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Modelling and Control of a Magnetic Levitation System

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Abstract— Magnetic Levitation Systems (MLS), or Maglev for short, utilise magnetic fields to levitate objects. They find applications in various scientific fields, particularly transportation, materials science, and biomedical engineering. Due to the diverse applications, different modelling and control approaches are necessary. The operation of each Maglev system depends on specific physical parameters. These key variables include the weight of the object being levitated, the current supplied to the system, the internal resistance and inductance of the electromagnet, and the distance between the object and the electromagnet. This research aims to understand the working principles of MLS. We will design and simulate a model based on real MLS hardware using MATLAB & Simulink. Additionally, we will create a functional Maglev prototype and program its control system using Arduino IDE and an Arduino microcontroller. MATLAB & Simulink offer a powerful tool for creating behavioral models for MLS. This model will then be integrated with Arduino programming to control the Maglev prototype.

Keywords: Magnetic Levitation System, Modelling and Control, PID, Arduino IDE

1. INTRODUCTION

The Maglev system, or MLS, is an electromechanical system that allows an object to be suspended in free space without any physical support. [1]. Magnetic levitation is a well-known type of system with numerous uses. Magnetic suspension technology is becoming increasingly popular because of its contactless, low-noise, and low-friction properties. [2]. Modelling the Maglev system is difficult since An open-loop unstable system with quick dynamics needs to be dealt with in addition to nonlinearities and a low natural damping degree. [3].

MLS comprises a suspended object or plant, a position sensor, an actuator, a power amplifier, a controller, and other components [1]Wrapping an electrically conductive wire around a high-permeability iron core forms an electromagnet. The actuator produces a magnetic field when an electrical current is delivered through the wires.

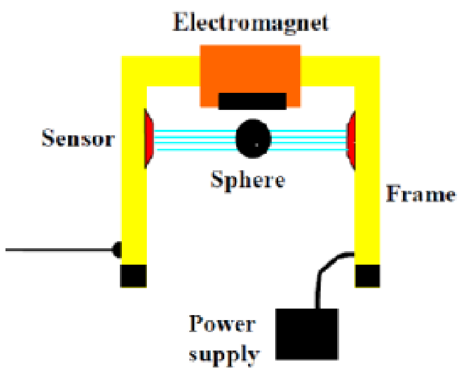

Fig. 1: Magnetic Levitation System [4]

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Any magnetic item put underneath this magnetic field experiences an upward attracting force. The suspended object is placed between the electromagnet and the sensor beneath the ferromagnetic ball. The ferromagnetic ball is moved by two forces: the gravity field and the electromagnetic force "Fem" produced by the magnetic field of the coil. [4].

2. METHODOLOGY

2.1 Modelling of the Magnetic Levitation System

In electromechanical dynamics modelling, Kirchhoff's voltage law can be used to achieve the electromagnetic force produced by a current within the coil. [5].

$$V(t) = V_R + V_L = R_i + \frac{d[L(x)i]}{dt} \tag{1}$$

V is the applied input voltage, i is the current in the coil, and R is the coil's resistance [5].

Newton's third Law of motion while ignoring the damping force & friction force of air, the total force acting on the coil is given as;

$$CapF_{acc} = F_{gravity} - F_{em} \tag{2}$$

$$m\ddot{x} = mg - k\,\frac{\ddot{\imath}^2}{x^2} \tag{3}$$

Mathematical modelling combines both mechanical and electromagnetic dynamic modelling. It is possible to define MLS in terms of the Equation below for this model, which is explained in [6].

$$\frac{dx}{dt} = V \tag{4}$$

$$e = R_i + \frac{d[L(x)i]}{dt} \tag{5}$$

$$m\frac{d^2x}{dt^2} = mg - c\,\frac{\ddot{\imath}^2}{x^2} \tag{6}$$

$$u = iR + L\frac{di}{dt} - c\left(\frac{1}{x}\right)^2\frac{dx}{dt} \tag{7}$$

Where v is the suspended ball's velocity, x is its position, m is its mass, c is the magnetic force constant, g is the gravitational constant, L and R are the coil's inductance and resistance, i is the current in the electromagnetic coil, and u is the system's applied voltage [6].

Taking $x = x_1$, $v = x_2$ and $I = x_3$ from the Equation above, the vector form of the mathematical model can be defined as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} x_2 \\ g - \frac{C}{m}\left\{\frac{x_3}{x_1}\right\}^2 \\ -\frac{R}{L}x_3 + \frac{2C}{L}\left\{\frac{x_2 x_3}{x_1^2}\right\} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} \tag{8}$$

$$y = [x_1 \;\; x_2 \;\; x_3]^T = [1 \;\; 0 \;\; 0] \tag{9}$$

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

At equilibrium, the rate of x with respect to time must be equal to zero ($x_{02} = 0$), and the equilibrium current must satisfy the following condition:

$$x_{03} = x_{01}\sqrt{\frac{gm}{c}} \tag{11}$$

Using all equations from above can form a linearized model, given as this state-space modelling;

$$A = \begin{bmatrix} 0 & 1 & 0 \\ Cx_{03}^2 & 0 & -2\frac{Cx_{03}}{mx_{01}^2} \\ 0 & 2\frac{Cx_{03}}{Lx_{01}^2} & -\frac{R}{L} \end{bmatrix} ;\ B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} ;\ C = [1 \quad 0 \quad 0]\ ; D = [0] \tag{12}$$

Replacing the values with the Equation above will give:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{g}{x_{01}} & 0 & -\frac{2}{x_{01}}\sqrt{\frac{gc}{m}} \\ 0 & \frac{2}{L}\sqrt{gmc} & -\frac{R}{L} \end{bmatrix} ; B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} ; C = [1 \quad 0 \quad 0]\ ; D = [0] \tag{13}$$

Table 1: The parameters of the proposed MLS

Parameter	Value	Unit
m (mass)	0.0185	kg
g (gravitational acceleration)	9.8	m/s^2
R (internal resistance)	18.2	Ohm
L (inductance)	58.1m	H
c (magnetic force constant)	0.000058	-
y (ball position)	0.012	m
x_{02} (velocity of the ball) (System is linear if this is equal to 0)	0.0	m/s
i (current)	0.67	A

The physical parameters of the proposed magnetic MLS are presented in Table 1:
From the parameters acquired from the system, a state space model can be calculated based on Equation (13):

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 816.67 & 0 & -29.21 \\ 0 & 0.111 & 313.25 \end{bmatrix} ;\ B = \begin{bmatrix} 0 \\ 0 \\ 17.21 \end{bmatrix} ;\ C = [1 \quad 0 \quad 0] \ ;\ D = [0] \tag{14}$$

The transfer function obtained from the space state model is:

$$T(s) = \frac{-502.7}{s^3 + 313.2s^2 - 813.4s - 255800} \tag{15}$$

2.2 *Model-Based Design in MATLAB/Simulink*

A proportional-integral-derivative controller (PID controller) is also included in the block diagram to ensure the stability of a closed-loop control system. For this project, the PID controller is used to regulate the output voltage for the electromagnet to levitate the magnet positioned under the sensor and the electromagnet. A PID controller continuously calculates an error value $e(t)$ as the difference between a desired setpoint and a measured process variable and applies a correction based on proportional, integral and derivative terms (denoted K_p, K_i and K_d , respectively). The overall control function of the PID controller is expressed as:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)d\tau + K_d \frac{d}{dt} e(t) \tag{16}$$

Based on the transfer function from Equation (15), a Simulink block diagram of the MLS has been created, as shown in Fig. 2:

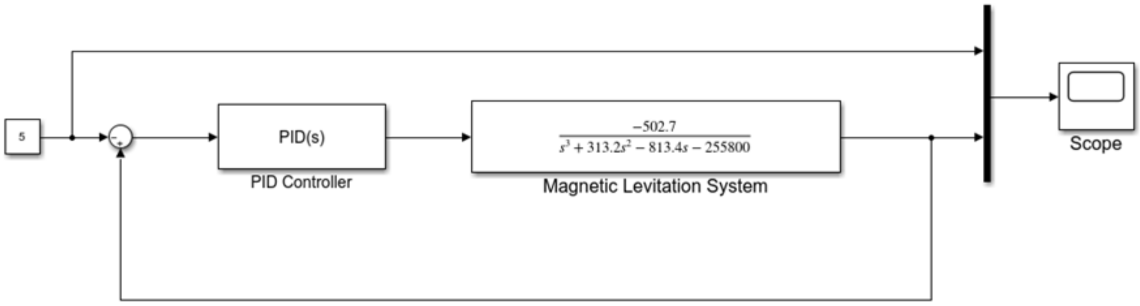

Fig. 2: Simulink block diagram of the MLS

2.3 Prototype Circuit Design

A 12V power supply is connected to the circuit to power up the magnetic levitation system. In contrast, the Arduino Mega can be powered up via the USB port while connected to a computer. The actuator consists of an electromagnet, a 1kΩ resistor, a diode and an NPN transistor. The transistor base is connected to the PWM digital pin, which acts as a switch to regulate and control the output current and voltage of the electromagnet. The Hall effect sensor is powered by a 5V pin and GND pin, while the OUT pin of the sensor is connected to an analogue pin of the Arduino Mega. The Arduino is programmed to increase the voltage when the neodymium magnet is far from the detection range, reduce the voltage when the magnet is too close, and levitate the magnet at a set point.

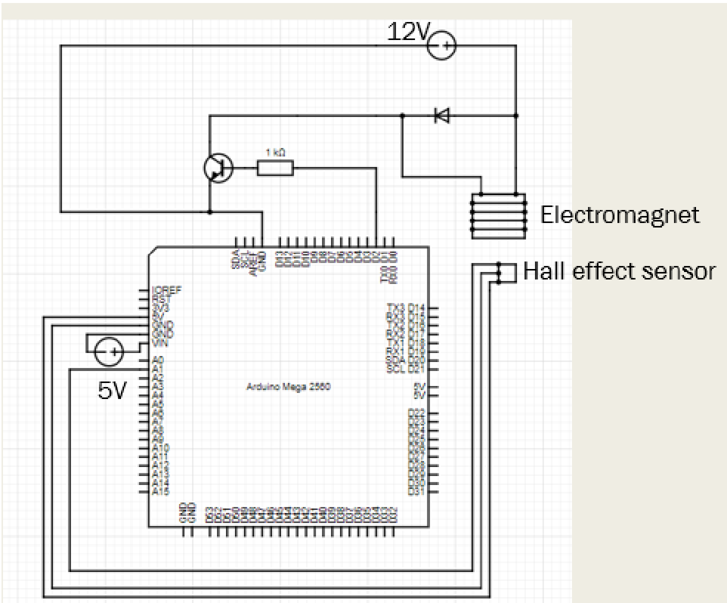

Fig. 3: Schematic diagram of the proposed circuit

3. RESULTS AND DISCUSSIONS

Fig. 4 shows the photograph of the experiment setup. The setup consists of a stand, which holds the electromagnet. A Hall effect sensor is attached about 5mm under the iron core of the electromagnet by placing a separator-like cardboard between the sensor and the electromagnet to reduce the influence of the magnetic field from the electromagnet. The electromagnet is connected to a breadboard, which houses the system circuitry. In contrast, the sensor is connected to Arduino Mega 2560, which returns magnetic field strength input to the Arduino. The circuit is connected to a 12V DC power supply. This magnetic levitation system prototype will be used in the experiment to test the PID gains acquired from the simulation in the Simulink block diagram.

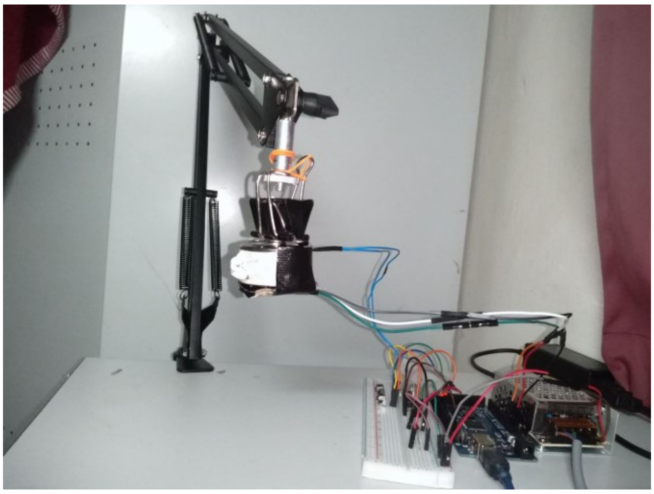

Fig. 4: Photograph of the experimental setup

3.1 Simulation Result

Firstly, the experiment starts with determining PID gains by simulating the block diagram from Fig. 2 in Simulink to generate a signal of the unit step response of the system. This was done using the PID Tuner App in Simulink to help the PID tuning process of a system much faster. The PID Tuner App automatically fills PID gains into the PID controller block parameter. The simulation is rerun to see the result:

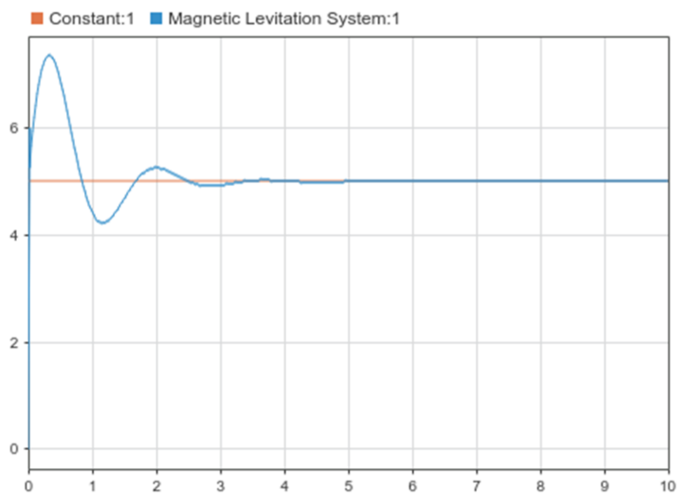

Fig. 5: Simulation result of the block diagram simulation

Based on the result above, when the values $P = 995.5$, $I = 2825.5$ and $D = 183.9$ are set into the PID controller, the system in the simulation becomes stable after passing its settling time at 2.5 seconds. To further test whether the PID gains generated by the Simulink software are entirely applicable to the real-life system, the PID gains are used in the source code for the Arduino Mega and uploaded into the controller with $K_p = 995.5, K_i = 2825.5$ and $K_d = 183.9$.

3.2 Arduino Serial Plotter Result

While testing the three values of PID gains into the Arduino Mega, the serial plotter from the Arduino IDE shows that the PID value increases way too much when the magnet is away from the sensor and decreases way too much when the magnet is close to the sensor, making it very hard for the system to stabilize. It shows that the PID gains are too high for the magnetic levitation system prototype. With high gains of PID, the increase and decrease of setpoints become harder to control, as shown in Fig. 6.

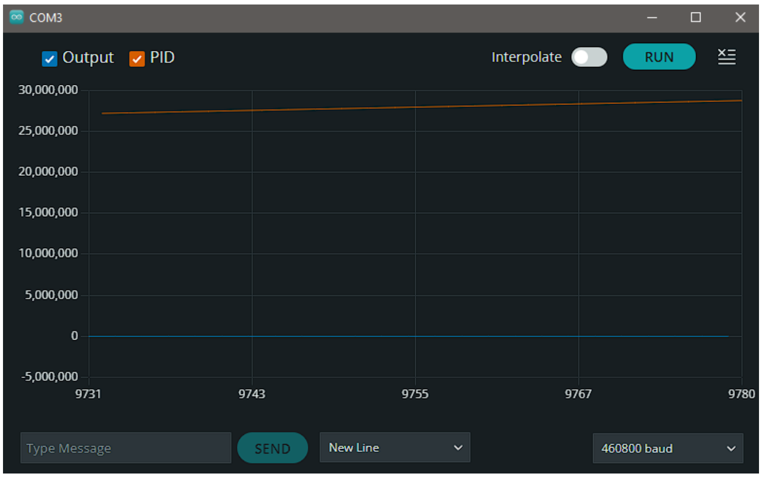

Fig. 6: Arduino serial plotter showing a very high gain in PID control function

To solve this issue, all the PID gains are reduced with a trial-and-error method to slow down its increase and decrease. The gains firstly are reduced by 10, followed by 100 and lastly 1000.

Fig. 7: PID control function after the PID gains are reduced by a factor of 10

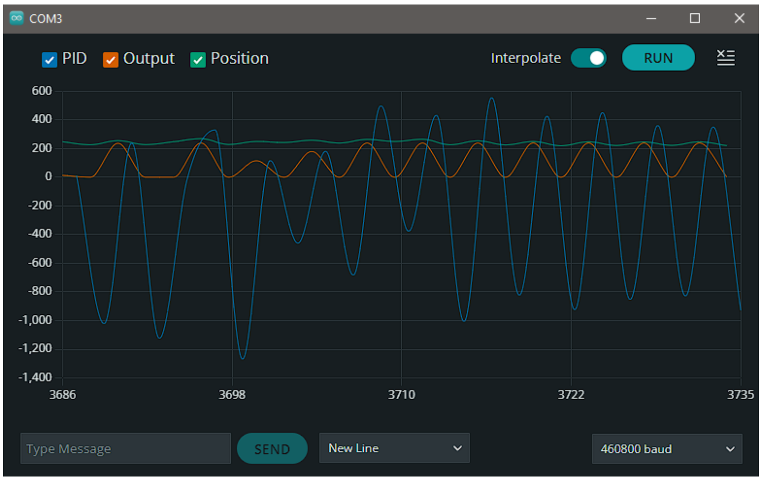

Fig. 8: PID control function after the PID gains are reduced by a factor of 100

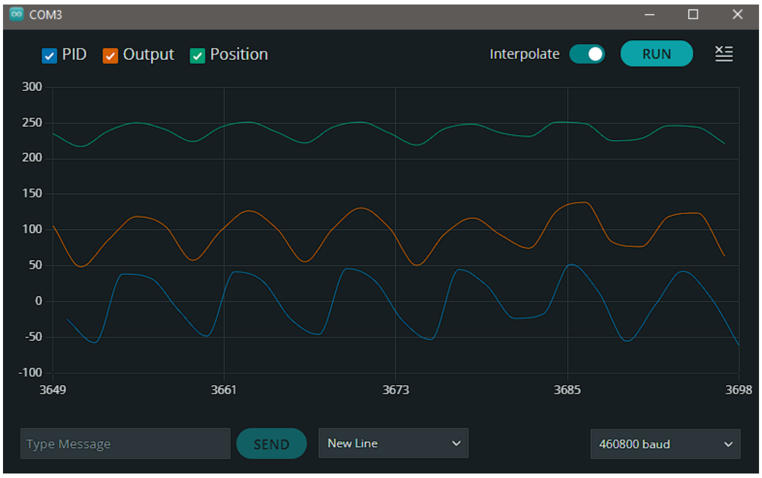

Fig. 9: PID control function after the PID gains are reduced by a factor of 1000

After the new PID gains, $K_p = 0.9955, K_i = 2.8255$ and $K_d = 0.1839$ are verified and uploaded into the Arduino, the Hall effect sensor measures an almost stable position of the permanent magnet.

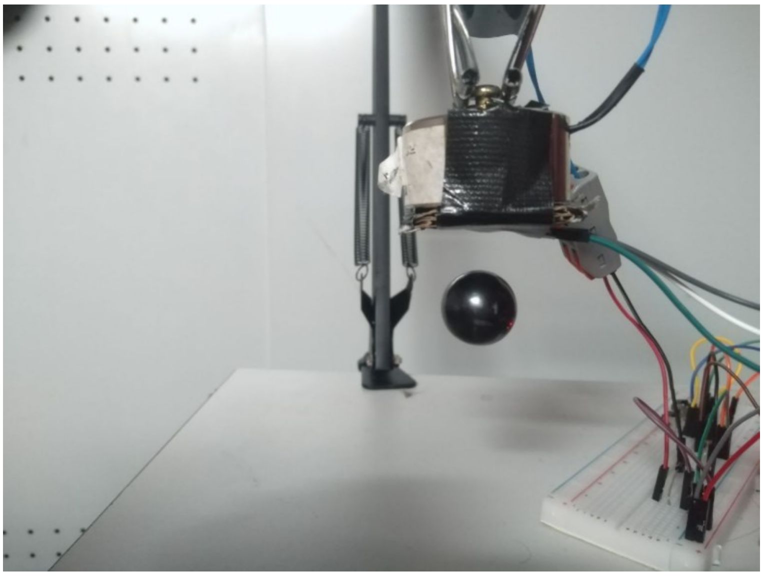

Fig. 10: MLS system with levitated ball magnet

4. CONCLUSION

This paper explores modelling a Magnetic Levitation System (MLS) through block diagram simulation in MATLAB/Simulink and controlling a real MLS using a digital PID controller implemented on an Arduino Mega. A simplified mathematical model was developed for the real system by measuring and identifying its components and hardware parameters. The project aimed to apply Proportional-Integral-Derivative (PID) control theory and program it into a functional, real-world prototype. After reducing the PID gains by 1000, the system achieved significant stabilization, resulting in the final gains of $K_p = 0.9955$, $K_i = 2.8255$, and $K_d = 0.1839$. However, minor oscillations were observed in the system due to external factors like the electromagnet overheating over time. Further finetuning of the PID gains may be necessary to minimize these oscillations.

REFERENCES

[1] A. Abbas *et al.*, "Design and Control of Magnetic Levitation System," *1st Int. Conf. Electr. Commun. Comput. Eng. ICECCE 2019*, no. July, pp. 24–25, 2019.

[2] S. M. R Rasid, M. B. Hossain, M. E. Hoque, M. A. A. Arif, and M. S. Ali Sarder, "Modeling and controlling a magnetic levitation system using an analogue controller," *Acta Electron. Malaysia*, vol. 3, no. 2, pp. 41–44, 2019.

[3] P. Balko and D. Rosinova, "Modeling of magnetic levitation system," *Proc. 2017 21st Int. Conf. Process Control. PC 2017*, pp. 252–257, 2017.

[4] J. de Jesús Rubio, L. Zhang, E. Lughofer, P. Cruz, A. Alsaedi, and T. Hayat, "Modeling and control with neural networks for a magnetic levitation system," *Neurocomputing*, vol. 227, pp. 113–121, 2017.

[5] M. J. Khan, M. Junaid, S. Bilal, S. J. Siddiqi, and H. A. Khan, "Modelling, Simulation & Control of Non-Linear Magnetic Levitation System," 2018.

[6] I. Ahmad, M. Shahzad, and P. Palensky, "Optimal PID control of Magnetic Levitation System using Genetic Algorithm," *Energycon 2014 - IEEE Int. Energy Conf.*, pp. 1429–1433, 2014.