DESIGN OF PID CONTROLLER FOR NONLINEAR MAGNETIC LEVITATION SYSTEM USING FUZZY-TUNING APPROACH

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This paper presents a dynamic model of a magnetic levitation system (Maglev) and suggests a Fuzzy Tuning of a proportional—integral--derivative controller (PID) that uses a fuzzy approach system to determine the PID controller's settings. The controller allows a steel ball to be suspended in free fall in the chosen position in reference to the electromagnet bottom end. The electromagnet levitation system can be controlled with a traditional PID controller, however because of the highly nonlinear of this system, it is unpredictable in the case of load and air gap changes. The fuzzy rules are developed to fuzzy tune PID while considering the control response and behavior of the system to find a solution to this problem. This paper shows excellent stability, rising time, settling time overshoot, and robust response results. The results reveal that this fuzzy PID controller solution can stabilize the ball's location and has strong disturbance rejection. The real time platform is designed for educational laboratory and test all the proposed control systems

Keywords: Magnetic Levitation System, Fuzzy PID tuning, Matlab implementation, Maglev System Dynamics and Modeling, Real time implementation

1. Introduction

Magnetic levitation technologies have been used in a wide range of applications in recent years, its major performance has led to its deployment in a wide variety of uses, including wind turbines, high-speed rails, building management systems, personal rapid transit, nuclear reactors, food inspection systems, military weapons, household appliances, and biomedical devices [1].
The magnetic levitation technology with no physical friction with the railway has advantages such as low noise, frictionless motion, and high speed in the process. The system's stability, on the other hand, is a difficult problem to solve [2].
There are a variety of controllers that may be used to design feedback systems in linear systems, but the PID controller is one of the most common. This controller is

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designed to strike a balance between the amount of control effort required and the system's reaction.

In an ideal world, the magnetic force produced by an electromagnet powered by electricity would be greater than the weight of the steel ball. However, because the fixed electromagnetic force is particularly sensitive to noise, the noise creates acceleration pressures on the steel ball, causing the Maglev system model to become unstable due to unstable (positive) poles, causing the ball to move into the unstable (unbalanced) zone.

In this research, the fuzzy logic (FL) approach is utilized to optimize the parameters of a (PID) controller for controlling the position of a suspended steel ball utilizing a magnetic levitation system to the required level. As a result, the results reveal that this optimal control strategy can stabilize the ball's location and has a strong stability even in the presence of disturbance using multi steps such as modeling, linearization and optimal strategy control (Fuzzy- PID controller).

2. MAGNETIC LEVITATION SYSTEM (MAGLEV)

This section is devoted to a thorough examination of the magnetic levitation system (Maglev) and nonlinear modeling. Analyzing the mechanical and electromagnetic subsystems yields the nonlinear model. The model's linearization is accomplished using the Jacobian formula [3].

a) Magnetic Levitation System overview

A ferromagnetic steel ball is suspended in a magnetic field (voltage-controlled) in the MAGLEV system considered. The schematic diagram of MAGLEV is shown in Fig. (1).

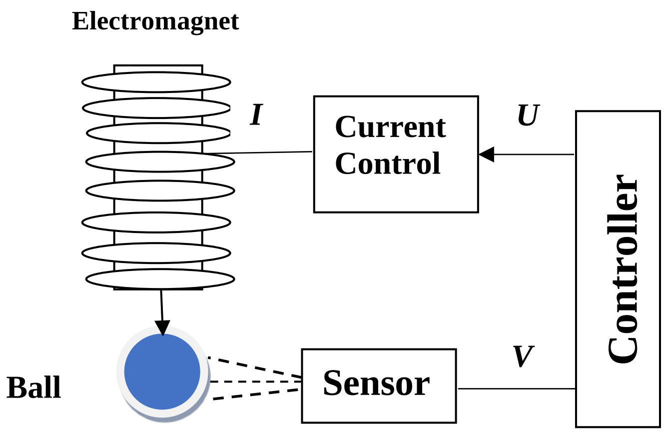

Fig.1. Magnetic Levitation System Schematic Diagram.

Ferromagnetic (steel) ball is moved by electromagnetism, while an optoelectronic sensor measures its position. Steel ball floats in mid-air due to a controller's ability to manage the flow of electricity in a circuit so that the electromagnetic force is equal to the weight of the steel ball. For an open-loop system, a nonlinear controller is required to keep it stable. [4].

b) The (Maglev) System Dynamics and Modeling

The magnetic levitation system's mathematical model can be found by constructing appropriate differential equations based on common electrical and mechanical principles. In the impending mode, the components' paths might be anticipated to be easier or more complex. Within the system, the energetic balance formula is [5][12]:

$$\Delta W elec = \Delta W mec + \Delta W ther + \Delta W mag \tag{1}$$

$\Delta W elec$: is the variance of the electrical energy,
$\Delta W ther$: is the variance of the thermal energy,
$\Delta W mec$: is the variance of the mechanical energy,
$\Delta W mag$: is the variance of the magnetic energy.

c) The Mechanical Subsystem Modeling

The variation of magnetic energy when levitated bodies move within a magnetic field and the magnetic fluxes vary is [6]:

$$\Delta W mag = i . \Delta \emptyset - F_{em}(x, i, t) . \Delta x \tag{2}$$

Where;

i: is the coil winding DC current,

$\Delta \emptyset$: represented the variation of magnetic flux through the magnetic field,

Δx: is the variance of levitated body (steal ball) position with respect to electromagnet coil.

$F_{em}(x, i, t)$: represents the electromagnetic sustentation Force.

The electromagnetic levitation force $F_{em}(x, i, t)$ can be calculated using the generalized forces theorems as follows:

$$\boldsymbol{F_{em}}(\boldsymbol{x},\boldsymbol{i},\boldsymbol{t}) = -\left(\frac{\partial Wmag}{\partial x}\right)_{i=cst} \tag{3}$$

A coil's specific magnetic energy is:

$$\boldsymbol{Wmag} = \frac{\emptyset.i}{2} = \frac{L(x).i^2}{2} \tag{4}$$

The inductivity $\boldsymbol{L}(\boldsymbol{x})$ can be determined directly or by utilizing the reluctance. According to this relationship, the coil inductivity $\boldsymbol{L}(\boldsymbol{x})$ is dependent on the ferromagnetic ball's position x: [4, 6]:

$$\boldsymbol{L}(\boldsymbol{x}) = \boldsymbol{L_o} + \boldsymbol{L_1}.\frac{x_o}{x} \tag{5}$$

Where:
$\boldsymbol{L_o}$: represented the coil inductivity when the ball is away,
$\boldsymbol{L_1}$: represented the coil inductivity when the ball is ready,
$\boldsymbol{x_o}$: represented the equilibrium position of the ball.

Substituting Eq. (4) and Eq. (5) into Eq. (3), yields:

$$\boldsymbol{F_{em}}(\boldsymbol{x},\boldsymbol{i},\boldsymbol{t}) = -\frac{i^2}{2}\frac{\partial L(x)}{\partial x} = -\frac{i^2}{2}\frac{\partial}{\partial x}\left(\boldsymbol{L_o} + \frac{L_1.x_o}{x}\right) = \boldsymbol{c}.\left(\frac{i}{x}\right)^2 \tag{6}$$

Where:

$\boldsymbol{c} = \frac{L_1.x_o}{2}$, is the magnetic force constant.

Fig. (2) depicts a ferromagnetic ball in equilibrium with its electromagnetic force$\boldsymbol{F_{em}}(\boldsymbol{x},\boldsymbol{i},\boldsymbol{t})$ and gravitational force $\mathbf{F_g}$.

Newton's 3rd law of motion determines the net force $\boldsymbol{F_{net}}$ acting on the ball [7]:

$$\boldsymbol{F_{net}} = \boldsymbol{F_g} - \boldsymbol{F_{em}}$$

$$\boldsymbol{m\ddot{x}} = \boldsymbol{m}\mathbf{g} - \boldsymbol{c}\left(\frac{i}{x}\right)^2 \tag{7}$$

$\boldsymbol{m}$: is the mass of the ball,
$\mathbf{g}$: is the gravitational acceleration constant.

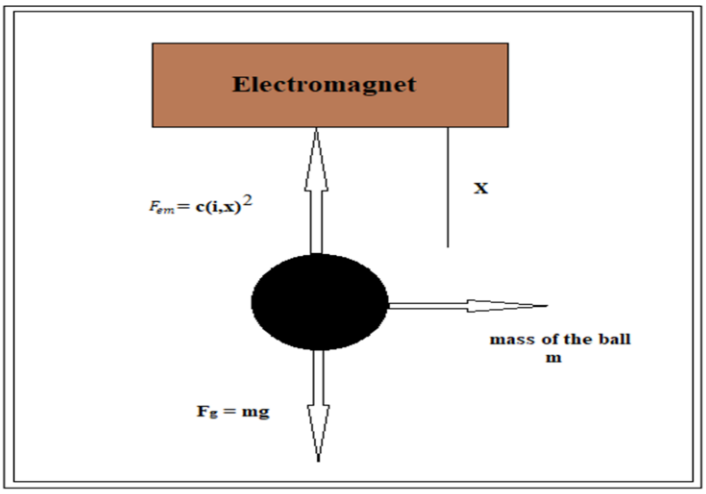

Fig.2. Free Body Diagram of Magnetic Levitation System. [8]

d) The Electromagnetic Subsystem Modeling

Kirchhoff's voltage law describes the magnetic force created by current:

$$\boldsymbol{u(t) = V_R + V_L = iR + \frac{dL(x)}{dt}} \tag{8}$$

Where;

$\mathbf{u(t)}$: Applied terminal voltage,
$\mathbf{V_R}$: Coil's resistance voltage.
$\mathbf{V_L}$: Coil's inductance voltage.
$\mathbf{i(t)}$: current flowing through an electromagnet's coil,
R: Coil's resistance; and,
$\mathbf{L(x)}$: Coil's inductance.

e) The Nonlinear Model

In the context of the situation, it is possible to isolate the dynamic model of the levitation system by using electro-mechanical modeling. The following equations describe this dynamic model of the system:

$$\boldsymbol{\frac{dx}{dt} = v}$$

$$\boldsymbol{u = R.i + \frac{d(L(x).i)}{dt} = R.i + L\frac{di}{dt} - 2.c\left(\frac{i}{x^2}\right)\frac{dx}{dt}} \tag{9}$$

$$\boldsymbol{m.\frac{dv}{dt} = m.\mathrm{g} - F_{em}(x,i,t) = m.g - c.\left(\frac{i}{x}\right)^2}$$

Based on the current system status, the mathematical model can be developed by considering state variables.

When $\boldsymbol{X = (x_1\ x_2\ x_3)^T = (x\ v\ i)^{\mathrm{T}}}$; then $\boldsymbol{x_1\ x_2\ x_3 =}$ $(\boldsymbol{position\ velocity\ current})$ Eq. (9) can be expressed in vector format in the following way;

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix} x_2 \\ \mathrm{g} - \frac{c}{m}\left(\frac{x_3}{x_1}\right)^2 \\ -\frac{R}{L}x_3 + \frac{2.c}{L}\left(\frac{x_2.x_3}{x_1^2}\right)\end{bmatrix} + \begin{bmatrix}0\\0\\ \frac{1}{L}\end{bmatrix}u$$

$$\dot{x} = \boldsymbol{f}(\boldsymbol{x}) + \mathbf{g}(\boldsymbol{x})\mathbf{u} \tag{10}$$

f) Maglev Linearization Model

In order that control the position of the ball to a desired position $\boldsymbol{x_{o1}}$, The MAGLEV system will be linearized around this equilibrium, if the ball position at equilibrium to $\boldsymbol{x_{o1}}$, then, the time rate derivative of ball position $\boldsymbol{x}$ is equal to zero, i.e.

$$\boldsymbol{x_{o2} = \frac{dx_{o1}}{dt} = \frac{dy_o}{dt} = 0} \tag{11}$$

The value of coil current $\boldsymbol{i_o}$ is obtained;

$$\boldsymbol{i_o = x_{o3} = x_{o1}\sqrt{\frac{mg}{c}}} \tag{12}$$

The linearized state equations are produced in the following formula using coefficient matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ by deriving the Jacobian formula and substituting the equilibrium vector $\boldsymbol{X_o} = [\boldsymbol{x_{o1}} \quad \boldsymbol{x_{o2}} \quad \boldsymbol{x_{o3}}]$ into this matrix:

$$\boldsymbol{A} = \begin{bmatrix} \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \dfrac{\boldsymbol{c.x_{o3}^2}}{\boldsymbol{m.x_{o1}^3}} & \mathbf{0} & -\mathbf{2}.\dfrac{\boldsymbol{x_{o3}}}{\boldsymbol{m.x_{o1}^2}} \\ \mathbf{0} & \mathbf{2}.\dfrac{\boldsymbol{c.x_{o3}}}{\boldsymbol{L.x_{o1}^2}} & -\dfrac{\boldsymbol{R}}{\boldsymbol{L}} \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \dfrac{\mathbf{1}}{\boldsymbol{L}} \end{bmatrix} \tag{13}$$

Where the foregoing coefficient matrices Eq. (13) can be used to illustrate the linearized system dynamics as follows:

$$\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bu} \tag{14}$$

3. Control System Design

Different techniques, such as the Proportional-Integral-Derivative (PID) controller, have been proposed in recent years. The design steps of a fuzzy PID controller to stabilize the nonlinear model of a Maglev system are presented in this section. [8] The optimum PID controller is determined by the parameters chosen. As a result, the Fuzzy system can be used to self-tune the PID parameters, combining the advantages of Fuzzy and PID controllers to produce optimal control strategies. The "self-tuning parameter fuzzy-PID controller" is portrayed in Fig. 3 as a general construction. Where $r(t)$ denotes the desired location and $y(t)$ denotes the ball's actual position. The fuzzy control's inputs are the error (e) and its change (Δe) and the outputs are the parameter changes (Kp, Ki, Kd). [9] [11]

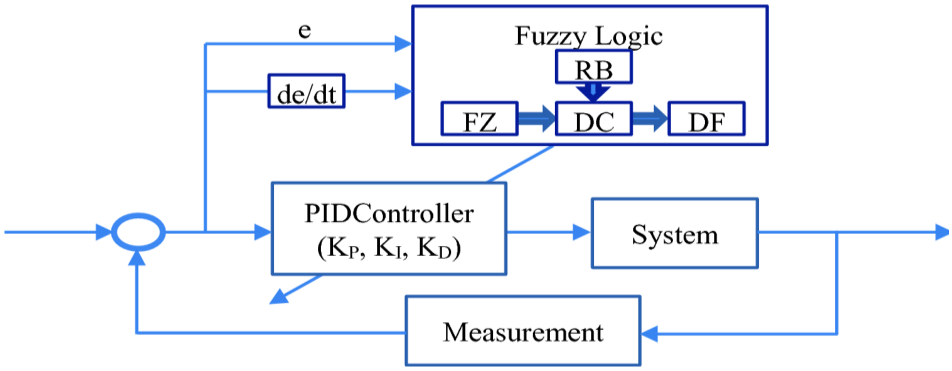

Fig. 3 Basic structure for “Self-Tuning Parameter Fuzzy PID Controller”.

a) Fuzzy PID Controller Design

It is necessary to control the ball position to x_{1ref}, thus if the ball position is at equilibrium to x_{1ref}, the time rate derivative of the ball position $\dot{x}_{1ref}$ is equal to zero, i.e.

$$x_{2ref} = \frac{dx_{1ref}}{dt} = 0 \tag{15}$$

Eqn. (15) is substituted into the velocity dynamics $\dot{x}_2$ (Eqn. (10) returns the value of coil current x_{3ref}:

$$x_{3ref} = x_{1ref}\sqrt{\frac{m\text{g}}{c}} \tag{16}$$

The nonlinear Maglev mathematical model [detailed in detail in the preceding section (Eq. (10)) coordinates are modified in the following manner:

$$\begin{aligned} z_1 &= x_1 - x_{1ref} \\ z_2 &= x_2 \\ z_3 &= x_3 - x_{3ref} \end{aligned} \tag{17}$$

With updated coordinates (Eq. (17)), it is evident that if the optimal controller succeeds in regulating Maglev model to the origin ($z_1 = z_2 = z_3 = 0$), the main objective of managing ball position $x_1 = x_{1ref}$ and the coil current $x_3 = x_{3ref}$ would be attained. Eq. (10) can now be reworked in the following manner: the nonlinear dynamical model:

$$\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\\ \dot{z}_3\end{bmatrix} = \begin{bmatrix} z_2 \\ \text{g} - \frac{c}{m}\left(\frac{z_3+x_{3ref}}{z_1+x_{1ref}}\right)^2 \\ -\frac{R}{L}\left(z_3 + x_{3ref}\right) + \frac{2.c}{L}\left(\frac{z_2.\left(z_3+x_{3ref}\right)}{\left(z_1+x_{1ref}\right)^2}\right) \end{bmatrix} + \begin{bmatrix}0\\0\\ \frac{1}{L}\end{bmatrix}u \tag{18}$$

Using the Jacobian formula, the new shifted coordinates Maglev system (Eq. (18)) may be linearized around the origin in order to regulate the ball's position to the desired position x_{1ref}. $[z_{1o} \quad z_{2o} \quad z_{3o}] = [0 \quad 0 \quad 0]$ is the equilibrium vector. The following formula, using matrices A and B as coefficients, yields the linearized state equations:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 2.\frac{c}{m}.\frac{\left(z_3+x_{3ref}\right)^2}{\left(z_1+x_{1ref}\right)^3} & 0 & -2.\frac{c}{m}.\frac{z_3+x_{3ref}}{\left(z_1+x_{1ref}\right)^2} \\ -4.\frac{c}{L}.\left[\frac{z_2.\left(z_3+x_{3ref}\right)}{\left(z_1+x_{1ref}\right)^3}\right] & 2.\frac{c}{L}.\left[\frac{z_3+x_{3ref}}{\left(z_1+x_{1ref}\right)^2}\right] & -\frac{R}{L} + 2.\frac{c}{L}.\left[\frac{z_2}{\left(z_1+x_{1ref}\right)^2}\right] \end{bmatrix}$$

$$B = \begin{bmatrix}0\\0\\ \frac{1}{L}\end{bmatrix} \tag{19}$$

Where the linearized system dynamics can be expressed as follows (Eq. (19)) using the following coefficient matrices:

$$\dot{x} = Ax + Bu \tag{20}$$

The structure of classical PID control law is taken as follows:

$$u^* = -k_{p1}z_1 - k_{d1}z_2 - k_{i1}\int_0^t z_1 dt - k_{p2}z_3 \tag{21}$$

To specify the performance of the Maglev system's reaction, a purposeful optimal selection of gain values utilizing the Fuzzy-Tuning approach should be made as follows:

i. Let

$$z_4 = \int_0^t z_1\, dt$$

$$\dot{z}_4 = z_1 \tag{22}$$

As a result, the control law (Eqn. (21)) will be as follows:

$$u = -k_{p1}z_1 - k_{d1}z_2 - k_{p2}z_3 - k_{i1}z_4$$

$$u = -kz = \begin{bmatrix} k_{p1} & k_{d1} & k_{p2} & k_{i1} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} \tag{23}$$

ii. It is possible to write the linear MAGLEV system dynamics as follows by augmenting the linearized system dynamics (Eqn. (20)) with Eqn. (22):

$$A_{au} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2.\dfrac{c}{m}.\dfrac{\left(z_3 + x_{3ref}\right)^2}{\left(z_1 + x_{1ref}\right)^3} & 0 & -2.\dfrac{c}{m}.\dfrac{z_3 + x_{3ref}}{\left(z_1 + x_{1ref}\right)^2} & 0 \\ -4.\dfrac{c}{L}.\left[\dfrac{z_2.\left(z_3 + x_{3ref}\right)}{\left(z_1 + x_{1ref}\right)^3}\right] & 2.\dfrac{c}{L}.\left[\dfrac{z_3 + x_{3ref}}{\left(z_1 + x_{1ref}\right)^2}\right] & -\dfrac{R}{L} + 2.\dfrac{c}{L}.\left[\dfrac{z_2}{\left(z_1 + x_{1ref}\right)^2}\right] & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

$$B_{au} = \begin{bmatrix} 0 \\ 0 \\ 1/L \\ 0 \end{bmatrix} \tag{24}$$

iii. Now the selection of the feedback gains $\begin{bmatrix} k_{p1} & k_{d1} & k_{p2} & k_{i1} \end{bmatrix}$, Follow the processes given in Tables 1, 2, 3, and 4, which illustrate the Fuzzy rules for tweaking the PID parameters in the following order: table 1, table 2, and table 3. Fig. 3 illustrates the membership function for the inputs (e *and* Δe) [10]:

Table (1):

Fuzzy rules for k_{p1}.

e	Δe						
	M.H	M.M	M.L	Z.E	A.L	A.M	A.H
M.H	A.H	A.H	A.M	A.M	A.L	A.M	Z.E
M.M	A.H	A.H	A.M	A.L	A.L	Z.E	M.L
M.L	A.M	A.M	A.M	A.L	Z.E	M.L	M.L
Z.E	A.M	A.M	A.L	Z.E	M.L	M.M	M.M
A.L	A.L	A.L	Z.E	M.L	M.L	M.M	M.M
A.M	A.L	Z.E	M.L	M.M	M.M	M.M	M.H
A.H	Z.E	Z.E	M.M	M.M	M.M	M.H	M.H

Table (2):

Fuzzy rules for k_{p2}.

e	Δe						
	M.H	M.M	M.L	Z.E	A.L	A.M	A.H
M.H	A.H	A.H	A.M	A.M	A.L	A.M	Z.E
M.M	A.H	A.H	A.M	A.L	A.L	Z.E	M.L
M.L	A.M	A.M	A.M	A.L	Z.E	M.L	M.L
Z.E	A.M	A.M	A.L	Z.E	M.L	M.M	M.M
A.L	A.L	A.L	Z.E	M.L	M.L	M.M	M.M
A.M	A.L	Z.E	M.L	M.M	M.M	M.M	M.H
A.H	Z.E	Z.E	M.M	M.M	M.M	M.H	M.H

Table (3):

Fuzzy rules for k_{i1}.

e	Δe						
	M.H	M.M	M.L	Z.E	A.L	A.M	A.H
M.H	M.H	M.H	M.M	M.M	M.L	Z.E	Z.E
M.M	M.H	M.H	M.M	M.L	M.L	Z.E	Z.E
M.L	M.H	M.H	M.L	M.L	Z.E	A.L	A.L
Z.E	M.M	M.M	M.L	Z.E	A.L	A.M	A.M
A.L	M.M	M.M	Z.E	A.L	A.L	A.M	A.H
A.M	Z.E	Z.E	A.L	A.L	A.M	A.H	A.H
A.H	Z.E	Z.E	A.L	A.M	A.M	A.H	A.H

Table (4):

Fuzzy rules for k_{d1}.

e	Δe						
	M.H	M.M	M.L	Z.E	A.L	A.M	A.H
M.H	A.L	M.L	M.H	M.H	M.H	M.M	Z.E
M.M	A.L	M.L	M.H	M.M	M.L	M.L	Z.E
M.L	Z.E	M.L	M.M	M.M	M.L	M.L	Z.E
Z.E	Z.E	M.L	M.L	M.L	M.L	M.L	Z.E
A.L	Z.E	Z.E	Z.E	Z.E	Z.E	Z.E	Z.E
A.M	A.H	M.L	A.L	A.L	A.L	A.L	A.H
A.H	A.H	A.M	A.M	A.M	A.L	A.L	A.H

b) Fuzzy-PID Controller Gain Calculation

Table (5) summarizes the system parameters, and the ideal controller design is based on the augmented linearized model (Eqn. (24) to get the best performance.

Table (5):

Physical Parameters of Magnetic Levitation System

Parameter	Value	Unit
m	0.05	kg
g	9.81	m/s^2
R	1.0	Ohms (Ω)
L	0.01	H
c	---	0.0001
x_{1ref}	0.6	m
x_{2ref}	0.0	m/s

In this case, we will assume that the desired ball position is $x_{1ref} = 0.6m$, and the augmented linearized model (Eqn. (24)) will be obtained after substituting the system parameters, the desired ball position x_{1ref} and the desired velocity x_{2ref}, and the equilibrium vector $[z_{1o} \quad z_{2o} \quad z_{3o}] = [0 \quad 0 \quad 0]$, the model will be:

$$A_{au} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1635 & 0 & -23.345 & 0 \\ 0 & 116.7262 & -100 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

$$B_{au} = \begin{bmatrix} 0 \\ 0 \\ 100 \\ 0 \end{bmatrix} \qquad (25)$$

It is determined whether or not the augmented system is stable by calculating the Eigen values of the system matrix A_{au}, which results in the following results:

$$eig(A_{au}) = [0 \quad -65.6864 + 29.9471i \quad -65.6864 - 29.9471i \quad 31.3728] \qquad (26)$$

The augmented system is unstable, as shown by the presence of a positive Eigen value, and hence the proposed optimal controller should be built to stabilize the system. Now, before calculating the optimal PID gain, it is necessary to evaluate the linearized model's controllability (Eq. (25), which is readily accomplished by computing the controllability matrix and determining its rank. The controllability matrix S is found to be:

$$S = \begin{bmatrix} 0 & 0 & -2334.5235 & 233452.3506 \\ 0 & -2334.5235 & 233452.3506 & -20800604.4383 \\ 100 & -10000 & 727500 & -45500000 \\ 0 & 0 & 0 & -2334.5235 \end{bmatrix} \quad (27)$$

The controllability matrix above has a full rank, which suggests that we may proceed with the controller design process. The second stage is to calculate the gains of controllers using the Fuzzy-PID method:

$$K = \begin{bmatrix} k_{p1} & k_{d1} & k_{p2} & k_{i1} \end{bmatrix} = \\ \begin{bmatrix} -1381359.567 & -35862.8766 & 9890.2456 & -9678.87 \end{bmatrix} \quad (28)$$

So the Eigen values of the closed-loop system $(A_{au} - B_{au}K)$ can be calculated to be:

$$eig(A_{au} - B_{au}K) = \begin{bmatrix} -989039.91 & -55.22480 & -29.41109 & -0.014065 \end{bmatrix} \quad (29)$$

It should be noted that all of the Eigen values are negative, indicating that the developed controller is capable of stabilizing the Maglev system and replacing the unstable Eigen values.

4. Simulation implementation

A Fuzzy PID Controller tuning was proposed in the previous sections to test the proposed tuning. Matlab/Simulink is used to simulate the best PID controller for the Maglev system. Fig. (4) depicts the Maglev system's Simulink model. Nonlinear system model of the Maglev (Eq. (10), which is a foundation for building a Maglev Simulink model, uses the optimal PID control law Eq. (25).

Fig. (7) depicts the effect of applying Fuzzy logic to the three PID parameters.

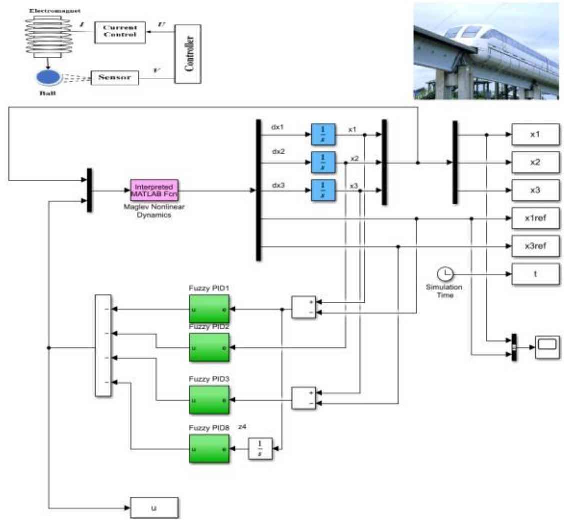

Fig.4 Matlab/Simulink Model of Maglev System with Optimal PID Controller.

Fig. (5), show the simulation results of time history of ball position x_1, it is obvious that the optimal PID controller succeed to bring the ball position from its initial position (0.2 mm) to its desired position (0.6) with no more than (0.2 sec) with a smooth exponential behavior. Fig. (6) demonstrates the behavior of ball velocity x_2, where the ball is suspended with zero velocity in less than (0.2 sec).

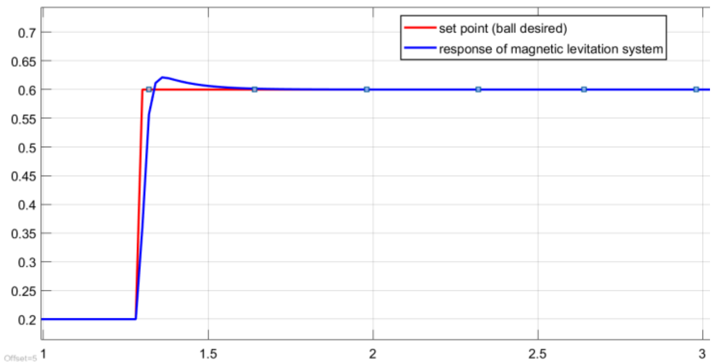

Fig.5 Simulation Results of Ball's Position x_1.

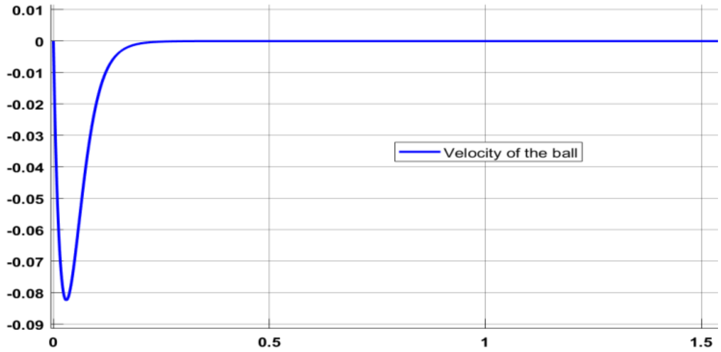

Fig.6 Simulation Results of Ball’s Velocity x_2.

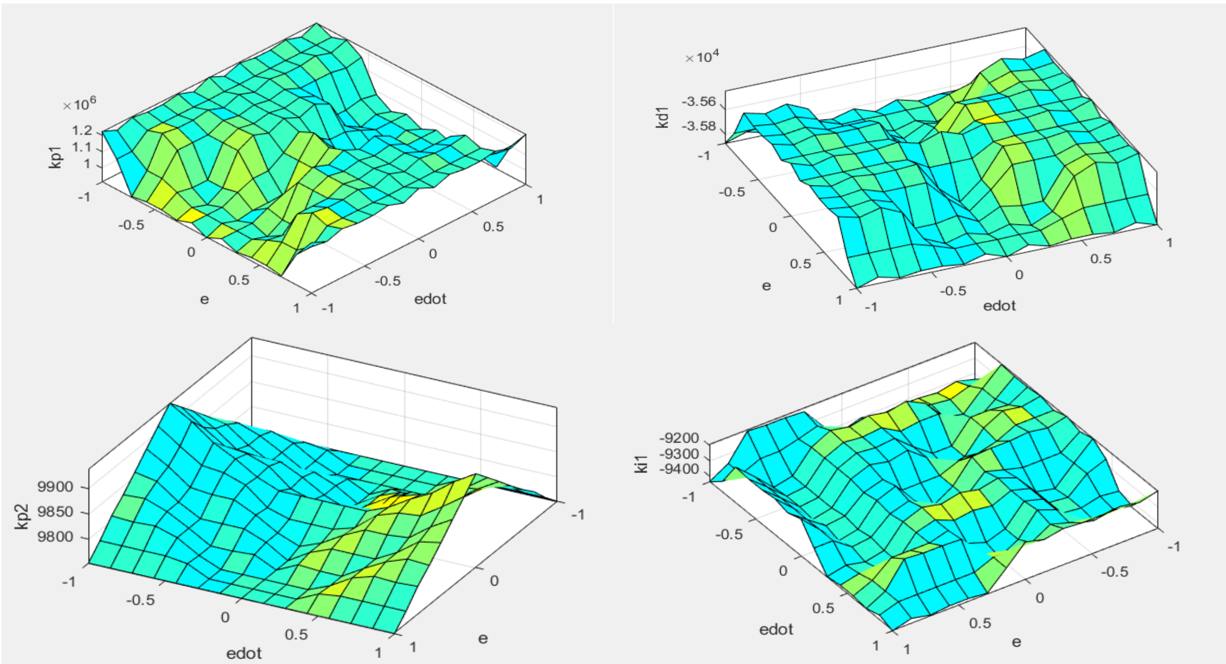

Fig.7. $\Delta Kp1, \Delta Kd1, \Delta Kp2, \Delta Ki1$ Response curve

5. Real time platform and implementation

In this section, the results of experiments and simulations is showed that were done using the methods from the previous section and the platform system design proposed educational laboratory stand. Fig. (8) shows the hardware-controlled unit parts interface. Simulink's real-time control feature for microcontrollers (Arduino) was used and depicts real-time operating environment with object.

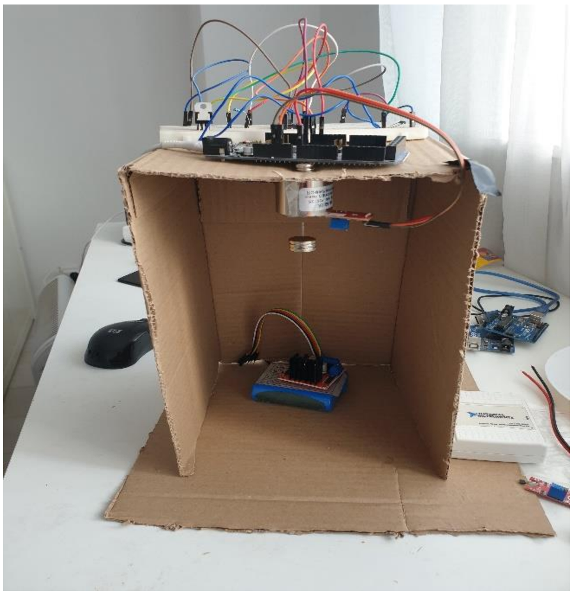

Fig.8 Proposed educational Laboratory Stand of MAGLEV

Fig. (9) depicts the total system architecture, which includes the data acquisition hardware Hall effect 49E sensor, electromagnetic coils, Arduino Due, and real-time operating environment.

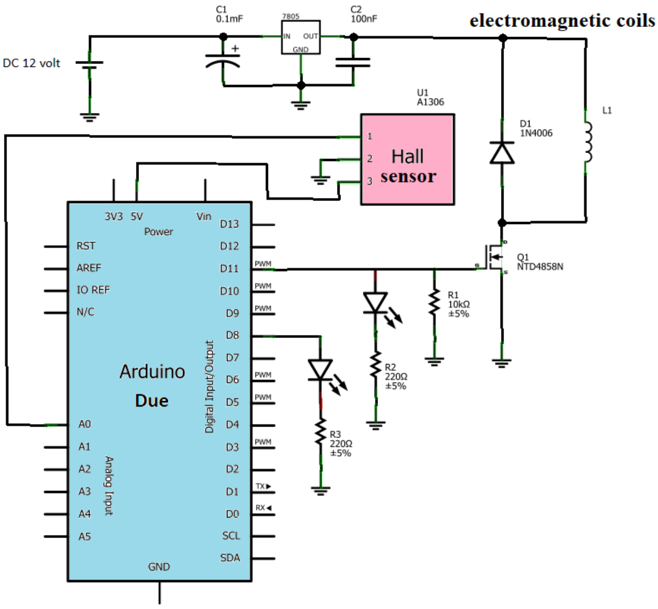

Fig.9 The Block diagram of the proposed MAGLEV system

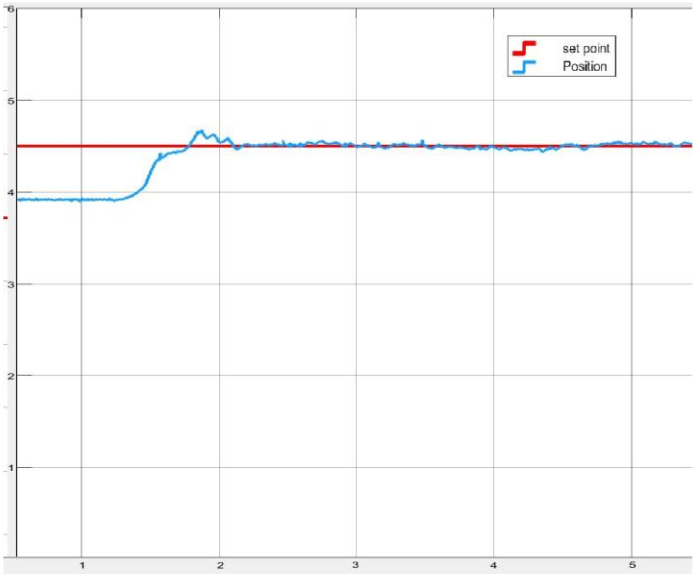

Fig.10 The response of System with tuned coefficients

The suggested platform has 10 kHz sampling rates and is flexible, complete, and inexpensive. Moreover, (the proposed platform) is fully integrated with MATLAB and Simulink. Arduino Due is used because has 96 Kbytes of SRAM and this point is very important to work with big data and blocks in Matlab-Simulink. Fig. (10) depicts the output controlled with the target.

6. Conclusion

The following findings can be drawn from the research:

1. A magnetic-levitation (maglev) system is the subject of this paper. Experimentation and computer simulations have both confirmed the effectiveness of the maglev transportation system's control strategy.
2. After linearizing around the operational point, the system is determined to be unstable using the nonlinear model of the Magnetic levitation system for the ball suspension problem.
3. Achieve desired ball location, ball velocity, and coil current by stabilizing the Maglev system. After the user sets the desired ball position, the desired ball velocity and coil current can be determined using the Maglev nonlinear mathematical model.
4. 3. The best PID controller structure is Eq. (21), where the integral control for the first objective (control the ball location) is deliberately introduced as a fake

state. With the maglev-shifted dynamics, this dummy state becomes a four state augmented system.

5. The augmented system is next subjected to the Fuzzy-PID Tuning technique in order to determine the appropriate controller gain values.
6. The simulation results show that the recommended controller can stabilize the Maglev system and replace unwanted Eigen values with good Eigen values.
7. The PID-Fuzzy control law was tested in a Matlab simulation by running regulation and tracking experiments. with the same PID-Fuzzy controller was done with the real-time platform system. The results of the experiments show that this method is very good with strong response and stable.

Smooth and exponential convergence of system variables (ball position, ball velocity, and coil's current) to their desired levels.

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