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Title

Artificial Intelligence Control of a Magnetic Levitation System

Defended on: 21/06/2025, before the jury composed of:

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وإلى من علمتني الأخلاق قبل أن أتعلمها، إلى النور الذي دلّني على كل خير، إلى الجسر الصاعد بي إلى الجنة، إلى الدعوة التي لا تنام... أمي ***رزيقة،*** *يا حبيبتي وملهمتي أنتِ الحنانُ إذا جفّت ينابيعُهُ والدفءُ إن غابتِ الشّمسُ وما طلعَ القمر.. أنتِ الدعاءُ الليليُّ في سكونِ السَّهرِ أنتِ الوردُ... بل كلُّ الزهرِ والعطرِ*

.كنتِ الوطن حين تاهت الخطى، وكنتِ الأمان حين كثرت المخاوف .علمتِني أن أكون، حتى عندما لم أكن أعرف كيف أبدأ .في عينيكِ... وجدت الطريق، وفي حضنكِ... عرفت الحياة

وإلى أختي، ***جميلة،*** *أختي الكبرى وسندي الأول، من كانت لي أمًّا ثانية، وأقرب الناس لروحي. كنتِ دائمًا هناك، تدفعين بي .للأمام، وتحتوين تعبي وضعفي بحنانكِ الكبير. أنتِ هديتي من الله*

أخواتي الحبيبات: ***هاجر، هيفاء، وخديجة،*** *أنتنَّ الضحكة التي لا .ثم إلى نِعم الأخوة... إلى من أضاءوا طفولتي وشبابي وإلى صغير العائلة، روحي الثانية، أخي أحمد، يا بهجة أيامي ومستقبلي .تغيب، والكتف الذي أتكئ عليه وقت الشدائد .المشرق*

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إلى الصديقات اللواتي صرن جزءًا من روحي رفيقة الدراسة، ورفيقة القلب ***ايناس، وزينب، وهالة، وجهينة*** *كنتنَّ النور في درب مظلم، والضحكة الصافية في أوقات الضيق. شكرًا لأنكن في حياتي*

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Table of Contents

Chapter 1

State of the Art and Modeling of a Magnetic Levitation System)

Chapter 2

Modeling and PID controller of Magnetic levitation system

Chapter 3

Type-2 Fuzzy Logic Control of a Magnetic Levitation System

Chapter 4

Type-2 Fuzzy Logic Control of a Magnetic Levitation System

List of figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

List of Tables

Symbols

u(t): the applied voltage

i(t): the current in the electromagnetic coil.

R: the resistance of the coil.

L: the inductance of the coil.

Maglev: Magnetic levitation.

PID: proportional integrator derivative.

$\boldsymbol{U_A}(x)$: appurtenance Function of fuzzy variable.

***Min**:* Minimum.

Max: Maximum.

FLS: Fuzzy logic systems.

FS: Fuzzy systems.

FOU: Footprint of Uncertainty.

FL: Fuzzy Logic.

NB: Negative big.

EZ: Ent of zero.

Symbols

PB: Positive grand.

PM: Positive medium.

NM: Negative medium.

PS: Positive small.

NS: Negative small.

IT2FLC: Interval type2 fuzzy logic controller.

T1FLC: type1 fuzzy logic controller.

General Introduction

Magnetic levitation technology (Maglev) is present in various fields such as industry, transportation, and commerce. It is a highly beneficial technology, and as such, its development has become a necessity for industries, a promising project for entrepreneurs, and a topic of significant interest for researchers and academics [1].

There are several types and methods of magnetic levitation. Among these, we highlight "magnetic levitation of a ball (or metallic sphere)", which is the central focus of our graduation project [1].

Research in the field of magnetic levitation has witnessed significant advancements over the past decades, particularly with the emergence of computing and embedded electronics. As a result, it has become increasingly complex and unrealistic to fully master all aspects of this subject [1].

Our work focuses on controlling a magnetic levitation system. Given that this system is classified as highly unstable, its control remains more challenging compared to other systems. Our contribution lies in designing classical controllers, such as the PID controller, to manage this system [2].

Recently, a powerful control technique based on fuzzy logic has emerged. This approach allows for the control of systems without requiring a precise mathematical model, although it does necessitate expert knowledge to accurately describe the system and its behavior. This technique will be implemented in our project to highlight its robustness and efficiency [3].

To this end, our thesis has been structured into four chapters

Chapter One is dedicated to providing a brief overview of the fundamental concepts of magnetic levitation and its various applications.
Chapter Two focuses specifically on the control of the Maglev system using the PID controller.
Chapter Three explores an artificial intelligence technique known as Type-1 fuzzy logic.

This chapter will cover all the essential concepts and definitions required to understand this technology. We will also introduce fuzzy controllers and apply these control strategies to a magnetic levitation system.

Chapter Four is devoted to the presentation of Type-2 fuzzy logic, along with a comparative study between the control techniques introduced in the second and third chapters. This comparison will be based on the simulation results obtained during the research.

Finally, this thesis will be concluded with a general summary that highlights the main ideas and results discussed throughout the different chapters. In addition, future perspectives will be presented, outlining possible improvements to this work and opening new research directions in the field of magnetic levitation systems and intelligent control techniques.

1.1 Introduction

Magnetic levitation, also known as Maglev1 or magnetic suspension, is a method by which an object is suspended without any support other than magnetic fields. Magnetic force is used to counteract the effects of gravitational acceleration and other types of acceleration.
The two main challenges in magnetic levitation are lift forces: providing sufficient upward force to counter gravity while ensuring the stability of the system. In this chapter, we will present the principle of magnetic suspension, the system components, and its established nonlinear model [4].

1.2 History

The concept of magnetic levitation began in the early 20th century when the scientist Emil Bachelet registered the first patent in 1904 for levitating objects using magnetic fields [5].

Between 1930 and 1960, initial experiments were carried out in Germany and Japan to develop small-scale Maglev systems. However, these early attempts faced challenges related to stability and control [6].

In 1979, Germany introduced the first functional Maglev train prototype known as Trans rapid, while Japan focused on developing systems based on superconductors to achieve higher speeds [7].

During the 1990s and beyond, commercial interest in Maglev technology grew significantly. In 2004, China launched the first commercial high-speed Maglev line connecting Shanghai to its airport, reaching speeds of over 430 km/h [7].

Since then, Maglev has become an active area of industrial and academic research, thanks to it's an advantages in reducing friction and noise while enabling high-speed transportation [8].

1.3 Working Principle of the Magnetic Levitation (Maglev) System

The magnetic levitation system operates by using magnetic fields to lift objects off the ground without any physical contact, allowing them to move without mechanical friction. For example, a metal ball can be levitated using an electromagnet and a position sensor to achieve a precise balance between magnetic attraction and gravitational force [9].

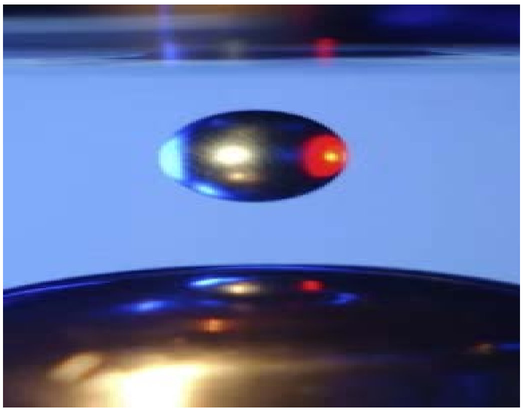


Figure 1.1: The magnetic levitation system.

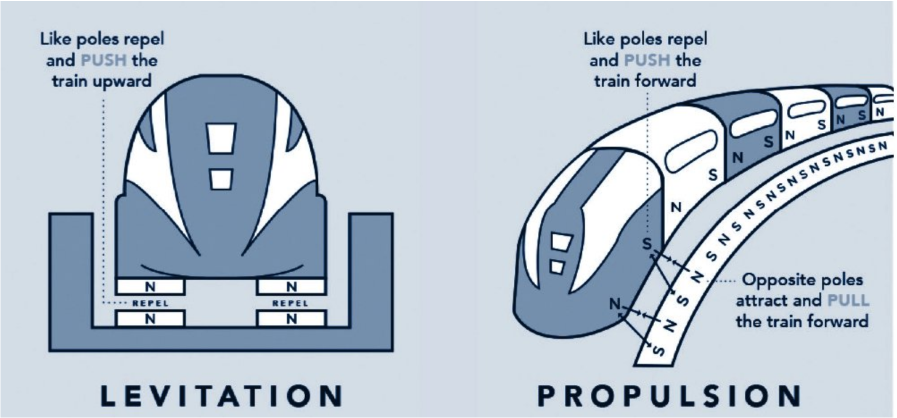


Figure 1.2: Working Principle of the Magnetic Levitation (Maglev) System.

In this setup, the metal ball is placed beneath an electromagnet fixed at the top. When electric current flows through the coil, it generates a magnetic field that pulls the ball upward. To prevent the ball from sticking to the magnet or falling, a sensor continuously measures the distance between the ball and the magnet and sends this data to an electronic controller. This controller adjusts the current intensity in real-time based on the ball’s position, keeping it suspended in the air in a stable equilibrium without touching any surface.

In this way, objects can be levitated without any friction, making the system ideal for applications such as high-speed trains or precision industrial systems [9].

1.4 Types of tic Levitation Systems

1.4.1 Electromagnetic Suspension (EMS)

This system uses electromagnets to attract the vehicle toward a ferromagnetic rail. It requires active control to maintain a stable air gap between the vehicle and the track [10].

1.4.2. Electrodynamic Suspension (EDS)

This system employs superconducting magnets or permanent magnets. Levitation occurs due to repulsive magnetic forces generated by eddy currents induced as the vehicle moves [10].

1.4.3. Hybrid Magnetic Suspension (HMS)

This type combines EMS and EDS technologies to benefit from both systems, offering improved stability and control efficiency [10].

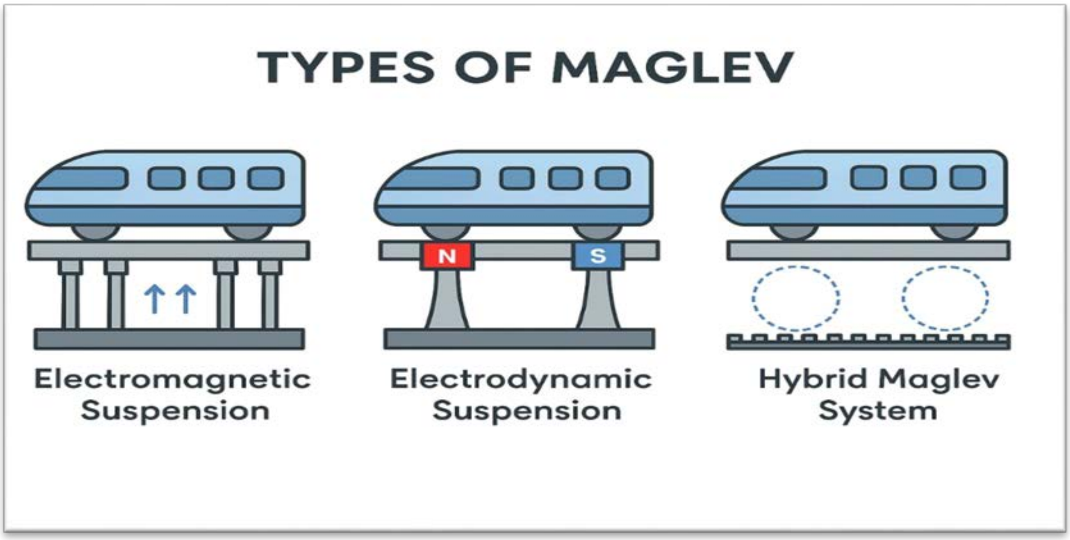


Figure 1.3: Types of Magnetic Levitation Systems

1.5 Components of a Magnetic Levitation System

A magnetic levitation system (Maglev) relies on magnetic forces to suspend an object without physical contact with a surface. It consists of several key components:

1.5.1 Magnets

Permanent Magnets: Provide a constant magnetic field without needing electrical power.

Electromagnets: Generate magnetic fields when current flows through them, allowing dynamic control [11]

1.5.2 Magnetic Fields and Stability

Levitation is achieved through magnetic repulsion (like poles pushing away) or magnetic attraction (opposite poles pulling together) [12].

Stability is maintained using active control mechanisms that adjust the field strength in real time.

1.5.3 Sensors

Hall Effect Sensors: Detect changes in magnetic fields and help adjust positioning. Laser or Optical Sensors: Measure distance between the levitated object and the base to ensure stability [13].

1.5.4 Control Systems

Uses PID controllers or adaptive algorithms to dynamically adjust the electromagnetic forces.

Some systems integrate neural networks or fuzzy logic for optimized real-time control [14].

1.5.5 Power Supply

Electromagnetic systems require continuous electrical power to generate magnetic fields. High-precision setups use digitally controlled power sources for stability [15].

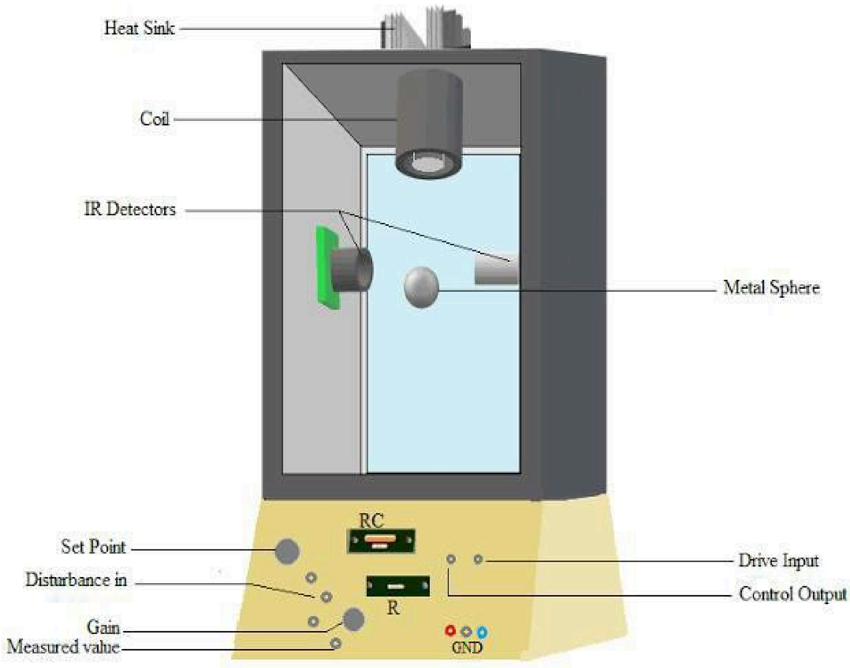


Figure 1.4: Magnetic Levitation Control System.

1.6 Applications of Magnetic Levitation (Maglev)

1.6 1. Maglev Trains

Maglev technology is widely used in high-speed trains, such as SC Maglev in Japan, which can reach speeds of up to 600 km/h. This system eliminates friction, reducing noise and increasing efficiency [16].

1.6 2. Magnetic Bearings

Used in turbines and industrial rotating systems, magnetic bearings operate without mechanical contact, reducing wear and improving equipment lifespan [17].

1.6 3. Wireless Power Transfer

Magnetic fields enable wireless energy transmission, such as wireless charging for electronic devices and electric vehicles [18].

1.6 4. Medical Applications

- Precision Medical Devices: Magnetic bearings are used in MRI machines to enhance imaging accuracy.
- Magnetically Controlled Capsules: Magnetic fields guide capsules inside the body for diagnostic and therapeutic purposes [19].

1.6 5. Magnetic Lifting Systems

Used in factories and ports to lift heavy objects like steel plates and metal pipes, improving handling efficiency [20].

1.6.6 Scientific and Research Applications

- Magnetic Levitation for Small Objects: Used in physics experiments to simulate zero-gravity environments.
- Plasma Control in Nuclear Reactors: Maglev technology stabilizes plasma in fusion reactors [20].

Figure 1.5: The different types of magnetic levitation (Maglev) systems.

1.7 Advantages of the Magnetic Levitation System

1.7.1. No Mechanical Friction

In magnetic levitation systems, the object (such as a platform or train) is suspended in the air using magnetic forces, with no physical contact between it and the supporting surface. This significantly reduces wear and friction compared to traditional systems that rely on wheels or bearings [10].

1.7.2. High Positioning Accuracy

Magnetic systems enable highly precise control of the object's position, making them ideal for applications requiring high-precision positioning, such as optical systems or sensitive medical devices [10].

1.7.3. Low Maintenance Requirements

Since there is no mechanical contact, parts do not wear out easily, reducing the need for frequent maintenance or replacement of components [10].

1.7.4. Silent Operation

Due to the absence of direct mechanical motion, the system operates silently, making it suitable for environments that require minimal noise levels [10].

1.7.5. Fast Dynamic Response

Thanks to the nature of magnetic forces and fast electronic control, the system can quickly respond to changes in load or input, allowing for real-time and accurate adjustments [10].

1.7.6. Applicability in Special Environments

This system can be used in environments where traditional systems are not suitable, such as sterile operating rooms or vacuum chambers, where friction-based systems are not effective [10].

1.8 Disadvantages of the Magnetic Levitation System

1.8.1Inherent Instability

By nature, the system is unstable without an active control mechanism. That means the object cannot remain levitated on its own without continuous electronic feedback to adjust the magnetic forces and maintain balance.

1.8.2 High Cost

The system requires precise equipment such as sensors, microcontrollers, and powerful magnets, which makes it more expensive than conventional mechanical systems.

1.8.3 Complex Design and Implementation

Designing a magnetic levitation system requires advanced knowledge in multiple fields such as electronics, control theory, and magnetism. Additionally, the system modeling and control are often nonlinear, which adds to the complexity of computation and programming.

1.8.4 Sensitivity to External Disturbances

The system can be affected by surrounding magnetic fields or sudden changes in load or temperature, which may cause instability or unwanted vibrations [10].

1.8.5 High Energy Consumption

Especially in active electromagnetic systems that rely on continuous power supply to the coils, energy consumption can be significant, particularly in large-scale applications such as maglev trains [10].

1.9 Conclusion

In this chapter, we reviewed the magnetic levitation system and its main components, gaining an initial understanding of its nonlinear physical nature. Given the importance of accurate modeling for achieving effective control, we will proceed in the next chapter to model the physical equations of this system as a preliminary step toward designing a control system based on the PID algorithm, aiming to ensure stability and control accuracy

2.1 Introduction

As Maglev systems are significantly nonlinear and unstable, they need highly accurate control techniques to keep the object stably levitated. Before sophisticated or intelligent control techniques are integrated, the more basic, classical control techniques are often utilized first to form a foundational understanding of system behavior.

A PID controller is an instrument used in industrial control applications to regulate temperature, flow, pressure, speed and other process variables. PID (proportional integral derivative) controllers use a control loop feedback mechanism to control process variables and are the most accurate and stable controller [1]. In this chapter, we will present the maglev established nonlinear model and PID controlling.

2.2 Modeling of the magnetic levitation system

The dynamics of the magnetic levitation system can be modeled by studying both the electromagnetic subsystem and the mechanical subsystem [4].

2.2.1 Modeling of the Electromagnetic Part

The electromagnetic force produced by the current is given by the following Kirchhoff's law [4].

$$\mathbf{U(t) = v_R + v_L = R_i(t) + \frac{dL(x)i(t)}{dt}} \tag{2.1}$$

With:

- u(t): the applied voltage
- i(t): the current in the electromagnetic coil.
- R: the resistance of the coil.
- L: the inductance of the coil.

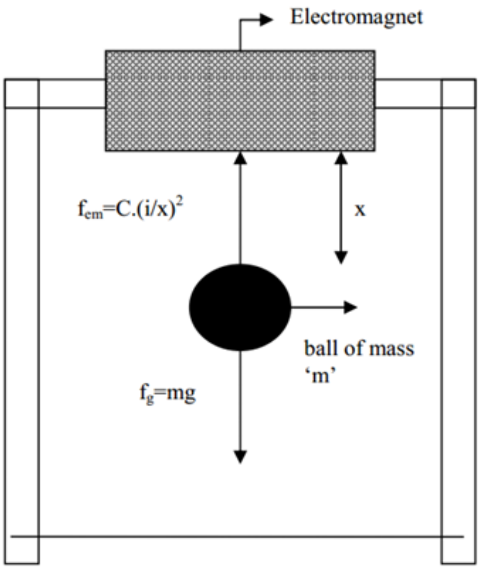


Figure 2.1: The forces acting on the ball.

2.2.2 Modeling of the Mechanical Part

The diagram of the ferromagnetic ball suspended by the balance between the electromagnetic force $f_{em}(x,i)$ and the gravitational force f_g is shown in Figure 1.6.

The resulting force applied to the ball is given by Newton's third law, neglecting friction and air resistance: [4]

$$f_{res} = f_g - f_m \tag{2.2}$$

$$m\ddot{x} = mg - c\left(\frac{i}{x}\right)^2 \tag{2.3}$$

2.2.3 The Nonlinear Model

$$\begin{cases} v = \dfrac{dx}{dt} \\ u = R_i + \dfrac{dL(x)}{dt} \\ m\ddot{x} = mg - C\left(\dfrac{i}{x}\right)^2 \\ L(x) = L + \dfrac{L_0 x_0}{x} \end{cases} \tag{2.4}$$

It is observed that L(x) is a nonlinear function of the ball's position. Different approximations have been used to determine the inductance of the system. In this thesis, the following approximation will be used: [4]

$$L(x) = L + \frac{L_0 x_0}{x} \tag{2.5}$$

2.3 State Representation of the System

Let us take $x_1 = x$, $x_2 = v$, $x_3 = i$ .We then declare that the state representation of the system is as follows: [4]

$$\begin{cases} \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{pmatrix} = \begin{pmatrix} \dot{x}_2 \\ g - \frac{c}{m}\left(\frac{x_3}{x_1}\right)^2 \\ -R \times 3 + 2\frac{C}{L}\left(\frac{x_2 x_3}{x_1^2}\right) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{L} \end{pmatrix} U \\ \mathrm{Y} = [1\ 0\ 0] \begin{pmatrix} \mathrm{x}_1 \\ \mathrm{x}_2 \\ \mathrm{x}_3 \end{pmatrix} \end{cases} \tag{2.6}$$

To simplify the model and the control synthesis, we will make the following change of variables:

$$\begin{cases} a_1 = -\frac{c}{m} \\ a_2 = -\frac{R}{L} \\ a_3 = \frac{2 \cdot C}{L} \\ a_4 = \frac{1}{L} \end{cases} \tag{2.7}$$

Then the system becomes: [4]

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = g + a_1 \cdot \left(\frac{x_3}{x_1}\right)^2 \\ \dot{x}_3 = a_2 \cdot a_3 + a_3 \cdot \frac{x_2 \cdot x_3}{x_1^2} \end{cases} \tag{2.8}$$

2.4 History of PID

Around the 18th century, the industry used controllers with mechanical feedback for process control. Generally, the controllers had only two actions of the Proportional, Integral and Derivative set, but never the three of them. At that time, the devices controlled the actuating speed of steam engines and aimed to provide greater stability to industrial machines operation.

In 1911, the businessman and inventor Elmer Sperry created the PID control (Proportional – Integral – Derivative), which combines these three actions. Sperry designed this controller for the United States Navy. He aimed to automate ship steering and emulate the behavior of a helmsman, who was capable of compensating persistent variances and predict future variations in the high seas. A few years after this creation, the engineer Nicolas Minor sky published the first theoretical analysis of PID control, describing its behavior in a mathematical formula that is used as a basis for calculation until today [23].

2.5 PID working principle and building blocks

The goal of a PID controller is to produce a control signal that can dynamically minimize the difference between the output and the desired set point of a certain system [24].

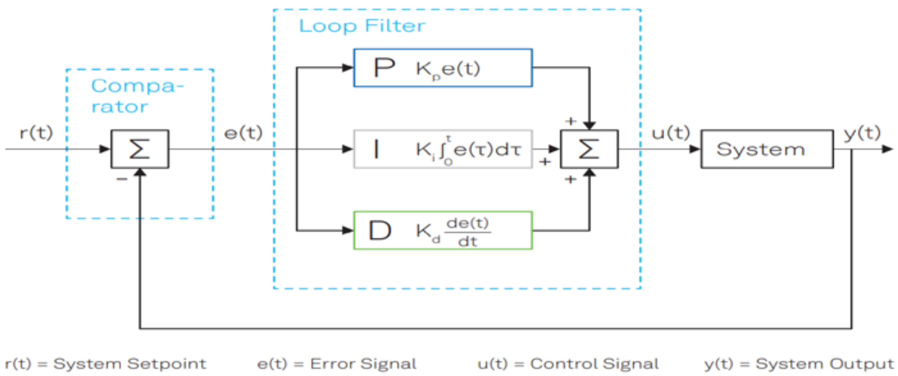


Figure 2.2: PID building.

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism widely used in industrial control systems. It attempts to correct the error between a measured process variable and a desired set point by calculating and then implementing a corrective action.

The PID controller involves three separate parameters. the Proportional, the Integral and Derivative values. The Proportional term produces a response that is proportional to the error signal, the Integral term examines the set point's offset over time and corrects it when and if necessary, while the Derivative term produces an output that is proportional to the rate of change of error. The sum of these three actions is collectively termed as PID control [24].

2.6 The different PID structures

Different combinations of the P, I, and D modules are possible. These structures are functionally equivalent, and it is easy to convert the coefficients used in one into those of another. The three most commonly used configurations are [25]:

2.6.1 Parallel (or Non-Interacting) Form

$$C(t) = k_p.e(t) + K_i.\int_0^t e(\tau)d\tau + K_d.\frac{de(t)}{dt}$$

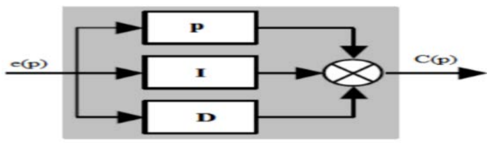


Figure2.3: parallel structure.

2.6.2 Ideal (or Standard) Form

$$\boldsymbol{C(t)} = k_p.e(t)\left[K_i.\int_0^t e(\tau)d\tau + K_d.\frac{de(t)}{dt}\right]$$

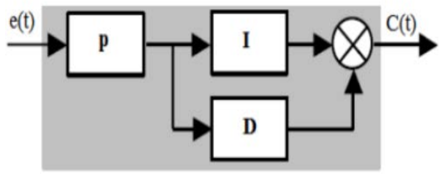


Figure2 4: mixed structure.

2.6.3 Series (or Interacting) Form

$$C(t) = k_p.e(t)\left[K_i.\int_0^t e(\tau)d\tau\right]\left[K_d.\frac{de(t)}{dt}\right]$$

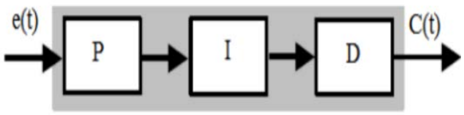


Figure2.5: series structure.

2.7 PID Controller Concept for Maglev system

For the magnetic levitation system, or Maglev as it is referred to, the difficult part of the process is suspending the metallic object in midair in a balance by controlling the electromagnetic force actively. Maintaining this system is both nonlinear and unstable; for example, input changes such as coil current can wreak havoc and output extensions such as the position of the object may deviate significantly. The PID controller has been selected because it is capable of error and real time stabilization in such systems.

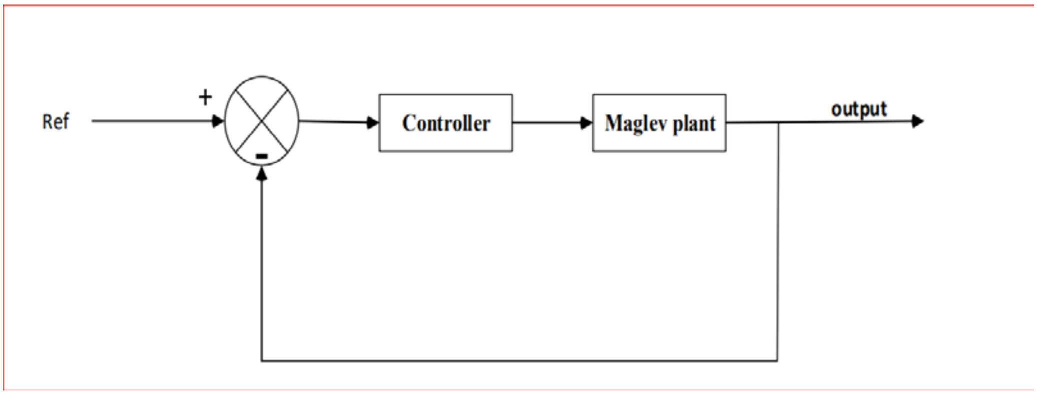


Figure 2.6: Schematic diagram of controller with the Maglev system.

2.8 Simulation results

2.8.1 Open-loop simulation of the magnetic levitation system

The state-space model of the magnetic levitation system was derived in the form of differential equations. The state variables considered are position, velocity, and current. The system is described by the equations (2.7) and (2.8).

Tab 2.1: The parameters of the system.

Parameter	**Unit**	**Value**
m	Kg	0.068
g	m/s^2	9.81
L	H	0.4125
C	F	0.00653
R	ohm	10

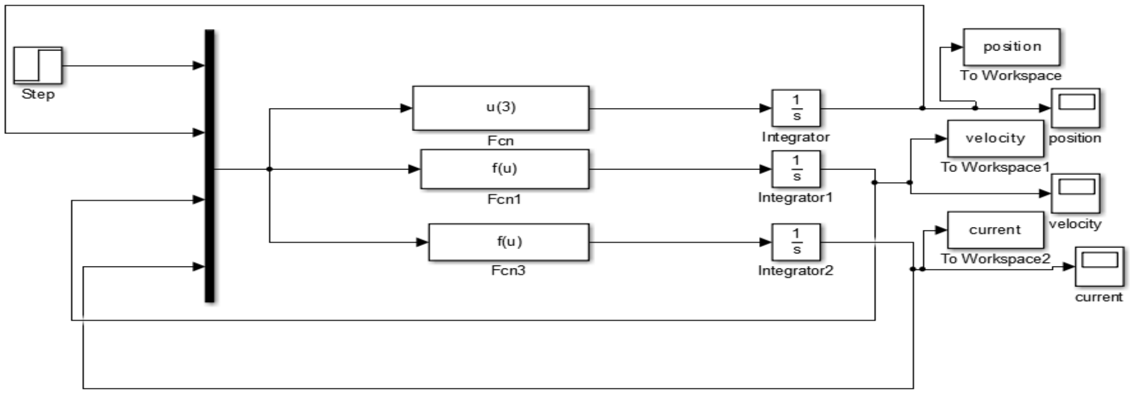


Figure2.7: Block diagram of the open-loop Maglev system.

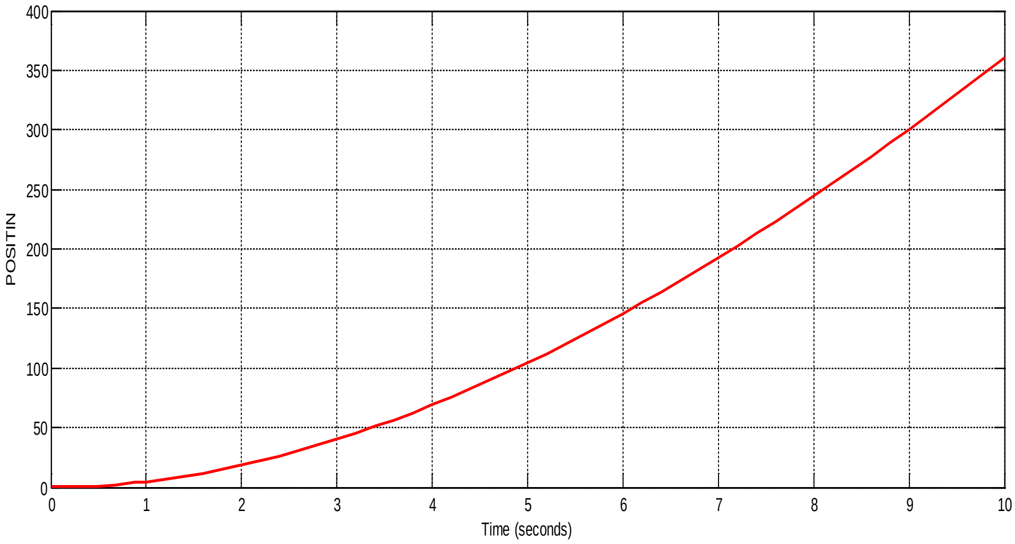


Figure2.8: Open-loop simulation of the magnetic levitation system.

2.8.2 Step Response of Maglev System with PID Controller

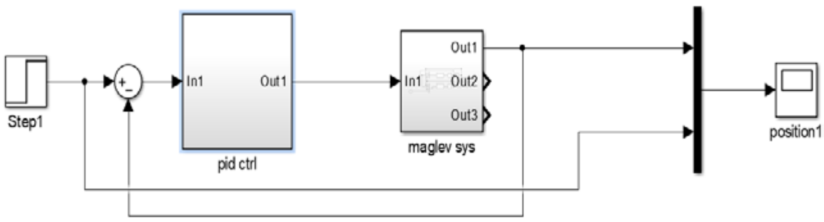


Figure 2.9: Block diagram of the PID controller withe Maglev system.

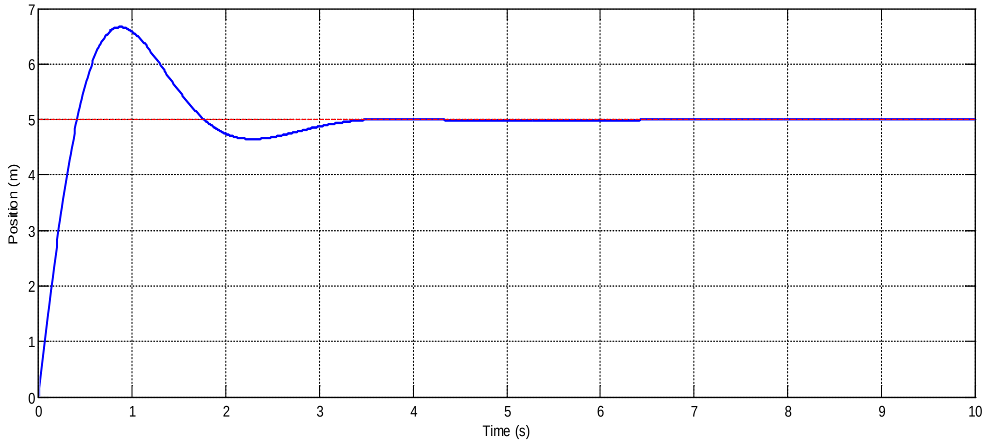


Figure 2.10: The position of the maglev system with PID controller.

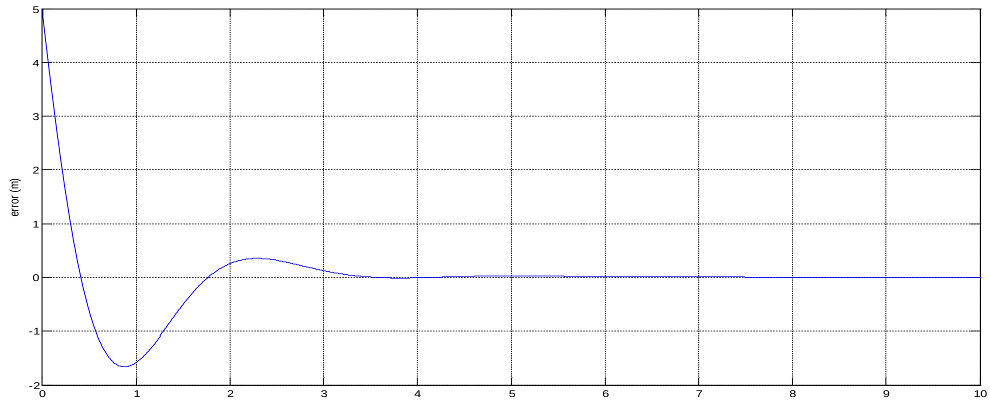


Figure 2.11: The error result of the maglev system with PID controller.

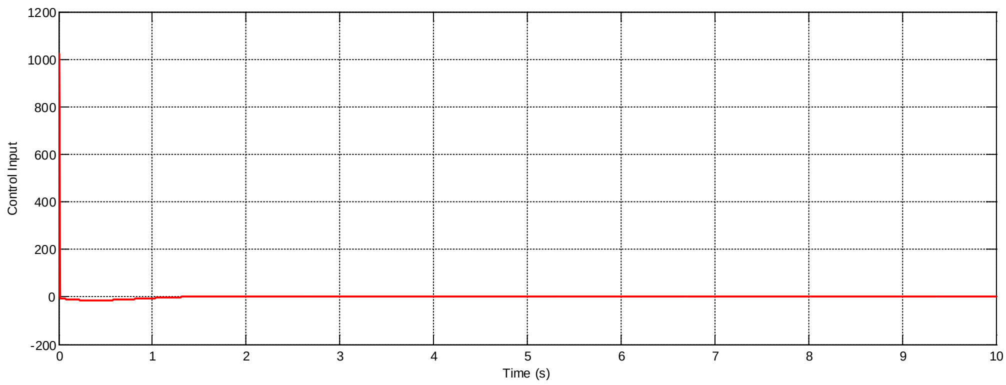


Figure 2.12: The command result of the maglev system with PID controller.

The figure shows the behavior of the system in time controlled by a PID controller. The blue curve displays the system behavior versus the red constant line that represents the reference input or the set point, which is 5 meters.

1. Rise Time Within around 1.2 seconds, the system reaches almost the reference value, meaning it has a very quick rise time. This shows the controller is achieving a fast response to changes in the reference.
2. Overshoot The maximum peak is about 6.5 meters against the set point of 5 meters. Thus, there is an overshoot of: Overshoot = ((6.5-5)/5) × 100% = 30%. This overshoot could be significant and acceptable depending on the application. It can be decreased by increasing the derivative gain Kd.

3. Settling Time, The output settles for 4 seconds around the reference. Beyond this point, no sustained oscillations are recorded for the response, indicating that the steady state has been reached.
4. Steady-State Error Once the system has settled, the output matches exactly to the set point of 5 meters, implying there is no steady-state error. The existence of integral action in the PID controller removes the steady-state error.
5. Stability The stability occurs since the system steadily approaches the reference without diverging or indefinitely oscillating.

2.9 Conclusion

In this chapter, it has been analyzed and evaluated through simulation how a PID controller is designed and how it performs. Different structures of PID controllers were introduced and discussed, these structures being parallel, ideal, series, and mixed. From the simulation results, PID offers rapid response, good stability, and zero steady-state error; however, a prominent overshoot was observed that may not fit the requirements for all processes. Although the PID shows good control performance, it does reveal some drawbacks: overshoot and nonlinearity issues with the system. To eliminate these drawbacks and achieve a better control performance, an advanced control would be implemented in the next chapter. More specifically, to improve system behavior and guarantee better response conditions, a fuzzy logic controller will be implemented.

3.1 Introduction

Magnetic Levitation (Maglev) systems are among the most advanced modern technologies, relying on electromagnetic forces to lift and move objects without mechanical contact. These systems offer significant advantages such as reduced friction, higher energy efficiency, and the ability to reach very high speeds, making them suitable for high-speed transportation and precision manufacturing applications [26].

Despite their advantages, Maglev systems face significant control challenges due to their nonlinear dynamics and inherent instability. Classical control techniques often struggle to provide effective control unless accurate system models or complex tuning are available.

In this context, intelligent control approaches, particularly Type-1 Fuzzy Logic, have emerged as promising solutions. Fuzzy logic can handle uncertainty and nonlinearities more effectively and does not require a precise mathematical model. It mimics human reasoning when making decisions, which makes it especially useful in ambiguous or imprecise environments.

Numerous studies have highlighted the success of fuzzy logic control in improving system performance and robustness (Alfi et al., 2011; Zadeh, 1973), paving the way for broader and more reliable applications in Maglev systems [26].

In this chapter, we present Type-1 fuzzy logic, its history, and applications, with a focus on its use in magnetic levitation systems and the control process using artificial intelligence.

3.2 History of fuzzy logic

- In 1965, Lotfi A. Zadeh, a professor of electronics at the University of California, Berkeley, published "Fuzzy Sets," introducing the theory of fuzzy sets as an extension of classical logic. Zadeh observed that classical logic has limitations and cannot represent vague or imprecise ideas. Therefore, he developed fuzzy logic to allow computers to mimic human reasoning processes [27].
- The first application of fuzzy logic was made by Mamdani in 1975 in London, who applied Zadeh's theory to the control of a steam engine [27].
- Various applications were observed in Europe, even in highly complex systems, such as the regulation of cement factory furnaces by the company F. L. Smidt-Fuller [27].
- In 1985, Seiji Yasunobu and Suji Miyamoto from Hitachi conducted simulations demonstrating fuzzy control systems on the Sendai railway. These fuzzy systems were

implemented when the line opened in 1987, enhancing acceleration and braking speeds [27].

- In 1987, during an international meeting of fuzzy researchers in Tokyo, Takeshi Yamakawa demonstrated the use of fuzzy control using dedicated fuzzy logic chips in an inverted pendulum experiment — a classic control problem. This system was also used in the Sendai subway [27].
- Thanks to the Japanese Researcher M. Suzuki, fuzzy logic was further integrated, especially in Japan. By 1990, the use of this technique had become widespread [27].

3.3 Domains of Application

Fuzzy logic is used in almost all fields, with some of its main applications being [28]:

- Robotics
- Expert systems
- Pattern recognition
- Classification
- Image processing
- Information retrieval
- Programming languages
- Industrial process control
- Artificial intelligence

These applications clearly demonstrate the flexibility and power of fuzzy logic in handling imprecise and uncertain information [28].

3.4 Fundamentals of Type-1 Fuzzy Logic

3.4.1 Definition of Fuzzy Logic

Fuzzy logic is a branch of artificial intelligence introduced by Lotfi Zadeh in 1965, designed to model systems that involve ambiguity or uncertainty. Unlike classical logic, which operates on binary values (true/false or 0/1), fuzzy logic allows for partial truth values between 0 and1, enabling it to express degrees of membership in variables [29].

This type of reasoning mimics human thinking in dealing with vague or imprecise information, such as stating: "The temperature is somewhat high" instead of assigning an exact value.

A Type-1 Fuzzy System consists of three main components:

- Fuzzification.
- Fuzzy inference based on rule base.
- Defuzzification.

3.4.2 Basic Concepts

3.4.2.1 The Set

A set, denoted by A, is a collection of elements or objects that share one or more common properties. It can be defined by explicitly listing all its elements $X \in A$. Another way to define a set is by specifying one or more conditions that the elements $X \in A$ must satisfy. In this case, A can be defined as follows [30]:

$$A = \{x | x \; satisfies \; some \; conditions\}$$

We can therefore define a binary membership function (also called a characteristic function) for A , denoted by$\mu_A(x)$, such that

$$A \Rightarrow \mu_A(x) = \begin{cases} 1 & si \; x \in A \\ 0 & si \; x \notin A \end{cases} \quad (3.1)$$

3.4.2.2 Linguistic Variables

When inferring a certain situation, describing a phenomenon, or analyzing a process, we often use fuzzy expressions such as: few, sometimes, many, large, warm, slow… These expressions allow us to define the values of linguistic variables [31].

A linguistic variable is a variable whose values are words or phrases in a natural or structured language, for example, is called a linguistic variable (e.g., temperature), and the terms that describe it such as (hot, warm, cold) are known as linguistic values.

3.4.2.3Universe of Discourse

The universe of discourse is defined as the numerical domain that contains all possible values a linguistic variable can take within a fuzzy system. This universe serves as the primary reference onto which linguistic values (such as "cold," "warm," "hot") are mapped using membership functions representing each linguistic value.

For example, if the linguistic variable is water temperature, the universe of discourse might be the range from 0 to 100 degrees Celsius.

This range is divided into regions representing the linguistic values, such that:

- "Cold" covers values from 0 to 30,
- "Warm" from 20 to 60,
- "Hot" from 50 to 100.

This process helps convert words into mathematical values that can be processed within the fuzzy control system [32].

The universe of discourse is often denoted by capital letters such as U or W, and is defined precisely because it forms the basis for creating fuzzy sets and membership functions in the system.

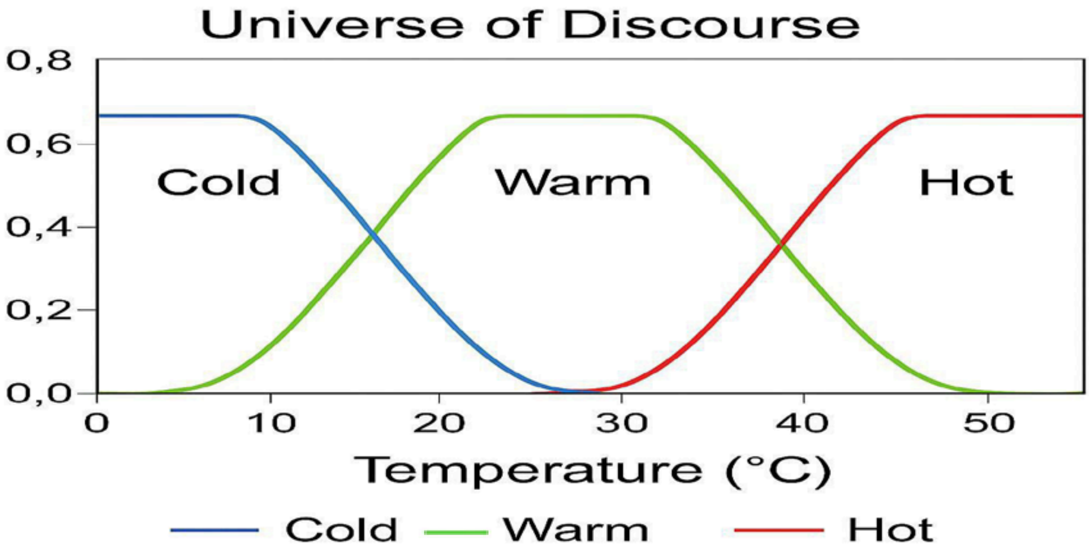
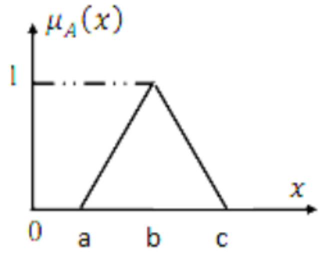
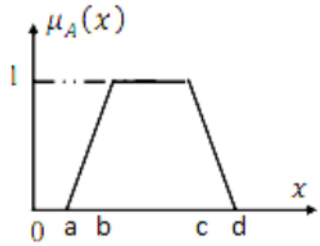
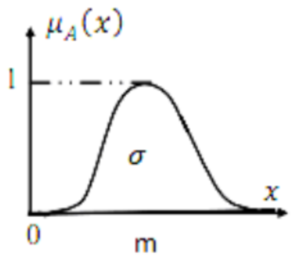
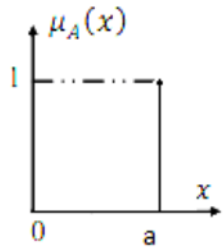


Figure 3.1: Example of the variation of a linguistic variable.

3.4.2.3 Membership Function

This section aims to link the degree of truth of a fuzzy variable to its corresponding numerical value. Fuzzy sets can be defined using a membership function that operates within the interval. The table below presents the most commonly used membership functions in fuzzy systems**.**

Table 3.1: Membership functions of Type-1 fuzzy logic [33].

Function	Algebraic form	Graphical form
Triangular function	$\mu A(x) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \le x < b \\ \frac{d-x}{d-c} & b \le x < c \\ 0 & x > c \end{cases}$	
Trapezoidal function	$\mu_A(x) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \le x < b \\ 1 & b \le x < c \\ \frac{d-x}{d-c} & c \le x < d \\ 0 & x > d \end{cases}$	
Gaussian function	$\mu\ (x) = \exp\ (-\frac{1}{2}(\frac{x-m}{\sigma})^2)$	
Singleton function	$\mu_A\ (x) = \begin{cases} 1 & x = a \\ 0 & x \ne a \end{cases}$	

The shapes of membership functions are usually chosen arbitrarily. Comparative studies have shown that results are generally very similar in closed-loop systems, regardless of the specific shape used. In fuzzy control applications, the triangular membership function is the most commonly employed due to its simplicity. Typically, an odd number of membership functions (such as 3, 5, or 7) is selected to cover the range of the studied variable, with the distribution centered around a reference value, often zero. The number of fuzzy sets depends on the level of control precision desired.

Finally, membership functions can be symmetrical or asymmetrical, and either equidistant or non-equidistant, depending on the nature of the system and the design requirements.

3.4.2.4 Operators of fuzzy logic

In classical set theory, the intersection (∩) the union (∪) and the complement ($\overline{\ }$) of a set are defined. These relations are translated in fuzzy set theory by the operators "and", "or", and "not". New membership functions associated with these operators are established as follows:

- **Intersection** : $x \in A \cap B \Leftrightarrow x \in \mu_{A\cap B} \mid \mu_{A\cap B}(x) = \min[\mu_A(x), \mu_B(x)]$.
- **Union** : $x \in A \cup B \Leftrightarrow x \in \mu_{A\cup B} \mid \mu_{A\cup B}(x) = \max[\mu_A(x), \mu_B(x)]$.
- **Complement (negation)**: $\forall x \in X, \mu_{\overline{A}}(x) = 1 - \mu_A(x)$ [18].

These operators allow for the manipulation of fuzzy sets in a manner similar to classical sets, while accounting for degrees of partial membership [34].

3.4.2.5Linguistic Rules:

At this stage, fuzzy rules are introduced that link the input and output subsets. This step aims to determine the relationships between the input set and the outputs. The inference rules can be written in three different forms: [34]

• Linguistic Form:

If (x is positive) and (y is zero), then (z is positive).

• Symbolic Form:

This is a simplified version of the linguistic form and corresponds to the five fuzzy sets of the output variable, where each rule represents a fuzzy deduction [34]:

If (x1 is NG and x2 is EZ), then z is PG or

If (x1 is NG and x2 is PM), then z is PM or

If (x1 is NM and x2 is EZ), then z is EZ or

If (x1 is NM and x2 is PM), then z is NM or

If (x1 is PG and x2 is EZ), then z is NG

• Inference Matrix: This is another simplification of the linguistic form using a graphical representation. The symbolic form previously written is translated as follows [34]:

Tab 3.2: Inference Matrix [34].

X2 \ X1	NG	NM	EZ	PM	PG
NG			**PG**	**PM**	
NM			**PM**	**EZ**	**NM**
EZ	**PG**	**PM**	**EZ**	**NM**	**NG**
PM	**PM**	**EZ**	**NM**		
PG		**NM**	**NG**		

In general, the number of rules is less than.r_{max} and the table is not necessarily complete

3.5 Structure of a Type-1 Fuzzy Controller

Fuzzy logic consists of three main components:

1. Fuzzification of inputs and outputs.
2. Fuzzy inference based on a rule base...
3. Defuzzification of the outputs

The architecture of a fuzzy controller is shown in the following diagram:

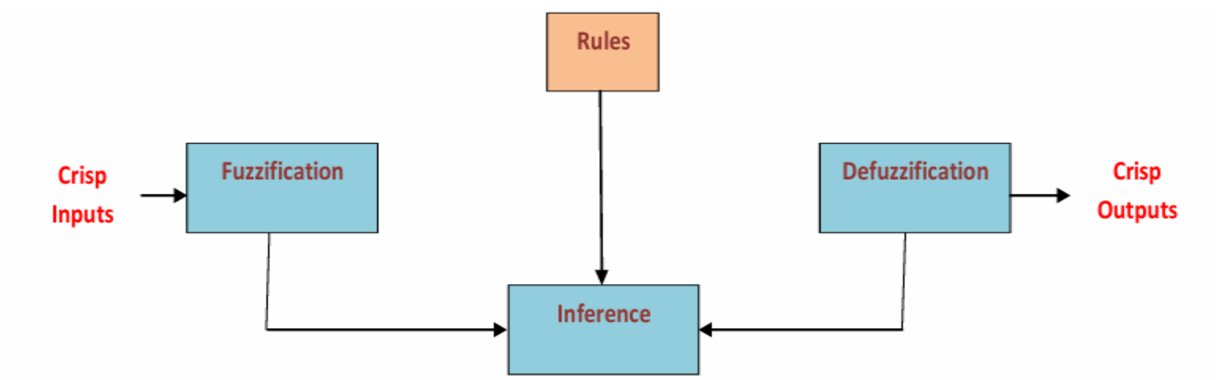


Figure 3.2: Block diagram of a Type-1 fuzzy controller**.**

3.5.1 Fuzzification

Fuzzification is the process of converting numerical values of inputs/outputs into fuzzy sets. In this way, they are represented as linguistic variables with a membership degree called a subset, which corresponds to each input point, known as the universe of discourse. For a membership function, the estimate is generally given in terms of degree rather than a precise value.

According to Boolean logic, where the response is either 0 or 1, the membership function's degree can take various values ranging from 0 to 1 [34].

Two fuzzification methods are available for this purpose:

- Defining membership classes for all input variables.
- Converting the physical quantity (temperature, pressure, age...) into a linguistic variable.

Choice of the fuzzification operator:

- The fuzzification operator associates a measurement of the variable with$\boldsymbol{X_0}$ A membership function $\boldsymbol{\mu_{X0}}$**(x).**
- If the measurement of X_0 If the measurement is exact, the membership function used is the singleton
- If the measurement is uncertain, the membership function commonly used is triangular or trapezoidal in shape.

3.5.2 Rule Base

It contains all the knowledge related to the application domain and the intended control objectives. It consists of [34]:

a) A database: that provides the necessary definitions for using fuzzy rules. It can be summarized as:

- Normalization of the universes of discourse.
- Choice of membership functions.

b) A fuzzy rule base: that defines the control strategy using a set of conditional statements. It can be summarized as:

- Selection of input variables.
- Source of fuzzy control rules.

3.5.3 Fuzzy Inference Mechanism

Inference in fuzzy systems is based on applying a set of logical rules that involve operators such as "AND", "OR", and "THEN", which are applied to the membership functions of the input variables [34]

There are three main inference methods commonly used in this context:

- The Max-Min method developed by Mamdani;
- The Max-Prod method introduced by Larsen;
- The Sum-Prod method proposed by Zadeh.

These methods are used to determine how different conditions within fuzzy rules are combined in order to derive the appropriate output based on the chosen inference logic...

3.5.4 Defuzzification:

Defuzzification is the final step in fuzzy logic. Its purpose is to convert the final activation curve, obtained during the aggregation stage, into a precise real-world value. There are two main methods used to determine the crisp value of the output variable:

- Mean of Maximum **(MOM)** Method: This method calculates the average of the most plausible output values, i.e., the peaks of the output membership function.

- Center of Gravity (Centroid) Method **(COG):** This method determines the output by computing the x-coordinate of the centroid of the area under the aggregated output curve [34].

3.5.4.1. Mean of Maximum (MOM) Method:

When multiple fuzzy sets share the same maximum height, this method is used to calculate the average of their peak values. It involves taking the mean of the x-coordinates corresponding to the maximum values.

3.5.4.2. Center of Gravity (Centroid) Method (COG):

The output corresponds to the x-coordinate of the centroid of the area under the resulting membership function [19].

$$\boldsymbol{X_0}=\frac{\sum_{i=1}^{ni} X_{ri}\mu\,(X_{ri})}{\sum_{i=1}^{ni}\mu(X_{ri})} \tag{3.2}$$

This method is the most computationally expensive, but it is also the most commonly used. It can be applied in two ways:

- The union of all fuzzy output subsets is taken, and the global centroid is computed (requires heavy computation).
- The centroid of each fuzzy subset is calculated individually, and then the average of all these centroids is taken [34].

3.6 Advantages and Disadvantages of Fuzzy Logic Control

3.6.1 Advantages

The main advantages of fuzzy controllers are as follows:

- Direct incorporation of fuzzy and linguistic information, provided by a human expert, into the fuzzy system.

- No need to create a mathematical model of the system to be controlled.
- The fuzzy system is a universal approximate, meaning it is general enough to generate any required action.
- Fuzzy logic is easy to understand even for non-specialists, as it mimics human reasoning strategies.
- It allows for control of nonlinear systems that are difficult to model.

3.6.2 Disadvantages

- Lack of precise guidelines for designing a controller.
- Generally low tuning precision [34].

3.7 Application of Type-1 Fuzzy Logic Control for Magnetic Levitation System.

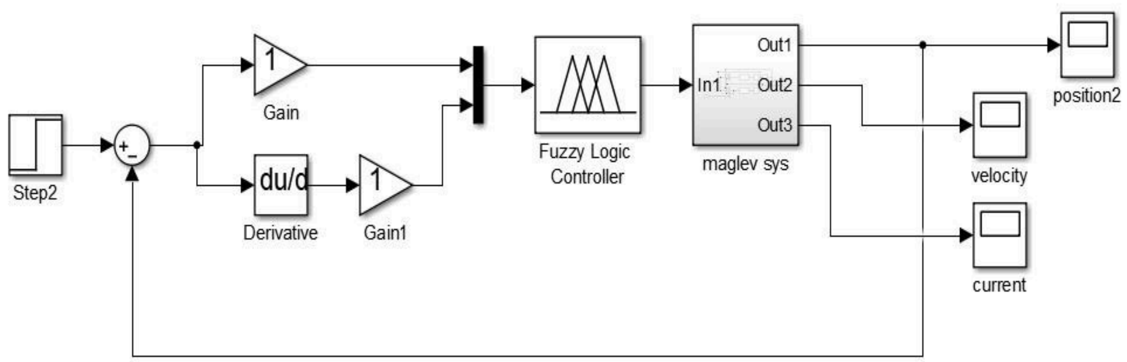


Figure 3.3: Block diagram of type 1 fuzzy logic control, magnetic levitation system.

Tab 3.3 : Table de règles.

		e						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
de	**NB**	NVB	NVB	NVB	NB	NM	NS	ZE
	NM	NVB	NVB	NB	NM	NS	ZE	PS
	NS	NVB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PVB
	PM	NS	ZE	PS	PM	PB	PVB	PVB
	PB	ZE	PS	PM	PB	PVB	PVB	PVB

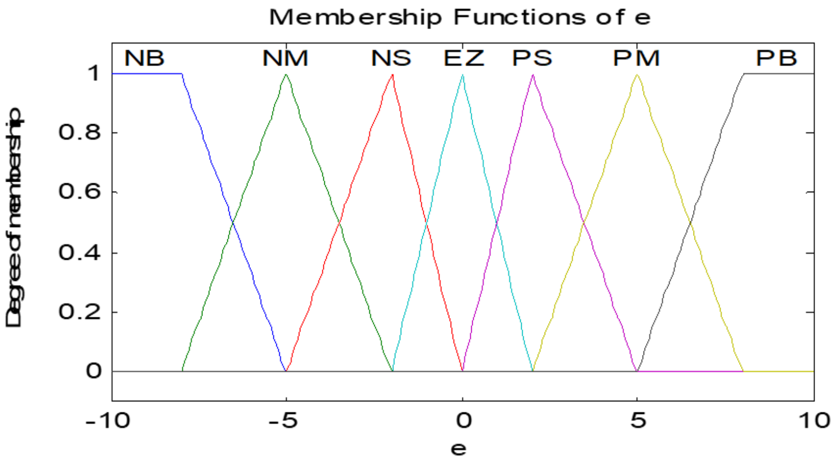


Figure 3.4: Membership function of the error.

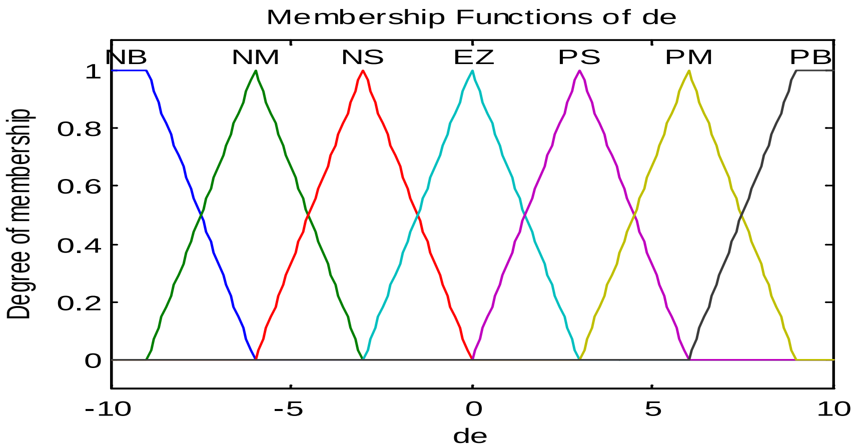


Figure 3.5: Membership function of the derivative of the error.

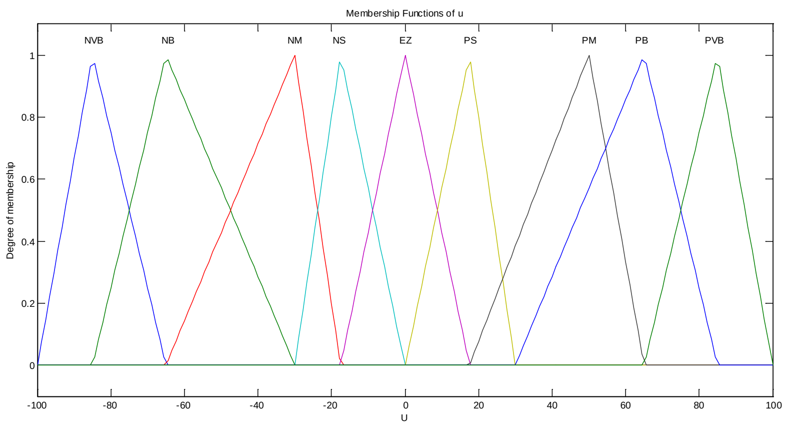


Figure 3.6: Membership function of the output.

3.8. Simulation Results of Type-1 Fuzzy Control of a Magnetic Levitation System

The results for position, control signal, and error with respect to a step reference are shown in Figure 3.7:

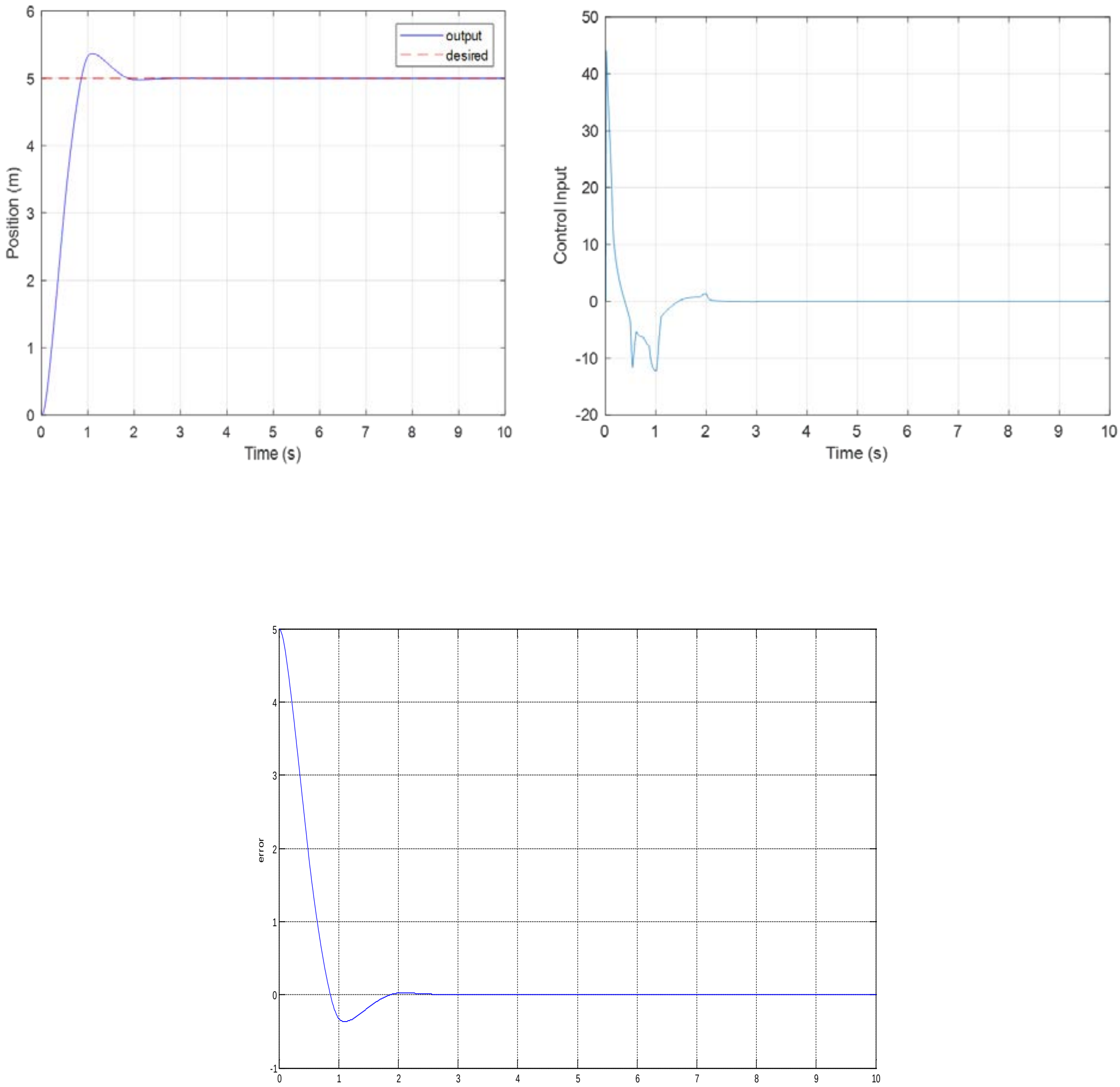


Figure 3.7: Simulation Results of Type-1 Fuzzy Logic Control for a Step Input.

3.9 Interpretation of Simulation Results

Based on the simulation results using Type-1 fuzzy logic control applied to the magnetic levitation system, it is observed that the performance was good in terms of response time, system stability, and accuracy in reaching the reference position. The system demonstrates the ability to achieve stable and effective control despite its nonlinear nature, which confirms the efficiency of this type of control in complex systems.

3.10 Conclusion

In this chapter, we presented a general overview of fuzzy logic concepts and its main components. We began with definitions such as linguistic variables, universe of discourse, and membership functions. Then, we discussed some of the most commonly used fuzzy logic operations. After that, we presented the structure of a fuzzy system with a brief explanation of its components, such as fuzzification and defuzzification. Type-1 fuzzy logic proves to be an appropriate solution for overcoming the limitations of traditional control methods, especially in nonlinear and complex systems such as the magnetic levitation system. In the next chapter, we will adopt a more advanced control approach using Type-2 fuzzy logic, with the aim of improving performance and increasing control accuracy.

4.1 Introduction

In 1975, Zadeh extended this idea by proposing Type-2 fuzzy sets [35-37]. Unlike Type-1 fuzzy sets—which use precise membership functions—Type-2 fuzzy sets model uncertainty within the membership functions themselves. This allows for the representation of higher levels of imprecision, making Type-2 fuzzy logic particularly suitable for applications involving noise, dynamic environments, or incomplete knowledge [38].

Magnetic Levitation (Maglev) systems are inherently nonlinear, unstable, and highly sensitive to external disturbances and parameter variations. The main challenge in controlling a Maglev system lies in maintaining a stable levitation position without physical contact, under uncertain conditions [39]. To overcome these limitations, researchers have explored the use of **Type-2 Fuzzy Logic Controllers (T2FLCs)**.

These controllers have demonstrated superior performance in handling uncertainties and disturbances, particularly in highly nonlinear systems like Maglev [41]. For instance, an interval Type-2 fuzzy logic controller was successfully applied to a Maglev platform, providing enhanced robustness and improved tracking performance [42].

Another study demonstrated that a single-input T2FLC significantly outperforms its Type-1 counterpart in maintaining stability under sensor noise and parameter variations [43]. Therefore, the application of Type-2 fuzzy logic in the context of Maglev systems presents a promising approach for achieving more stable, adaptive, and resilient control. The following sections of this chapter will detail the design, implementation, and simulation of a Type-2 fuzzy logic controller tailored for magnetic levitation, emphasizing its advantages over traditional control strategies.

4.2 Basic Concepts of Type-2 Fuzzy Logic

4.2.1 Fuzzy Sets

4.2.1.1 Definition 1

A Type-2 fuzzy set, denoted as Ã, is defined by a three-dimensional membership function $\mu_{\tilde{A}}(x, u)$, **i. e**:

$$\tilde{A} = \int_{x \in X} \int_{u \in J_x} u_{\tilde{A}}(x, u) \,/\, (x, u) \; J_x \subseteq [0\ 1] \tag{3.1}$$

Where $\iint$ denotes the union of all elements of the Cartesian product over x and u with:

$$0 \leq u_{\tilde{A}}(x, u) \leq 1$$

For each fixed point x in X, J_x is the primary membership of x, and x is called the primary variable [44].

4.2.1.2 Definition 2

For each value of x, define x = x′. The two-dimensional plane whose axes are u and μ_Ã (x, u) is called the vertical slice of μ_Ã (x, u). The vertical slice for x′ = 5 Is illustrated in Figure (3.1). [45].

Thus, for x'∈ X and ∀ u ∈ $J_{x'}$⊆ [0 1] we have :

$$u_{\tilde{A}}(x = x', u) = u_{\tilde{A}}(x') = \frac{\int f_{x'}(u)}{u} J_{x'} \subseteq [0\ 1] \tag{3.2}$$

Where: $0 \leq f_{x'}(u) \leq 1$.

Since ∀ x', this x' Will belong to X, i.e. x'∈ X, Therefore, we write the secondary membership function as $u_{\tilde{A}}$(x), which is a Type-1 fuzzy membership function.

Based on the concept of secondary sets, a Type-2 fuzzy set can be reinterpreted as the union of all secondary sets, i.e., using Equation (3.2) [46]. We can write $\tilde{A}$ in the following form :

$$\tilde{A} = \{(x, u_{\tilde{A}}(x)) \,/\, \forall x \in X\} \tag{3.3}$$

Where it takes the form

$$\tilde{A} = \int_{x \in X} u_{\tilde{A}}(x) / x = \int_{x \in X} \left[\int_{u \in J_x} f_x(u) \;/u\right] / x \; J_x \subseteq [0\ 1] .$$

4.2.1.3 Definition 3

The domain of the secondary membership function is called the primary membership of x, denoted J_x, such that: $J_x \subseteq [0\ 1]$ ∀ x ∈ X [46].

4.2.1.4 Definition 4

The amplitude of the secondary membership function is called the secondary membership degree, denoted as: $f_x(u)$ [46].

4.2.1.5 Definition 5

A Type-2 fuzzy set is composed of secondary membership functions, which are Type-1 sets in the form of intervals:

$$f_x(u) = 1, \forall\, u \in J_x \subseteq [0\ 1], \forall\, x \in X \tag{3.4}$$

Interval Type-2 fuzzy sets reflect the uniformity of uncertainty at the level of the primary membership function. This type of membership function is the most commonly used in Type-2 fuzzy systems. It is important to note that this type of membership function differs only by its domains (intervals), which can be described using the left and right bounds [l, r], or by their centers and widths. [c -s, c+s] where c = (l + r) / 2 and s = (r - l) / 2 [11].

4.2.1.6 Definition 6

Let us consider that each secondary membership function of a Type-2 fuzzy set has a single unit membership degree. The primary membership function is then defined as the union of all these points: [46]

$$M_{\text{principale}}(x) = \int_{x \in X} u / x \quad \text{où} \quad f_x(u) = 1 \tag{3.5}$$

In an interval Type-2 fuzzy set, the primary membership function is the union of all the average membership values of the primary membership function. Note that when the uncertainty in the membership functions disappears, the membership function of a Type-2 fuzzy set reduces to the primary membership function. [46]

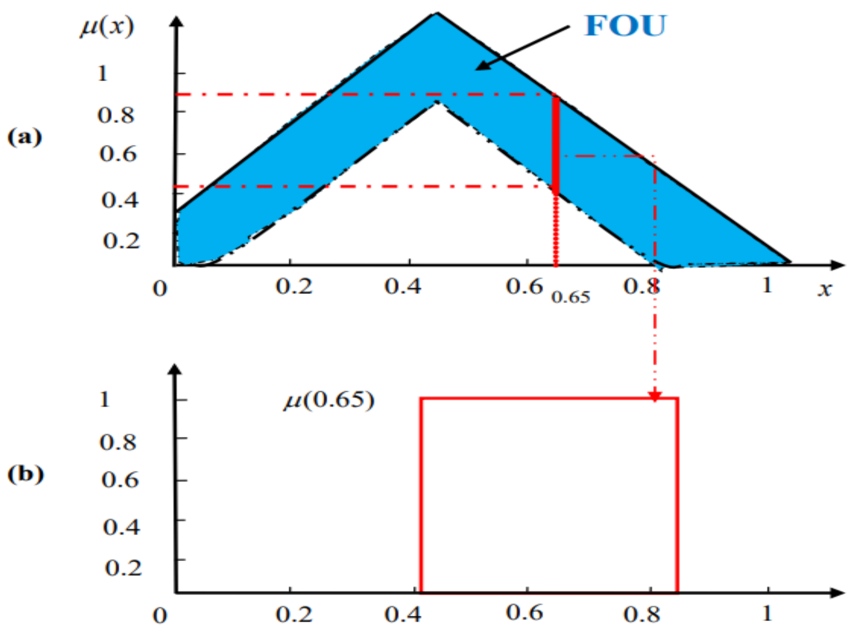


Figure 4.1: Schematic representation of an interval Type-2 fuzzy set [46].
(a) Primary membership. (b) Secondary membership.

4.3 Types of Type-2 Fuzzy Sets

Gaussian Type-2 Fuzzy Set: Each point in the domain has a Type-1 Gaussian membership function, meaning that the membership grade follows a Gaussian (normal) distribution shape. The domain of the secondary membership functions lies within the interval [0, 1]. This type models uncertainty with smooth, bell-shaped membership grades [47] [49].

Triangular Type-2 Fuzzy Set: Each point is modeled as a Type-1 fuzzy set with a triangular membership function, defined within the interval [0, 1]. This provides a piecewise linear and simpler shape compared to Gaussian sets, often used for computational efficiency and easier interpretation [48] [50].

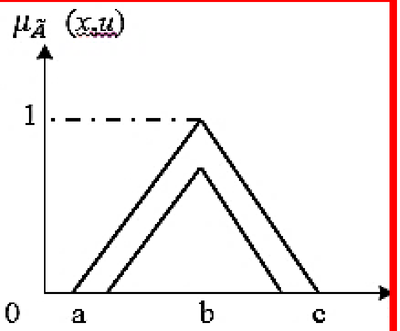
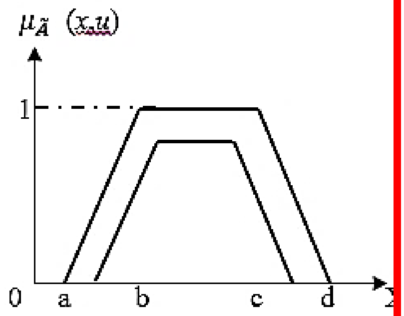
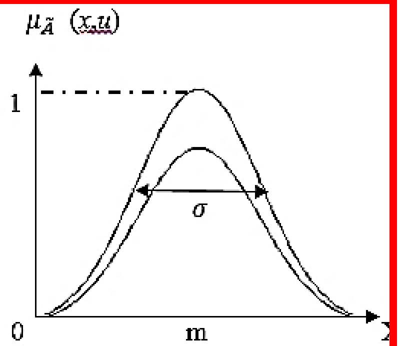
Interval Type-2 Fuzzy Set: Each point belongs to an ordinary (crisp) set, and the secondary membership grades are all equal to 1 over an interval domain [0, 1]. This means the uncertainty is captured solely by the range (interval) of the membership function, which simplifies calculations while still modeling uncertainty effectively [47] [51].

4.4 Membership functions

There is no modification to the basic fuzzy sets from Type-1 to Type-2 in the foundations of fuzzy logic, and in general, they do not vary for any type n. As the number of types increases, what changes is the nature of the membership functions.

In this case, the secondary memberships are equal to 1. The table below illustrates the most commonly used membership functions:

Tab 4.1: Type-2 Triangular, Gaussian, and Trapezoidal Membership Functions [52]

Function	Algebraic Form	Graphical Form
Triangulaire Function	$\mu\tilde{A}(x) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \leq x < b \\ \frac{c-x}{c-b} & b \leq x < c \\ 0 & x > c \end{cases}$ $\mu\tilde{A}(x) = \begin{cases} 0 & x < (a+\alpha) \\ (1-a)\frac{x-(a+a)}{b-(a+a)} & (a+a) \leq x < b \\ (1-a)\frac{x-(a+a)}{b-(a+a)} & b \leq x \leq (c-\alpha) \\ 0 & x > (c-\alpha) \end{cases}$	
Trapezoidal Function	$\overline{\mu A(x,u)} = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \leq x < b \\ 1 & b \leq x < c \\ \frac{d-x}{d-c} & c \leq x < d \\ 0 & x > d \end{cases}$ $\mu\tilde{A}(x,u) = \begin{cases} 0 & x < (a+\alpha) \\ (1-a)\frac{x-(a+a)}{b-(a+a)} & (a+a) \leq x < b \\ (1-a)\frac{(d-a)-x}{(d-a)-c} & b \leq x \leq (d-\alpha) \\ 0 & x > (d-\alpha) \end{cases}$	
Gaussian Function	$\overline{\mu A\ (x,u)} = \exp(-\frac{1}{2}(\frac{x-m}{\sigma})^2)$ $\overline{\mu A\ (x,u)} = (1-a)\exp(-\frac{1}{2}(\frac{x-m}{\sigma})^2)$	

The definition of an interval Type-2 membership function is based on the presence of an upper membership function (UMF) and a lower membership function (LMF). The UMF is equivalent to a traditional Type-1 membership function.

The LMF is less than or equal to the UMF for all possible input values. The region between the UMF and the LMF is called the Footprint of Uncertainty (FOU). The diagram below illustrates the UMF (in red), the LMF (in blue), and the FOU (shaded area) for a Type-2 triangular membership function (Figure 4.2) [53].

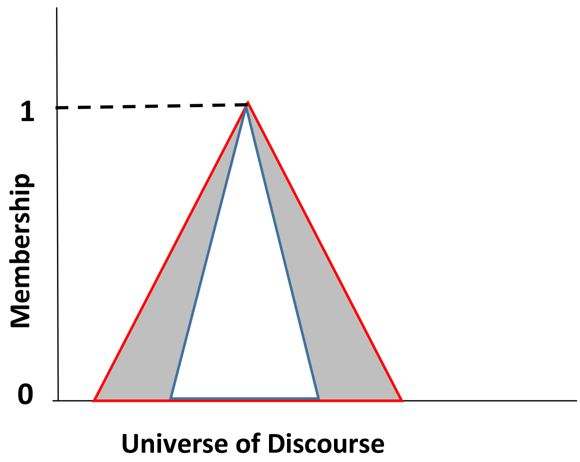


Figure 4.2 : Fonction d’appartenance triangulaire type 2 [53].

4.5 Opération sur les ensembles flous type 2

Consider two fuzzy sets of type-2, $\tilde{A} \in X$ and $\tilde{B} \in X$ let $\mu\tilde{A}(x)$ and $\mu\tilde{B}(x)$ be the membership grads of $\tilde{A}$ and $\tilde{B}$, It will be necessary to extend (generalize) the min, max, and negation operations, which initially deal with ordinary values, and then move toward fuzzy sets [54].
To this end, we will use Zadeh's well-known extension principle.
The membership functions for intersection, union, and complementation are as follows [20] :

- **Intersection:** $\tilde{A} \cap \tilde{B} = \sum_{i,j}(f_x\,(u_i) \wedge g_x(w_j))\,/u_i \wedge w_j$.
- **Union :** $\tilde{A} \cup \tilde{B} = \sum_{i,j}(f_x\,(u_i) \wedge g_x(w_j))\,/u_i \wedge w_j$.
- **Complementation :** $\overline{\tilde{A}} = \sum_i f_x(u_i)\,/(1\text{-}\mu_i)$; $\overline{\tilde{B}} = \sum_i g_x\,(w_j)\,/(1\text{-}w_j)$.

4.6 Structure of a Type-2 Fuzzy Controller

There are four modules in a fuzzy logic controller:

-Fuzzification of inputs and outputs.

-Fuzzy inference based on a rule base.

-Type reduction.

-Defuzzification of the outputs.

The architecture of a fuzzy controller is given by the following diagram [55]:

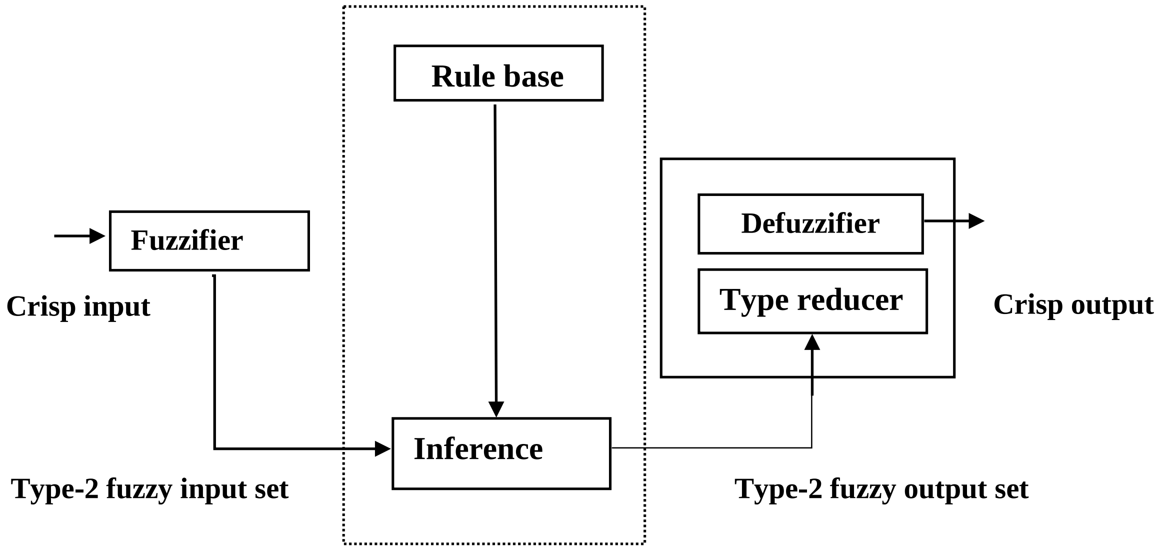


Figure 4.3: Block diagram of a Type-2 Fuzzy Controller [55].

4.6.1 Fuzzification

The fuzzification interface associates the deterministic input with a fuzzy set, which can generally be a Type-2 fuzzy set. However, in our work, singleton-type fuzzification will be used. In other words, the fuzzy input is a single point with a membership value equal to one [55].

4.6.2 .1 Rule Base

The difference between Type-1 and Type-2 fuzzy systems lies solely in the nature of the membership functions. Therefore, the rule structure in the case of Type-2 remains exactly the same. The only distinction is that some (or all) of the membership functions are of Type-2. It is not necessary for all membership functions in the premises and consequents to be of Type-2.

It is sufficient for only one membership function in either a premise or a consequent to be of Type-2 for the entire system to be considered a Type-2 fuzzy system.

4.6.2.2Inference

Inference techniques for type-1 and type-2 fuzzy sets are identical, with the only difference being that the input and output values for type-2 systems are fuzzy sets Ã. Therefore, type-2 systems use upper and lower membership functions for efficient processing.

In type-2 fuzzy inference systems, the input values are fuzzified by finding the corresponding degrees of membership with respect to both the Upper Membership Function (UMF) and the Lower Membership Function (LMF) from the antecedent of the rule. Each type-2 membership function generates two fuzzy values.

In Figure 3.6, fuzzification is illustrated by showing the membership value in the upper membership function (f_u) and the lower membership function (f_L) [52].

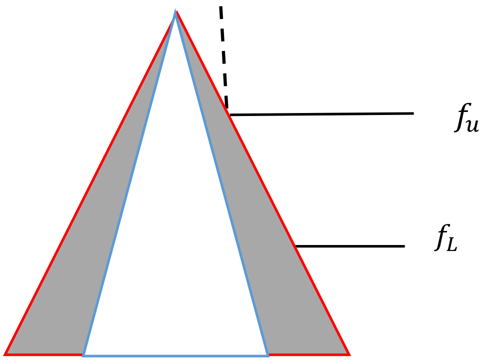


Figure 4.4: Membership function to be fuzzified [52].

Next, a range of rule firing strengths is determined by applying the fuzzy operator to the fuzzy values of the type-2 membership functions, as shown in the figure below. The maximum value of this range (W_u) is the result of applying the fuzzy operator to the fuzzy values from the Upper Membership Functions (UMFs).

The minimum value (W_l) is obtained by applying the fuzzy operator to the fuzzy values from the Lower Membership Functions (LMFs) [52].

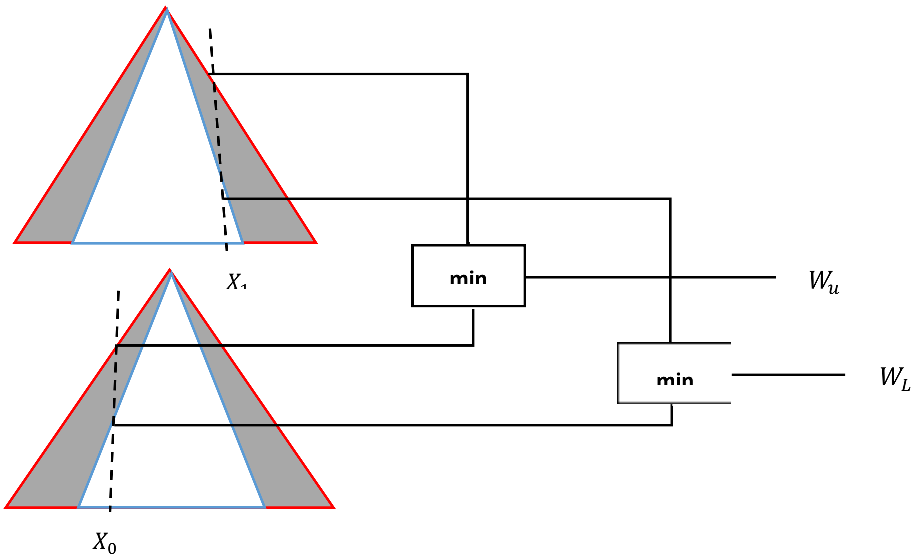


Figure 4.5: Two Membership function to be fuzzified [52].

4.6.3 Type-Reduction

In a type-1 fuzzy system, where the output sets are type-1 fuzzy sets, we perform defuzzification in order to obtain a crisp numerical value (type-0 set) representing the combination of the output fuzzy sets.

In the case of a type-2 fuzzy system, the output sets are type-2 fuzzy sets. Therefore, we must use extended versions of type-1 defuzzification methods, called type-reduction [52].

This operation transforms the resulting type-2 fuzzy set into a type-1 fuzzy set, called the type-reduced set, which will then be defuzzified.

The type-reduced set retains more information about the uncertainties in the rules than a single crisp value.

Common type-reduction methods include:

- Center of Gravity type-reduction.
- Height type-reduction.
- Center of Sets type-reduction [56].

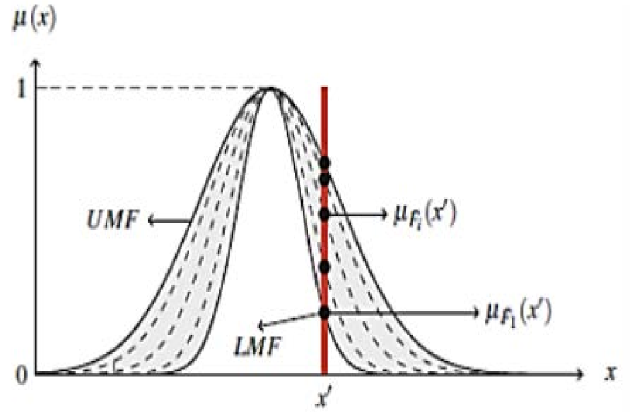


Figure 4.6: Footprint of Uncertainty and Upper and Lower Membership Functions [57].

4.6.4 Defuzzification

At the end of the type-reduction step, we obtain a type-reduced set which is a type-1 fuzzy set. Therefore, it is necessary to transform it into a well-defined numerical value [Kar-99].

The most natural way to do this is to find the center of gravity of the type-reduced set. Calculating the center of gravity is equivalent to finding a weighted average of the outputs of all the type-1 fuzzy sets embedded within the type-2 fuzzy system, where the weights correspond to the memberships in the type-reduced set [54].

4.7 Application of Type-2 Fuzzy Control to a Maglev System

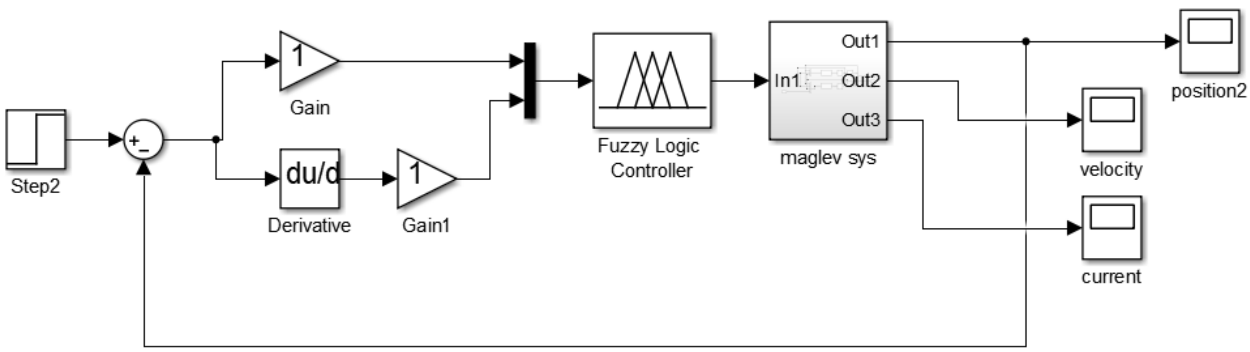


Figure 4.7: Block Diagram of Type-2 Fuzzy Logic Control for a Maglev System.

The membership functions of the input variables, the input derivative, and the output are defined by triangular and trapezoidal shapes (Figures 4.8, 4.9, and 4.10).

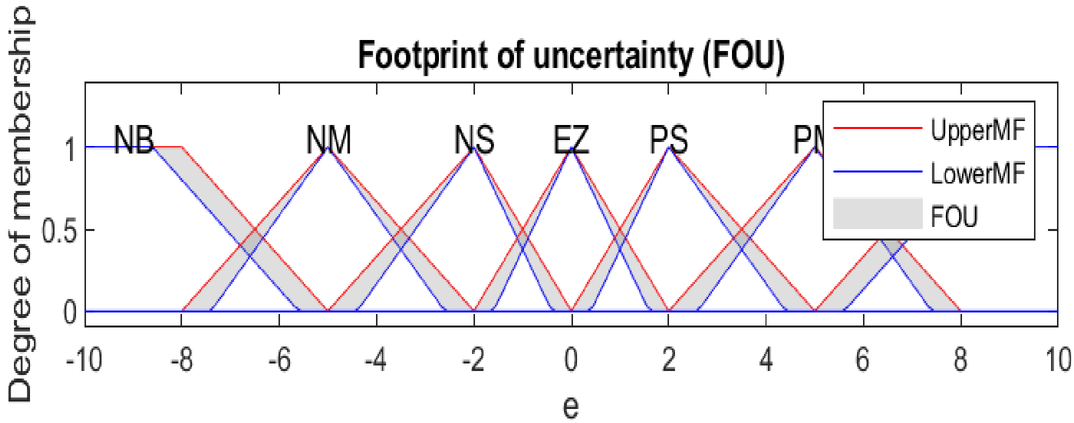


Figure 4.8: The membership functions of the Error.

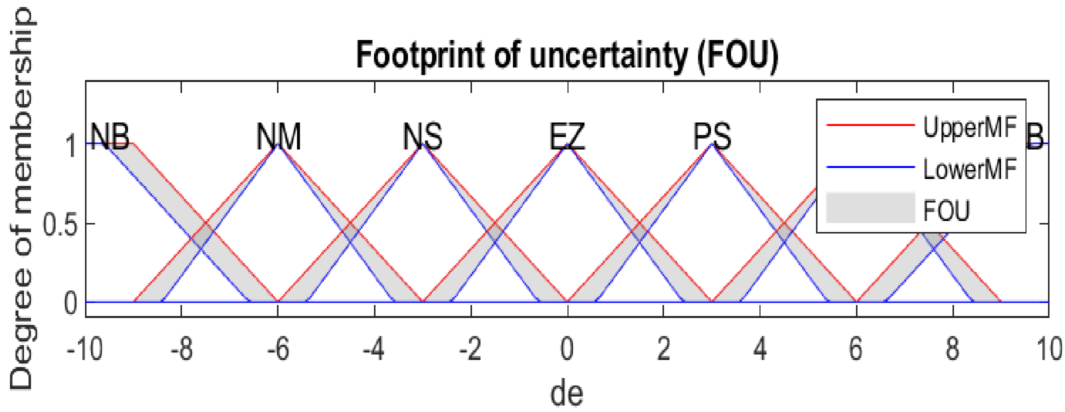


Figure 4.9: The membership functions of the Derivative of the error.

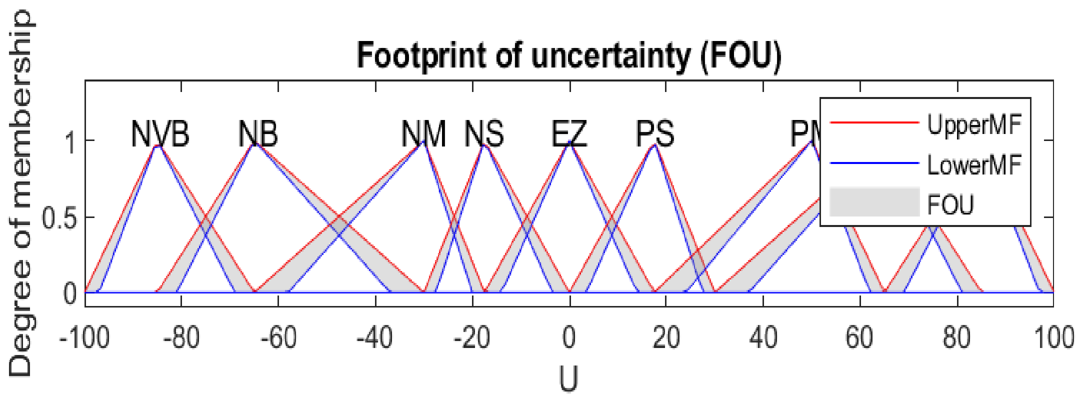


Figure 4.10: The membership functions of the output.

4.8 Simulation results of the type-2 fuzzy control of a maglev system

The results of the position, the control input, and the error are shown in the figure.4.11:

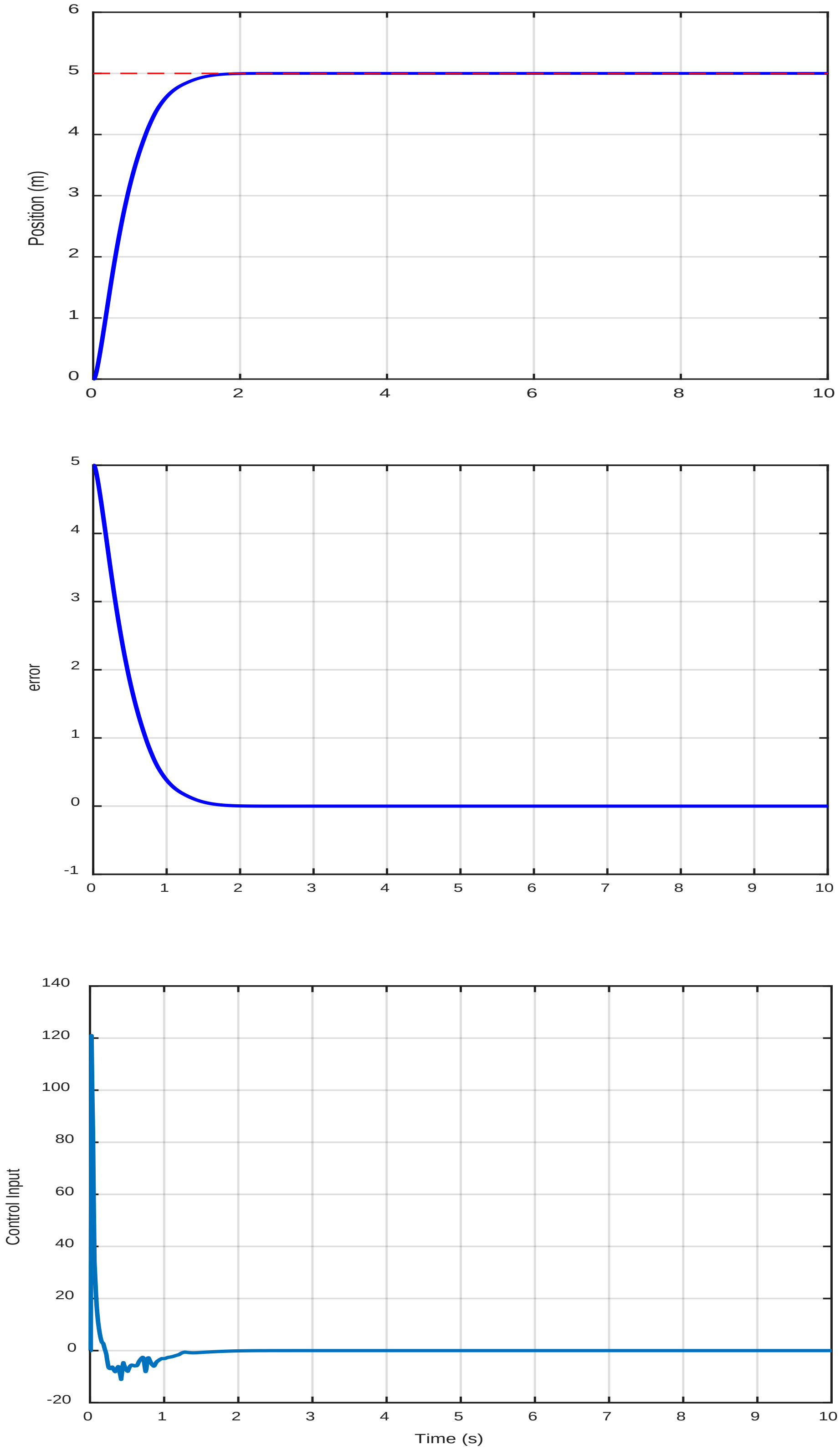


Figure 4.11: Simulation results of the type-2 fuzzy control of a maglev system.

4.8. Interpretation of the Simulation Results

1. **Fast Rise Time**: The position quickly rises from 0 mm and approaches the reference value within approximately 1.5 seconds.
2. **Minimal Overshoot:** There is little to no overshoot, indicating the controller is not overly aggressive and avoids instability.
3. **Good Steady-State Behavior:** After around 2 seconds, the position stabilizes very close to the reference value. The system shows very low steady-state error, which means the controller successfully maintains the desired position.
4. **Smooth Response:** The transition is smooth without oscillations, which indicates good damping and well-tuned control parameters.

4.9 Comparative study between the simulation results of the different developed control laws:

Tab 4.2: Comparative study between the simulation results of the different control laws

Performance Metric	PID Controller	FLC1	FLC2
Rise Time (s)	0.8	1.0	1.2
Overshoot (%)	35	10	0
Settling Time(s)	4.5	2.5	1.8
Steady-State Error	0.0	0.0	0.0
Peak Value (m)	6.75	5.5	5.0

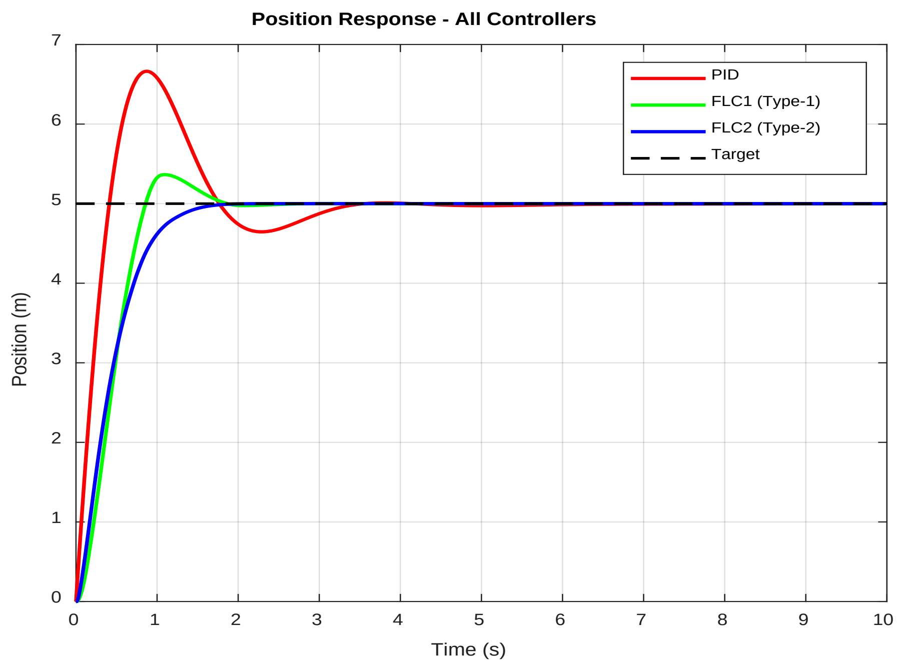


Figure 4.12: The simulation results of the output responses under the control strategies (PID, Type-1 Fuzzy Logic, and Type-2 Fuzzy Logic).

The performance comparison of the three controllers—PID, Type-1 Fuzzy Logic Controller (FLC1), and Type-2 Fuzzy Logic Controller (FLC2)—for the magnetic levitation system reveals significant insights into their control effectiveness. The PID controller, although fast in response, suffers from a high overshoot and visible oscillations before settling, which can be problematic for systems requiring precision and stability. The Type-1 Fuzzy Logic Controller improves upon this by reducing the overshoot and minimizing oscillations, offering a more stable response compared to PID. However, the most impressive results are observed with the Type-2 Fuzzy Logic Controller. FLC2 achieves an almost perfect response: it eliminates overshoot, shows negligible oscillations, and settles to the target position faster than the other two. This high performance can be attributed to the enhanced capability of Type-2 fuzzy systems to handle uncertainty and noise within the control environment. By incorporating an additional degree of freedom in the form of a footprint of uncertainty (FOU), FLC2 manages imprecision in a more robust manner, leading to improved system behavior. Therefore, the Type-2 Fuzzy Controller demonstrates the most effective and reliable control strategy for magnetic levitation, especially in scenarios that demand high precision and robustness.

4.10 Conclusion

This chapter focused on the application and analysis of the Type-2 Fuzzy Logic Controller for the magnetic levitation system. After introducing the main concepts and structure of Type-2 fuzzy logic, we highlighted its key advantage: the ability to handle uncertainty in the membership functions through the type-reduction process. We compared three control methods—PID, Type-1 Fuzzy, and Type-2 Fuzzy—using simulation results. The comparison showed that the PID controller has a fast but unstable response with overshoot. The Type-1 fuzzy controller improved stability and reduced oscillations. However, the Type-2 fuzzy controller demonstrated the best overall performance with enhanced stability, less overshoot, and faster settling time. In conclusion, the Type-2 fuzzy logic controller offers a significant improvement over traditional PID and Type-1 fuzzy controllers, making it a more effective and robust solution for controlling nonlinear systems such as magnetic levitation.

General Conclusion

This thesis has focused on the modeling and intelligent control of a magnetic levitation system, a nonlinear and unstable system that requires precise and robust control strategies.

In chapter 1, we presented an overview of the magnetic levitation system, including its working principles, applications, and control challenges. The importance of choosing an appropriate control strategy was highlighted due to the system's inherent instability.

In chapter 2, we developed the mathematical model of the magnetic levitation system based on the fundamental physical laws. This chapter also included the design and implementation of a PID controller. While PID control is widely used in practice for its simplicity, simulation results showed that it offers limited performance for highly nonlinear systems. The response exhibited overshoot, oscillations, and slower convergence to the desired position.

In chapter 3, we introduced the Type-1 Fuzzy Logic Controller (FLC1). This controller allowed us to incorporate expert knowledge through linguistic rules and membership functions. Compared to the PID controller, FLC1 provided better performance by reducing overshoot and improving the system's stability.

In chapter 4, we extended the fuzzy logic approach by implementing a Type-2 Fuzzy Logic Controller (FLC2). This advanced controller introduced a Footprint of Uncertainty (FOU) in the membership functions, making it more capable of handling noise and modeling uncertainty. Simulation results demonstrated that FLC2 offered the best performance among the three controllers, with a fast response, minimal oscillations, and high robustness under varying conditions.

To conclude, the comparative study between PID, Type-1 FLC, and Type-2 FLC clearly showed that the Type-2 Fuzzy Logic Controller is the most suitable for the magnetic levitation system due to its superior accuracy, adaptability, and robustness. This work highlights the potential of intelligent control techniques for the regulation of complex nonlinear systems.

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Résumé

Ce travail porte sur le contrôle intelligent d'un système de lévitation magnétique, en utilisant les techniques PID, la logique floue de type 1 et de type 2. L'objectif principal est d'améliorer la stabilité et la rapidité de réponse du système dans un environnement incertain ou bruité. Des simulations ont été effectuées sous MATLAB/Simulink pour valider l'efficacité de chaque méthode de contrôle. Les résultats montrent que la logique floue de type 2 offre de meilleures performances dynamiques, notamment en conditions non idéales.

Mots clés : Lévitation Magnétique, PID, Logique Floue, Type-1, Type-2, Contrôle Intelligent, MATLAB, Simulink.

Abstract

This work presents an intelligent control approach applied to a magnetic levitation system using PID, Type-1, and Type-2 Fuzzy Logic Controllers. The main objective is to enhance the system's stability and response under uncertain and noisy conditions. Simulations are conducted using MATLAB/Simulink to validate the performance of each control technique. The results show that Type-2 Fuzzy Logic offers superior dynamic performance, especially in the presence of disturbances and uncertainties.

Key words: Magnetic Levitation, PID, Fuzzy Logic, Type-1, Type-2, Intelligent Control, MATLAB, Simulink**.**

الملخص

يتناول هذا العمل دراسة التحكم الذكي في نظام الرفع المغناطيسي، باستخدام تقنياتPID ، والمنطق الضبابي من النوع الأول والنوع الثاني .يهدف البحث إلى تحسين استقرار النظام وسرعة استجابته في ظل وجود ضوضاء أو عدم تيقن في البيئة .تم تنفيذ عمليات المحاكاة في بيئة الماطلاب للتحقق من فعالية كل تقنية. وقد أظهرت النتائج أن استخدام المنطق الضبابي من النوع الثاني يوفر أداءً ديناميكياً أفضل مقارنةً بباقي الأساليب، خاصة في الظروف غير المثالية.

الكلمات الرئيسية: الرفع المغناطيسي، المنطق الضبابي، النوع 1، النوع 2، التحكم الذكي، الماطلاب.