest in using FLC.

FL systems are the suitable approach for handling uncertain and non-linear dynamics to overcome the weakness of a traditional controller using simple solutions [3]. FLC has several advantages over PID controllers, as FLC is cheaper to develop. Its operation covers a wider range of operating conditions, more readily, customizable in linguistic terms, and provides short rise time and small overshoot for the controlled system [14].

However, the complexity of fuzzy controllers had increased exponentially with respect to the number of input variables. Furthermore, fuzzy controllers are similar to the standard Proportional-Derivative (PD) controllers, which the SSE of the CV is difficult to eliminate [20], and the response of a FLC is much slower than a PID controller.

Thus, it is probable to develop a controller that applying FLC with a conventional controller to overcome the problem of FLC as well as compensate the back draw of the conventional controller. There are a lot of literatures that show the effectiveness of hybrid fuzzy- PID controller on servomechanism in different application area, such as robot arm control [11], anti-swing on crane applications and furthermore, weapon control [21].

CHAPTER 3

METHODOLOGY

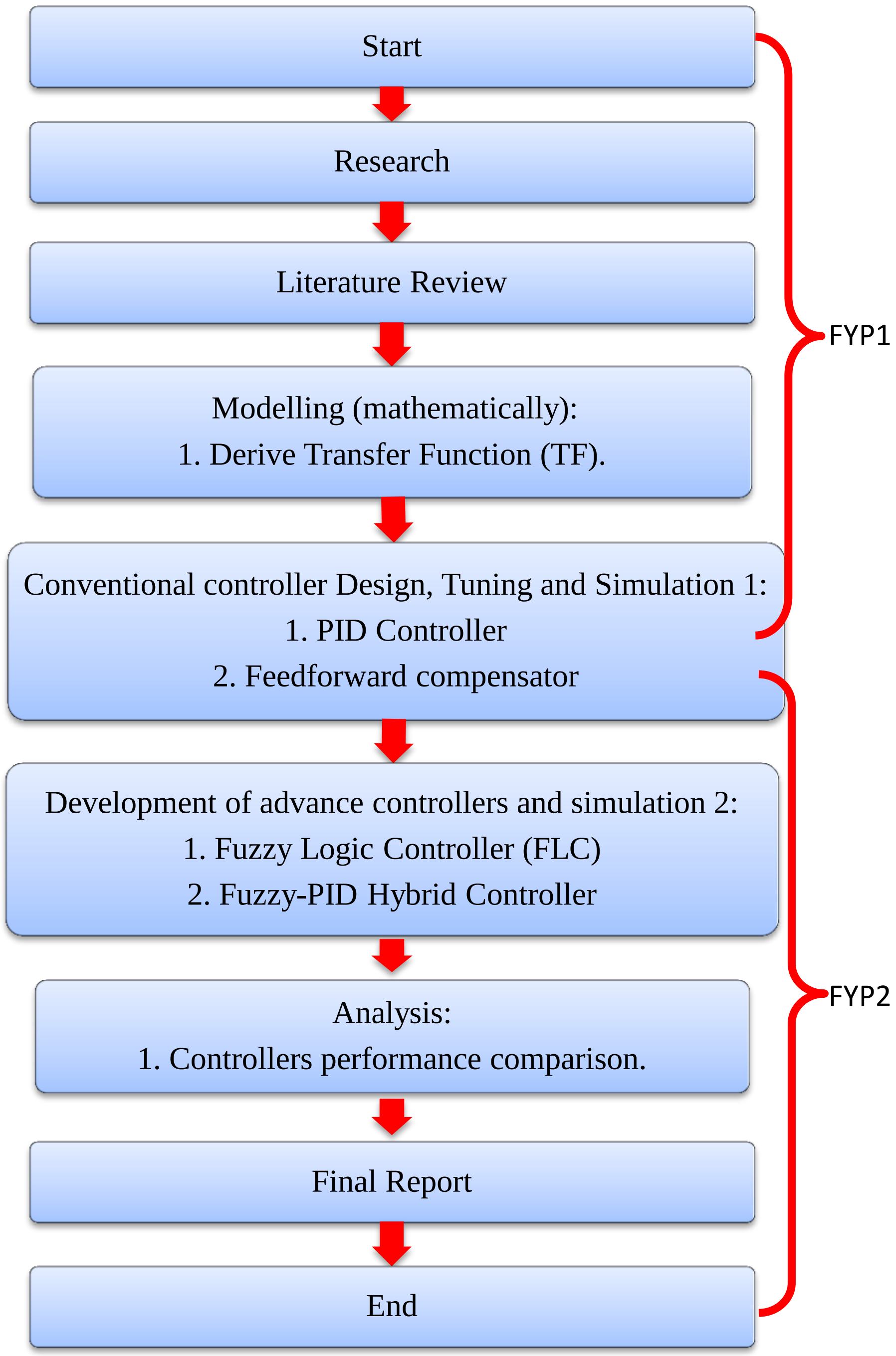


Figure 10: Project Activities Flow

This Final Year Project (FYP) is a simulation basic project that has 3 main parts, which are modelling the DC servomotor, designing and simulating the PID controller and advance controllers, which are FLC and the Hybrid of Fuzzy-PID. The important data will be obtained from the MS150 Servomotor Modular before modelling and controller designing process. The data then can be simulated by MATLAB/SIMULINK, which is using the control algorithms to alter the error signals to drive the servomotor to the desire response. As a consequence, this design can be the reference controller variables of the system to apply in various industries' servomechanisms. The details of the main parts on this project will discuss at the following units and the full project activities flow will show at APPENDIX II.

3.1 DC Servomotor Modelling

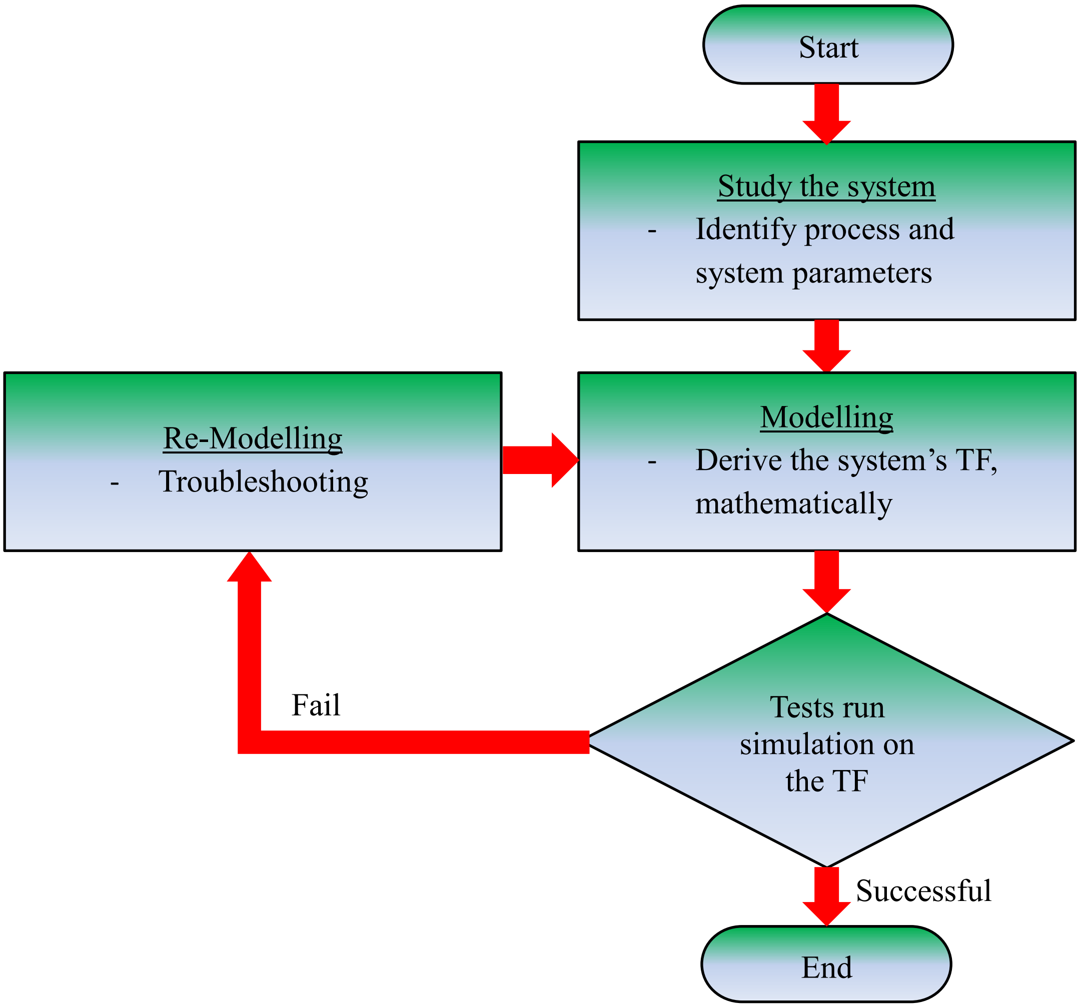


Figure 11: DC servomotor modelling flow.

The servomotor was modelled based on the Feedback group's educational purpose servomotor modular (MS150). System identification technique is using to identify MS150's important parameters, from the devices' name plates, manuals and etc. Henceforth, the TF of the DC servomotor can be derived mathematically to build a virtual servomotor plant in the MATLAB/SIMULINK that equivalent to the real servomotor system. The TF's mathematic derivation is shown in Chapter 2 and the system's block diagram will be show at Chapter 4.

3.2 PID controller design and simulation

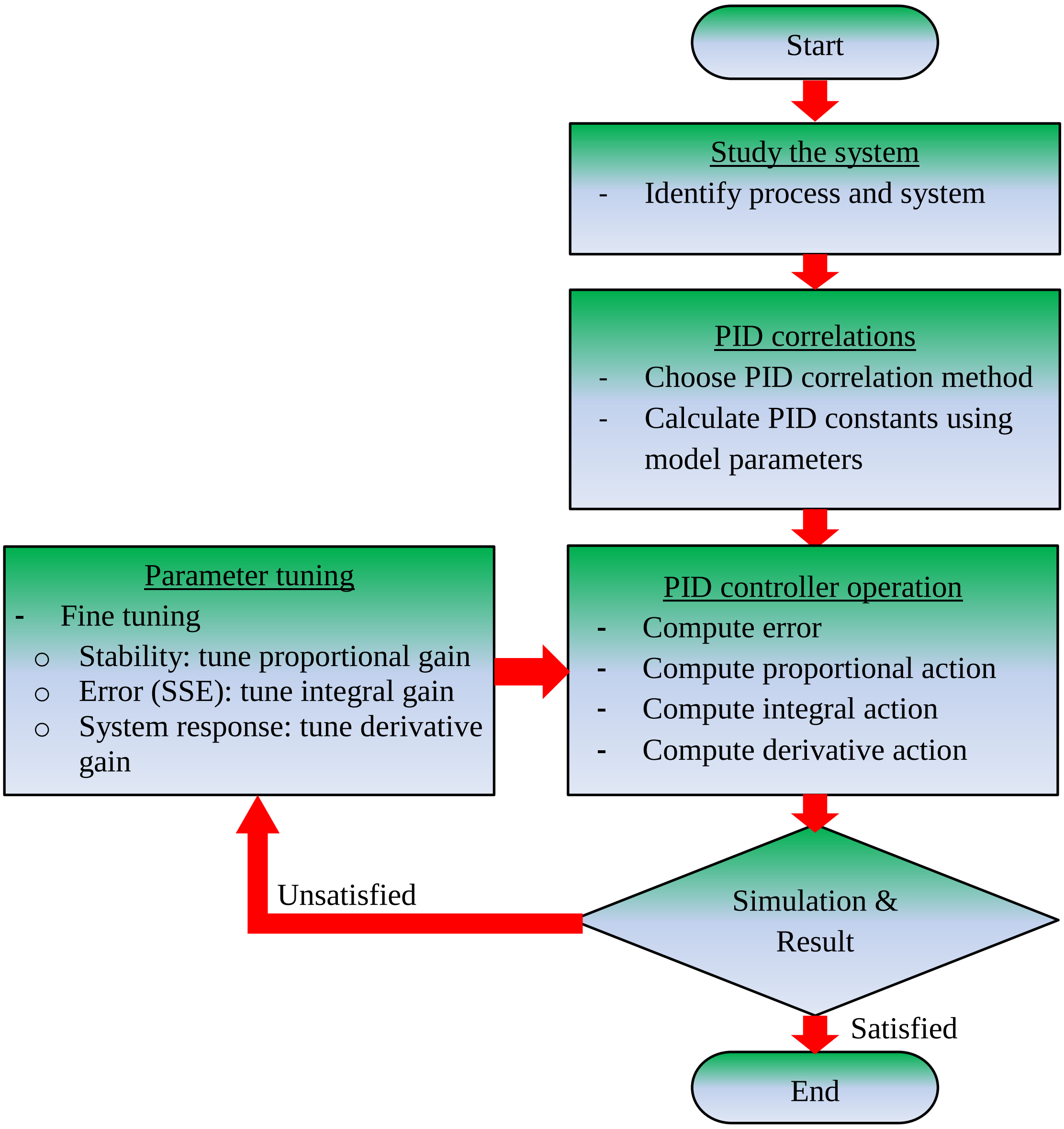


Figure 12: PID controller design and simulation flow.

Table 4 shows that the ZN tuning method is the suitable approach to get the PID controller's correlations. However, this method can be divided into open-loop tuning method and closed-loop tuning method. The ZN open-loop tuning method also named as ZN Process Reaction-Curve (PRC) method due to it is based on the PRC of the open-loop system. The most important criteria for the obtained PRC are it needs to reach steady-state within the process duration. Figure 13 shows the open-loop response of the MS150. It shows that the ZN open-loop tuning method is not suitable for the system because the open-loop system PRC does not reach steady-state when step is applied.

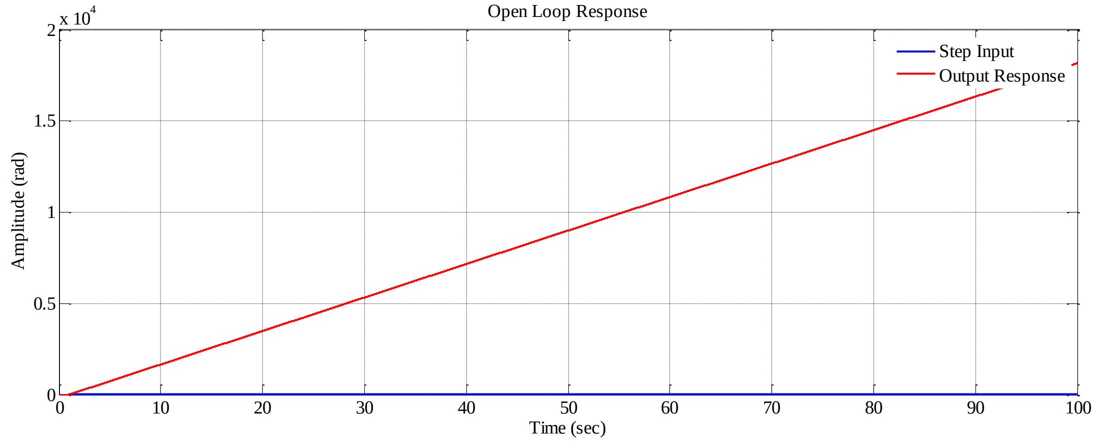


Figure 13: Open-loop response of MS150

Thenceforth, the ZN closed-loop tuning method that is suitable to apply on system that having dynamics of third or higher order is certainly used to obtain the ultimate values and then the PID controller's parameters. After obtaining the controller parameter, the system can be simulated and the control performance will be analysed. If the control performance was not reach satisfaction level, fine tuning will be carrying out using the trial-and-error method, based on the basic knowledge of control.

FF compensator also been applied to the system together with the PID controller to reject the external disturbance that cause the system output drift away from desire response. The TF of the FF sensor is derives as Chapter 2. The PID constants and some of the motor's parameters were applied on Eq. (2.24) to obtain the FF compensator's TF.

3.3 FLC design and simulation

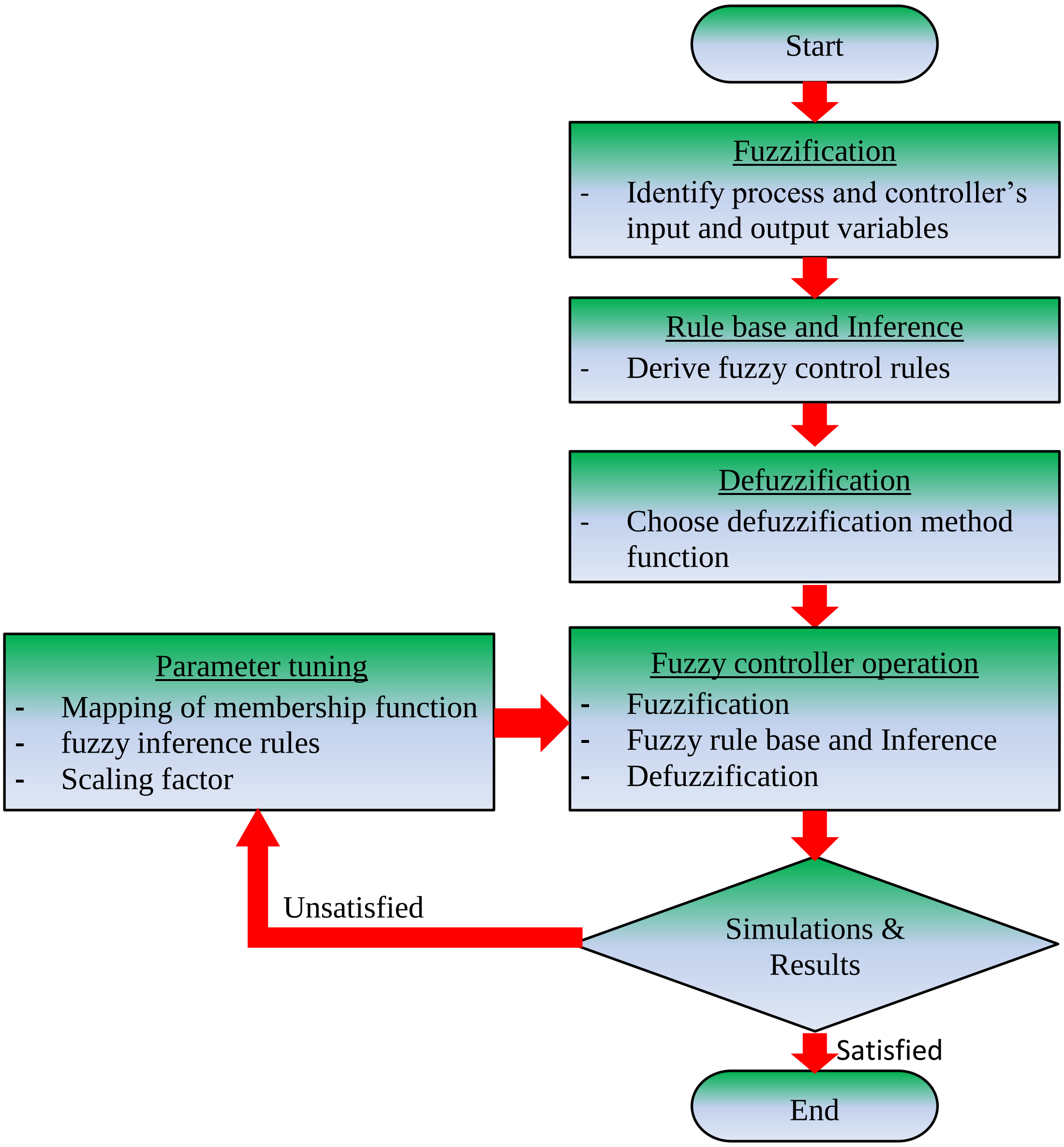


Figure 14: FLC design and simulation flow.

As Chapter 2, FLC comprises of three principal components, which are fuzzifier, rule base and inference engine, and finally defuzzifier. Thus, each of these components has to be design before FLC can operate on the servomotor system. After designing the controller, the system can be simulated using FLC. The control performance then will be analysed and compared with the PID controllers. Parameter tuning needs to be carried out if the control performance does not give satisfaction control response.

Besides, student also analyzes the effect of the number of rules and fuzzy logic MFs onto the system response in terms of SSE. Hence, the comparison is makes between 5 × 5, 7 × 7 and 9 × 9 FLCs to pick up the best FLC, with minimum SSE value to control the servomotor.

3.4 Fuzzy-PID Hybrid Controller design and simulation

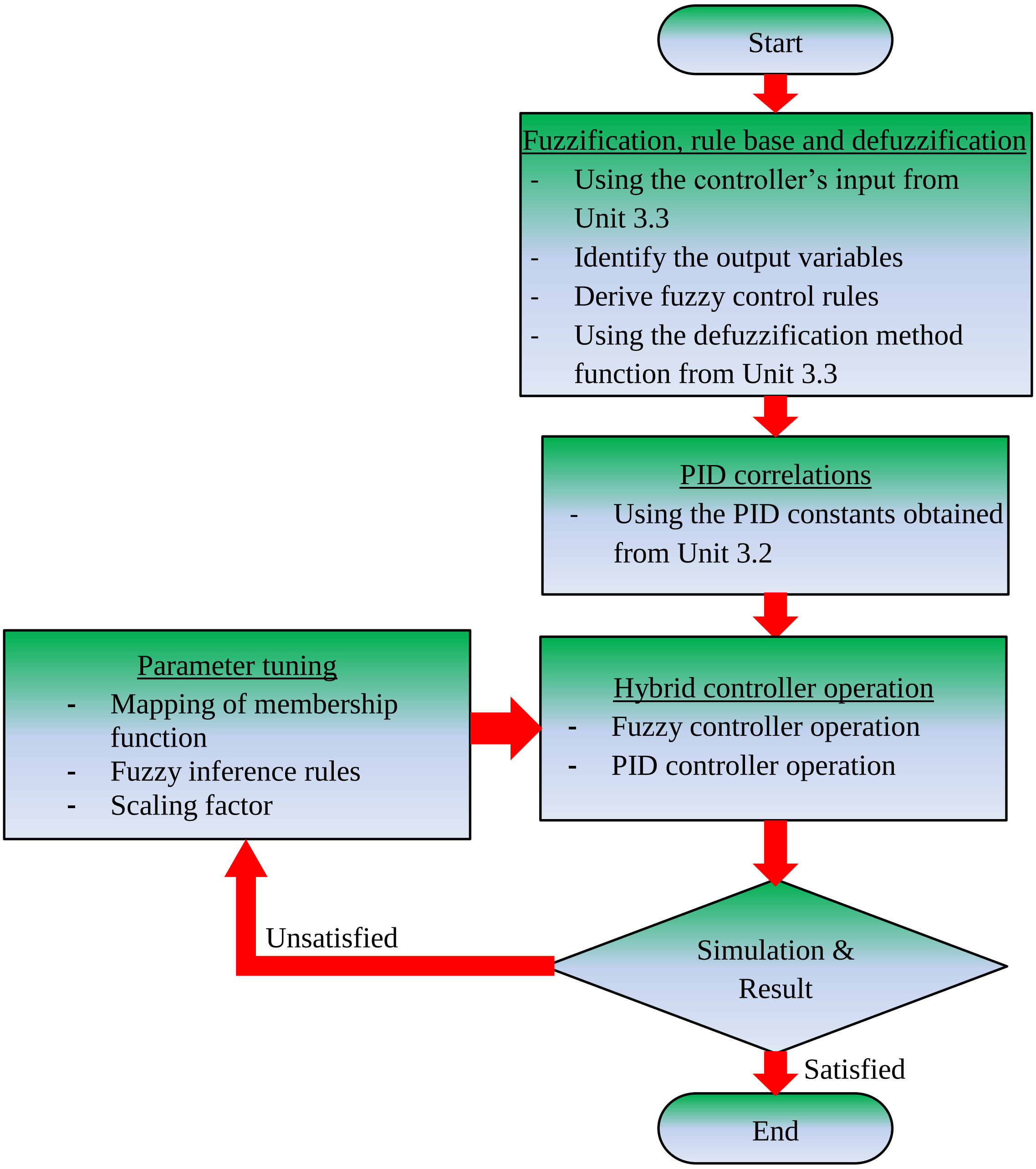


Figure 15: Fuzzy-PID Hybrid controller design and simulation flow.

Hybrid of FLC and PID controller is to apply the FLC together with the conventional PID controller to gain each other's strength and cope with their disadvantages. Therefore, each of these controllers has to be design or modify from the previous model before they can put with each other to operate jointly on the servomotor system. Minor or no modification will be done on PID controller, yet the output variable and rule base for the FLC needs to be redesigned to cope with the PID controller. From only one output, the FLC design at Unit 3.3 will be modify to three outputs, henceforth, the each output variable responsible to tune a P, I, or D parameter. Different types of combination, like FLC parallel with PID and FLC series with PID been designed and the controller performance will be analyse to identify the best hybrid combination for MS150. This Hybrid controller output response will be compare with the ordinary FLC and PID controller too.

The performance indicator in Figure 16 was an approach to obtain the value of overshoot (O.S), rising time, t_r, settling time, t_s and steady-state error (SSE). Designed controller is desired to have minimum value of overshoot (O.S), rising time, t_r, settling time, t_s and steady-state error (SSE). Parameter tuning needs to be carried out if the control performance does not give satisfaction control response.

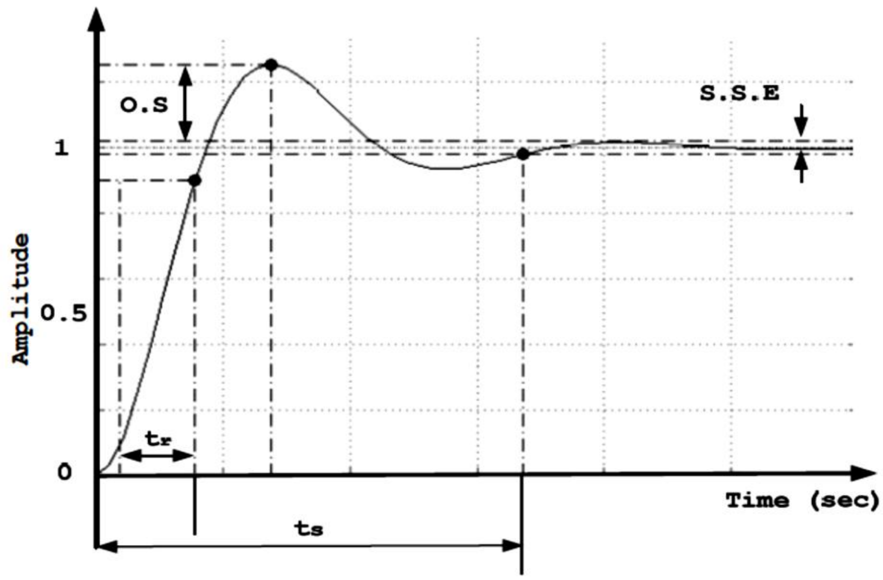


Figure 16: Control performance indicator.

3.5 Activities/Gantt Chart and Milestone

Please refer to APPENDIX III.

CHAPTER 4

RESULTS AND DISCUSSION

As described in Chapter 2, the Feedback Group's educational purpose servomotor been modelled and the motor's TF is shown at Eq. (2.11). However, to efficiently operate the servomotor modular there are some others equipment or encoders are needed. The input/output encoder that converts angular to the motor's input, which is the voltage, while, the tacho-generator feedback the motor's output speed to the motor in the form of voltage. The plant's TF is derived at Eq. (2.13) in Chapter 2. These TF is then modelled into subsystems as shown in APPENDIX IV.

Before any controller been applied the system been tested in two conditions in closed-loop, when no load disturbance and when a load disturbance is applied. Throughout the simulations the applied step change is 1 and load is 13.7 times of the motor shaft's weight. The closed-loop plant performance for these two conditions are shown as below.

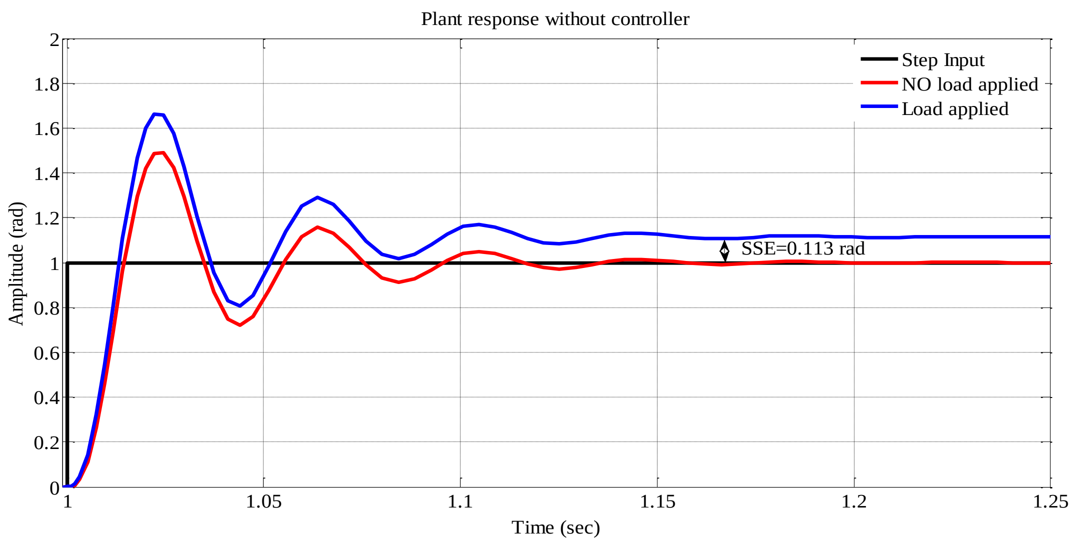


Figure 17: System responses before any controller been applied

The plant responses had been summarizing into Table 8 below.

Table 8: Control performances for MS150

	NO Load applied	Load applied
O.S (rad)	0.489	0.668
t_r (sec)	0.014	0.013
t_s(sec)	0.154	0.154
SSE (rad)	Zero	0.113

Load torque disturbance was effected the system's response. Even though this disturbance brings positive effect to the rising time, t_r, while, the steady-state offset was appear and the overshoot become higher with the appearing of load disturbance.

4.1 Conventional Controller (PID)

Figure 18 shows the block diagram of the MS150 Servomotor Modular controlling by PID controller. The subsystems of PID controller and MS150 modular were shown in APPENDIX IV.

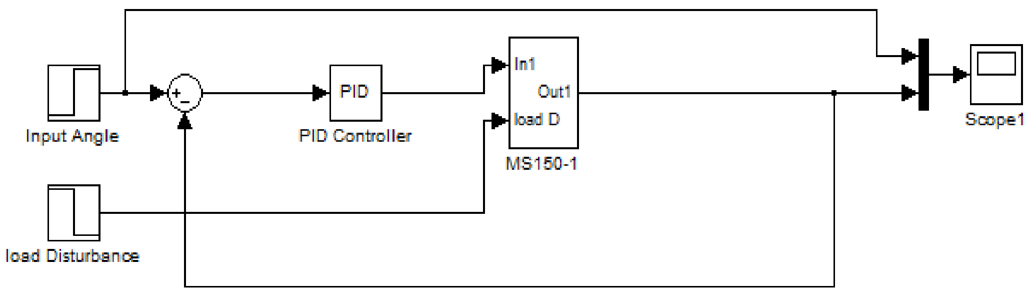


Figure 18: Block Diagram of plant controlling by PID controller.

4.1.1 Obtain ultimate values and PID controller parameters

The reason ZN ultimate tuning method is using to obtain the PID controller's parameters is explained in Chapter 3. In order to calculate the PID constants based on Table 6, the ultimate gain, K_{p-u} and ultimate period, P_u of the closed-loop system need to be obtained.

The ultimate value found by increasing the proportional gain, K_p in PID controller until system response is oscillating at the almost same amplitude and frequency, while, integral gain, K_I and derivative gain, K_D leave at zero to achieve the motor's ultimate response as Figure 19 below. The system reaches ultimate response when the proportional gain, K_p was 2.0373.

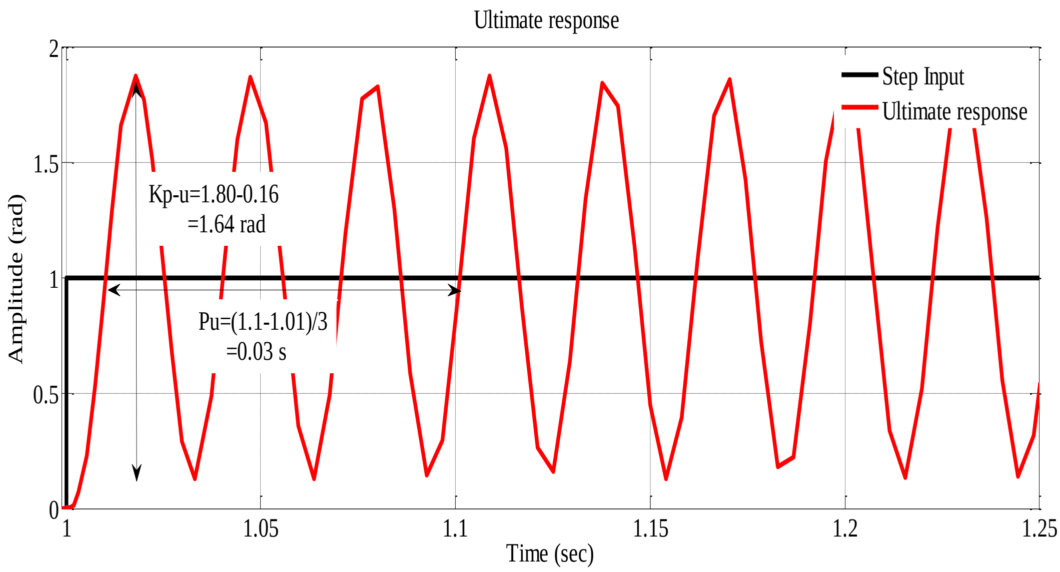


Figure 19: The system's ultimate response.

The obtained ultimate gain, K_{p-u} and ultimate period, P_u for this plant was 1.64 rad and 0.03 sec. With these ultimate values, PID controller parameters are calculated based on the formulas in Table 6. The PID parameters for this system show in Table 9 below.

Table 9: PID parameters for MS150

Control Type	***Kp***	***Ki***	***Kd***
P-only	0.82	-	-
PI	0.74	29.6	-
PID	0.98	65.3	3.7×10^{-3}
PD	0.98	-	3.7×10^{-3}

Hence, these 4 types of conventional controller will be simulated to choose the best controller that can drive the MS150 Servomotor Modular output response closest to the desired output response, no matter load is applied or not.

4.1.2 NO load disturbance

The results obtain for P-only, PI, PID and also PD controller with the PID parameters obtained above.

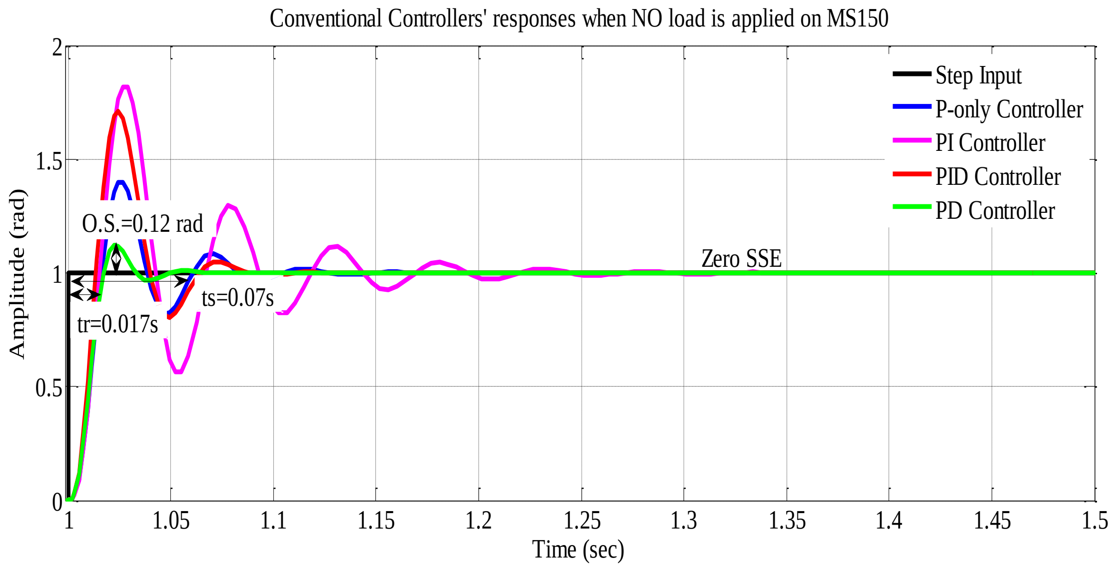


Figure 20: Control performances when no load applies to the servomotor.

The control performances have been summarized into Table 10 below.

Table 10: Control performances when MS150 in no load condition.

	P-only	**PI**	**PID**	**PD**
O.S (rad)	0.40	0.82	0.71	0.12
t_r (sec)	0.016	0.015	0.013	0.017
t_s(sec)	0.15	0.29	0.12	0.07
SSE (rad)	Zero	Zero	Zero	Zero

From Table 10, PD controller gives the best performance when there is no load applied to the motor, with the lowest overshoot value and settling time, even the rising time is a little bit higher than other conventional controllers.

4.1.3 With load disturbance

The results for P-only, PI, PID and also PD controller when a load is applied to motor with the PID parameters obtained at Table 9.

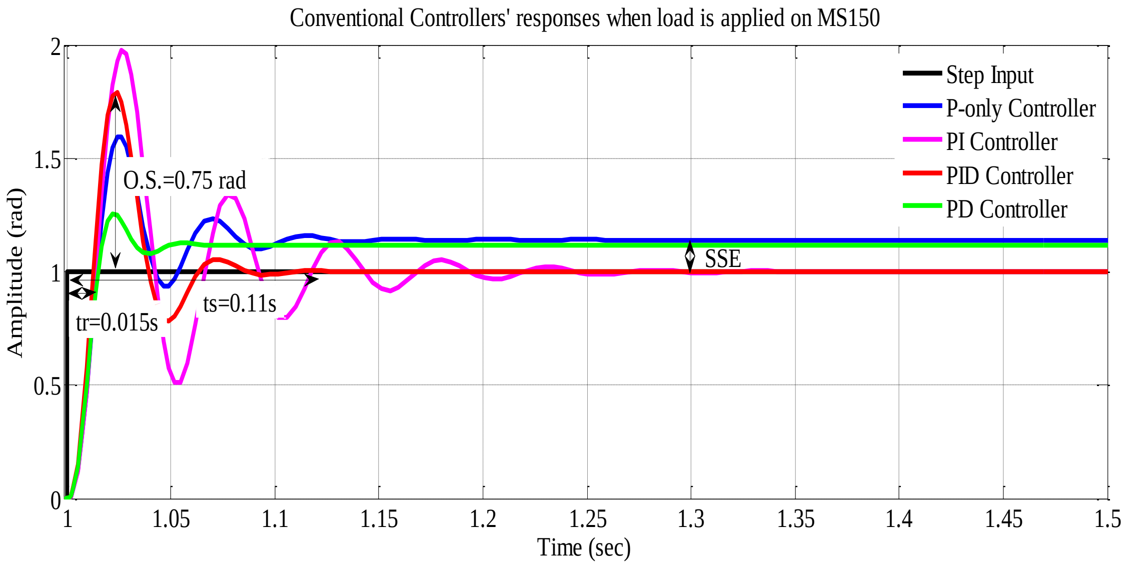


Figure 21: Control performances when a load is applied to the servomotor.

The control performances have been summarized into Table 11 below.

Table 11: Control performances when MS150 is with load condition.

	P-only	PI	PID	PD
O.S (rad)	0.60	0.98	0.75	0.25
t_r (sec)	0.015	0.014	0.015	0.016
t_s(sec)	0.19	0.30	0.11	0.08
SSE (rad)	0.14	Zero	Zero	0.12

From Table 11, PID controller gives the best performance when a load is applied to the motor, with the lowest rising time and zero steady-state error. The settling time is higher than the PD controller but 0.11 seconds is acceptable. In terms of overshoot PD controller have the lowest overshoot, PID controller says gives the best controller performance because it achieves zero steady-state error. The integral mode in the controllers can eliminate offset error.

4.1.3.1 Fine tuning

The PID controller that achieved previously at Unit 4.1.3 does not ideal for a motor controlling due to the controller action to seek for steady-state. Even though, the second O.S. (before the motor settle down) is approximately quart of the first O.S., there is an O.S and undershoot in the response. The reaction will cause friction on motor's component especially on the gear that in a long term may cause if to worn-out and hence cause maintenance and other issue.

Therefore, fine tuning had been carrying on the PID controller when the load is applied on MS150. With the basic knowledge of control and also trial and error method, the PID parameters for the best PID control performance when the motor is with load are obtained as following: K_p = 0.98, K_I = 32.65, and K_D = 0.0074, where the K_p value is maintained. K_I value is decreased by 2 times from the original 65.3, while K_D value is increased by 2 times from the original 0.0037. The control performance with overshoot values of 0.3 radians, rising time of 0.02 seconds, settling time of 0.11 seconds and zero steady-state error was achieved. This control performance will show at APPENDIX V.

Control performance after fine tuning is better compare to before fine tuning in terms of smaller O.S. value. Before fine tuning, the PID controller results in 0.75 rad of O.S., 0.015 sec of rising time, t_r and 0.11 sec of settling time, t_s and achieve zero SSE. After fine tuning, the O.S. value was gradually reduced from 0.75 rad to 0.3 rad, while, the rising time, t_r and the settling time, t_s were increased to 0.02 sec and 0.15 sec. The SSE was not affected, which still maintained at zero SSE. Consequently, the PID controller after fine tuning produced better performance with smaller overshoot. Figure 22 shows the output responses of PID controller, before and after fine tuning, when a load is applied.

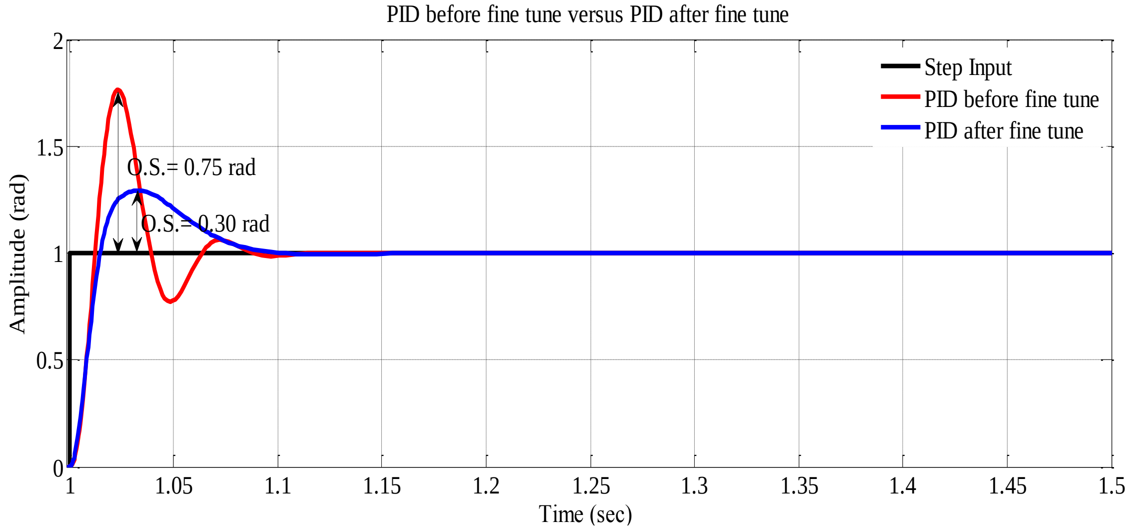


Figure 22: Comparison before and after fine tuning of PID controller.

4.1.3.2 FFPID Controller

The main purpose FF compensator applied to the system with the PID controller is to reject the external disturbance that cause the system output drift from desire response. The FF compensator's TF is derived by substituting the PID and R-L parameters into Eq. (2.24) in Chapter 2, and hence, the TF for FF compensator is:

$$G_{cd}(s) = \frac{8.6 \times 10^{-3}s^2 + 3.2s}{3.126 \times 10^{-3}s^2 + 0.414s + 13.8} \qquad (4.1)$$

The block diagram of the MS150 Servomotor Modular controlling by FFPID controller was shown at Figure 23.

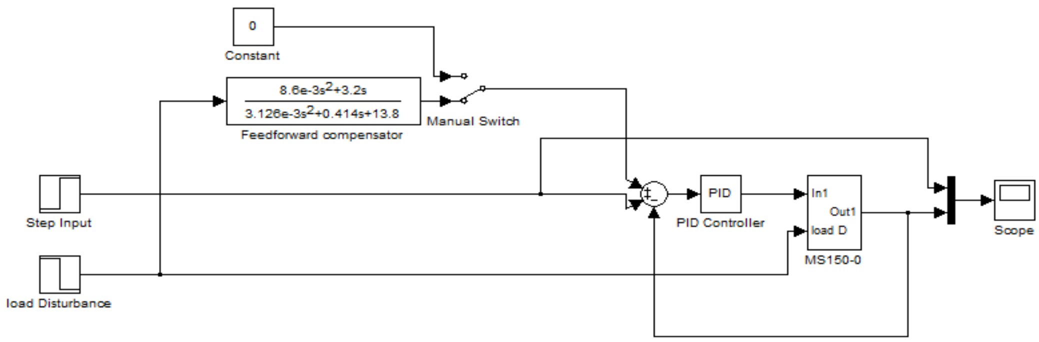


Figure 23: Block Diagram of plant controlling by FFPID controller.

Figure 24 shows the comparison of the control performances of PID controller and FFPID controller.

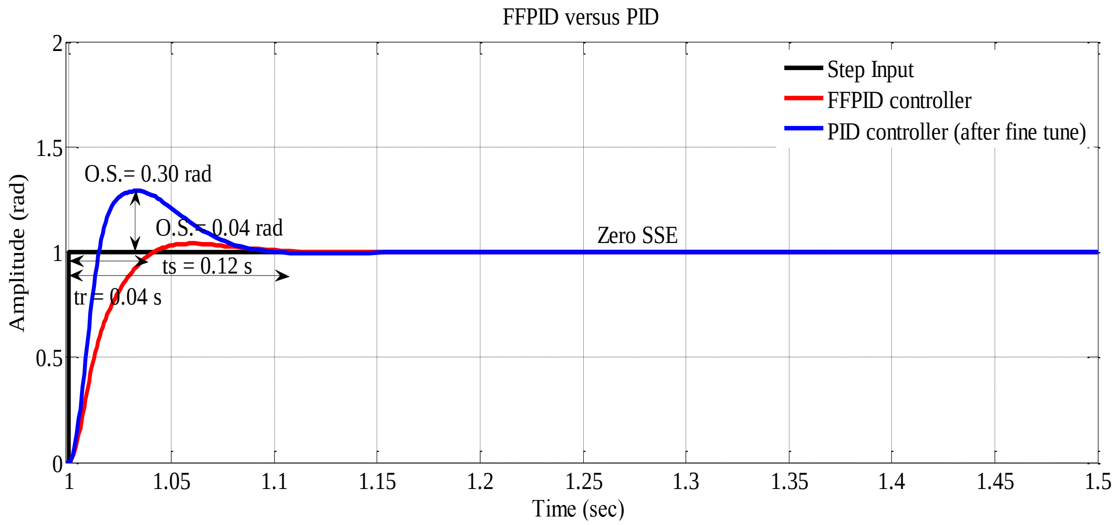


Figure 24: Comparison the step responses of FFPID and PID controllers when a load is applied on MS150

The FFPID controller successfully improved the servomotor's control performance by producing a very small O.S. which is 0.04 rad and also reduces the settling time, t_s from 0.15 sec to 0.12 sec. However, it increased the rising time, t_r by 0.02 sec. The comparison between these two controllers is summarized into Table 12.

Table 12: Control performances of FFPID and PID controllers

	FFPID	**PID**
O.S (rad)	0.04	0.3
t_r (sec)	0.04	0.02
t_s(sec)	0.12	0.15
SSE (rad)	Zero	Zero

This proves that feedforward control can eliminate the effect of the measured disturbance. The combination of feedforward control and feedback control perform better than feedback controller alone.

4.2 Fuzzy Logic Controller (FLC)

Figure 25 shows the block diagram of the MS150 Servomotor Modular controlling by FLC.

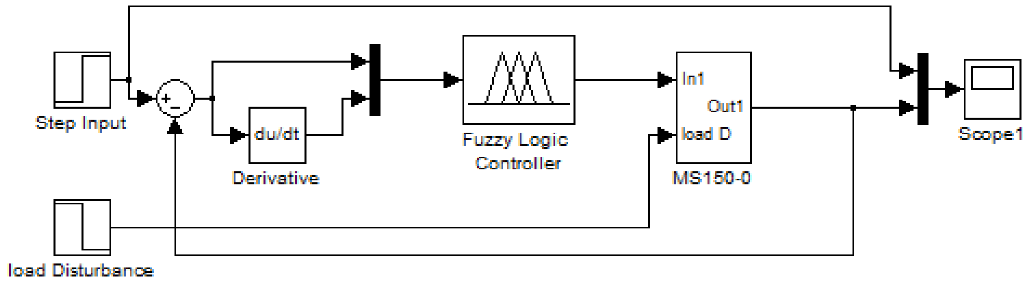


Figure 25: Block Diagram of plant controlling by FLC.

Simulations had been doing on five, seven and nine MFs' FLC to pick up the best FLC, with minimum SSE value to control the servomotor. The MATLAB/SIMULINK for the Fuzzy Inference Engine for all types MFs' FLC was designed to be two inputs, which are error, e and change of error, Δe and one output which is the change in the control signal, Δu. The relationships between inputs and output, the MF and the surface view of fuzzy inference system (FIS) for the five, seven and nine MF's FLC were shown in APPENDIX VI. The FLCs' rule bases are based on the following rules of thumbs:

1) If e is large and Δe is large then Δu has to be large.
2) If e is large and Δe is small then Δu has to be moderate.
3) If e is small and Δe is large then Δu has to be moderate.
4) If e is small and Δe is small then Δu has to be small.
5) If e is positive large and Δe is negative large then Δu will be zero and vice-versa.

The inputs range is [-0.5236 0.5236] radian, which when convert to degree is [-30 30]. The error limit is ±30 degree because the SP may vary between 0 to ±180 degree while according to the MS150 user manual the output range is limited to ±150 degree only. When the output exceeds these values the motor will turn uncontrollable and non-stop. The range for the change of error could be [-6.283 6.283] radian, which when convert to degree is [-360 360] as the SP can be vary on the equipment for ±360 degree. The output range is [-2.618 2.618] radian, which is [-150 150] in degree according to the instruction manual of the MS150.

4.2.1 NO load disturbance

The control performances that compared the control performance between 5 × 5, 7 × 7 and 9 × 9 FLCs when NO load is applied on MS150 is shown at Figure 26.

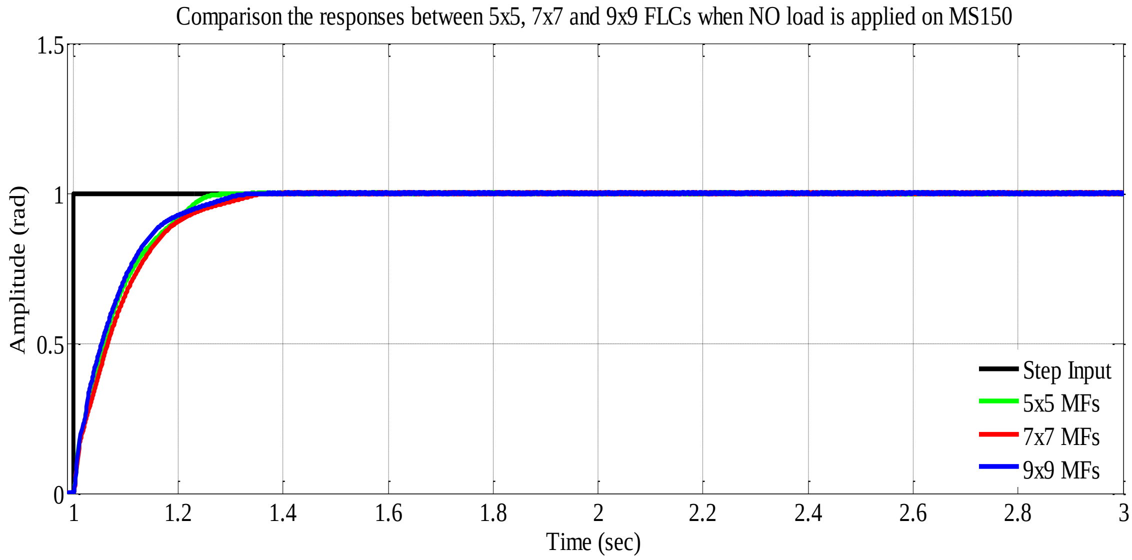


Figure 26: Comparison of the step responses between 5 × 5, 7 × 7 and 9 × 9 FLCs when NO load is applied on MS150.

The control performances have been summarized into Table 13 below.

Table 13: Control performances of the FLCs when MS150 is NO load condition

	5 × 5 MFs	**7 × 7 MFs**	**9 × 9 MFs**
O.S (rad)	Zero	Zero	Zero
t_r (sec)	0.28	0.35	0.35
t_s(sec)	0.28	0.35	0.35
SSE (rad)	Zero	Zero	Zero

From Table 13, FLC with lesser MF has better control performances compare to FLC with more MFs in terms of time specifications when there is no load applied to the motor.

4.2.2 With load disturbance

The control performances that compared the control performance between 5 × 5, 7 × 7 and 9 × 9 FLCs when a load is applied on MS150 is shown at Figure 27.

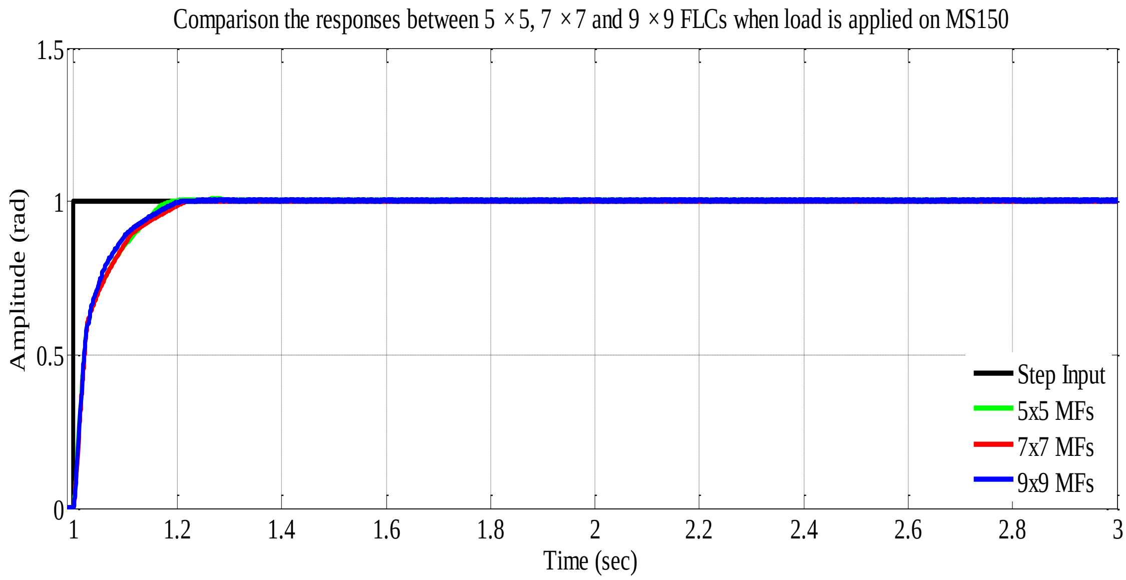


Figure 27: Comparison of the step responses between 5 × 5, 7 × 7 and 9 × 9 FLCs when a load is applied on MS150.

The control performances have been summarized into Table 14 below.

Table 14: Control performances of the FLCs when MS150 is with load condition.

	5 × 5 MFs	**7 × 7 MFs**	**9 × 9 MFs**
O.S (rad)	Zero	Zero	Zero
t_r (sec)	0.19	0.22	0.20
t_s(sec)	0.22	0.22	0.22
SSE (rad)	Zero	Zero	Zero

When a load is applied on the servomotor, the FLC with seven MFs produced a better control response. It gives the smallest SSE that was negligible, even it produce slightly bigger rising time, t_r compare to the FLC with five and nine MFs. All the FLCs, although they have different MFs, are having the same settling time, t_s. Hence, I conclude that the FLC with seven MFs will be the best FLC for MS150 in terms of it produced smallest SSE compare to the other two FLC with five and nine MFs. This also answered the reason of FLC with 7 × 7 MFs is most preferable among researchers that studying motor control using FLC.

4.2.3 Comparison with PID controllers

The control performance of this 7 × 7 MFs' FLC will be compared with the performances of PID controller and FFPID controller that had discuss previously. Figure 28 compared of the control performances for the controllers mention above.

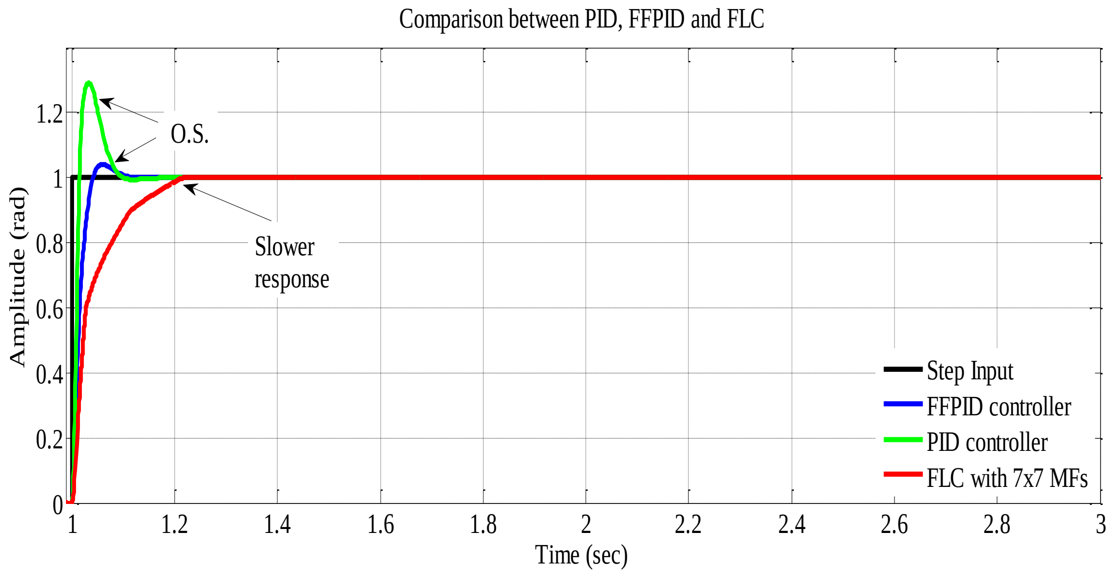


Figure 28: Comparison the step responses of FLC, FFPID and PID controllers when a load is applied on MS150

The control performances have been summarized into Table 15 below.

Table 15: Control performances of FLC, FFPID controller and PID controller

	FLC 7 × 7 MFs	**FFPID**	**PID**
O.S (rad)	Zero	0.04	0.3
t_r (sec)	0.22	0.04	0.02
t_s(sec)	0.22	0.12	0.15
SSE (rad)	Zero	Zero	Zero

FLC successfully eliminated the O.S. when a load disturbance is applied to the motor. However, this controller had the disadvantage on the time specifications and also the SSE is hardly to be eliminated as the conventional controller. Thus, the combination of FLC and PID been suggested to overcome each other's drawbacks with each other's potencies.

4.3 Fuzzy-PID Hybrid Controller

There are three types of Fuzzy-PID hybrid controllers been designed and analysed in this project:

1) FL parallel integral controller (FLIC) as in [3],
2) FL parallel PID controller (FLPID-P) as in [29], and
3) FL series PID controller (FLPID-S) [3].

The Fuzzy Inference Engine for the FLC of FLPID-P and FLPID-S were designed to be two inputs, which are error, e and change of error, Δe and three outputs, which are the error rates for P, I and D gain [Δe_P, Δe_I, Δe_D]. The relationships between inputs and output, the MF and the surface view of FIS for the FLC were shown in APPENDIX VI. The three outputs [Δe_P, Δe_I, Δe_D] will be added to the P, I and D gains to automatic tune the P, I, and D parameters and hence controlling the plant. The subsystems for different types of Fuzzy-PID Hybrid controller were shown in APPENDIX IV. Figure 29 shows the block diagram of the MS150 Servomotor Modular controlling by Fuzzy-PID Hybrid Controller.

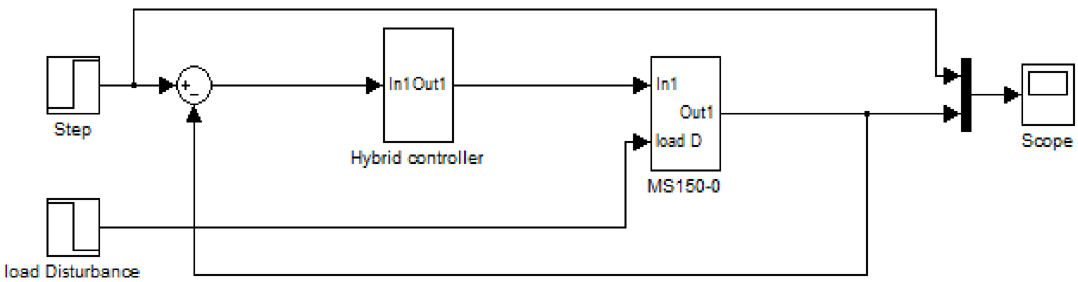


Figure 29: Block Diagram of plant controlling by Fuzzy-PID Hybrid Controller.

The FLC's rule bases are built according to the previous rules of thumbs at Unit 4.2, as well the inputs range were maintained, as the FLC design, which the error range was [-0.5236 0.5236] radian and the range for change of error was [-6.283 6.283] radian. Meanwhile, the outputs range for Δe_P is [0 0.00245], Δe_I is [0 0.08163] and Δe_D is [0 1.85e-005]. The outputs' ranges are 0.25% of the P, I and D parameters from the PID controller after fine tuning at Unit 4.1.3.1, which means the tolerance error for the hybrid controllers are 0.25%.

4.3.1 NO load disturbance

Figure 30 shows the comparison of the control performances of MS150 controlled by the hybrid controllers when NO load disturbance.

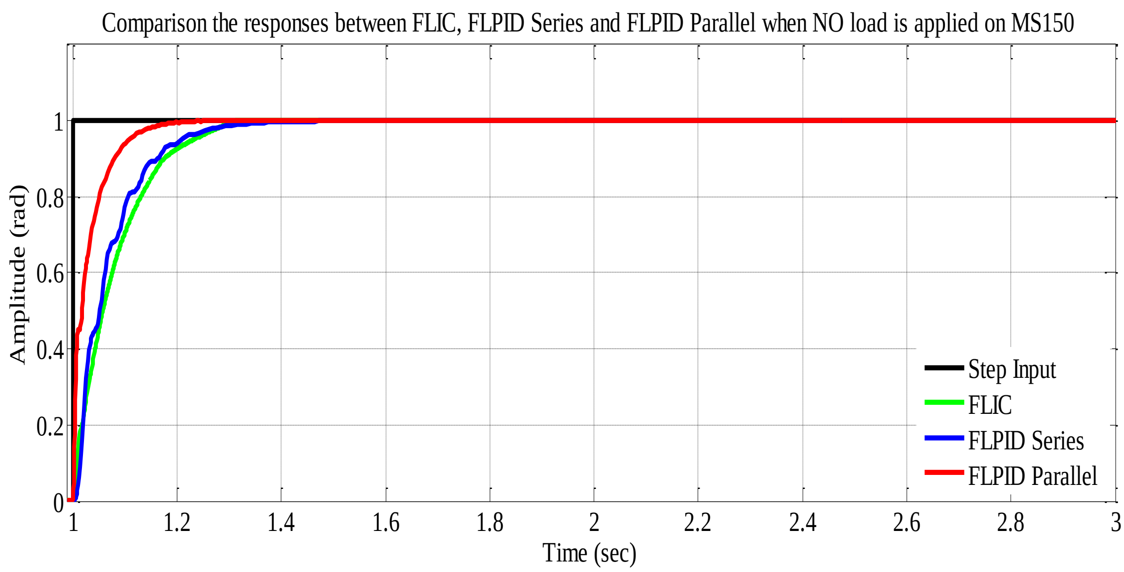


Figure 30: Comparison the step responses FLIC, FLPID-P and FLPID-S hybrid controllers when NO load disturbance on MS150.

The control performances have been summarized into Table 16 below.

Table 16: Control performances of the hybrid controllers when No load is applied on MS150

	FLIC	**FLPID-P**	**FLPID-S**
O.S (rad)	Zero	Zero	Zero
t_r (sec)	0.33	0.19	0.31
t_s(sec)	0.33	0.19	0.31
SSE (rad)	Zero	Zero	Zero

Compared to the FL parallel integral controller and the FL series PID controller, the designed FL parallel PID controller results better control response without any SSE and O.S., as well as have the shortest settling time, t_s, and rising time, t_r. Hence, FLPID-P was the best controller to control a DC servomotor without load disturbance.

4.3.2 With load disturbance

Figure 31 shows the comparison of the control performances of MS150 controlled by the hybrid controllers when a load is applied on motor.

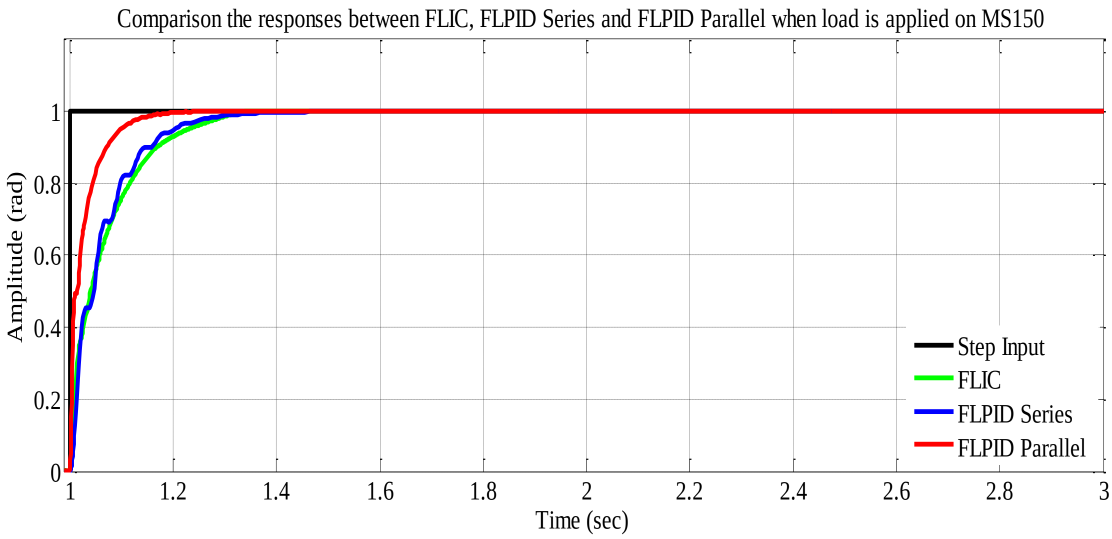


Figure 31: Comparison the step responses FLIC, FLPID-P and FLPID-S hybrid controllers when a load is applied on MS150.

The control performances have been summarized into Table 17 below.

Table 17: Control performances of the hybrid controllers when a load is applied on MS150

	FLIC	FLPID-P	FLPID-S
O.S (rad)	Zero	Zero	Zero
t_r (sec)	0.33	0.19	0.31
t_s(sec)	0.33	0.19	0.31
SSE (rad)	Zero	Zero	Zero

The hybrid of FLC and PID controller has successfully results a better control performance to the DC servomotor by eliminating the SSE and the O.S. Among the three designs, the designed FL parallel PID controller performs better control response with shortest settling time, t_s, and rising time, t_r. Hence, FLPID-P was the best controller to control a DC servomotor with or without load disturbance. FLPID-S is not suitable as the DC motor controller because of the resulting simulation control performance was not as smooth as the parallel structure. This is cause by the motor's dynamics that operates by mechanical gears.

4.3.3 Comparison with conventional FLC and PID controllers

The control performance of the FLPID-P will be compared with the control performances of conventional FLC, PID controller and FFPID controller that had discuss previously. Figure 32 shows the comparison of the control performances for the controllers mention above.

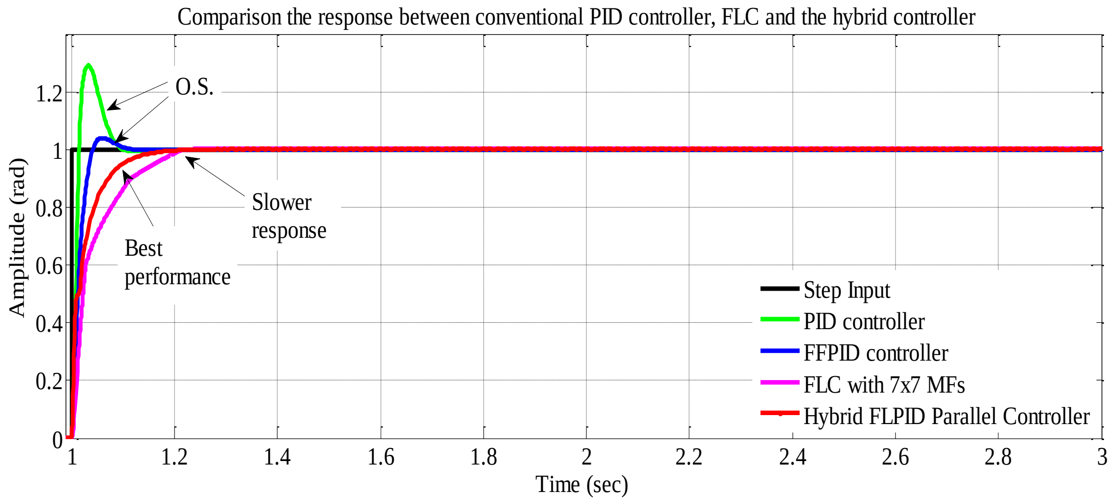


Figure 32: Comparison the step responses of Hybrid, FLC, FFPID and PID controllers when a load is applied on MS150

The control performances have been summarized into Table 18 below.

Table 18: Control performances of Hybrid, FLC, FFPID controller and PID controller

	FLPID-P	**FLC 7 × 7 MFs**	**FFPID**	**PID**
O.S (rad)	Zero	Zero	0.04	0.3
t_r (sec)	0.19	0.22	0.04	0.02
t_s(sec)	0.19	0.22	0.12	0.15
SSE (rad)	Zero	0.001	Zero	Zero

The project's objectives achieved, the combination of FLC and PID was successfully eliminated each other's step-back with each other's potencies and hence, the hybrid of FLC and PID controller produced the control performance with zero SSE and O.S. However, conventional FLC alone give the acceptable control performance that almost approximate with the hybrid controller's performance, with weaker performance on time specifications. Nevertheless, compare to the hybrid controller, PID controller have the advantage on time specification, while it produce the undesired O.S. on the response.

The hybrid controller gains the advantages of the fuzzy controller and the accuracy which is guaranteed by the classical PID controller to produce a robust controller that effective to implement in industrial. Not like the classical PID controller, the Fuzzy-PID hybrid controller uses FL reasoning to tune the PID gain automatically, and hence, the hybrid controller is said robust than a conventional PID controller. The simulation results on different types of input will be attached in APPENDIX V.

4.3.4 Input/ SP and Load Variations

Hybrid controller is recommended due to its robustness, besides the automatically tuning specification. Simulation had done on varying the SP and load disturbance values and the robustness of FLPID controller was proven. With any changes of SP or load or both, this controller still produced the same process reactions, which are zero SSE and O.S. and approximately 0.2 sec of rising and settling times.

4.3.4.1 Input/ SP Variations

Figure 33 and 34 show the example that the hybrid controller when the input/ SP is varied.

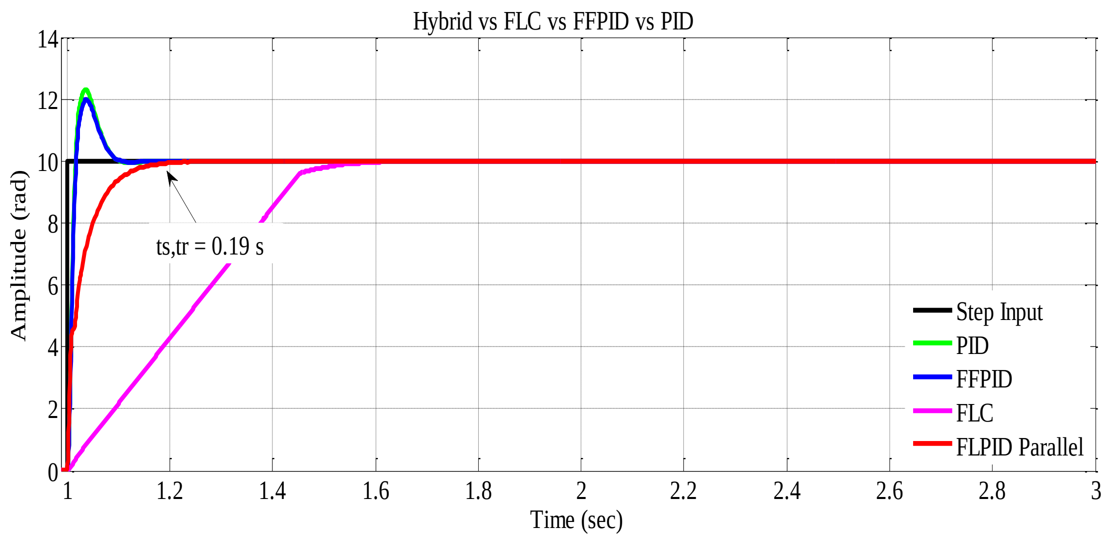


Figure 33: The controllers' performances when input value is increased to 10 radians.

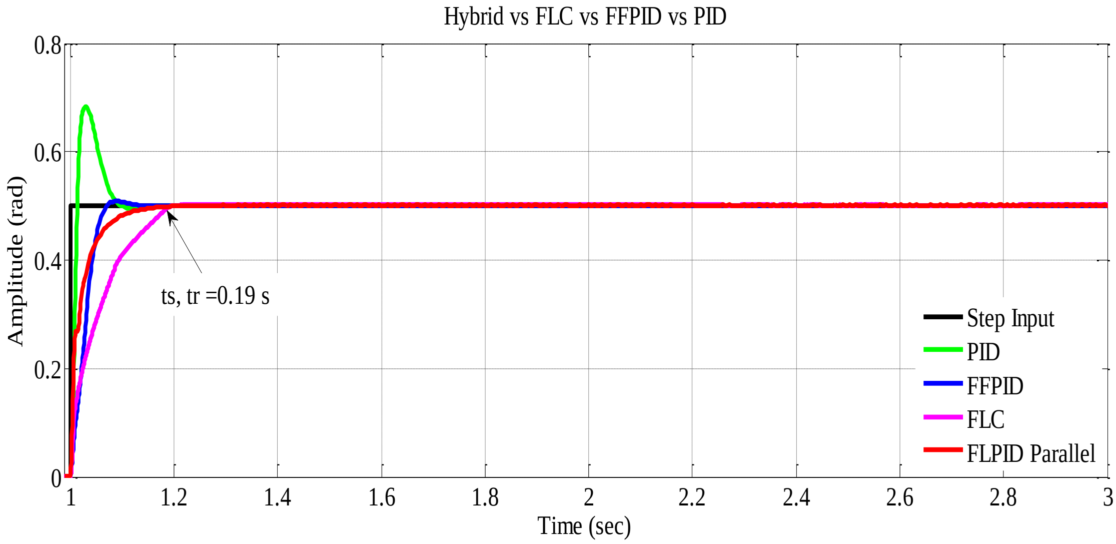


Figure 34: The controllers' performances when input value is decreased to 0.5 radians.

The O.S. of FFPID increased from 4% to approximately 20%, while the O.S. of PID decreased from 30% to approximately 20% when the SP value is increased. Furthermore, the increasing of SP causes the increasing of the FLC's rise time, t_r and settling time, t_s. Decreasing of SP value does not give significant impact to the response of the designed controllers.

4.3.4.2 Load Variations

The example simulation results on load variations are attached in Figure 35 and 36 below.

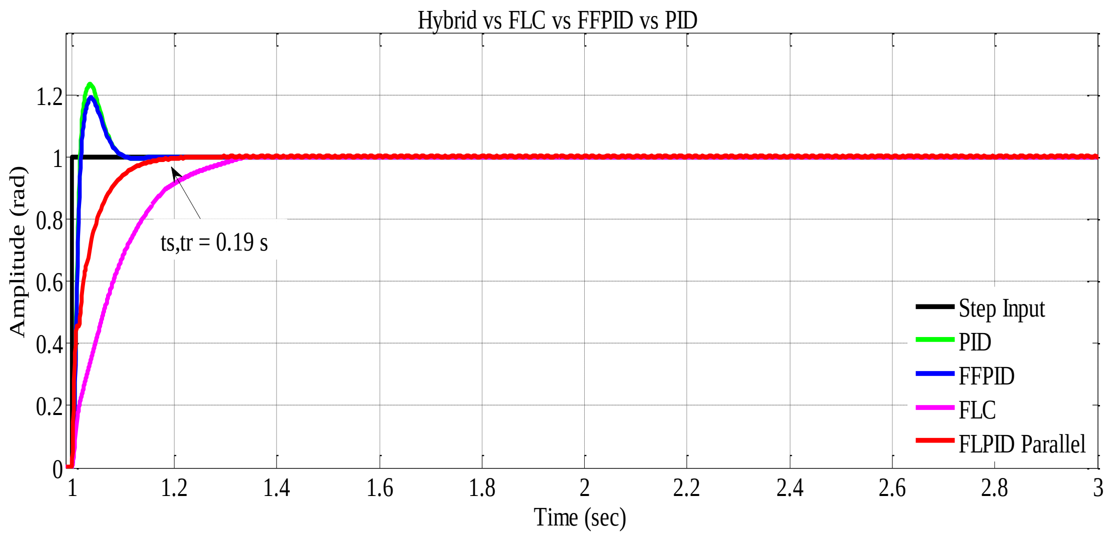


Figure 35: The controllers' performances when load is 100 times of motor shaft weight.

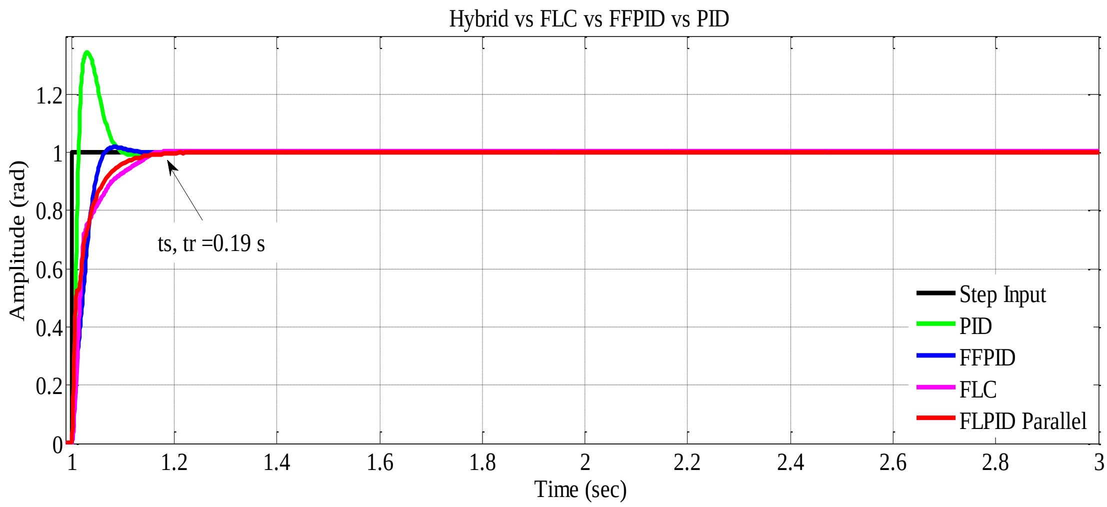


Figure 36: The controllers' performances when load is 8 times of motor shaft weight.

The O.S. of FFPID increased from 4% to approximately 20%, while the O.S. of PID decreased from 30% to approximately 20% when the load weight is increased to 100 times of shaft weight. However, load weight with 8 times of motor shaft weight does not give significant impact to the response of FLC and FFPID. Yet, for the motor with PID controllers, the decreasing of load value under certain value will cause the O.S. increase accordingly.

Author found that MS150 does not ideal to cope with the loads those less than 8 times of motor shaft weight. The performances of the designed controllers with the load those only 3 times of motor shaft weight are shown in Figure 37. Responses with variety load weights were attached at APPENDIX G. They showing that motor do not perform well with light loads.

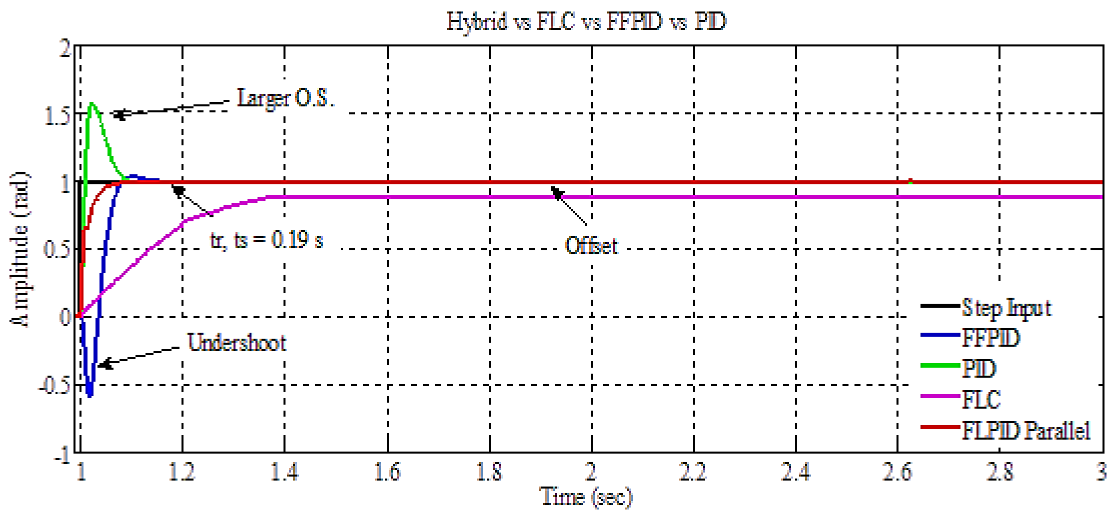


Figure 37: The controllers' performances when load is 3 times of motor shaft weight.

The load-inertia, time and load relationship was shown in the time, torque, and load-inertia triangle below.

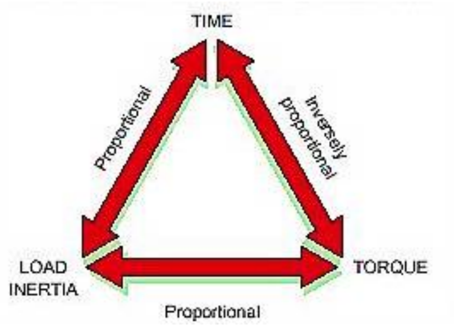


Figure 38: Time, torque, load-inertia triangle. [31]

According to Steve Meyer in [31], the load weight is directly proportional to the system inertia too. Thus, the losing of weight will cause the tendency of an object to resist any change in its motion decrease. Furthermore, load is proportional to the torque [31]. Light load that produce lesser torque that ineffective to trigger or pull the motor to operate accordingly. Hence, offset happened on the motor controlled by FLC.

As soon as a thing reaches its extremity, it reverses its course. In order to for the FF compensator to reject load disturbances as well to maintain the motor operations, undershoot happens when the load weight is too small.

For the motor that handled by PID controller, the O.S. transients increase with the decreasing of load weight, under a certain weight. Responses with variety load weights were attached at APPENDIX G. Hence, the ideal load weight for the motor under this controller is limited from 10 times of motor shaft weight until infinity under the control of this controller.

Hence, author concluded that MS150 does not ideal to handle the light loads those less than 8 times of motor shaft weight. Neglecting the O.S., PID controller would be the considerable controller to control a servomotor with large load. However, FLC and FFPID controller performed well in handling servomotor with small SP change and light load.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Servomotors are applied in variety of industrial applications, which required reliable and precise for their position and speed control of the servomotors on the mechanism's joints. Hence, the aims of the project which are to design and develop an advanced controller (i.e. hybrid PID-Fuzzy controller) for servomotor application and to investigate the control performance of PID, Fuzzy and Hybrid PID-Fuzzy controllers. The project objectives are achieved, a Hybrid PID-Fuzzy controller that has better control performance on servomotor compared to conventional FLC and PID controller is successfully designed. Based on simulation result, this controller effectively controls the MS150 without any SSE and O.S. appeared.

The conventional continuous FB control is PID controller, has a good control performance but is not robust enough when there is disturbance or non-linear dynamics, such as when the load is changing the P, I, and D parameters are needed to re-tune. Even though, a FF compensator that been added to the PID controller for load disturbance rejection had successfully increased the control performance by decreased the O.S. value when a load distribution is added, but the P, I and D gains are needs to derive the FF compensator's TF.

The FLC designs for this study are based on trial and error method and it is not optimized. Further, optimization and tuning will be carrying out in future. Based on literature summary, FL systems are suitable for handling the uncertain or non-linear dynamics to overcome the weakness of conventional controllers. No doubt that there are difficulties in designing the fuzzy controller, which the complexity of fuzzy controller increases exponentially when the number of input variables increases, it gives slower response compare to PID controller and the SSE are hardly to eliminate. The simulation results show that FLC is feasible to apply on DC servomotor, while further tuning and optimization works should be carrying out.

The hybrid of fuzzy and PID controllers takes the advantages on the non-linear characteristics of the fuzzy controller and the accuracy that near to set point (eliminate SSE) which is guaranteed by the classical PID controller.

5.2 Recommendations

- This project is focused on the positioning control of servomotor using PID controller, FLC and the hybrid of PID-FLC. It can be extending to position and speed control of a servomotor.
- Research can be extending to Neural Network Control (NNC) and the hybrid of NNC-FLC too.
- Good researches have to study in different approaches. Thus, for the FLC, Mamdani approach may be replaced by Takagi-Sugeno model and compared with Mamdani. Different method of inference engine and defuzzification methods should be analysing too.
- In the proposed design is completely off-line simulation. It can be extending to an on-line controlling servomotor.
- The works in this project were based on conventional PID control structure, which is a linear controller. Since servomotor is nonlinear system, research can be extending to apply nonlinear controllers such as sliding mode control algorithms.

REFERENCES

[1] T. Kissel, 2002, *Motor Control Technology for Industrial Maintenance*, New Jersey 07458: Prentice-Hall, Inc., Upper Saddle River.

[2] J.J. Crage, 2005, *Introduction to Robotics Mechanics and Control*, 3rd Edition, Prentice Hall.

[3] Oyas Wahyunggoro, N. Saad, 2008, "Development of Fuzzy-Logic-Based Self Tuning PI Controller for Servomotor". *10th International Conference on Automation, Robotics, Control and Vision (ICARCV 2008), Hanoi, Vietnam.*

[4] B. Lacevic, J. Velagic, and N. Osmic, "Design of Fuzzy Logic Based Mobile Robot Position Controller Using Genetic Algorithm," *International Conference on Advanced Intelligent Mechatronics, IEEE/ASME 2007*, 2007, pp. 1-6.

[5] B.C. Kuo, F. Golnaraghi, 2003, *Automatic Control System*, 8^{th} Edition, John Wiley.

[6] N.S. Nise, 2004, *Control System Engineering*, 4^{th} Edition, John Wiley.

[7] S. Chopra, R. Mitra and V. Kumar, 2005, "Fuzzy Controller: Choosing an Appropriate and Smallest Rule Set," *International Journal of Computational Cognition*, Vol. 3, No. 4.

[8] M-Y. Shieh, T-H.S. Li, 1997, "Design and Implementation of Integrated Fuzzy Logic Controller for a Servomotor System," *Mechatronics 8 (1998)*, 217-240.

[9] Shinners SM, 1978, *Modern Control System Theory and Application.* Addison Wesley.

[10] Phillips CL, Nagle HT, 1990, *Digital Control System Analysis and Design*, 2^{nd} Ed. Prentice-Hall.

[11] A.Z. Alassar, I.M. Abuhadrous and H.A. Elaydi, 2009, "Comparison between FLC and PID Controller for 5DOF Robot Arm", *The 2^{nd} IEEE International Conference on Advanced Computer Control,* Shenyang.

[12] A.Z. Alassar, I.M. Abuhadrous and H.A. Elaydi "Modeling and Control of 5DOF Robot Arm Using Supervisory Control", *The 2nd Conference on Computer and Automation Engineering,* Singapore, Jan. 2010.

[13] C. Johnson, 1993, *Process Control Instrumentation Technology*, New Jersey: Prentice Hall International, Inc. Englewood Cliffs.

[14] Pornjit Pratumsuwan et. al., 2010, "A Hybrid of Fuzzy and Proportional-Integral-Derivative Controller for Electro-Hydraulic Position Servo System", *Energy Research Journal 1 (2): 62-67*.

[15] M.F. Rahmat, Mariam MB Ghazaly, 2006, "Performance Comparison between PID and Fuzzy Logic Controller in Position Control System of DC Servomotor", *Jurnal Teknologi, Universiti Teknologi Malaysia*, 45(D), 1-17.

[16] L. Wang, 1997, *A Course in Fuzzy System and Control*, Upper Saddle River, New Jersey 07458: Prentice-Hall, Inc, A Division of Simon and Schuster.

[17] Mohammed T. Hayajneh et. al., 2006, "Fuzzy Logic Control for Overhead Crane", *Engineering Computations: International Journal for Computer-Aided Engineering and Software* Vol. 23 No. 1, pp. 84-98.

[18] Abdullah I. Al-Odienat, Ayman A. Al-Lawama, 2008, "The Advantages of PID Fuzzy Controllers over the Conventional Type", *American Journal of Applied Sciences 5 (6): 653-658*.

[19] Ahmed, M. S., Bhatti, et. al., 2001, Design of a Fuzzy Servo-Controller, *Fuzzy Sets and Systems*, vol. 124: 231-247

[20] Kim, J.H. et. al., 1994, A two-layered fuzzy logic controller for systems with dead zones. *IEEE Trans. Ind. Elect.*, 41: 155-162.

[21] Zhou S.Q. et. al., "The Simulation and Design of Automatic Attacking Weapon Base on Fuzzy-PID Control", *Engineering Institute of Engineer Crops, PLA University of Science & Technology, Nanjing 210007, China*

[22] Luís Brito Palma and Fernando Vieira Coito, 2000, "Modelling and Hybrid Control of a Nonlinear DC Servomotor", *4th Protugese Conference on Automatic Control. ISBN 972-98603-0-0.*

[23] M-L. Hung et. al , 2010, “Intelligent Control Design and Implementation of DC Servomotor”, *2010 IEEE International Symposium on Computer, Communication, Control and Automation.*

[24] Finn Haugen, 2010, “Article: Ziegler-Nichols’ Open-Loop Method”, *17th July 2010 TechTeach.*

[25] Finn Haugen, 2010, “Article: Ziegler-Nichols’ Closed-Loop Method”, *17th July 2010 TechTeach.*

[26] A.Z. Alassar, I.M. Abuhadrous and H.A. Elaydi “Control of 5DOF Robot Arm Using PID Controller with Feedforward Compensation”, *Accepted in the 2nd Conference on Computer and Automation Engineering*, Singapore, 5. Dec. 2009.

[27] S.W. Zhao and N.C. Cheung, “Disturbances Rejection for Precise Position Control of Linear Switched Reluctance Motors,” *Proceedings of the 17th World Congress the International Federation of Automatic Control*, July. 2008.

[28] R. E. Samin, M. S. Ramli and M. A. Ahmad, “Performance Comparison of PD-type Fuzzy Logic Controller of USBM Simplified Model,” *The 2ndInternational Power Engineering and Optimization Conference (PEOCO2008), Shah Alam, Selangor, MALAYSIA. 4-5 June 2008.*

[29] M.I. Solihin, Wahyudi, and A. Legowo, “Fuzzy-tuned PID Anti-swing Control of Automatic Gantry Crane,” *Journal of Vibration and Control, vol. 16, 2010, pp. 127-145.*

[30] Hoang Le-Huy and Maher Hamdi, “Control of Direct Drive DC Motor by Fuzzy Logic”, *IEEE Transactions, pp. 732-738, 1993*

[31] Steve Meyer, 2001, “Article: Time, torque, and inertia”, *1st March 2001 Machine Design by Engineers for Engineers.com*.

APPENDICES

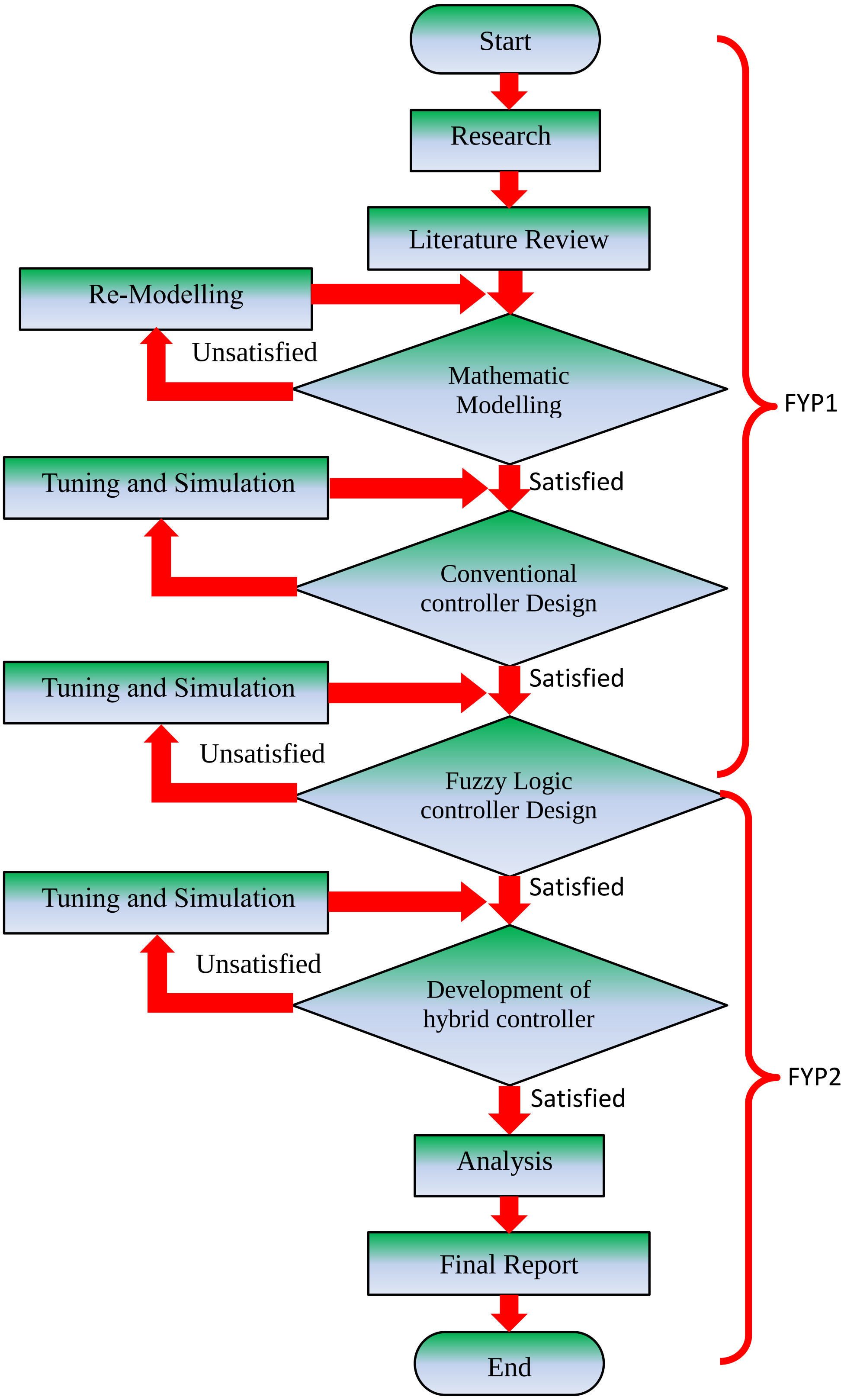
APPENDIX A

THE OVERVIEW OF THE STUDY RELATED RESEARCH TOPICS

No.	Year	Author	Title and Source	Findings
1. [8]	1998	1. M-Y Shieh 2. T-H. S. Li	"Design and Implementation of Integrated Fuzzy Logic Controller for a Servomotor System", *Mechatronics 8 (1998)*, 217-240.	• Proposed an integrated fuzzy logic control (IFLC) structure • Improves existing PID control systems on position control of a DC-servomotor.
2. [22]	2000	1. Lu ́s Brito Palma 2. Fernando Vieira Coito	"Modelling and Hybrid Control of a Nonlinear DC Servomotor", *4th Portuguese Conference on Automatic Control. ISBN 972-98603-0-0.*	• Presented hybrid controller architecture by combining of a PID controller and a Fuzzy PID controller. • Get the best performance on the modelled DC servomotor with the presence of a load disturbance.
3. [17]	2005	1. Mohammed T. Hayajneh 2. Saleh M. Radaideh 3. Issam A. Smadi	"Fuzzy Logic Control for Overhead Crane", *Engineering Computations: International Journal for Computer-Aided Engineering and Software* Vol. 23 No. 1, pp. 84-98.	• Proposed a fuzzy logic controller (FLC) that can be implemented to move the overhead crane along a desired path while ensuring that the payload is swing free at the end of the motion. • The performance of the proposed FLC is compared with a PD controller to demonstrate the effectiveness of the proposed FLC. ✓ FLC improved the response of the system over the PD controller. ➢ Reduced overshoot ➢ Faster settling time
4. [15]	2006	1. M.F. Rahmat 2. Mariam MB Ghazaly	"Performance Comparison between PID and Fuzzy Logic Controller in Position Control System of DC Servomotor", *Jurnal Teknologi, Universiti Teknologi Malaysia,* 45(D), 1-17.	• Compared the time specification performance between PID controller and Fuzzy Logic Controller (FLC) in position control system of a DC motor. ✓ FLC have better performance in terms of OS%. ✓ The PID controller performs better in term of time rise and time settling.
5. [18]	2008	1. Abdullah I. Al-Odienat 2. Ayman A. Al-Lawama	"The Advantages of PID Fuzzy Controllers over the Conventional Type", *American Journal of Applied Sciences 5 (6): 653-658.*	• Discussed about the advantages of PID-fuzzy controllers over the conventional PID and also fuzzy logic controllers.
6. [3]	2008	1. Oyas Wahyunggoro 2. Nordin Saad	"Development of Fuzzy-Logic-Based Self Tuning PI Controller for Servomotor". *10th International Conference on Automation, Robotics, Control and Vision (ICARCV 2008), Hanoi, Vietnam.*	• Performed some evaluations using a fuzzy-logic-based self-tuning PI controller compare to fuzzy-logic-based self-tuning PID controller, fuzzy logic controller, PID controller and PI controller on a DC servomotor system. ✓ Hybrid of fuzzy-logic and PI controllers are better than conventional controllers.
7. [11]	**2009**	**1. A.Z. Alassar 2. I.M. Abuhadrous 3. H.A. Elaydi**	**"Comparison between FLC and PID Controller for 5DOF Robot Arm", *The 2nd IEEE International Conference on Advanced Computer Control,* Shenyang.**	**• Presented a fuzzy logic controller for manipulating 5DOF robot arm based on the independent joint control method to overcome the drawbacks of the classical PID controller. • Compared the performance of FLC and PID for Lynx6 robot arm in terms of time response specification. ✓ FLC provides better performance as compared with PID controller for tracking the desired response.**
8. [23]	2010	1. Meei-Ling Hung 2. Pi-Yun Chen 3. Her-Terng Yau 4. Yuan - Hung Su	"Intelligent Control Design and Implementation of DC Servomotor", *2010 IEEE International Symposium on Computer, Communication, Control and Automation.*	• Studied the position feedback control problem of DC servomotor of the conventional PID controller • Enhance the controller by Evolutionary Programming (EP) method and hybrid of Fuzzy- PID controller. ✓ The transient response of the optimal PID controller (PID+EP) is better than the conventional PID controller. ✓ Better control response can be obtained by combining the FLC with optimal PID control.

APPENDIX B

PROJECT FLOW



APPENDIX C

ACTIVITIES/GANTT CHARTS AND MILESTONES

FYP1

No.	Detail/week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1.	Selection of Project Topic	D	D						Mid- Semester Break							
2.	Preliminary Research Work		D	D	D	D										
3.	Submission of Extended Proposal Defence						●									
4.	Modelling: 1. Derive Transfer Function							D		D						
6.	Proposal Defence										●					
7.	Conventional controller Design, Tuning and Simulation 1: 1. PID Controller											D	D	D		
6.	Submission of Draft Interim Report														●	
7.	Submission of Interim Report															●

● Suggested Milestone

■ Process

■ D Process Done

FYP2

No.	Detail/week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1.	Design (part 1): Fuzzy Logic Controller (FLC)	D	D	D					Mid- Semester Break							
2.	Simulation 2 (part 1): Fuzzy Logic Controller (FLC)			D	D											
3.	Design (part 2): Hybrid Controller (Fuzzy –PID)				D	D	D	D		D						
4.	Submission of Progress Report									●						
5.	Simulation 2 (part 2): Hybrid Controller (Fuzzy –PID)									D	D	D				
6.	Analysis										D	D	D			
7.	Pre- EDX												●			
8.	Submission of Draft Report													●		
9.	Submission of Dissertation (Soft Bound)														●	
10.	Submission of Technical Paper														●	
11.	Oral Presentation															●
12.	Submission of Dissertation (Hard Bound)															●

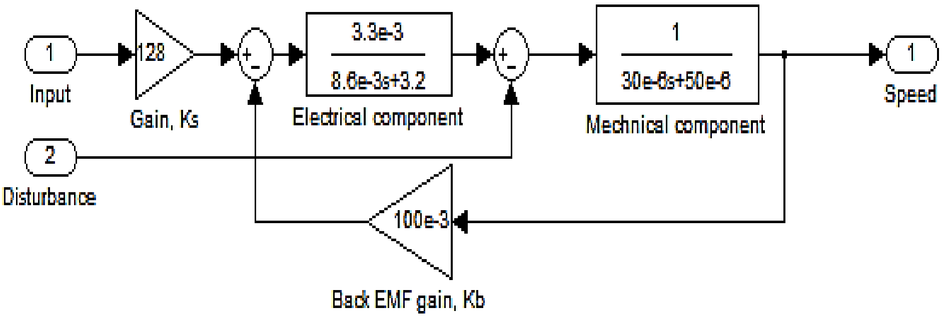
● Suggested Milestone

Process

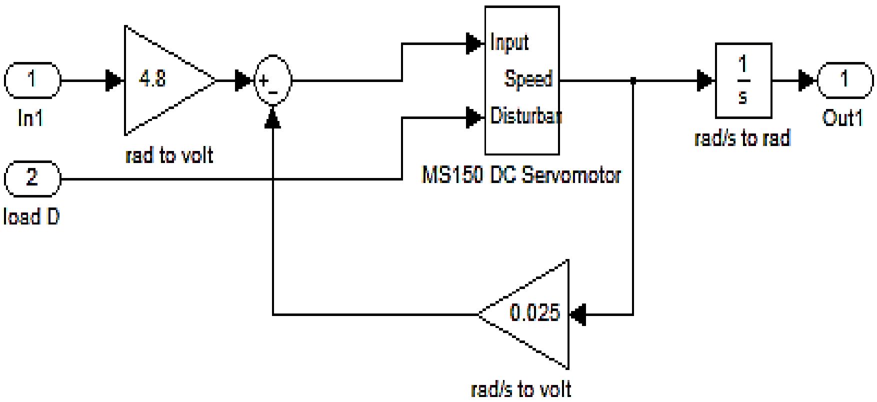
D Process Done

APPENDIX D

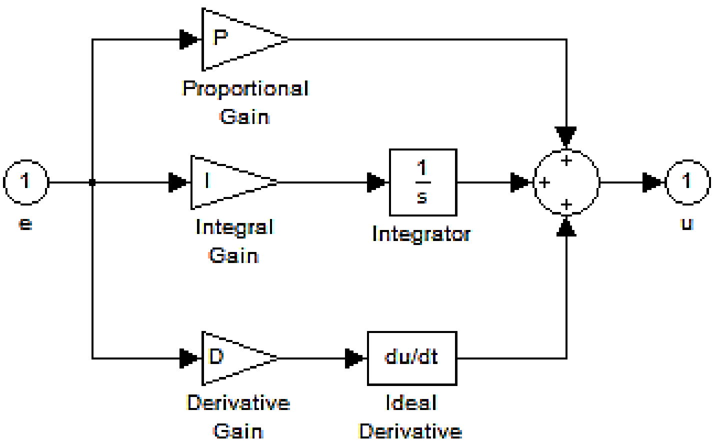
SIMULINK MODEL SUBSYSTEM



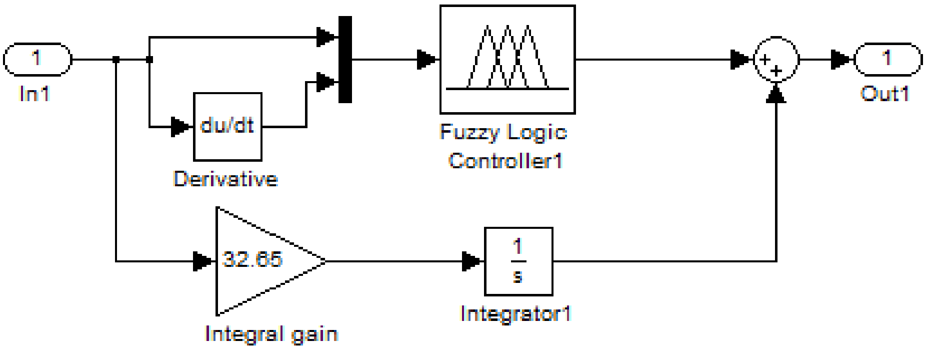
Subsystem of MS150 DC servomotor



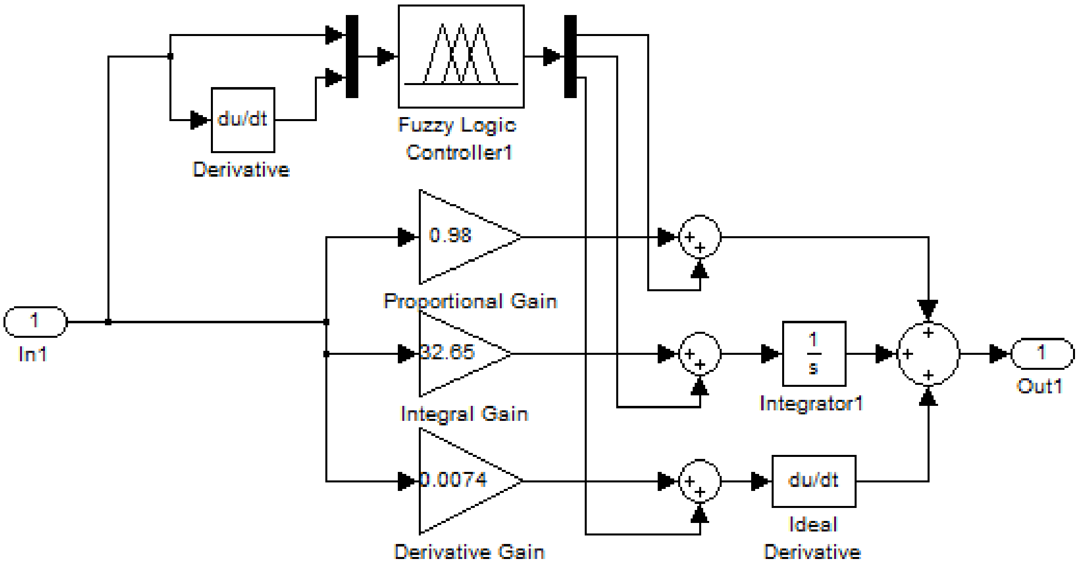
Subsystem of the plant



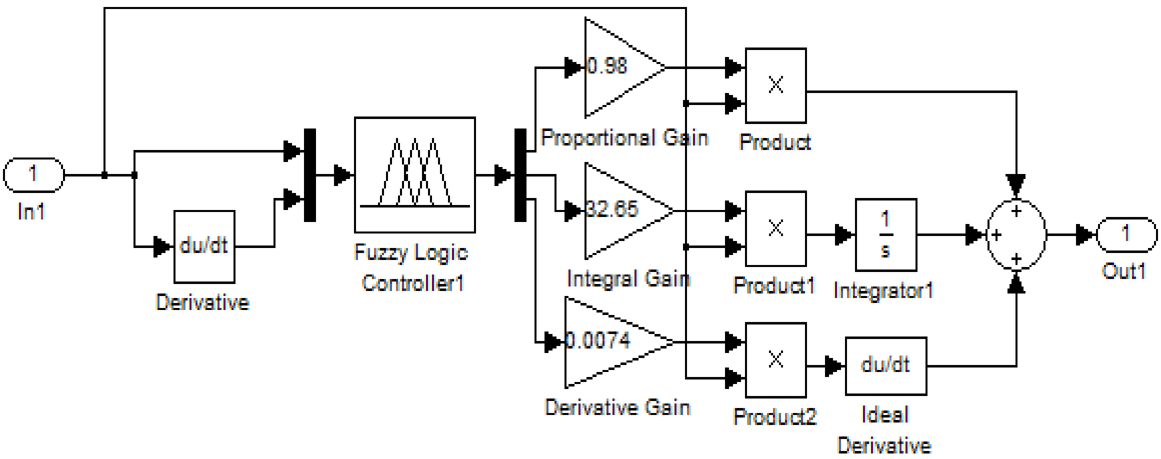
Subsystem of the PID controller



Subsystem of the FLIC hybrid controller



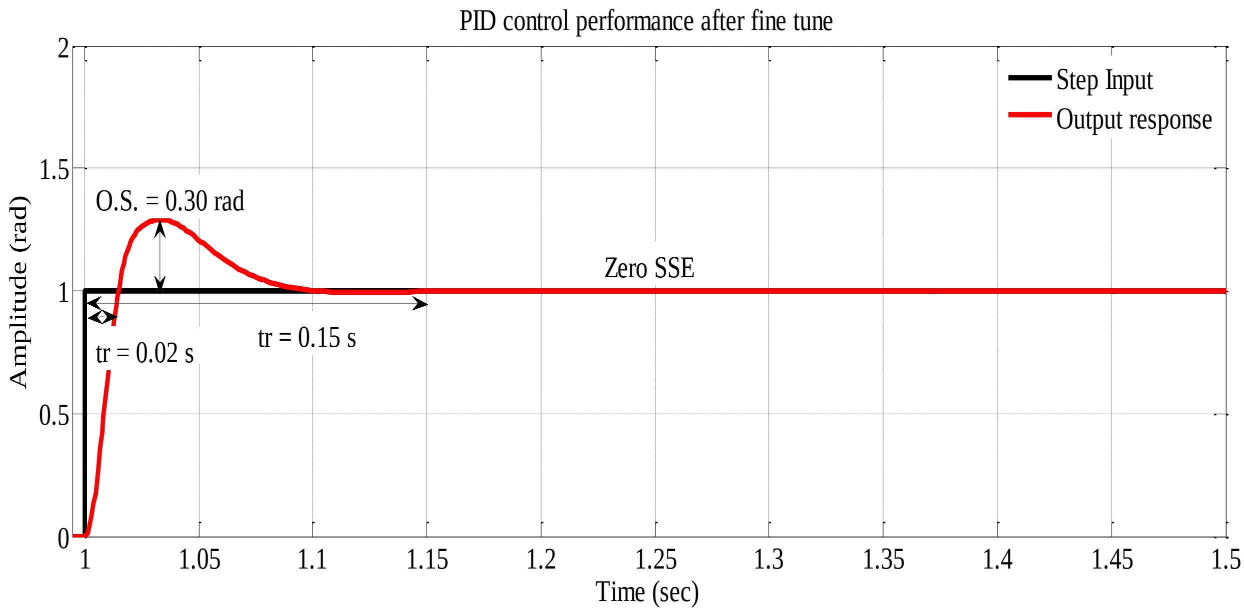
Subsystem of the FLPID-P hybrid controller



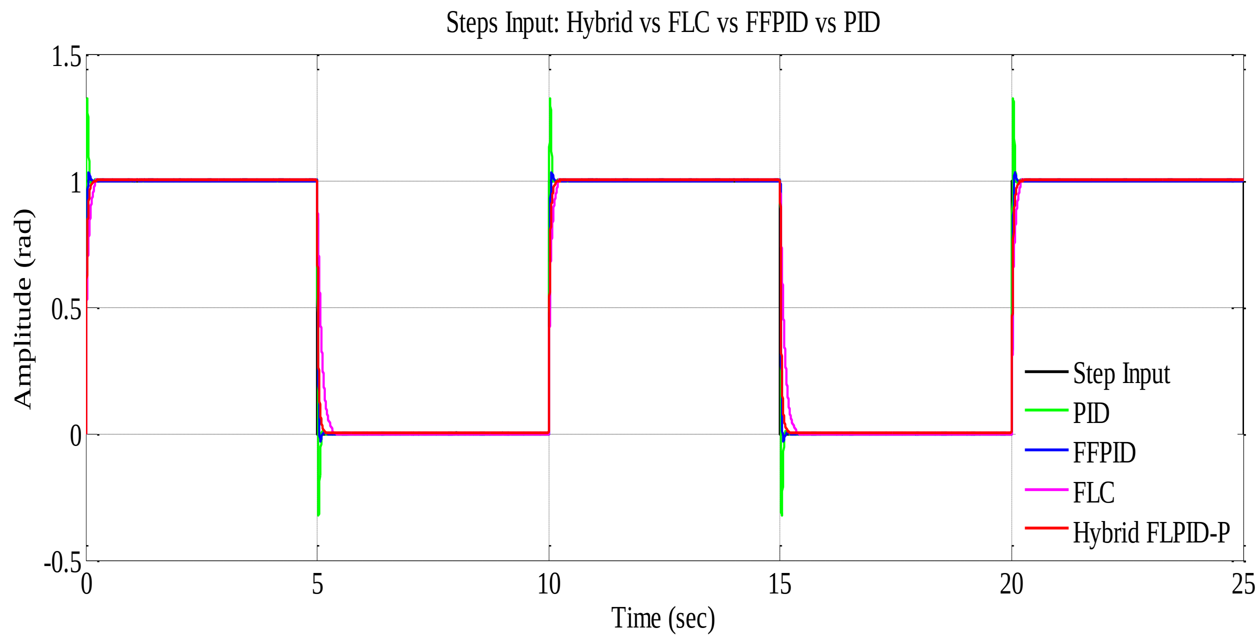
Subsystem of the FLPID-S hybrid controller

APPENDIX E

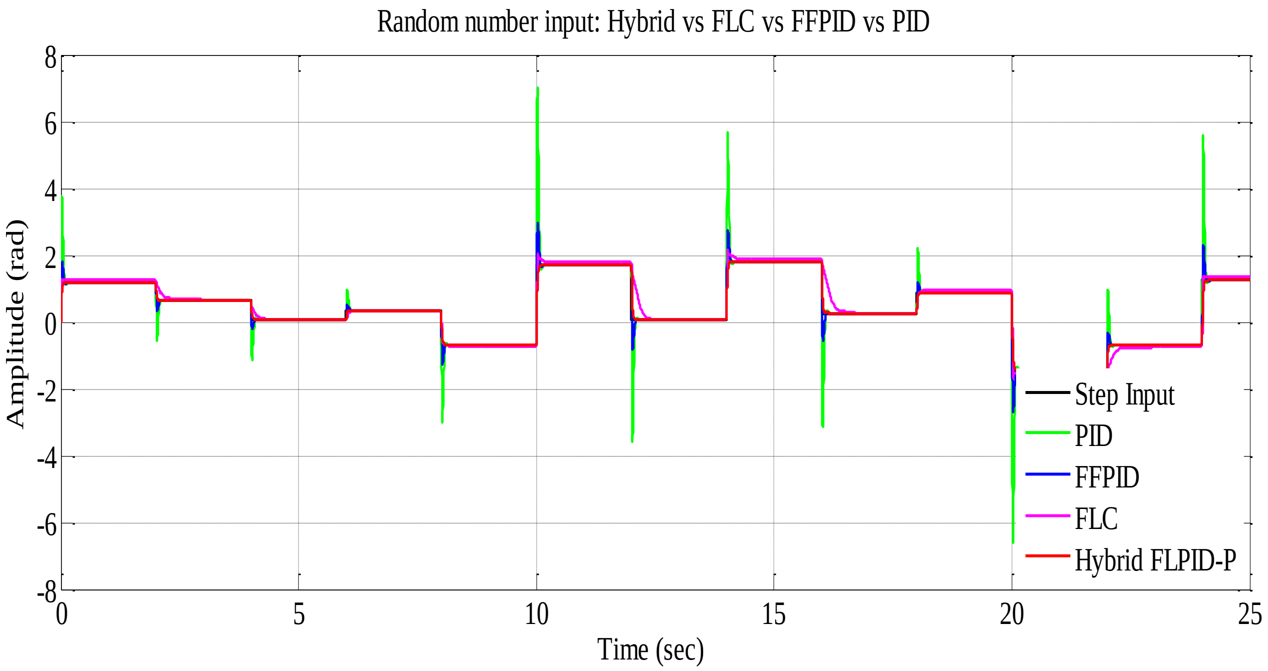
CONTROL PERFORMANCES



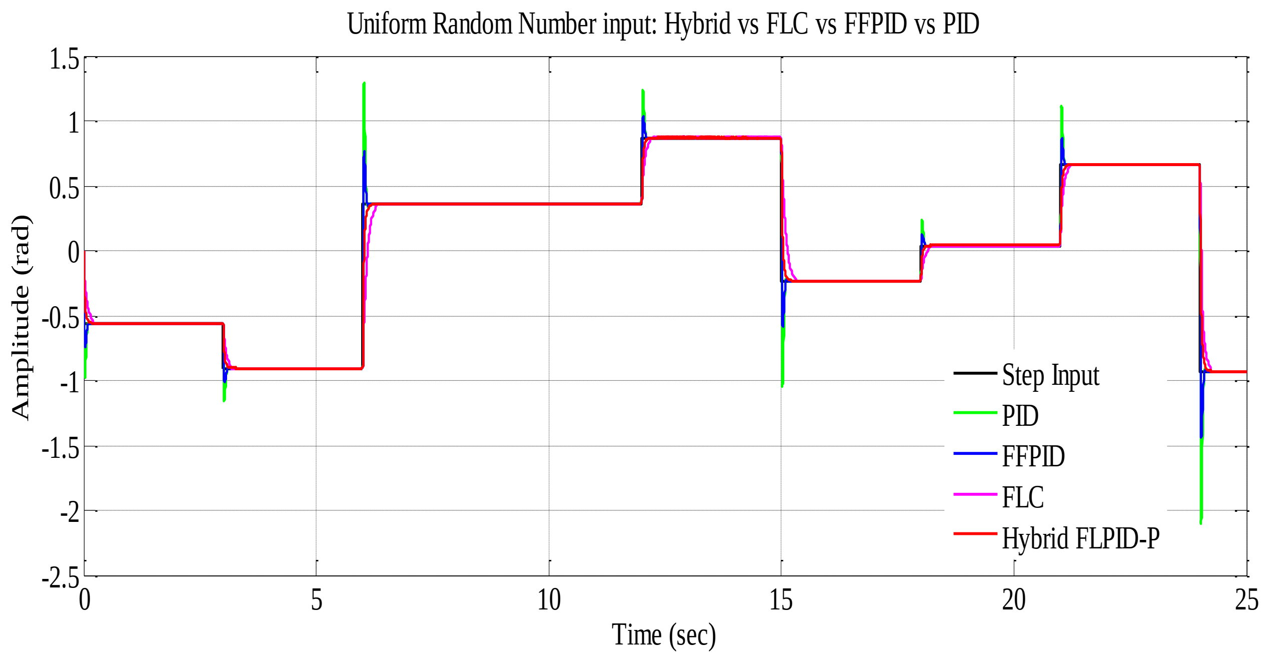
The best control performance after the fine tune of PID controller when load is applied to the motor



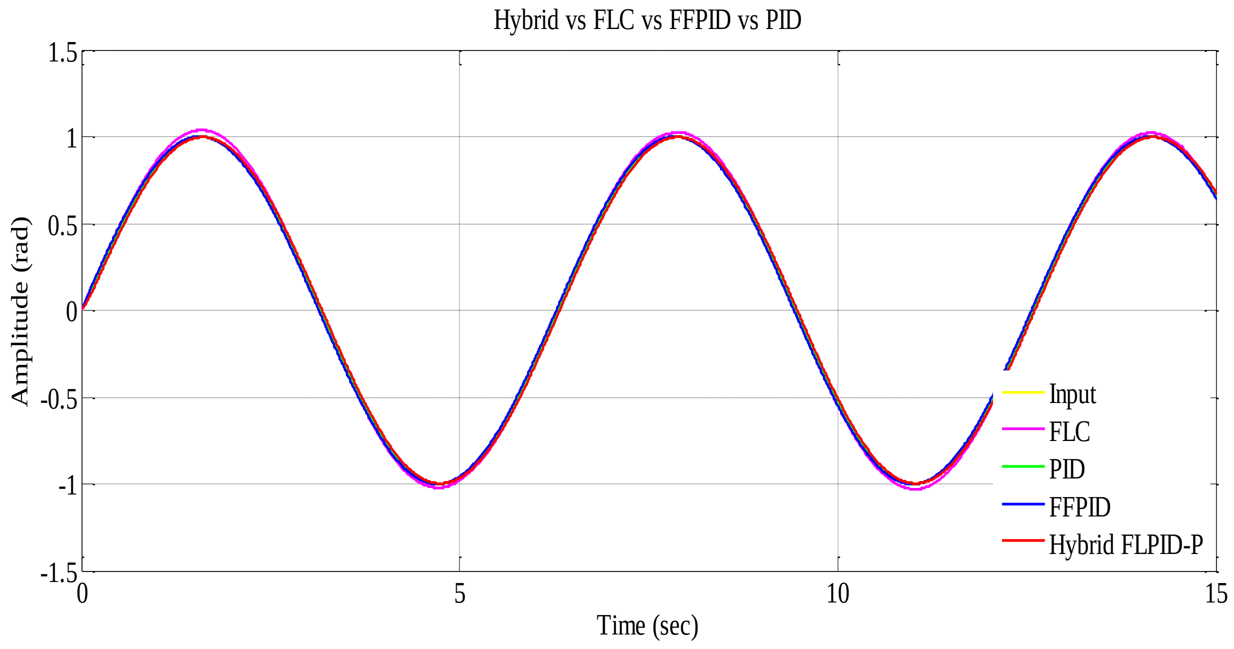
Control performances with steps as input



Control performances with random number as input



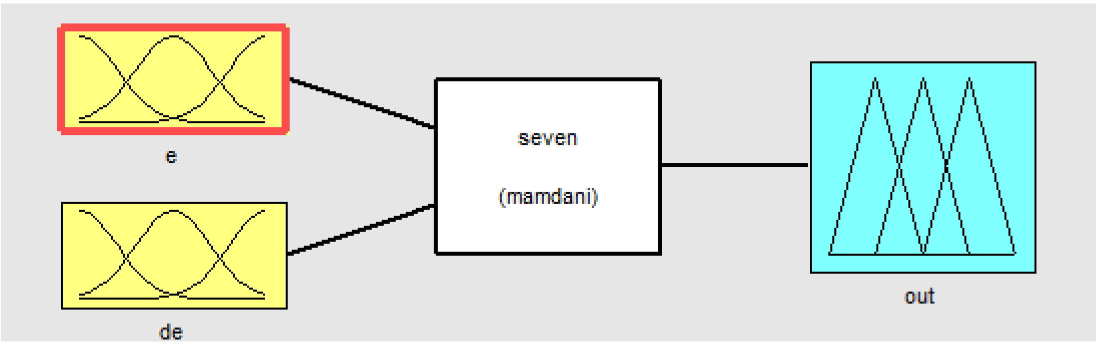
Control performances with uniform random number as input



Control performances with sinusoidal input

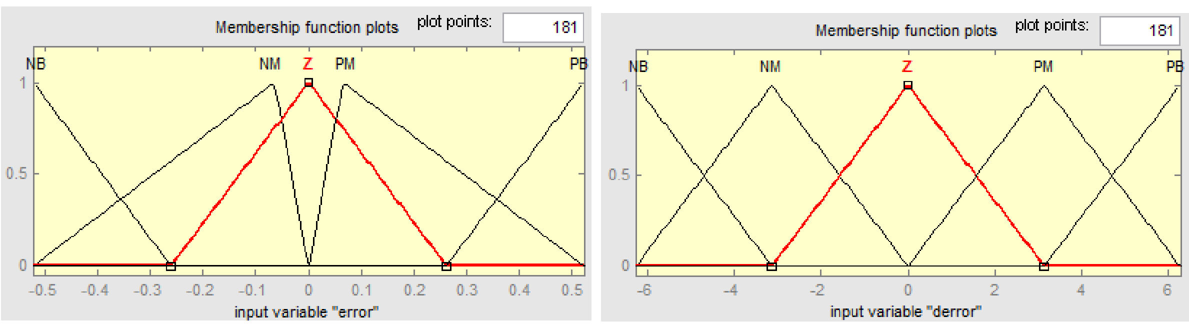
APPENDIX F
FLCs' 3 principle components

FLCs



Inputs, Inference Engine and output for conventional FLC

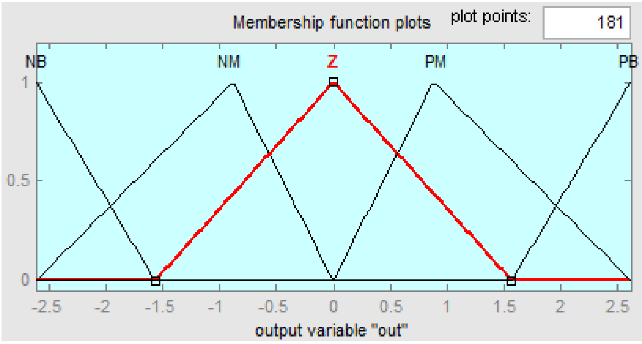
5 MFs's FLC:



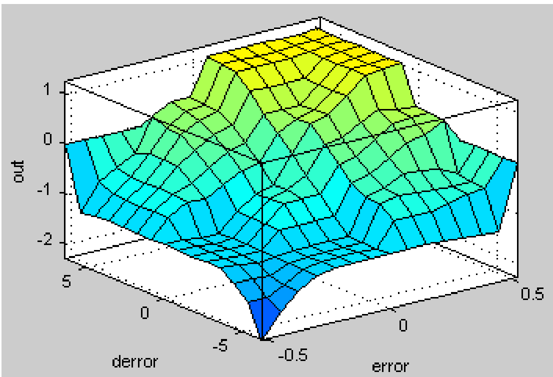
MFs' for error, e and change of error, Δe

Rules for 5 MFs

e / Δe	**NB**	**NM**	**ZE**	**PM**	**PB**
NB	NB	NM	NM	NM	ZE
NM	NM	NM	NM	ZE	PM
ZE	NM	NM	ZE	PM	PM
PM	NM	ZE	PM	PM	PM
PB	ZE	PM	PM	PM	PB



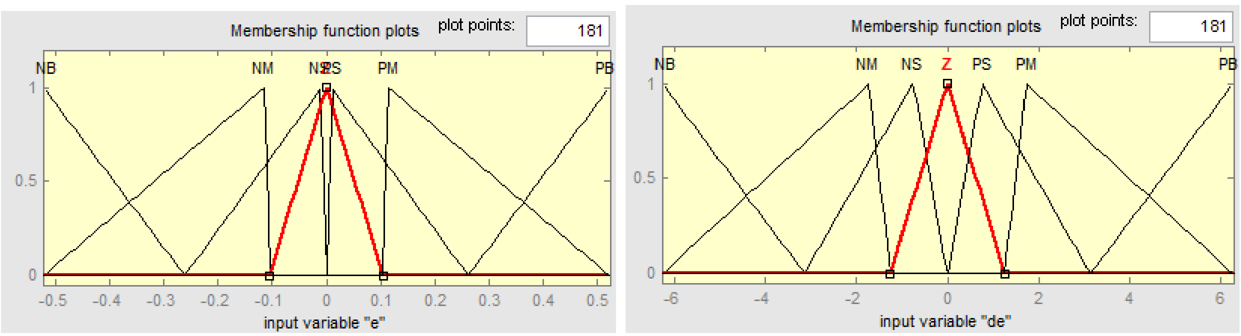
MFs for output, Δu



Surface view of FIS

\

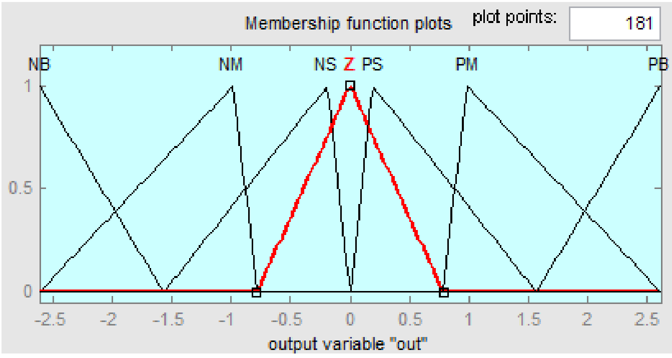
7 MFs's FLC:



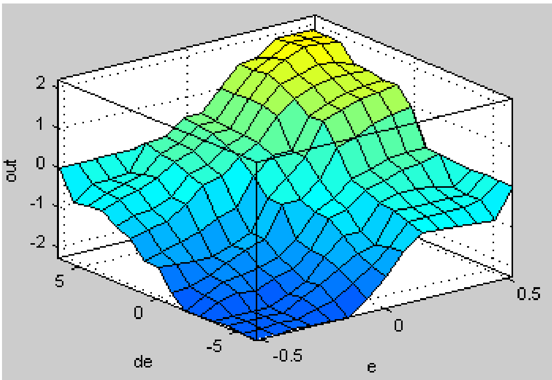
MFs' for error, e and change of error, Δe

Rules for 7 MFs

e / Δe	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NB	NM	NS	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PS	PM	PB	PB
PB	ZE	PS	PS	PM	PM	PB	PB

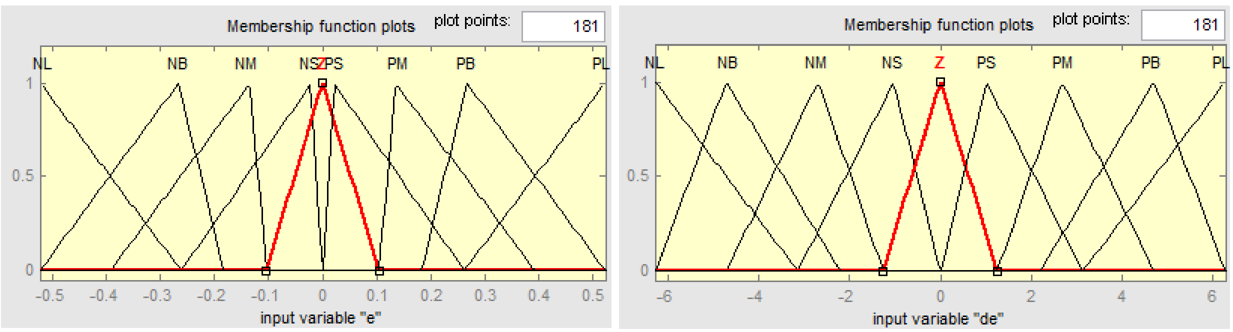


MFs for output, Δu



Surface view of FIS

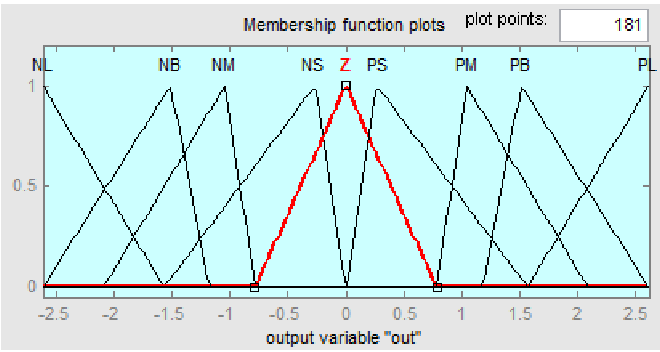
9 MFs's FLC:



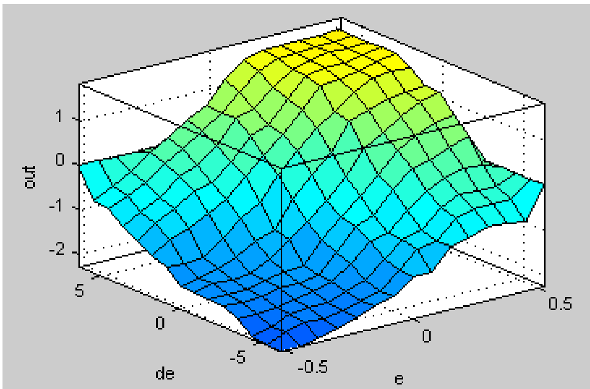
MFs' for error, e and change of error, Δe

Rules for 9 MFs

e / Δe	**NL**	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**	**PL**
NL	NL	NL	NB	NB	NM	NM	NS	NS	ZE
NB	NL	NB	NB	ZB	NM	NS	NS	ZE	PS
NM	NB	NB	NB	NM	NS	NS	ZE	PS	PM
NS	NB	NB	NM	NM	NS	ZE	PS	PM	PM
ZE	NB	NM	NM	NS	ZE	PS	PM	PM	PB
PS	NM	NM	NS	ZE	PS	PM	PM	PB	PB
PM	NM	NS	ZE	PS	PS	PM	PB	PB	PB
PB	NS	ZE	PS	PS	PM	PB	PB	PB	PL
PL	ZE	PS	PS	PM	PM	PB	PB	PL	PL

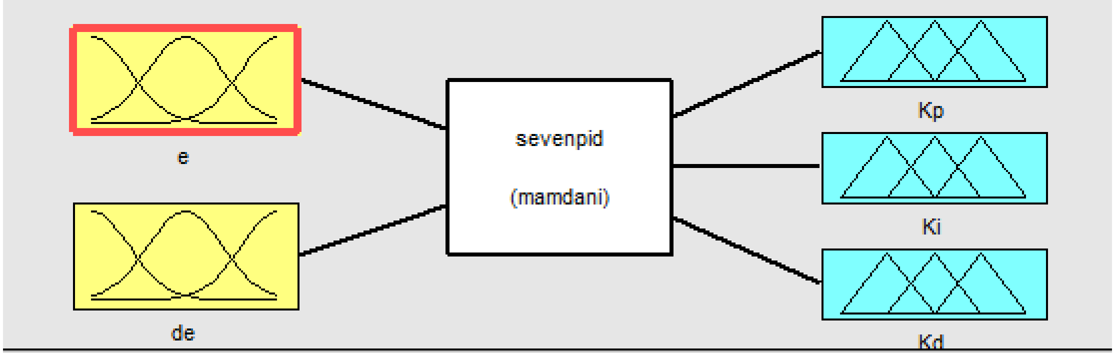


MFs for output, Δu

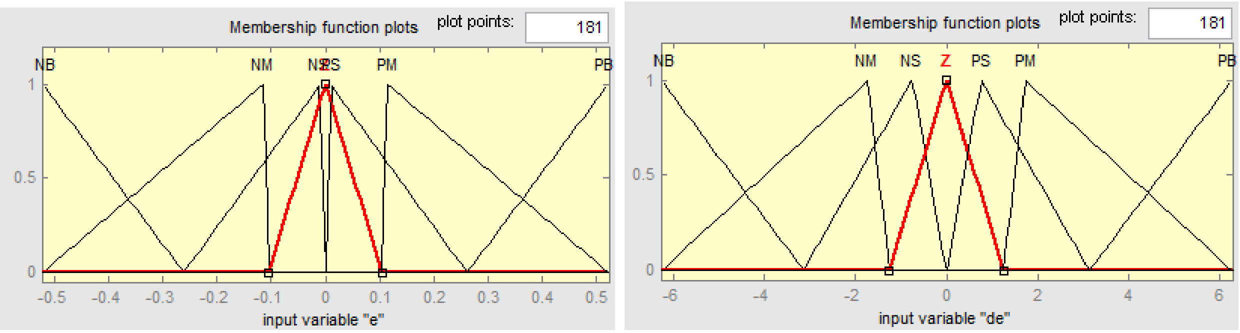


Surface view of FIS

<u>Hybrids (7 × 7 MFs):</u>



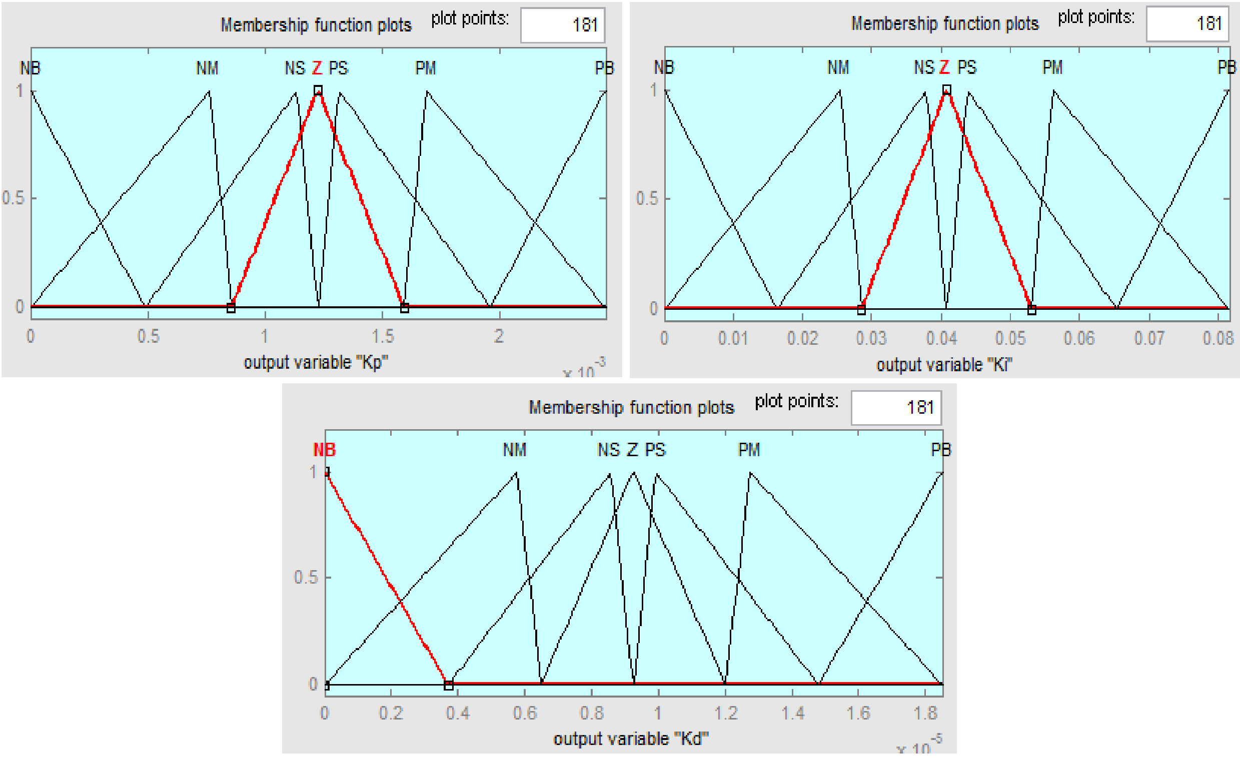
Inputs, Inference Engine and output for FLC-PID



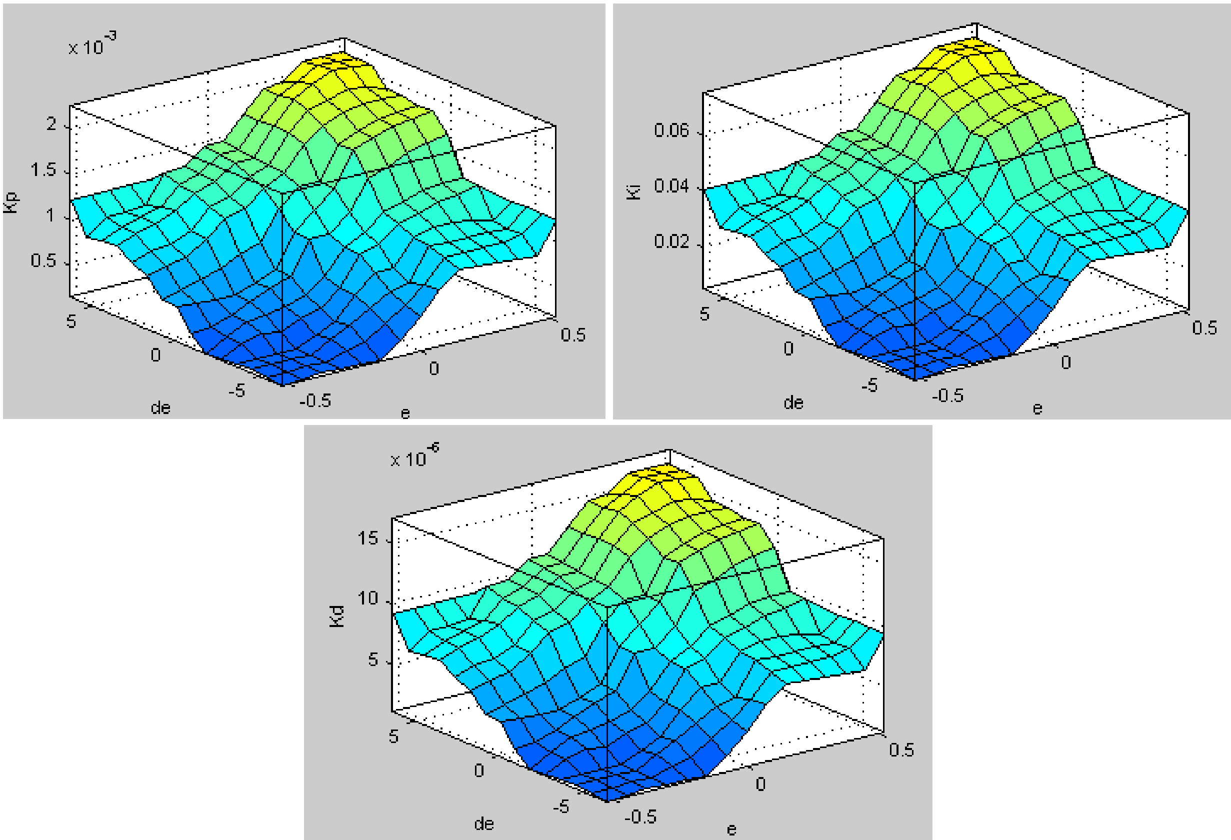
MFs' for error, e and change of error, Δe

Rules for ΔP, ΔI and ΔD

e / Δe	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NB	NM	NS	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PS	PM	PB	PB
PB	ZE	PS	PS	PM	PM	PB	PB

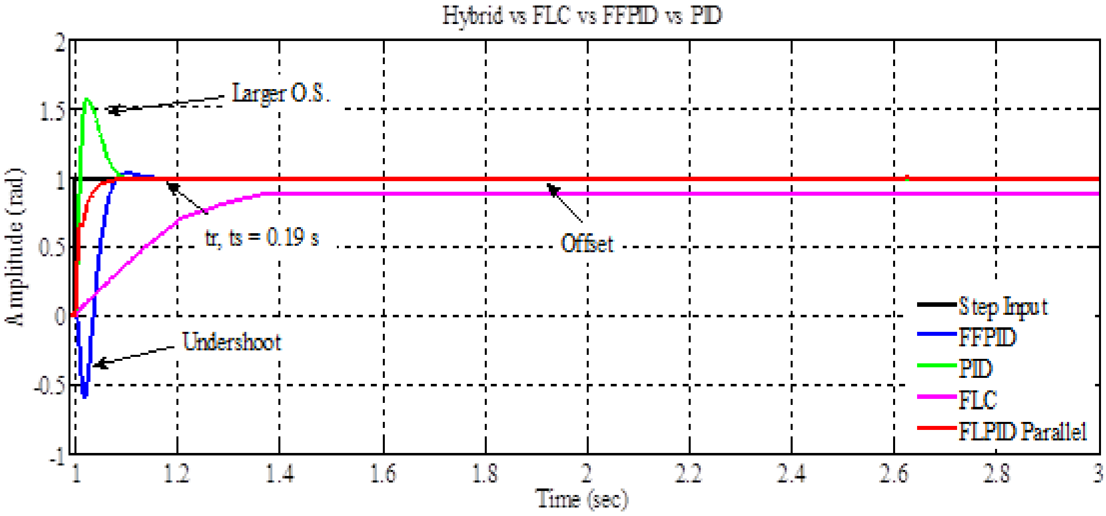


MFs for ΔP, ΔI and ΔD

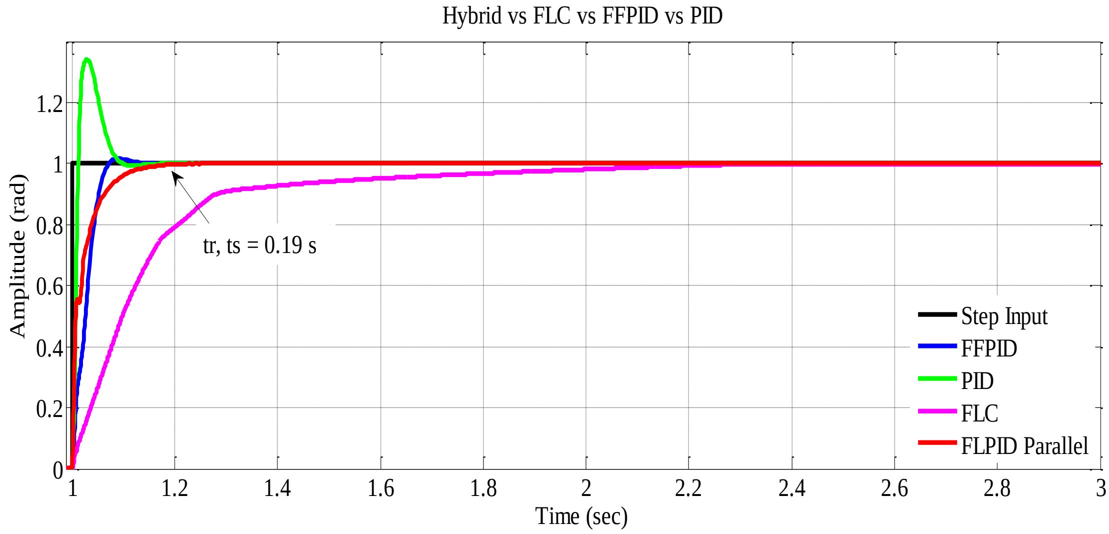


Surface view of FIS for ΔP, ΔI and ΔD

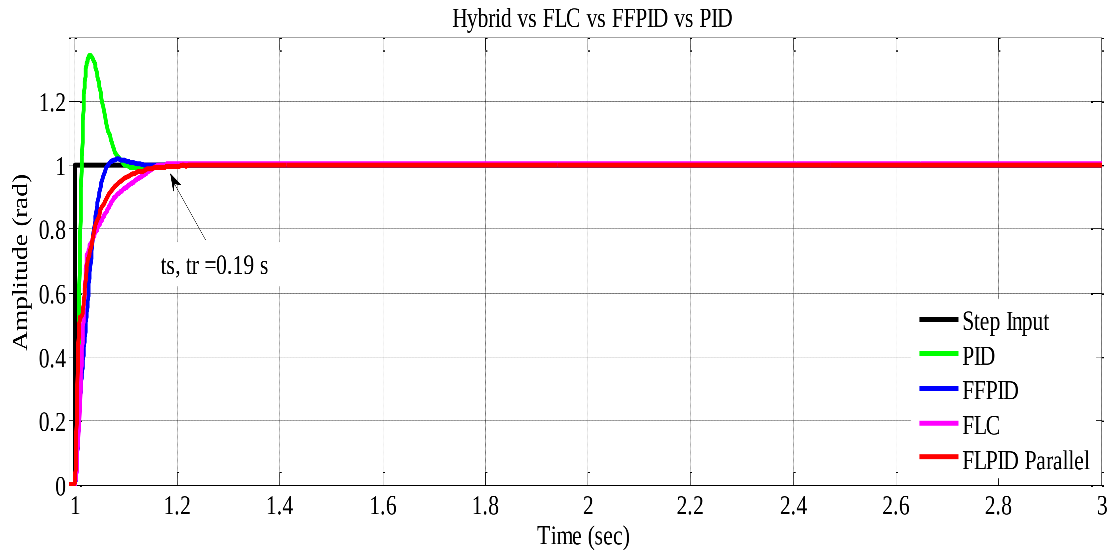
APPENDIX G
Load Variations' Control Performances



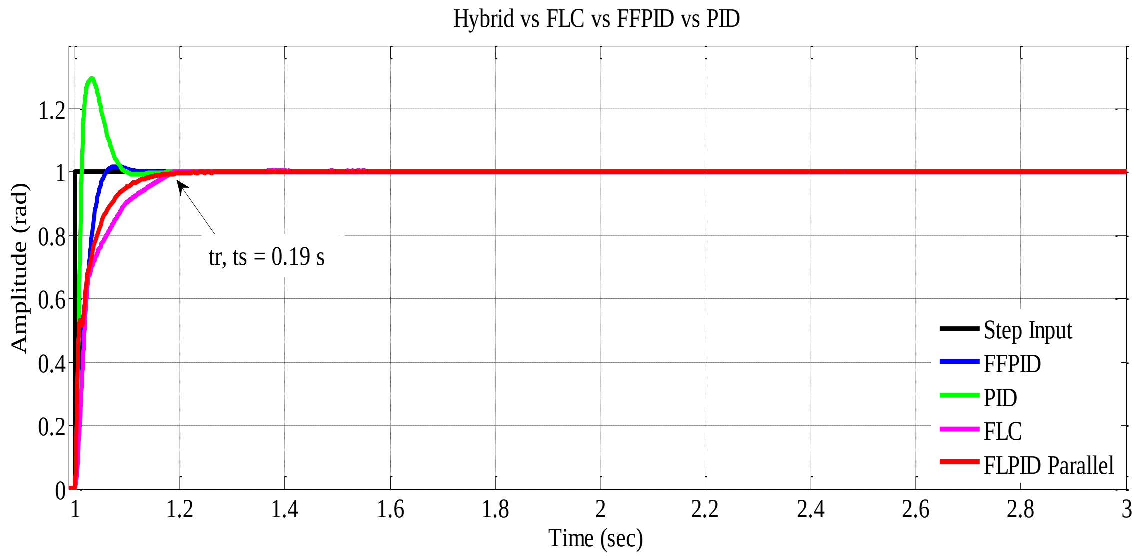
The controllers' performances when load is 3 times of motor shaft weight.



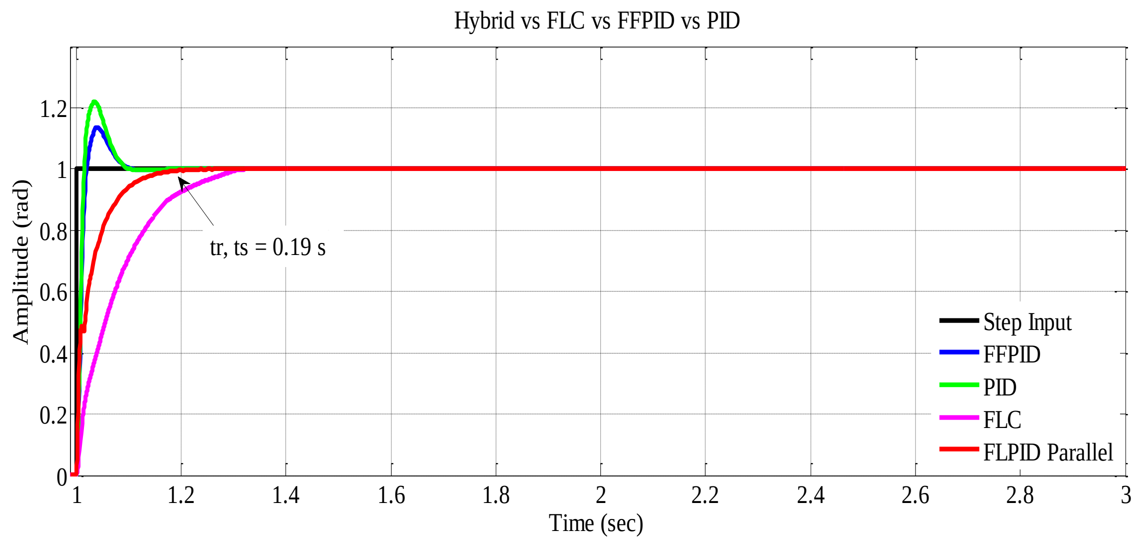
The controllers' performances when load is 7 times of motor shaft weight.



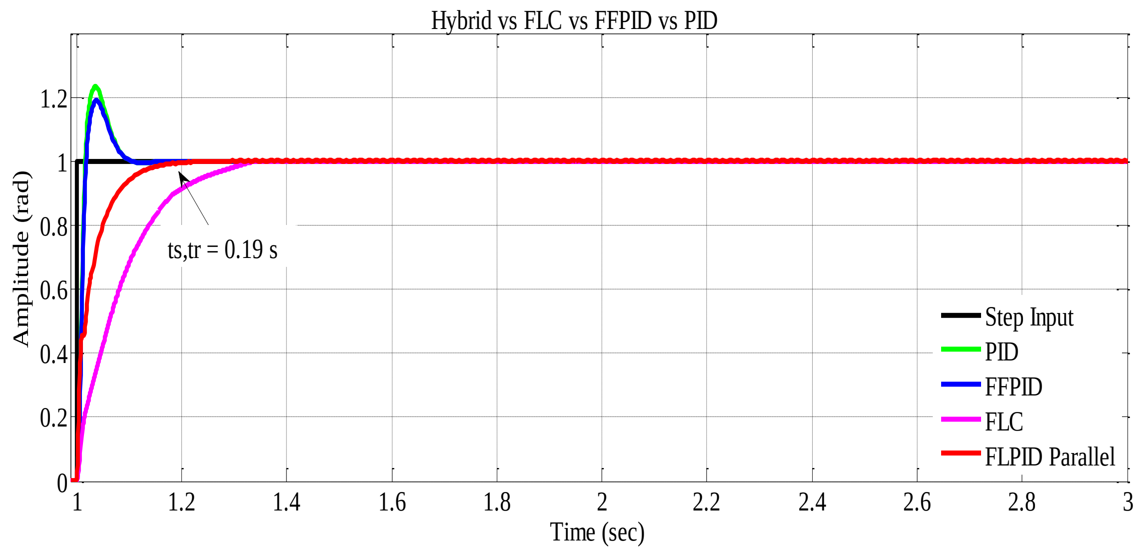
The controllers' performances when load is 8 times of motor shaft weight.



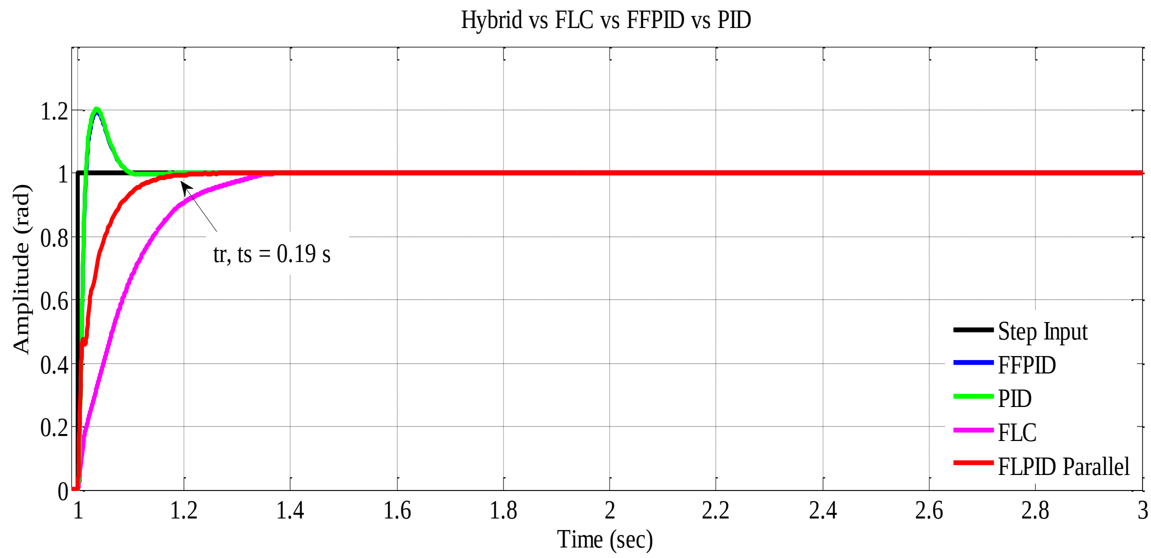
The controllers' performances when load is 10 times of motor shaft weight.



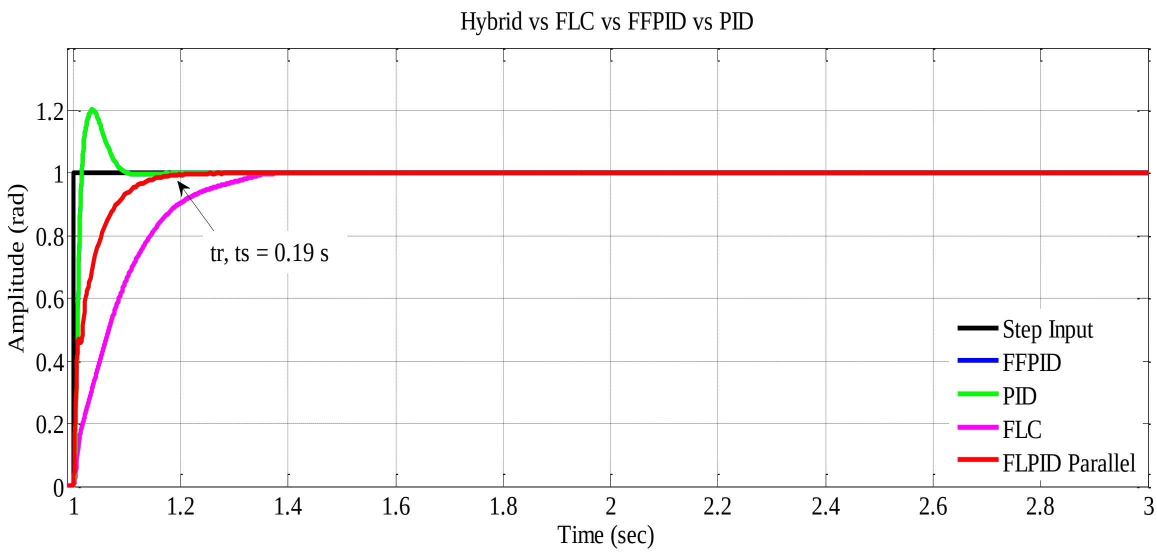
The controllers' performances when load is 50 times of motor shaft weight.



The controllers' performances when load is 100 times of motor shaft weight.



The controllers' performances when load is 500 times of motor shaft weight.



The controllers' performances when load is 500,000 times of motor shaft weight.