Fuzzy Logic Based Motor Control

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Dissertation Submitted in partial fulfilment of
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CERTIFICATION OF APPROVAL

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Approved by,

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CERTIFICATION OF ORGINALITY

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.

Haytham Mohamed Fayek

ABSTRACT

This report presents the detailed design of both Type-1 Fuzzy logic PI controller and Type-2 Fuzzy Logic PI controller to control the speed of a DC servomotor. Both controllers are explored extensively in terms of number and type of membership functions and the defuzzification technique used. Rise time, Settling time, Percent overshoot and Integral Absolute error are used to judge between controllers during a unity step response, load disturbance and noise disturbance.

Using Simulink Matlab, simulation to show the behavior of the DC servomotor will be carried; to compare type-2 fuzzy logic against conventional type-1. Moreover, explain the advantages and disadvantages of fuzzy logic over conventional PID controllers.

A DC servo motor model was built and the performance of a PID controlled system was simulated. Afterwards, type-1 fuzzy logic controller was simulated to determine the system performance. Moreover, both types of controllers were compared against each other to determine the advantages and disadvantages of both. Furthermore, type-1 fuzzy logic controller was explored further where judgment of the performance of the system was carried by varying the number of membership functions, type of membership functions and defuzzification methods. Afterwards, type-2 fuzzy logic controller was simulated and explored in the same manner as type-1 fuzzy logic controller. Both controllers were compared to analyze the advantages and disadvantages of each.

A comparative analysis with the conventional type-1fuzzy logic PI controller shows that overall, type-2 showed much improved results. This improvement is evident when it comes to handling of load disturbance and noise added to the system.

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ABBREVIATIONS

IAE: Integral Absolute Error

MF: Membership Function

T1FL: Type-1 Fuzzy Logic

T2FL: Type-2 Fuzzy Logic

FOU: Footprint Of Uncertainty

LMF: Lower Membership Function

UMF: Upper Membership Function

Sett. Time: Settling Time

% O.S.: Percent Overshot

CHAPTER 1: INTRODUCTION

1.1 Background of the study

There are two types of motors: DC motors, and AC motors. DC motors have better starting torque than AC motors. Servomotors use feedback controller to control the speed or the position, or both. Any motor can be used as a servomotor. Servomotors are used in various applications in industrial electronics and robotics that includes speed control as well as precision positioning. The basic continuous feedback control is PID controller. The PID controller exhibits good performance but is not adaptive enough (Oyas & Nordin, 2008). This is evident in a system when the load is changed or in a noisy system, where the original controller generally cannot maintain the design performance and thus should be re-designed for the new system conditions.

Professor L.A. Zadeh presented the fuzzy sets in 1965, which have the ability to process data and information affected by unprobabilistic uncertainty. Intelligent Systems based on fuzzy logic are fundamental tools for nonlinear complex system modelling. Fuzzy sets are considered a generalization of the classic set theory. Type-1 Fuzzy sets and fuzzy logic are the basis for fuzzy systems, where their objective has been to model how the brain manipulates inexact information.

Prof. Zadeh answered the questions doubting the ability of type-1 fuzzy logic of handling uncertainty by proposing the concept of type-2 fuzzy in 1975. Type-2 fuzzy sets are used for modelling uncertainty and imprecision in a better way. They are very useful in circumstances where it is difficult to determine an exact membership function for a fuzzy set; hence they are very effective for dealing with uncertainties. Type-2 fuzzy logic has found applications in various fields (H. C. Nejad, 2011). A good explanation about type-2 fuzzy logic is presented in this paper (J. M. Mendel & R. I. Bob John, 2002)

Fuzzy Logic Control has demonstrated superiority over PID controllers in terms of: (Nalunat Khongkoom et al., 2000)

- Better noise rejection
- More flexible
- FLC use human knowledge, not accurate mathematical model
- Less sensitive to inertia Variation
- Better overall system performance

This project investigates the performance of a small and fast DC servomotor with Type-2 and Type-1 Fuzzy logic PI controllers. Simulations are executed to judge the performance of the servomotor with different number of membership functions and types of membership. Three different scenarios are simulated, which are unity step response, load disturbance to the servomotor and noise disturbance. The performance parameters are Rise time, Settling time, Percent overshoot, and Integral Absolute error. Simulations were done using Matlab/Simulink, Fuzzy Logic Toolbox and Interval Type-2 Fuzzy Logic Toolbox (J.R. Castro et al., 2007)

1.2 Problem Statement

Type-2 fuzzy logic systems have been an attractive research area in recent years. However, they are more difficult to understand and implement than conventional type-1 fuzzy logic systems. Hence, there are lots of unexplored areas to be explored in type-2 fuzzy logic when it comes to control applications. The effect membership functions, rules and different methods of fuzzification and de-fuzzification are still case-specific and more cases are being simulated by researchers to generalize the behaviour of fuzzy sets. Moreover, doubts on whether PID controllers still have a better response than fuzzy sets in motor control applications.

1.3 Objectives

- Model & Simulate PI controlled DC Servomotor
- Explore & Simulate Type-1 Fuzzy Logic PI Controller
    - Effect of Number of Membership Functions
    - Effect of Type of Membership Functions
    - Effect of different defuzzification techniques
- Explore & Simulate Type-2 Fuzzy Logic PI Controller
    - Effect of Number of Membership Functions
    - Effect of Type of Membership Functions
    - Effect of different defuzzification techniques
- Comparative Analysis Between Type-1 fuzzy logic and Type-2 fuzzy logic

1.4 Scope of Study

The scope of this project consists of research, simulation and analysis. The research is essential for better understanding on the theory and concept of fuzzy logic. Simulation must be carried out using Simulink/Matlab to determine the behaviour of each controller; PID controller, Type-1 fuzzy logic PI based controller and type-2 fuzzy logic PI based controller; exploring different number and types of membership functions. Furthermore, analysis of the results and comparing type-1 against type-2 as well as PID are included in the scope of this project.

CHAPTER 2: LITERATURE REVIEW

2.1 DC Servomotor

Servomotors are used in various applications in industrial electronics and robotics that needs speed control and precision positioning. Any motor can be used in a servo mechanism. In general, motors are divided into two categories: DC motors, and AC motors. Mostly, DC motors have better starting torque than AC motors although they are more expensive than AC motors.

"Servomotors use feedback controller to control the speed or the position, or both. The basic continuous feedback control is PID controller. The PID controller possesses good performance but is not adaptive enough. This is appealing when the load is changed, where the original controller generally cannot maintain the design performance and thus should be re-designed for the new system conditions." (Oyas & Nordin, 2008)

A model of DC servomotor is shown in Figure 1.

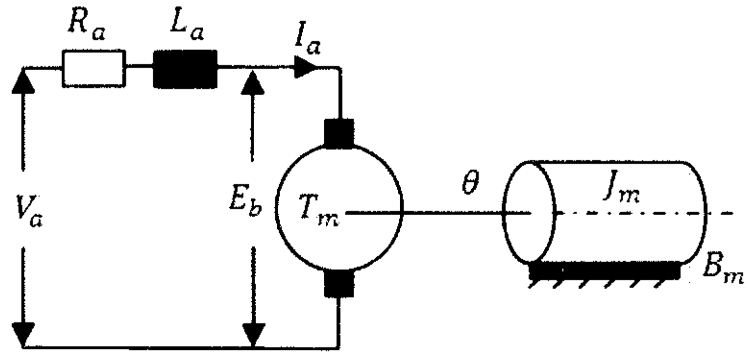

Figure 1: DC Servomotor Model

The relation between the rotor shaft speed and the applied armature voltage is represented by the following transfer function:

$$\frac{W(s)}{V(s)} = \frac{Ke}{JL\,s^2 + (JR+LB)s + (Kt.Ke+RB)} \qquad (1)$$

where,

W = angular Speed (rad/s)

V = armature voltage (V)

R = armature resistance (Ω)

L = armature inductance (H)

J = rotor inertia (Kgm^2)

B = viscous friction coefficient (Nms/rad)

Ke = torque constant (Nm/A)

Kt = back emf constant (Vs/rad)

This model was based on an actual DC servomotor. The motor chosen is a very small brushless DC servomotor used in the PCB industries. It is a Faulhaber brushless DC servomotor (Series 1226012B) which is characterized by:

FAULHABER

- High speed
- Small inertia
- High accuracy and Precession

The application of this kind of series of micro motors is PCB industry where speed and accuracy are essential. Technical Specifications of this motor are attached in Appendix B.

2.2 PI Controller

PID controllers are widely used in industrial control applications due to their simple structures, comprehensible control algorithms and low costs. Figure 2 shows the schematic model of a control system with a PID controller.

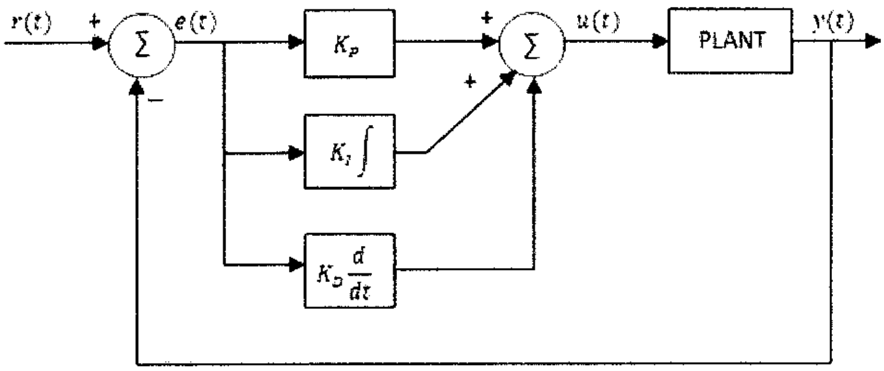

Figure 2: PID Controller

PI controller uses control signal u(t), which is a linear combination of error e(t), and its integral as shown in equations 2 & 3.

$$u(t) = K_p e(t) + K_I \int e(t)\, dt \qquad (2)$$

$$u(t) = K_p \left(e(t) + \frac{1}{T_I} \int e(t)\, dt\right) \qquad (3)$$

where,

K_p = proportional gain

K_I = integral gain

T_I = integral time

PID controllers are usually tuned using hand tuning or Ziegler-Nichols methods to obtain the desired performance according to meet preset criteria.

2.3 Fuzzy Logic

The fuzzy sets were presented by L.A Zadeh in 1965. The objective of the fuzzy sets is to process data and information affected by unprobabilistic uncertainty. These sets were designed to mathematically represent the vagueness and uncertainty of linguistic problems (Oscar Castillo et al., 2008); and therefore obtaining formal tools to work with intrinsic imprecision in different types of problems.

The classical or digital logic operates on two distinct values which are either 0 or 1. Fuzzy logic is considered a generalization of classic logic, in which fuzzy logic can be defined as a mathematical system that analyzes analogue input values in terms of logical variables that take on continuous values between 0 and 1 (Juan R. Castro et al., 2008).

A fuzzy control system is a control system based on fuzzy logic. Fuzzy logic is widely used in machine control. It is very advantageous when it comes to concepts that cannot be expressed as "true" or "false" but rather as "partially true". Although genetic algorithms and neural networks can perform just as well as fuzzy logic in some cases, fuzzy logic is superior in problems that the solution can be resolved in terms that human operators can understand, so that their experience can be employed in the design of the controller (Yong Yin et al., 2008). This makes it easier to automate tasks that are successfully performed by humans when the classical theory has failed.

A type-1 fuzzy logic system is shown in Figure 3.

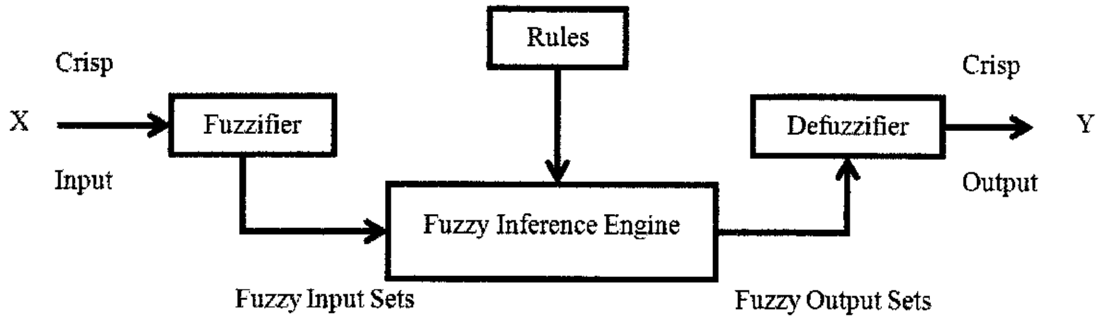

Figure 3: Fuzzy Logic System

The input variables in a fuzzy control system are mapped into fuzzy sets, known as "Membership Functions". The process of converting a crisp input value to a fuzzy value is called "fuzzification". The output variables experience the opposite process, which is converting the fuzzy value to a crisp values, it is known as "defuzzification".

The membership function is a graphical representation of the magnitude of participation of each input. The role of the membership functions is to:

- Assign a weighting to each of the inputs that are processed,
- Define functional overlap between inputs,
- And finally, determines an output response.

The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. Once the functions are inferred, scaled, and combined, they are defuzzified into a crisp output which drives the system. There are different memberships functions associated with each input and output response. Membership functions have numerous types, for example triangular shaped, trapezoidal shaped or bell shaped; as show in figure 4. More than one type of membership functions can be used in the same system.

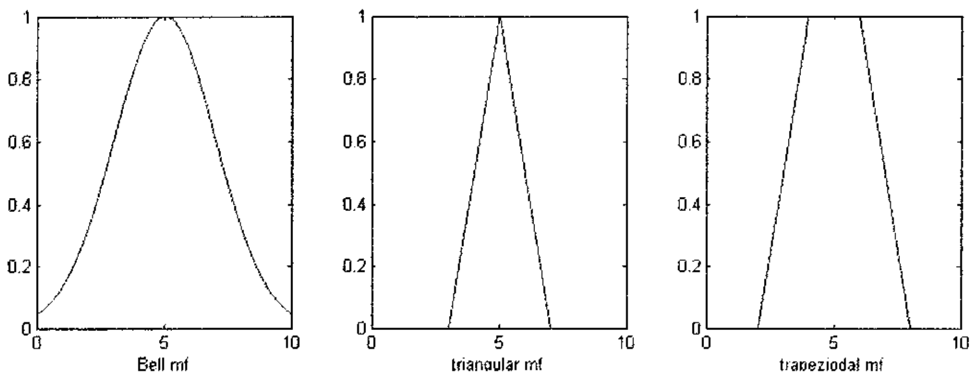

Figure 4: Various types of Type-1 Membership Functions

The fuzzy propositions are divided in two types; the first one is called atomic, such as

x is A

where, x is a linguistic variable & A is a linguistic value.

The second one is called compounded, such as

x is A AND y is B OR z is NOT C

where, x, y, z are linguistic variables & A, B, C are linguistic values.

The "AND", "OR" and "NOT" are called connector, and they represent fuzzy intersection, union and complement respectively. Using the fuzzy propositions we can obtain fuzzy relationships.

The fuzzy rules combine one or more fuzzy sets of entry, called antecedent, and are associated with one output fuzzy set, called consequents. The Fuzzy Sets of the antecedent are associated by fuzzy operators AND, OR, NOT and linguistic modifiers. The fuzzy rules allow expressing the available knowledge about the relationship between antecedent and consequents, using several rules grouped to form what it is known a rule base. The number of rules is determined using equation 4.

$$R_N = M^N \qquad (4)$$

where, R_N is the number of rules, M is the number of membership functions, and N is the number of inputs.
i.e. A system having 2 inputs and 7 membership functions , will have $7^2 = 49$ rules.

The rule base is used to express the known relationships between antecedent and consequents. The fuzzy rules are basically

IF <Antecedent> THEN <Consequent>

and expresses a fuzzy relationship or proposition (Oscar Castillo et al., 2008).

Defuzzification can be defined as the process of finding one single crisp value that summarizes the fuzzy set that defines the fuzzification. Numerous defuzzification techniques can be utilized to perform defuzzification. The defuzzification techniques used in this project are (D. H. Rao & S. S. Saraf, 1996):

- **Centroid (Center of Area):** It is the most common defuzzification techniques used, especially in fuzzy logic control. This technique determines the center of the area of the combined membership function. It utilizes the area of the union of fuzzy sets
- **Center of Sums (COS):** This technique is very similar to Centroid technique but faster. This technique avoids the computation of the union of fuzzy sets. It takes into account the contribution of the area of each fuzzy set on its own. Basically, Centroid technique takes the union of fuzzy sets, while center of sums technique takes the sum of the fuzzy sets.
- **First of Maxima (FOM):** This technique uses the union of the fuzzy sets and takes the smallest value of the domain with maximal membership degree.
- **Last of Maxima (LOM):** This technique uses the union of the fuzzy sets and takes the largest value of the domain with maximal membership degree.
- **Middle of Maxima (MOM):** This technique like FOM and LOM uses the union of the fuzzy sets but instead of using the first or the last from all values, it takes the average of these two values.

2.4 Type-2 Fuzzy Logic

Type-1 fuzzy sets were criticized for its inability to handle uncertainty and impression although the named "Fuzzy" is used. Prof. Zadeh answered the questions doubting the ability of type-1 fuzzy logic of handling uncertainty by proposing the concept of type-2 fuzzy in 1975. Type-2 fuzzy sets are used for modeling uncertainty and imprecision in a better way. There are different sources of uncertainty. The five types of uncertainty that emerge from the imprecise knowledge are (Juan R. Castro et al., 2008):

- Measurement uncertainty, which is the error on observed and measured variables.
- Process uncertainty, which is the dynamic randomness.
- Model uncertainty, which is the inaccurate specification of the model structure.
- Estimate uncertainty, which is the result of any of the previous uncertainties or a combination of them, it is also known as inexactness and imprecision.
- Implementation uncertainty, which is the consequence of the variability that results from sorting politics, i.e. incapacity to reach the exact strategic objective.

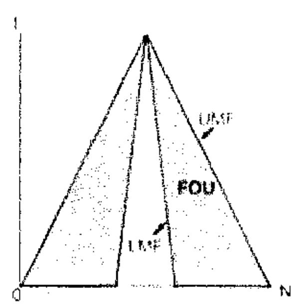

Figure 5: Type-2 Membership Function

Type-2 fuzzy sets are essentially "fuzzy fuzzy" sets where the membership function itself became fuzzy. Type-2 fuzzy set membership functions has become three dimensional having a superior membership function and an inferior membership function; these two functions can be represented each one by a type-1 fuzzy set membership function. The interval between these two functions represents the footprint of uncertainty (FOU), which is used to characterize a type-2 fuzzy set

(Philip A.S. Birkin & J.M. Garibaldi, 2009). The superior membership function is denoted by Upper membership Function (UMF), while the inferior membership function is denoted by Lower Membership function (LMF) (I. Robandi, & B. Kharisma, 2009). Interval type-2 membership function is shown in Figure 5.

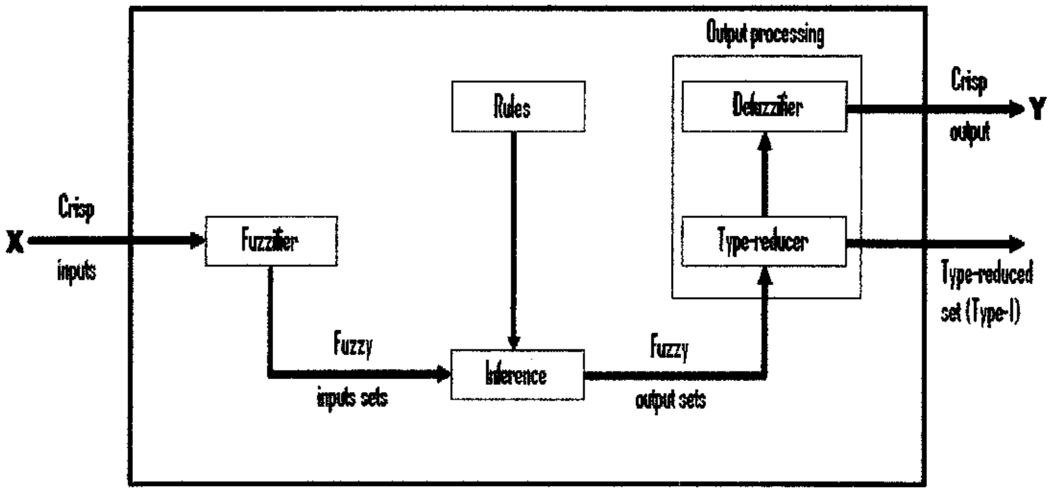

Figure 6: Structure of Type-2 Fuzzy Logic System

Mendel and Liang introduced the Type-2 Fuzzy Logic Control System (E. Kayacan et al., 2010). The type-2 fuzzy logic system is demonstrated in Figure 6.

The structure of a fuzzy logic type-2 system includes 4 components (O. Castillo et al., 2008):

- ***Fuzzifier:*** Translates inputs (real values) to fuzzy values.
- ***Inference System:*** Applies a fuzzy reasoning mechanism to obtain a fuzzy output.
- ***Type Defuzzifier/Reducer:*** The defuzzifier translates one output to precise values; the type reducer transforms a Type-2 Fuzzy Set into a Type-1 Fuzzy Set.
- ***Knowledge Base:*** Contains a set of fuzzy rules, and a membership functions set known as the database.

In type-1 fuzzy logic system, the defuzzifier combines the output sets corresponding to all fired rules to find obtain a crisp output value. In type-2, the output set corresponding to each fired rule is assumed to be a type-2 set. In which, a type-reducer is required to combine all these output sets (in same manner as a type-1 defuzzifier) and then perform defuzzification calculation on this type-2 set, which leads to a type-1 set called "type-reduced" set. Type-2 defuzzification techniques are (N. N. Karnik, et al., 1999):

- **Centroid:** Centroid technique combines the output type-1 sets and then finds the center of the area of the combined membership function of this set. This technique combines all the output type-2 sets by finding their union
- **Height:** Height defuzzification technique replaces each rule output set by a singleton at the point having maximum membership in that output set and then calculates the centroid of the type-1 set of these singletons. The height reducer replaces each output set by a type-2 singleton. This singleton can be chosen to be the point having the highest membership in the output set.
- **Center of Sets:** In this technique each rule consequent set is replaced by a singleton situated at its centroid and then the centroid is deduced of the type-1 sets which consist of these singletons. The center-of-sets type reducer replaces each consequent set by its centroid and finds a weighted average of these centroids.

2.5 Fuzzy Logic PI Controller

A fuzzy logic controller is usually combined with either a PI or PD controller in motor control applications. PI controller was chosen, as it had better overall system performance. Moreover, PD fuzzy logic controller usually results in steady state error, as it lacks integral function in its control nature (M.A. Ahmad et al., 2010).

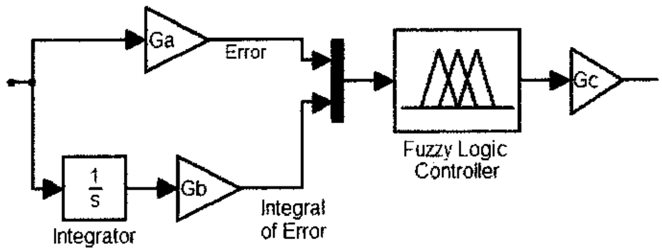

Figure 7: Fuzzy Logic PI Controller

The Fuzzy Logic PI Controller has 2 inputs; which are error and integral of error and it has 1 output. The parameters of the tuned PI controller namely proportional gain and integral gain are used to compute the gains for the fuzzy logic PI controller G_a, G_b and G_c as shown in equations 5 & 6 (Manefeddin N and Onur B., 2010). Where, G_a and G_b are the gain of the inputs for the fuzzy controller; error and integral of error respectively and G_c is the gain for the output of the fuzzy controller. The parameters computed were fitted in the system as shown in figure 7.

$$G_a \times G_c = K_P \qquad (5)$$

$$\frac{G_b}{G_a} = K_I \qquad (6)$$

CHAPTER 3: METHODOLOGY

3.1 Methodology

This project will follow the following methodology to meet the objectives. This project is divided into four major groups which are modelling of the DC servomotor, PI controller simulations, type-1 fuzzy logic PI based controller and finally type-2 fuzzy logic PI based controller. The performance of the 3 types of controllers will be examined. Type-1 and type-2 fuzzy logic PI controllers will be explored extensively in the sense of different types of membership functions, different number of membership functions and different defuzzification techniques.

Firstly, the concept and theory of fuzzy logic shall be gathered and understood. The second step will be the review of current progress in this research area and the latest updates in the fuzzy logic field. Next, is to model the chosen DC servomotor and simulate it on Simulink. The next step is simulating a PI controller to control the motor and tune this PI controller to give the best performance. Afterwards, simulation of type-1 fuzzy logic PI based controller shall be carried out using the Fuzzy toolbox in Simulink. Exploring type-1 shall be done extensively in terms of evaluating different types of membership functions such as triangular, Gaussian and trapezoidal; and their effect of the controllability of the motor. Other simulations will be carried out to evaluate the effect of the number of membership, different defuzzification techniques.

Moreover, type-2 fuzzy logic PI based controller will be modelled to control the servo motor. A toolbox was obtained to conduct simulations (J.R. Castro et al., 2007). Same procedures shall be carried out as type-1 but in a deeper manner; as type-2 remains relatively unexplored compared to the conventional type-1. The effect of various numbers and types of membership functions on the performance of the motor, as well as different defuzzification techniques.

Comparisons between all 3 types of controllers shall be done to identify the advantages and disadvantages of each controller in controlling a servo motor. Figure 8 shows the simplified methodology which has been explained earlier while Table 1 and Table 2 show the project activities for two semesters.

3.2 Tools & Technology

- Faulhaber DC Brushless Servomotor (Series 1226012B): The servomotor that was chosen to be modeled. Data Sheet is attached in Appendix B
- Simulink/Matlab: Used to conduct the simulations
- Fuzzy Logic Toolbox: Used to build type-1 fuzzy logic system
- Interval Type-2 Fuzzy Logic Toolbox: Used to build type-2 fuzzy logic system (J.R. Castro et al., 2007).

3.3 Flow Chart

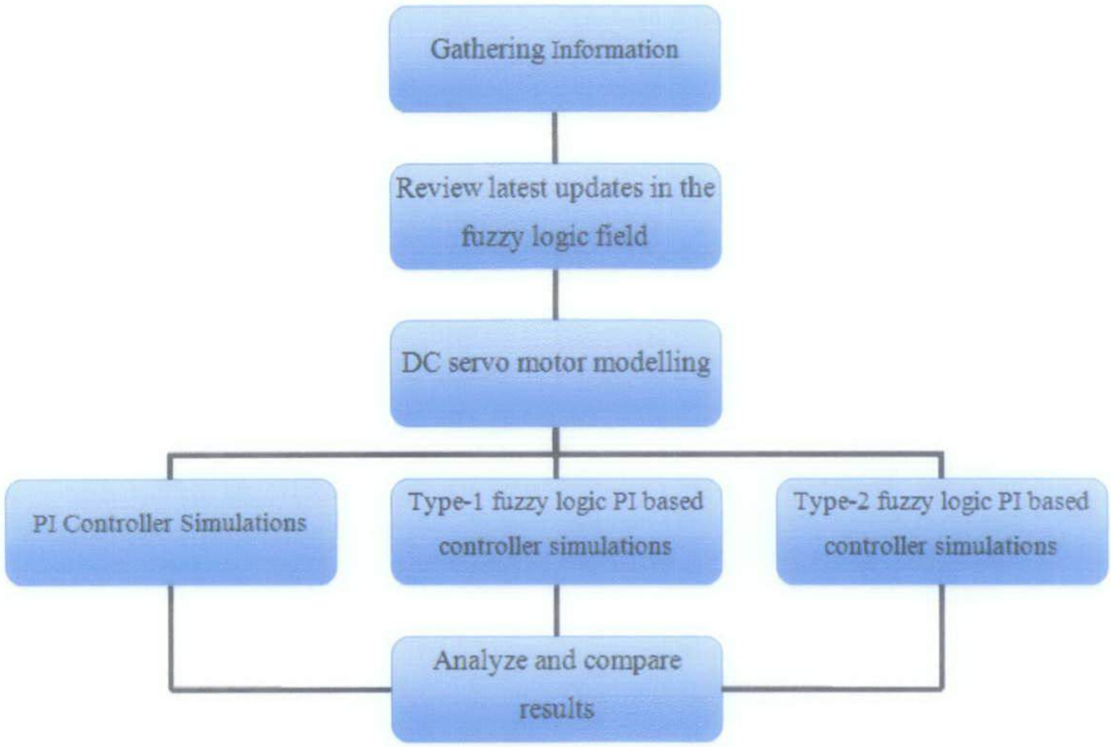

Figure 8: Flowchart of the Project

3.4 Gantt Chart

Gantt chart is attached in Appendix A

CHAPTER 4: MATERIALS AND METHODS

Both type-1 fuzzy logic PI controller and type-2 fuzzy logic PI controller were simulated in three different cases; which are unity step response, load disturbance and noise disturbance. The performance criteria selected for the step response were Rise time, Settling time, Percent overshoot, and Integral Absolute error (IAE). While, the performance criteria for load disturbance and noise disturbance is IAE only.

$$IAE = \sum_{K=1}^{N} \left| e(k) \right| \qquad (7)$$

where, N is the number of points in the simulation and $e(k)$ is the error at k^{th} point.

4.1 DC Servomotor Model

A DC servomotor model was modelled in MATLAB/SIMULINK. From the technical specification sheet attached in Appendix B, we can obtain the values the terminal resistance, back-EMF constant, torque, Inductance and rotor inertia to come up with the transfer function and thus the motor model shown in figure 9.

R = armature resistance (Ω) = 5.3 Ω
L = armature inductance (H) = 80×10^{-6} H
J = rotor inertia (Kgm^2) = 0.145×10^{-7} Kgm^2
B = viscous friction coefficient (Nms/rad) = 7.8×10^{-8} Nms/rad
K_e = torque constant (Nm/A) = 4.09×10^{-3} Nm/A
K_t = back emf constant (Vs/rad) = 4.09×10^{-3} Vs/rad

$$\frac{W(s)}{V(s)} = \frac{0.00409}{(1.16 \times 10^{-12})s^2 + (7.686 \times 10^{-8})s + (1.714 \times 10^{-5})}$$

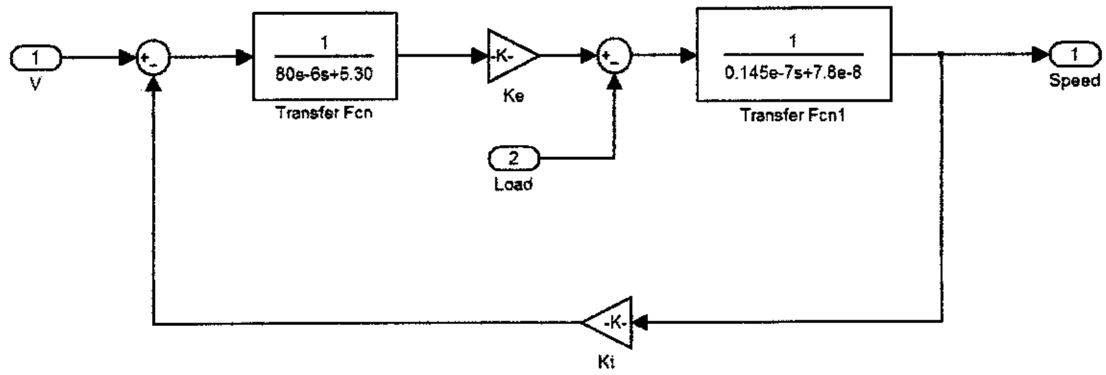

Figure 9: Motor Model in Simulink

4.2 PI Controller

PI controller was used to simulate a closed loop response of the system. The model was constructed in SIMULINK. Then, The PI controller was tuned using the Simulink tuning block followed by hand tuning to give the following parameters:

Proportional (P) = 0.002168,

Integral (I) = 730.7

A unity step input was added, as well as a scope to monitor the output and a display to display the IAE at the end of the simulation. At the end, the block diagram is shown in figure 10.

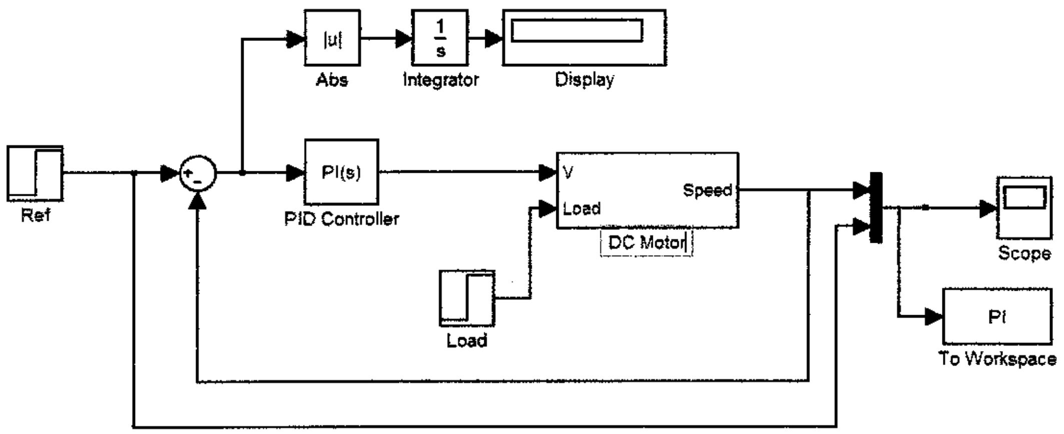

Figure 10: Block Diagram - PI Controller

The closed loop response of the previous system responding to a unity step input is shown in figure 11.

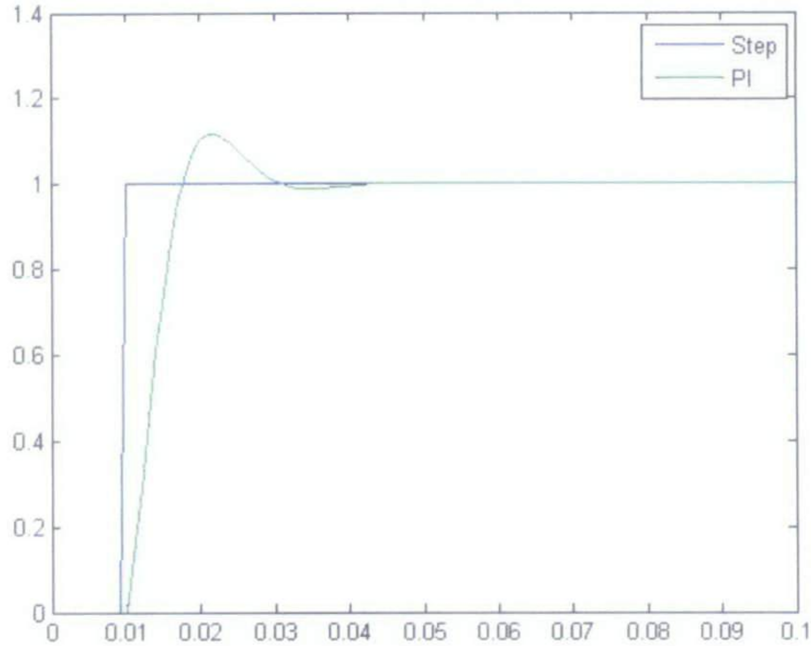

Figure 11: System Response to unit step input - PI controller

Table 3 shows the performance parameters of the PI controlled system due to a unity step input.

Table 1: Performance Parameters - PI Controller

Performance Parameter	Attribute
Rise Time	0.0056 s
Settling Time	0.0288 s
Percent Overshoot	11.65%
IAE	0.0044

4.3 Fuzzy Logic PI Controller

PI controller was replaced in the system with Type-1 Fuzzy logic PI Controller. Three gains were added to the controller; which were obtained from PI controller tuned values using equations 5 and 6.

$$Ga \times Gc = 0.002168$$

$$G_b/G_a = 730.79$$

Therefore, $G_a = 0.1$, $G_b = 73.079$, $G_c = 0.02168$

Figure 12 shows the Fuzzy logic PI controlled system.

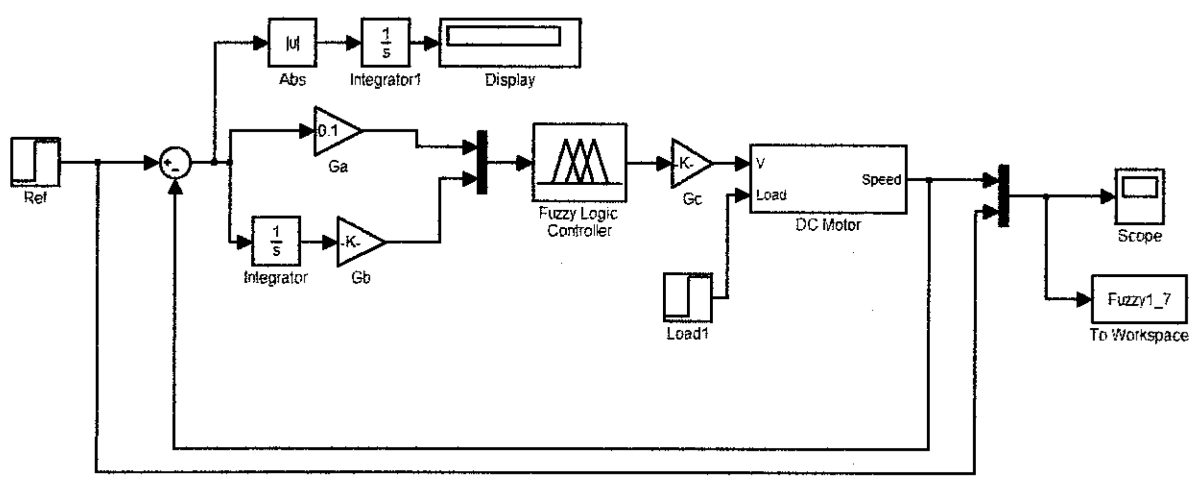

Figure 12: Type-1 Fuzzy logic PI controlled System

Fuzzy interference system needs to be set first; where the input and output membership functions (MF) are defined, as well as the rule base is set. Rule bases for 3 MFs, 5 MFs and 7 MFs are displayed in Tables 4, Table 5 and Table 6 respectively.

Table 2: Rule base for 3 MFs

E / DE	**Neg**	**Zero**	**Pos**
Neg	Neg	Neg	Zero
Zero	Neg	Zero	Pos
Pos	Zero	Pos	Pos

Table 3: Rule base for 5 MFs

E / DE	**BNeg**	**Neg**	**Zero**	**Pos**	**BPos**
BNeg	BNeg	BNeg	BNeg	Neg	Zero
Neg	BNeg	Neg	Neg	Zero	BPos
Zero	BNeg	Neg	Zero	Pos	BPos
Pos	BNeg	Zero	Pos	Pos	BPos
BPos	Zero	Pos	BPos	BPos	BPos

Table 4: Rule base for 7 MFs

E / DE	**BNeg**	**MNeg**	**Neg**	**Zero**	**Pos**	**MPos**	**BPos**
BNeg	BNeg	BNeg	BNeg	MNeg	Neg	Neg	Zero
MNeg	BNeg	MNeg	MNeg	MNeg	Neg	Zero	Pos
Neg	BNeg	MNeg	Neg	Neg	Zero	Pos	MPos
Zero	BNeg	MNeg	Neg	Zero	Pos	MPos	BPos
Pos	MNeg	Neg	Zero	Pos	Pos	MPos	BPos
MPos	Neg	Zero	Pos	MPos	MPos	BPos	BPos
BPos	Zero	Pos	Pos	MPos	BPos	BPos	BPos

Where,

BNeg: Big Negative

MNeg: Medium Negative

Neg: Negative

Zero: Zero

Pos: Positive

MPos: Medium Positive

BPos: Big Positive

All the membership functions used in the simulation had an overlap of 50%, which is the most natural and unbiased choice (M. Tushir & S. Srivastava, 2011). Moreover, Mamdani method - also known as Max-Min method - was used in the simulations. Numerous numbers and types of membership functions were used throughout the simulations. Figure 13 shows 5 triangular MFs, 7 Gaussian MFs and 7 Trapezoidal MFs respectively.

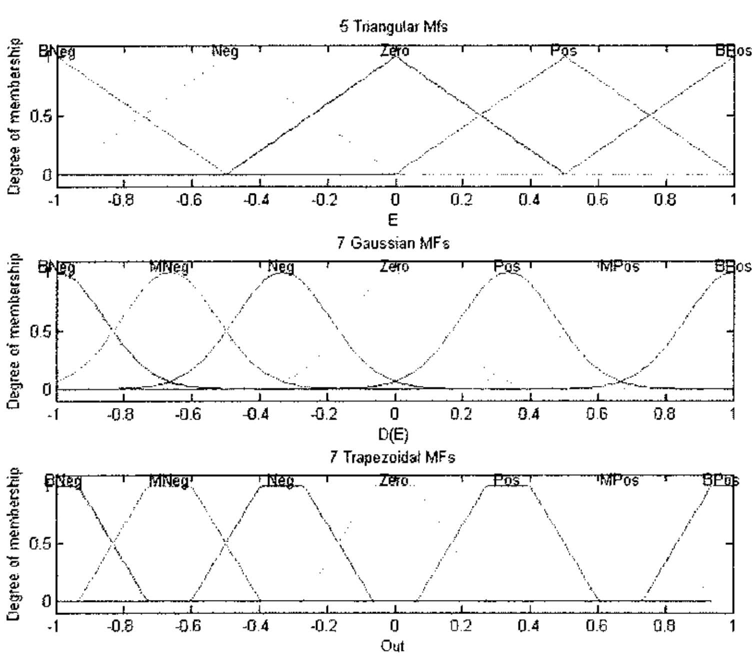

Figure 13: Various Types of Type-1 Membership Functions

4.4 Type-2 Fuzzy Logic PI Controller

Type-2 Fuzzy Logic PI controller follows the same rule base and same settings as type-1 explained in section 4.3. Figure 14 show the Simulink block for the Type-2 System. The block diagram consists of an input that is a step function connected to type-2 fuzzy PI controller. The DC servomotor has 2 inputs, which are the voltage and the load. The load input is used to simulate the load disturbance and is kept to zero in case of unity step response. Integral absolute error is displayed at the end of each simulation.

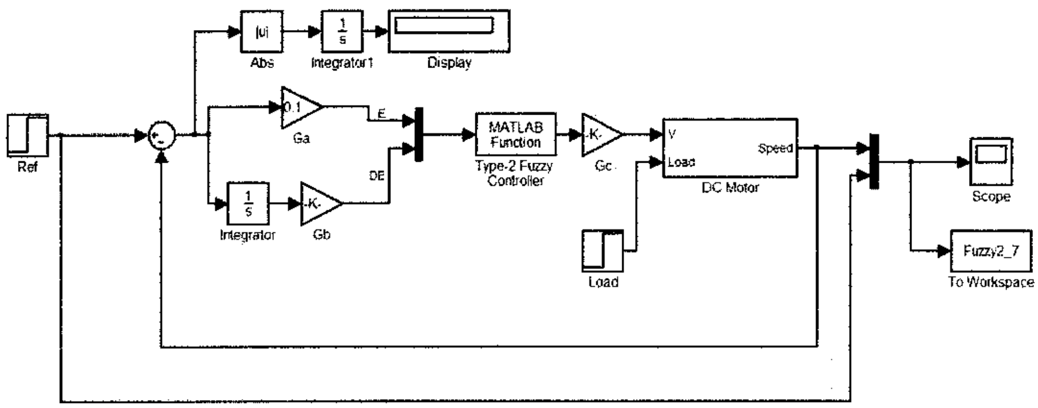

Figure 14: Type-2 Fuzzy logic PI controlled System

Numerous types and numbers of membership functions were used in the simulation, Figure 10, displays selected types and numbers of type-2 membership functions, which are 5 triangular MFs, 7 Gaussian MFs and 7 trapezoidal MFs respectively.

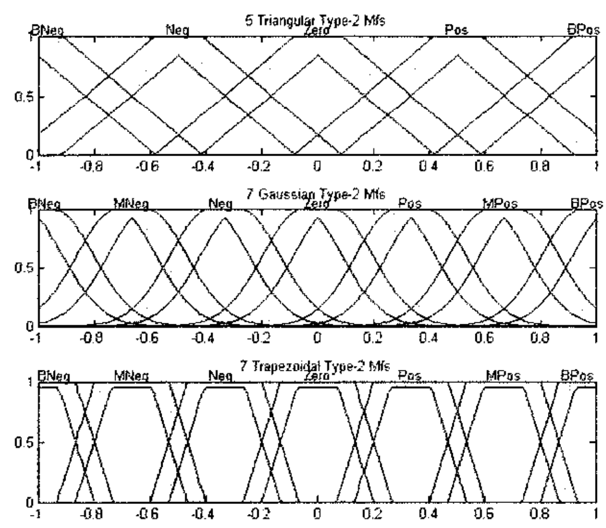

Figure 15: Various Types of Type-2 Membership Functions

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Step Response

The performance of the DC servomotor in response to a unity step response is simulated. A unity Step response occurs at t = 0.01s. The effect of varying the number of MFs on the performance of the system is plotted in Figure 16 and Figure 17 for Type-1 and Type-2 respectively. Table 7 and compares the effect of number of the membership functions on the performance of the motor of both type-1 and type-2 fuzzy logic PI controller. The best performance in the table is highlighted in bold.

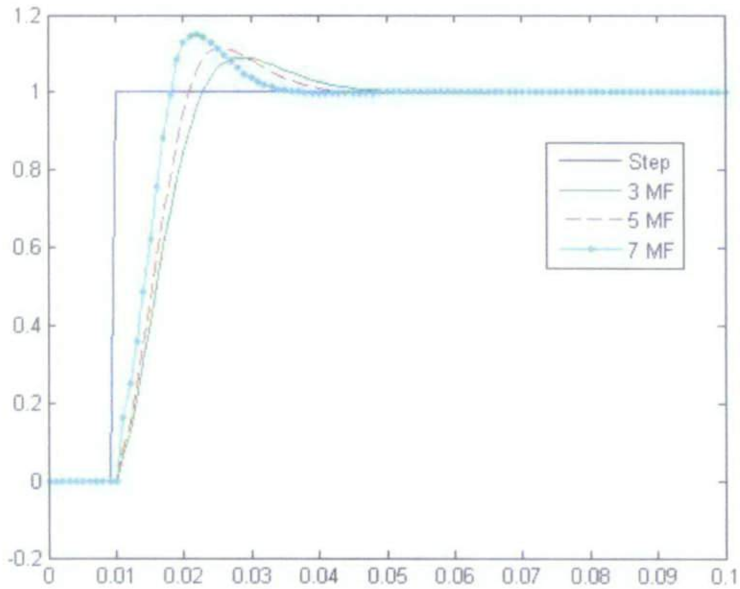

Figure 16: Type-1 controlled system Response with different numbers of MFs

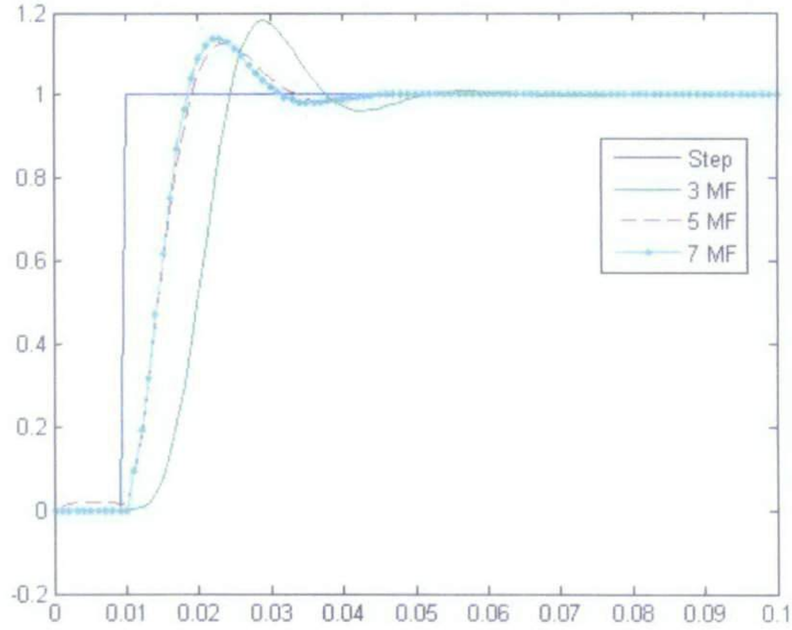

Figure 17: Type-2 controlled system Response with different numbers of MFs

Table 5: Performance Attributes with various numbers of MFs

Number of MFs	**Shape of MFs**	**Defuzzification Technique**	**Attributes**	**Type-1 Fuzzy logic PI Controller**	**Type-2 Fuzzy logic PI Controller**
3	Triangular	Centroid	Rise Time	0.0093s	0.0079s
			Sett. Time	0.0416s	0.0477s
			% O.S.	8.8633%	18.0644%
			IAE	0.007261	0.01138
5	Triangular	Centroid	Rise Time	0.0081s	0.0066s
			Sett. Time	0.0375s	0.0315s
			% O.S.	11.3230%	12.3803%
			IAE	0.006613	0.005738
7	Triangular	Centroid	Rise Time	**0.0065s**	**0.0062s**
			Sett. Time	**0.0318s**	**0.0298s**
			% O.S.	**14.9086%**	**13.7310%**
			IAE	**0.005313**	**0.005425**

The simulations carried out demonstrate that 7 membership functions are more superior compared to less number of membership functions in both types. The IAE is 0.005313 and 0.005425 for type-1 and type-2 respectively, which is less that the other controllers using 3 and 5 membership functions. Type-2 shows better performance attributes, as it has better rise time, settling time and percent overshoot. Despite that, Type-1 has better IAE. We can deduce that both performances are very similar.

Simulations were then carried out by varying the type of membership functions to observe the effect of the type of MFs on the performance of the system. Three types were selected to perform the simulations which are Triangular, Gaussian and Trapezoidal. This selection was based on the fact the three types are the most popular and that the same shapes are present in type-1 as well as type-2. Figure 18 and Figure 19 demonstrate the performance of each type of MFs due to a step response for type-1 and type-2 respectively. Table 8 and compares the effect of type of the membership functions on the performance of the motor of both type-1 and type-2 fuzzy logic PI controller. The best performance in the table is highlighted in bold.

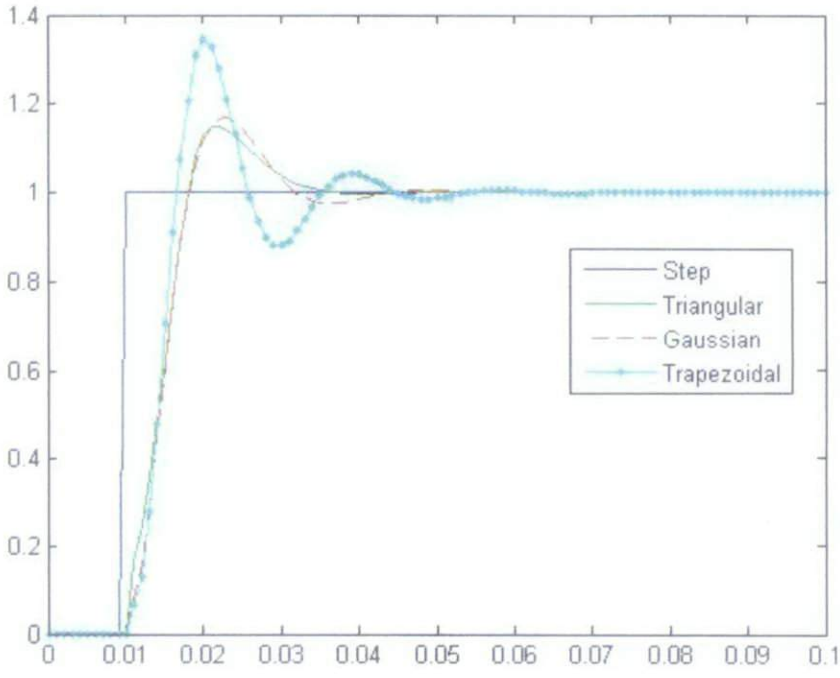

Figure 18: Type-1 System Response with different MF Shapes

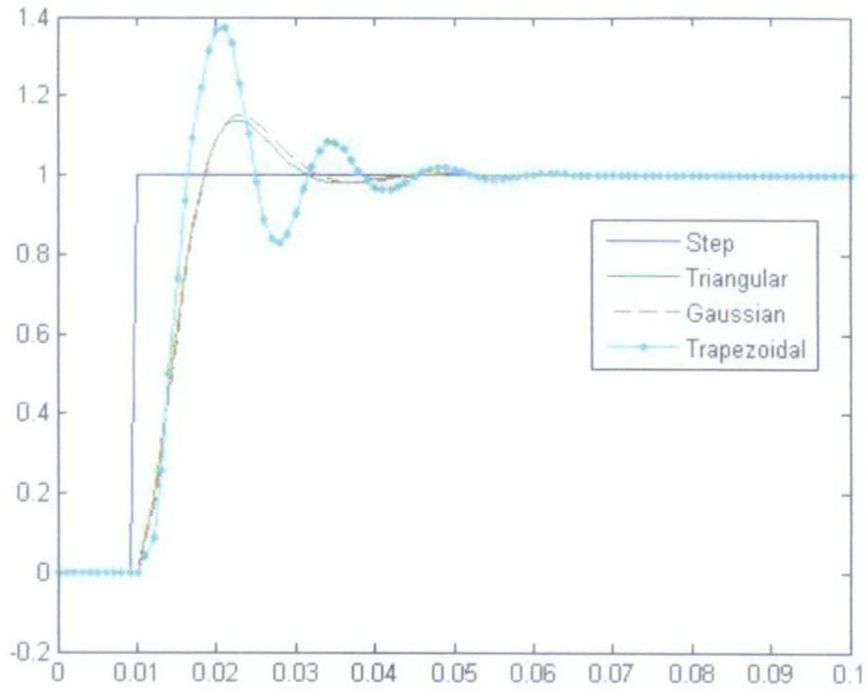

Figure 19: Type-1 System Response with different MF Shapes

Table 6: Performance Attributes with various types of MFs

Number of MFs	**Shape of MFs**	**Defuzzification Technique**	**Attributes**	**Type-1 Fuzzy logic PI Controller**	**Type-2 Fuzzy logic PI Controller**
3	Triangular	Centroid	Rise Time	0.0093s	0.0079s
			Sett. Time	0.0416s	0.0477s
			% O.S.	8.8633%	18.0644%
			IAE	0.007261	0.01138
5	Triangular	Centroid	Rise Time	0.0081s	0.0066s
			Sett. Time	0.0375s	0.0315s
			% O.S.	11.3230%	12.3803%
			IAE	0.006613	0.005738
7	Triangular	Centroid	Rise Time	**0.0065s**	**0.0062s**
			Sett. Time	**0.0318s**	**0.0298s**
			% O.S.	**14.9086%**	**13.7310%**
			IAE	**0.005313**	**0.005425**

Triangular membership functions showed the best performance with IAE of 0.005313 and 0.005425 for type-1 and type-2 respectively. It must be noted that each type of membership functions has its own characteristics; such that trapezoidal type demonstrate the best rise time (0.0044s and 0.0037s for type-1 and type-2 respectively), while triangular membership functions have the best percent overshoot (14.9% and 13.7% for type-1 and type-2 respectively) and settling time (0.0318s and 0.0298s for type-1 and type-2 respectively). It can be concluded that using a variety of types of membership functions at the same time will give the best performance. Overall, type-2 shows better performance over the conventional type-1.

Different defuzzification techniques were used and judged against each other. Seven triangular membership functions were used in this simulation with varying defuzzification techniques. Figure 20 and Figure 21 show the performance of the system using different defuzzification techniques for type-1 and type-2 respectively. Table 9 and compares the effect of type of the membership functions on the performance of the motor of both type-1 and type-2 fuzzy logic PI controller. The best performance in the table is highlighted in bold.

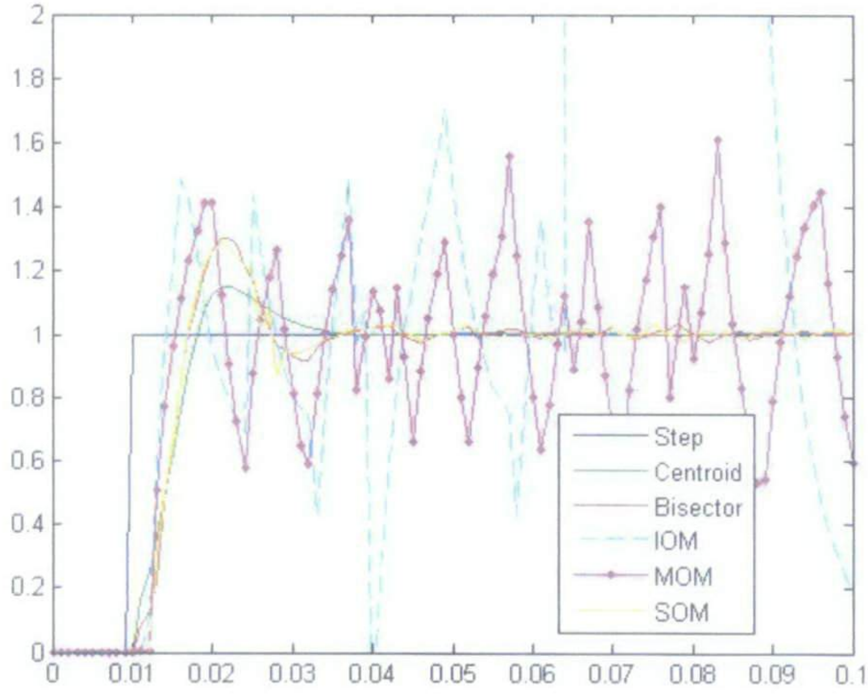

Figure 20: Type-1 System Response for different defuzzification techniques

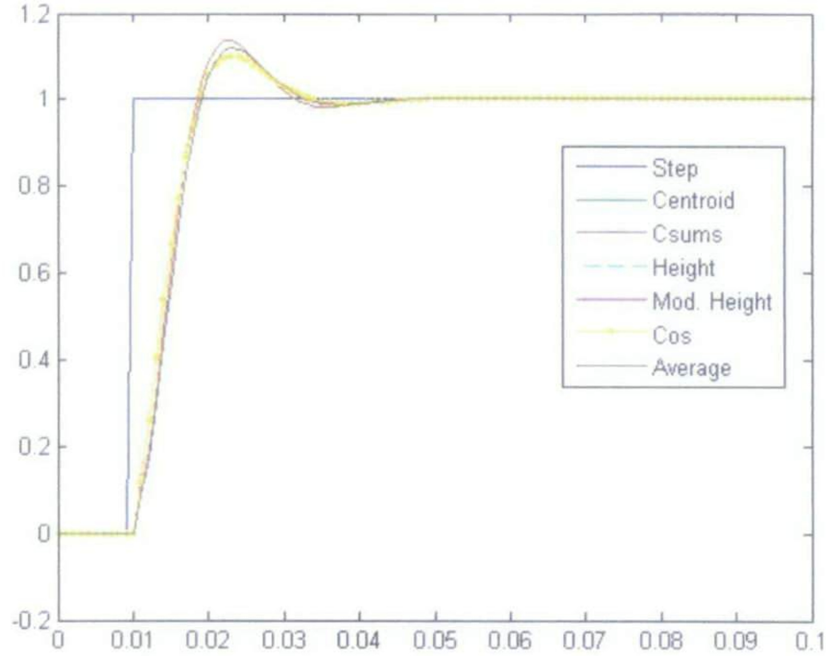

Figure 21: Type-2 System Response for different defuzzification techniques

For type-1, centroid technique shows superiority over other defuzzification techniques with IAE of 0.005313. For type-2, height technique shows superiority over other defuzzification techniques with IAE of 0.004881. Overall, type-2 shows better performance over the conventional type-1 as it has better settling time, percent overshoot and IAE.

Table 7: Performance Attributes with various defuzzification techniques

Number of MFs	Shape of MFs	*Defuzzification Technique of Type-1*	*Defuzzification Technique of Type-2*	Attributes	Type-1 Fuzzy logic PI Controller	Type-2 Fuzzy logic PI Controller
7	Triangular	*Centroid*	*Centroid*	Rise Time	**0.0065s**	0.0062s
				Sett. Time	**0.0318s**	0.0298s
				% O.S.	**14.9086%**	13.7310%
				IAE	**0.005313**	0.005425
7	Triangular	*Bisector*	*Center of Sums*	Rise Time	0.0049s	0.0062s
				Sett. Time	0.0874s	0.0298s
				% O.S.	29.82%	13.731%
				IAE	0.0071	0.005425
7	Triangular	*LOM*	*Height*	Rise Time	0.000095s	**0.0066s**
				Sett. Time	0.0083s	**0.0311s**
				% O.S.	23643%	**10.15%**
				IAE	2.037	**0.004881**
7	Triangular	*MOM*	*Cos*	Rise Time	0.000098s	0.0066s
				Sett. Time	0.0999s	0.0311s
				% O.S.	171.6%	10.15%
				IAE	0.02065	0.004881
7	Triangular	*SOM*	*Average*	Rise Time	0.0040s	0.0066s
				Sett. Time	0.0985s	0.0308s
				% O.S.	30.02%	11.86%
				IAE	0.007074	0.005524

It is evident that using 7 triangular membership functions with centroid defuzzification technique will yield the best performance for type-1, while using 7 triangular membership functions with height defuzzification technique will yield the best performance for type-2. Both performances are plotted against each other in Figure 22.

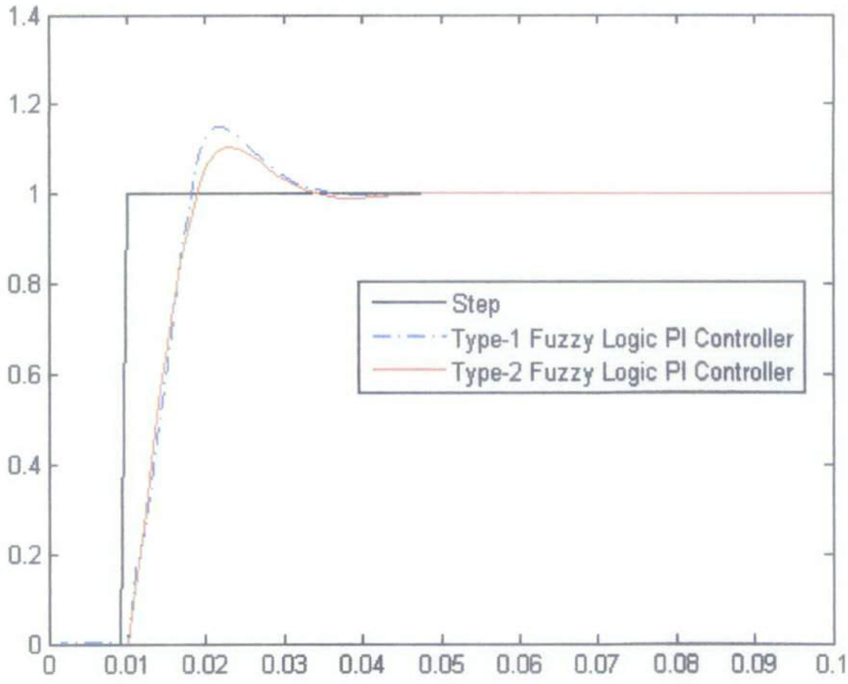

Figure 22: Type-1 vs Type-2 - Step Response

5.2 Load Disturbance

In this section, in addition to the step response at t = 0.01s, at t = 0.06s, the servomotor will suffer nearly 20 % load disturbance. Table 10 displays the integral absolute error. In an attempt for a better analysis, difference in error, *DE* will be calculated; *IAE* calculated due to step response will be subtracted from *IAE* calculated due to load disturbance, as shown in equation 8. This will enable us to take a closer look at the error only due to the load disturbance.

$$DE = \left| IAE_{(load\,distrubane)} - IAE_{(Step\,Response)} \right| \qquad (8)$$

Table 8: IAE for load Disturbance

Number of MFs	Type of MFs	Defuzzification Technique		Type-1 Fuzzy logic PI	DE	Type-2 Fuzzy logic PI	DE
		Type-1	Type-2				
3	Triangular	Centroid	Centroid	0.009631	0.002370	0.01293	0.001550
5	Triangular	Centroid	Centroid	0.008458	0.001845	0.007004	0.001266
7	Triangular	Centroid	Centroid	0.006699	0.001386	0.006526	0.001101
7	*Triangular*	Centroid	Centroid	0.006699	0.001386	**0.006526**	**0.001101**
7	*Gaussian*	Centroid	Centroid	**0.007092**	**0.001228**	0.007029	0.001234
7	*Trapezoidal*	Centroid	Centroid	0.008075	0.001129	0.008179	0.000784
7	Triangular	*Centroid*	*Centroid*	0.006699	0.001386	0.006526	0.001101
7	Triangular	*Bisector*	*Center of Sums*	0.008203	0.001101	0.006526	0.001101
7	Triangular	*LOM*	*Height*	10.25	8.213000	0.006115	0.001234
7	Triangular	*MOM*	*COS*	0.0189	0.001750	0.006115	0.001233
7	Triangular	*SOM*	*Average*	0.008173	0.001099	0.006661	0.001137

Simulations carried out show that type-2 fuzzy logic controller shows much improved results than type-1, as the difference error shows that type-2 is less sensitive to load disturbance. The difference error for 7 Triangular membership functions shows an improvement of 20.5 % (Difference error is 0.001386 and 0.001101 for type-1 and type-2 respectively). At a closer look, it can be noticed that the most influential factor for both types is the type of the membership function. Trapezoidal type shows the least sensitivity to load disturbance with difference error is 0.001129 and 0.000784 for type-1 and type-2 respectively. Although, *IAE* has to be considered as well, that is the reason why Gaussian was chosen as the best performance for type-1 as it has small error as well as better difference error. For type-2, the best overall performance is the triangular type, as error and difference are relatively small. Figure 12 shows Type-1 fuzzy logic PI controller (7 MFs/Gaussian/Centroid) versus Type-2 Fuzzy logic PI controller (7 MFs/Triangular/Centroid).

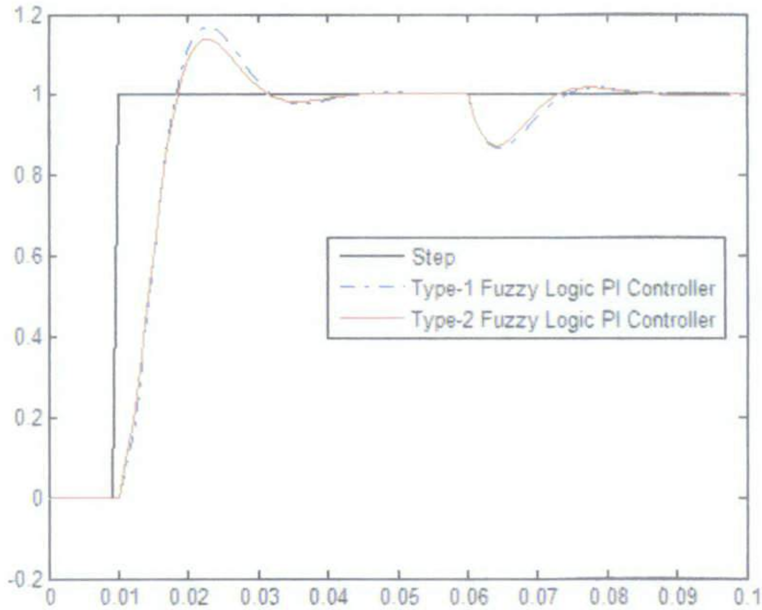

Figure 23: Load Disturbance - Type-1 Fuzzy Logic PI vs Type-2 Fuzzy Logic PI

5.3 Noise Disturbance

In an attempt to analyze the performance of a fuzzy logic controller to noise added to the system, noise with a mean = 0 and variance = 0.01 was added to the system. Both type-1 and type-2 fuzzy logic PI controller were simulated and *IAE* was deduced. Table 11 displays the IAE of each type of controller. In an attempt for a better analysis, DE was calculated; IAE calculated due to step response and load disturbance will be subtracted from IAE calculated due to noise disturbance, as shown in equation 9. This will enable us to take a closer look at the error only due to the noise disturbance.

$$DE = \left| IAE_{(noise\ distrubance)} - IAE_{(load\ distrubance)} \right| \qquad (9)$$

Table 9: IAE for noise Disturbance

Number of MFs	Type of MFs	Defuzzification Technique		Type-1 Fuzzy logic PI Controller	DE	Type-2 Fuzzy logic PI Controller	DE
		Type-1	Type-2				
3	Triangular	Centroid	Centroid	0.01044	0.000809	0.01381	0.000880
5	Triangular	Centroid	Centroid	0.009468	0.001010	0.007992	0.000988
7	Triangular	Centroid	Centroid	0.008023	0.001324	0.007732	0.001206
7	*Triangular*	Centroid	Centroid	0.008023	0.001324	0.007732	0.001206
7	*Gaussian*	Centroid	Centroid	**0.008271**	**0.001179**	0.008171	0.001142
7	*Trapezoidal*	Centroid	Centroid	0.009083	0.001008	0.009332	0.001153
7	Triangular	*Centroid*	*Centroid*	0.008023	0.001324	0.007732	0.001206
7	Triangular	*Bisector*	*Center of Sums*	0.00806	0.000143	0.007732	0.001206
7	Triangular	*LOM*	*Height*	2.068	8.182000	**0.007297**	**0.001104**
7	Triangular	*MOM*	*COS*	0.01623	0.002670	0.007296	0.001181
7	Triangular	*SOM*	*Average*	0.00888	0.000715	0.007856	0.001195

A trade-off between error and difference in error has to be chosen to decide on the best performance among each type. For type-1, 7 Gaussian shaped membership functions proved to be the best performance, as it has the least IAE and difference error (0.008271 and 0.001179 respectively). While, for type-2, 7 triangular shaped membership functions had the best performance among the rest, as it has the least IAE and a relatively good difference error (0.007297 and 0.001104 respectively).

Type-2 Fuzzy Logic controller shows outstanding results over conventional type-1 controller. As the difference error for 7 Triangular membership functions shows an improvement of 23.3% of type-2 over type-1. Figure 24 shows Type-1 fuzzy logic PI controller (7 MFs/Gaussian/Centroid) versus Type-2 Fuzzy logic PI controller (7 MFs/Triangular/Height).

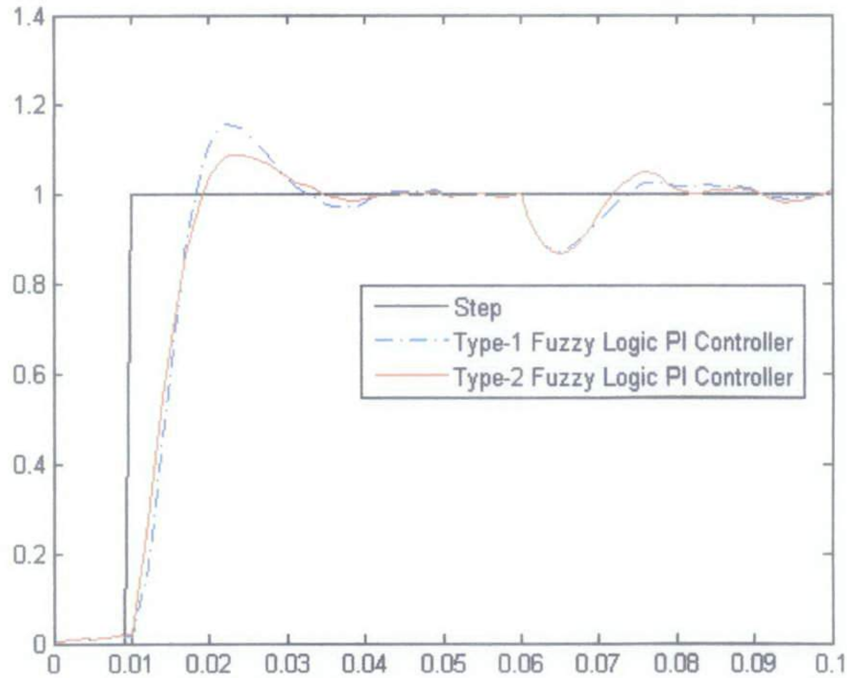

Figure 24: Noise Disturbance - Type-1 Fuzzy Logic PI vs Type-2 Fuzzy Logic PI

CHAPTER 6: CONCLUSION AND RECOMENDATIONS

6.1 Conclusion

Fuzzy logic PI controller was used to control a DC servomotor. Two controllers were simulated and judged against each other; which are type-1 fuzzy logic PI controller and type-2 fuzzy logic PI controller. Simulations show the effect of number and type of membership functions, as well as defuzzification techniques on the performance of the system. A comparison for each type and number of membership functions and defuzzification technique was done between type-1 fuzzy logic PI controller and type-2 fuzzy logic PI controller.

Overall, type-2 showed much improved results over the conventional type-1. This improvement is evident when it comes to handling of load disturbance and noise added to the system.

6.2 Recommendations

- Type-2 Fuzzy logic control of a DC servomotor is a vast unexplored field. After carrying out this project, there are yet more topics to be explored such as using Takagi-Sugeno-Kang (TSK) method.
- Fuzzy logic can be combined with other techniques such as genetic algorithms or neural networks to further enhance the performance of the controller.
- Type-2 fuzzy logic simulations require extensive mathematical calculations. A simulation for one case may take up to an hour. Faster and simplified calculations would enable a better implementation of the controller which should be the focus of researcher at the moment
- Further studies can be done on the actual servomotor used in this study to compare the simulated results against the practical performance under the same conditions.
- Furthermore, an actual type-2 fuzzy logic PI controller can be implemented and used to control the servomotor; the actual performance shall then be compared to the simulated results discussed earlier.

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APPENDICES

Appendix A

Gantt chart of the project

Gantt chart for the First semester

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Proposing the topic														
Information gathering														
Prelim. Report submission						★								
Review latest updates in the fuzzy logic field														
Servomotor Modelling														
PI controller Simulations														
Progress report submission									★					
Seminar														
Fuzzy type-1 PI based controller simulations														
Interim report submission														★
Oral presentation														★

Legend :

Deadline ★

Current progress

Future progress

Gantt chart for the Second Semester

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fuzzy type-1 PI based controller simulation														
Fuzzy type-2 PI based controller simulation														
Progress report submission								★						
Seminar								★						
Analysis of the results														
Poster exhibition										★				
Dissertation submission													★	
Oral presentation													★	
Project Dissertation submission														★

Legend :

Deadline ★

Current progress

Future progress

Appendix B

Technical Specifications of DC Servomotor

FAULHABER

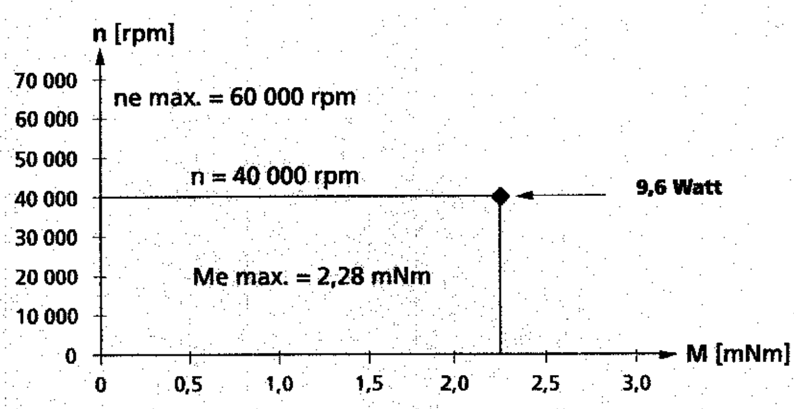
ɪshless DC-Servomotors 2,2 mNm

For combination with
Gearheads:
10/1, 12/3, 12/4, 12/5
Drive electronics:
Speed Controller, Motion Controller

ies 1226 ... B

1226 S			006 B	012 B	
ominal voltage	U_N		6	12	Volt
erminal resistance, phase-phase	R		2,30	5,30	Ω
ıutput power [1]	$P_{2\,max.}$		9,6	9,3	W
fficiency	$\eta_{max.}$		68	69	%
lo-load speed	n_o		20 100	27 200	rpm
lo-load current (with shaft ø 1,2 mm)	I_o		0,088	0,074	A
tall torque	M_H		7,19	9,21	mNm
riction torque, static	C_o		0,079	0,079	mNm
riction torque, dynamic	C_v		$8{,}2 \cdot 10^{-6}$	$8{,}2 \cdot 10^{-6}$	mNm/rpm
peed constant	k_n		3 447	2 335	rpm/V
ack-EMF constant	k_E		0,290	0,428	mV/rpm
orque constant	k_M		2,77	4,09	mNm/A
urrent constant	k_I		0,361	0,244	A/mNm
lope of n-M curve	Δn/ΔM		2 862	3 026	rpm/mNm
erminal inductance, phase-phase	L		35	80	µH
1echanical time constant	τ_m		4	4	ms
otor inertia	J		0,145	0,145	gcm²
ɪngular acceleration	$\alpha_{max.}$		496	635	$\cdot 10^3$rad/s²
hermal resistance	$R_{th\,1}$ / $R_{th\,2}$	7 / 38,0			K/W
hermal time constant	τ_{w1} / τ_{w2}	3 / 186			s
)perating temperature range:					
motor		– 20 ... +100			°C
coil, max. permissible		+125			°C
haft bearings		ball bearings, preloaded			
haft load max.:					
radial at 10 000/30 000 rpm (3,7 mm from mounting flange)		4,9 / 4,0			N
axial at 10 000/30 000 rpm (push-on only)		2,6 / 1,1			N
axial at standstill (push-on only)		11			N
haft play:					
radial	≤	0,012			mm
axial	=	0			mm
lousing material		aluminium, black anodized			
Veight		13			g
)irection of rotation		electronically reversible			
nmended values - mathematically independent of each other					
peed up to [2]	$n_{e\,max.}$		60 000	60 000	rpm
orque up to [1)2)]	$M_{e\,max.}$		2,28	2,21	mNm
:urrent up to [1)2)]	$I_{e\,max.}$		0,97	0,64	A

' at 40 000 rpm
' thermal resistance $R_{th\,2}$ by 55% reduced

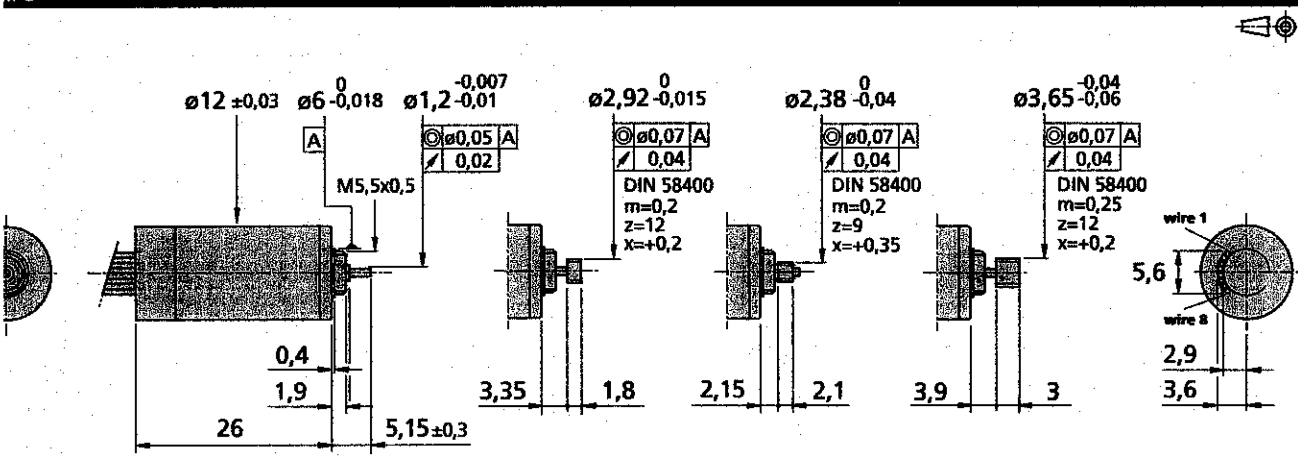


Recommended area for continuous operation

:es on technical data and lifetime performance
ı "Technical Information".

Options
K1855:
Motors for operation with Motion Controllers
MCBL 3003 S/C, MCBL 3006 S/C.

.. B



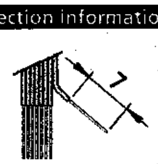
1226 S

1226 M
for Gearhead 10/1

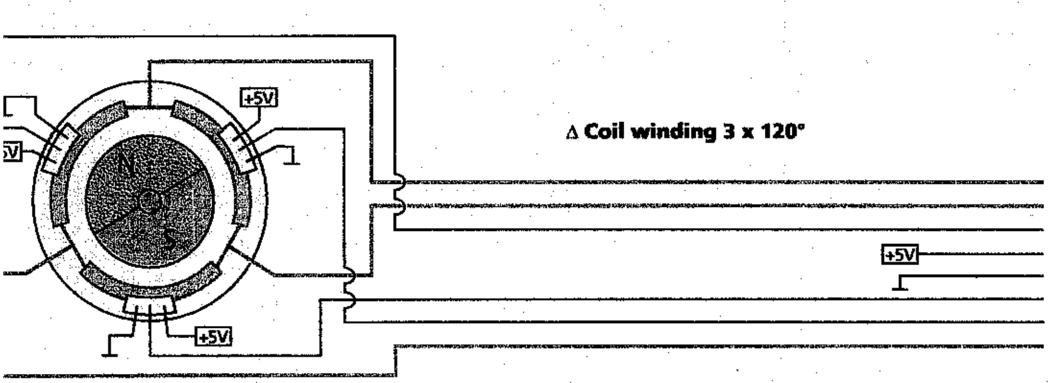
1226 E
for Gearheads 12/3, 12/5

1226 A
for Gearhead 12/4

and connection information



Cable
Single wires, material PTFE
Length 80 mm ± 3 mm
8 conductors, AWG 30



Δ Coil winding 3 x 120°

Connection

No.	Function	Colour
1	Phase C	yellow
2	Phase B	orange
3	Hall sensor C	grey
4	Logical supply +5V	red
5	Logical GND	black
6	Hall sensor A	green
7	Hall sensor B	blue
8	Phase A	brown

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"Technical Information"