UNIVERSITY OF GREENWICH

2023-2024

PORTFOLIO

MAGNETIC LEVITATION

Cristhian Michael Quezada Riofrio

UNIVERSITY OF GREENWICH

cristhian.michael24@gmail.com

TABLE OF CONTEXT

1 LOGBOOK OF MEETINGS

Appendix A: Log of Meetings

Note: You are required to attend a **minimum of 10 meetings** with you supervisor (ONLINE and/or PHYSICAL). Please get your supervisor to sign this document for every date you meet. This will be submitted as part of your project portfolio document.

S/No.	Meeting Date	Supervisor Signature	Supervisor Comments
1	6/10/23		#1 Meeting
2	20/10/23		Good progress
3	10/11/23		Good progress
4	8/12/23		Good progress
5	26/1/24		Good progress
6	23/2/24		〃 〃
7	21/3/24		Great work
8	28/3/24		Report Stage
9	5/4/24		Good Report
10			

2 PUBLICATION PORTFOLIO

2.1 First Journal Paper

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received January 6, 2020, accepted January 24, 2020, date of publication February 4, 2020, date of current version March 3, 2020.
Digital Object Identifier 10.1109/ACCESS.2020.2971631

Design and Real-Time Implementation of Takagi–Sugeno Fuzzy Controller for Magnetic Levitation Ball System

JINGGANG ZHANG, XINYUAN WANG, AND XUEJUAN SHAO
Department of Automation, Taiyuan University of Science and Technology, Taiyuan 030024, China
Corresponding author: Jinggang Zhang (jg_zhang65@163.com)

This work was supported in part by the Basic Research Project of Shanxi Province under Grant No.201901D111263, and in part by the Shanxi Postgraduate Education Reform Project under Grant No.2019JG165.

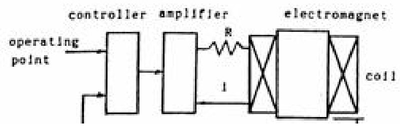
2.2 Second Journal Paper

196 IEEE TRANSACTIONS ON EDUCATION, VOL. E-29, NO. 4, NOVEMBER 1986

Design of a Magnetic Levitation Control System—An Undergraduate Project

T. H. WONG

***Abstract*—A magnetic levitation control system is built as a classroom demonstration device for systems and control courses. System linearization and phase-lead compensation techniques are used to control the unstable nonlinear system.**



2.3 Third Journal Paper

2016 International Conference on Cogeneration, Small Power Plants and District Energy (ICUE 2016)
BITEC, Bang-Na, Thailand, 14-16 September 2016

PID, Fuzzy and LQR Controllers for Magnetic Levitation System

[1,*]Arjun C. Unni, [2]A.S. Junghare, [3]Vivek Mohan, [4]Weerakorn Ongsakul
[1,4] Energy FoS, SERD, Asian Institute of Technology, Pathumthani, Thailand – 12120.
[2]Department of Electrical & Electronics Engineering, Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India - 440010
[3]Department of Electrical and Electronics Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India – 641112

2.4 Fourth Journal Paper

2018 IEEE 4th International Symposium on Robotics and Manufacturing Automation (ROMA)

PID Controller design for a Magnetic Levitation system

M.K.A.Ahamed Khan[1*],Shahid Manzoor[1],H. Marais[2],Ms Kalaiselvi Aramugam[3],I.Elamvazuthi[4],S.Parasuraman[5]

[1,3]Faculty of Engineering, Technology & Built Environment, UCSI University, 56000, Malaysia, Kuala Lumpur, Malaysia,
[2]Department of Electronics and Digital Technologies, École Polytechnique de l'université de Nantes, France,
[4]Department of Electrical and Electronics Engineering, University Technology PETRONAS,
[5]School of Engineering, Monash University, Malaysia
[1*]Email : mohamedkhan@ucsiuniversity.edu.my[Corresponding Author]

2.5 Fifth Journal Paper

MAGNETIC LEVITATION SYSTEM: CONTROL AND DESIGN

Author: Sánchez Bas, Pedro
Director: Juan Luis Zamora Macho
Entity: ICAI – Comillas Pontifical University

2.6 Sixth Journal Paper

IEEE TRANSACTIONS ON EDUCATION, VOL. 47, NO. 2, MAY 2004 165

PWM Control of a Magnetic Suspension System

William Gerard Hurley, *Senior Member, IEEE*, Martin Hynes, and Werner Hugo Wölfle

2.7 Seventh Journal Paper

Proceedings of IMECE2005
2005 ASME International Mechanical Engineering Congress and Exposition
November 5-11, 2005, Orlando, Florida USA

IMECE2005-81600

ANALOG AND LABVIEW-BASED CONTROL OF A MAGLEV SYSTEM WITH NI-ELVIS

R. SINHA
Cooling Design Center - Large Power Systems Division,
Caterpillar Inc., Mossville, IL 61552, USA
sinha_rishabh@cat.com

M.L. NAGURKA
Department of Mechanical & Industrial Engineering,
Marquette University, Milwaukee, WI 53201, USA
mark.nagurka@marquette.edu

3 PROJECT OUTPUTS

3.1 Sketches

The initial sketches are shown in the following illustrations. Three different methods for achieving levitation are shown in Figure 1, taking account for different factors. For this project, the attracting levitation method was judged to be the most beneficial of these. The material qualities seen during the preliminary testing were the main factor in this decision. The object exhibited attraction only towards the solenoid, with no signs of repulsion. Consequently, the initial design was chosen for implementation.

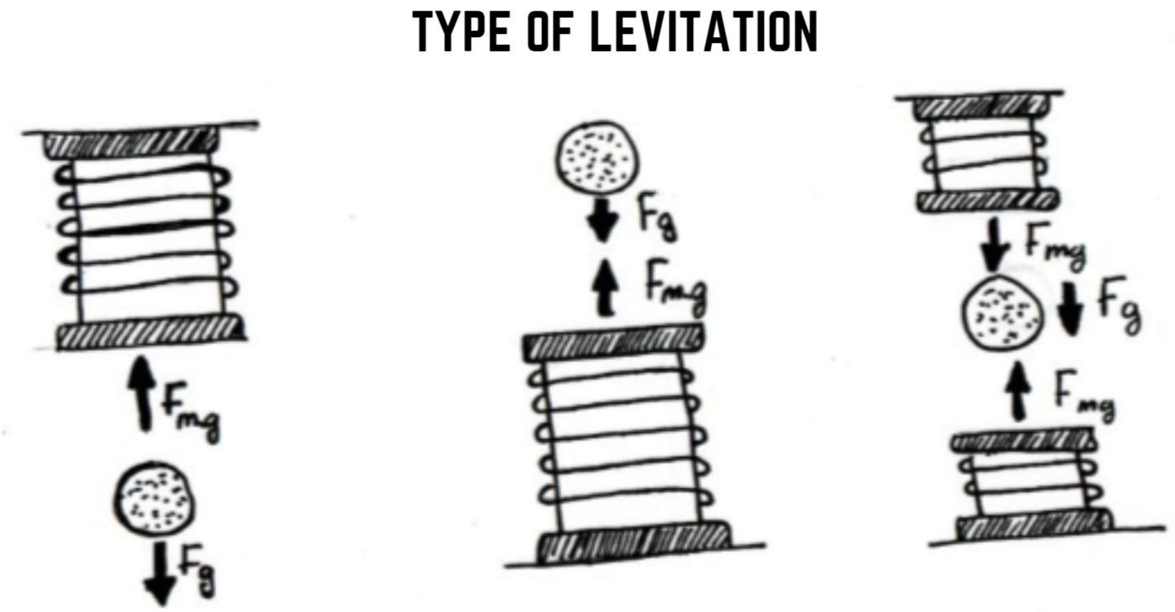


Figure 1: Type of levitation sketches.

Figure 2 illustrates the initial design for the machine structure. In this project, option two was preferred over option one. The reasoning for this choice is that the second structure allows for the incorporation of crystal or clear plastic materials. This inclusion helps to reduce any external disturbances caused by air, improving the system's overall stability.

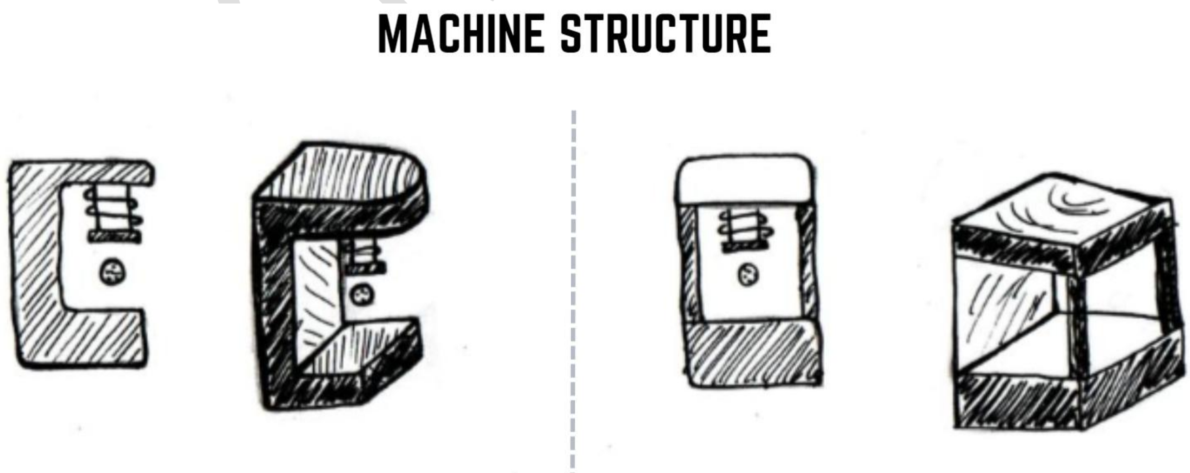


Figure 2: Machine structure sketches.

3.2 Flow Chart

The images below depict the flow charts used in the programming aspect of the project. Figure 3 depicts the algorithm used to control the desired levitation distance based on the button press.

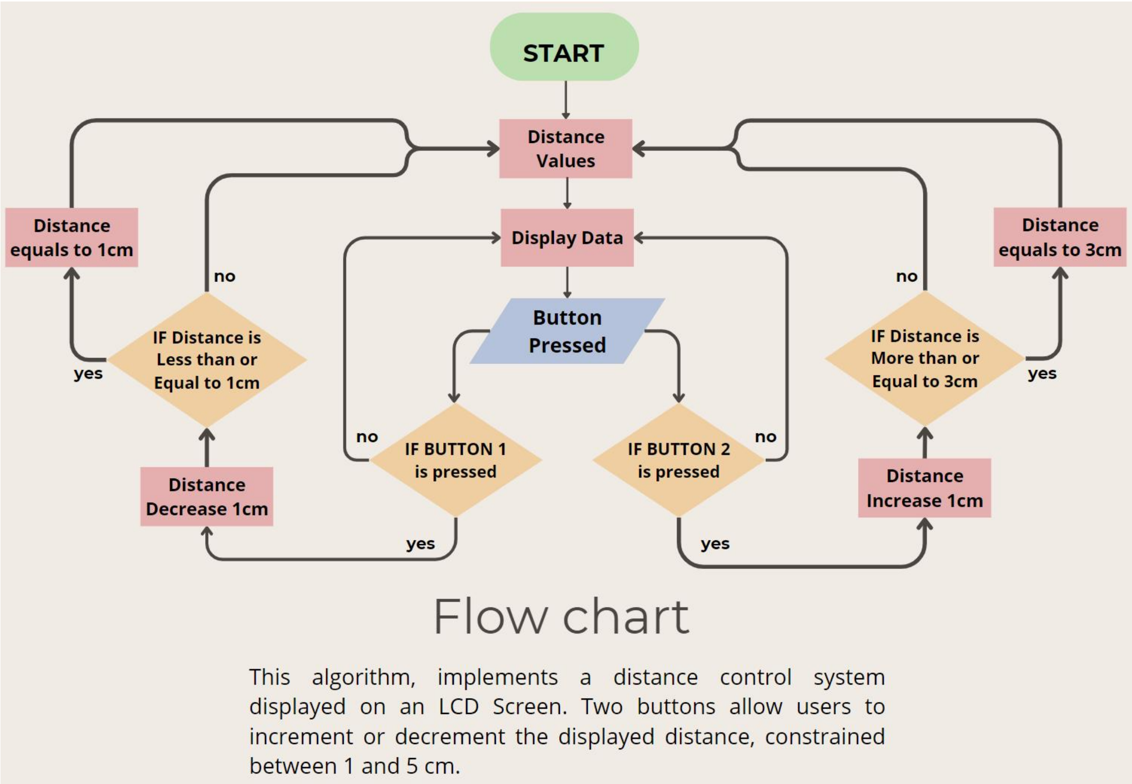


Figure 3: Distance desired algorithm.

Figure 4 illustrates the algorithm used to manage the LCD screen, which varies based on whether the sensor detects changes in the distance between the object and the solenoid.

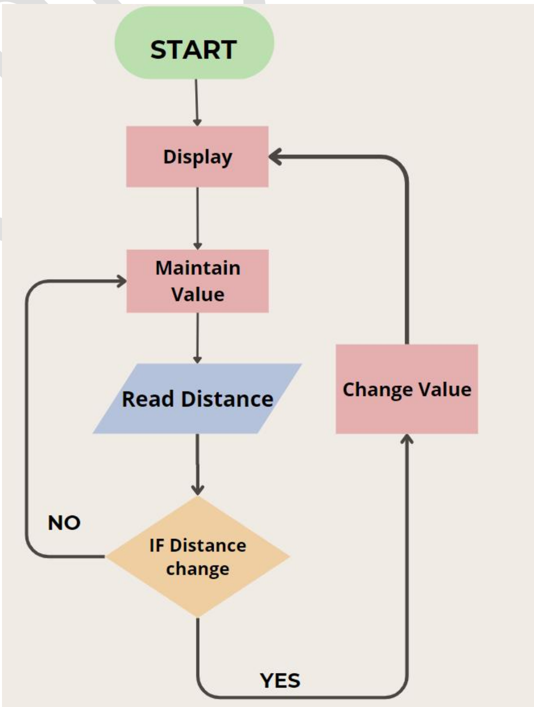


Figure 4: LCD algorithm.

Figure 5 illustrates the algorithm used to regulate the PWM signal that controls the solenoid, which is adjusted based on sensor data.

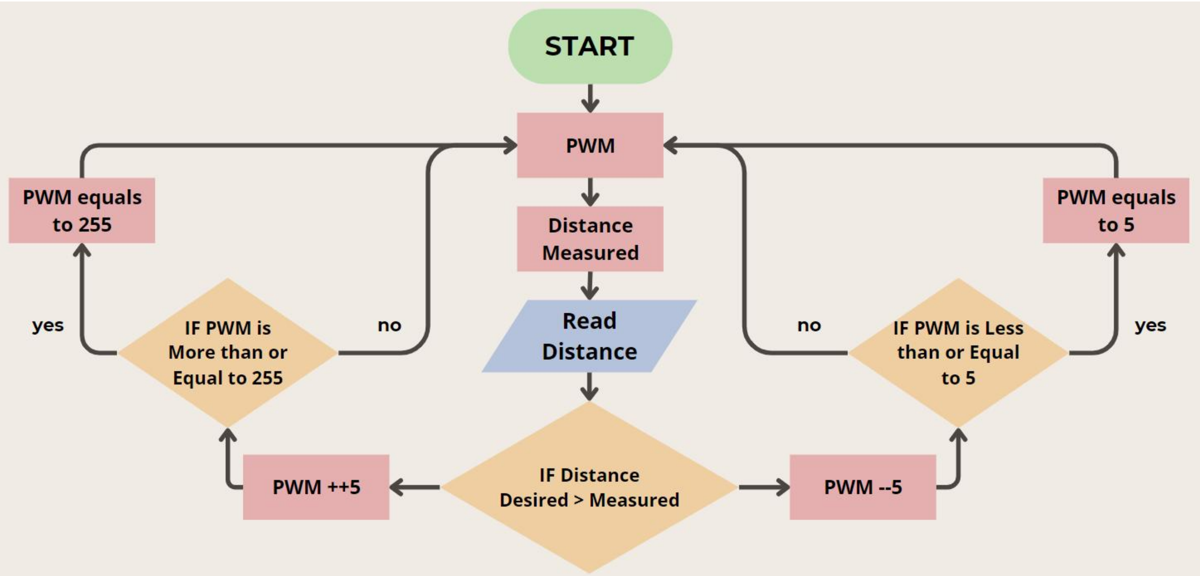


Figure 5: PWM algorithm.

3.3 Prototype

The following images show the dimensions of the various components used in this project. Figure 6 shows the dimensions of the solenoid structure.

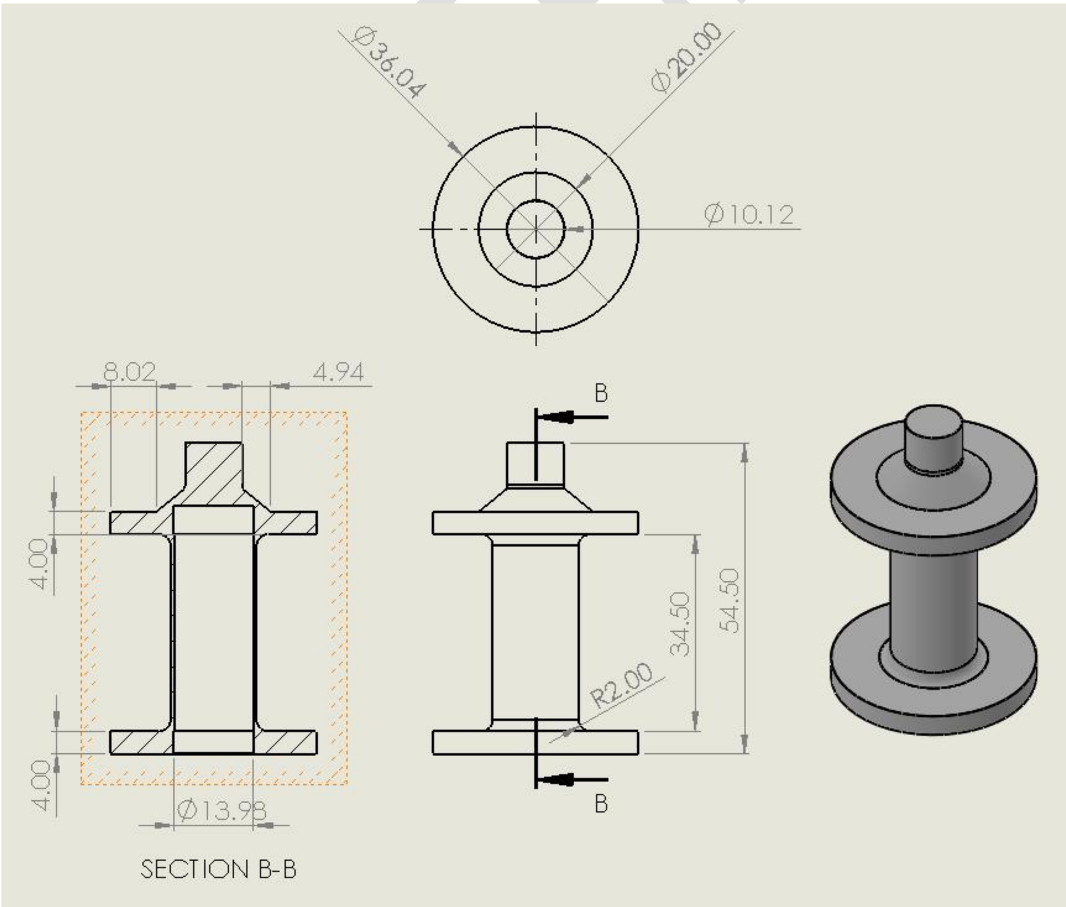


Figure 6: Solenoid's structure.

Figure 7 represents the structure that houses the LCD screen, as well as the buttons that allow users to control distance adjustments.

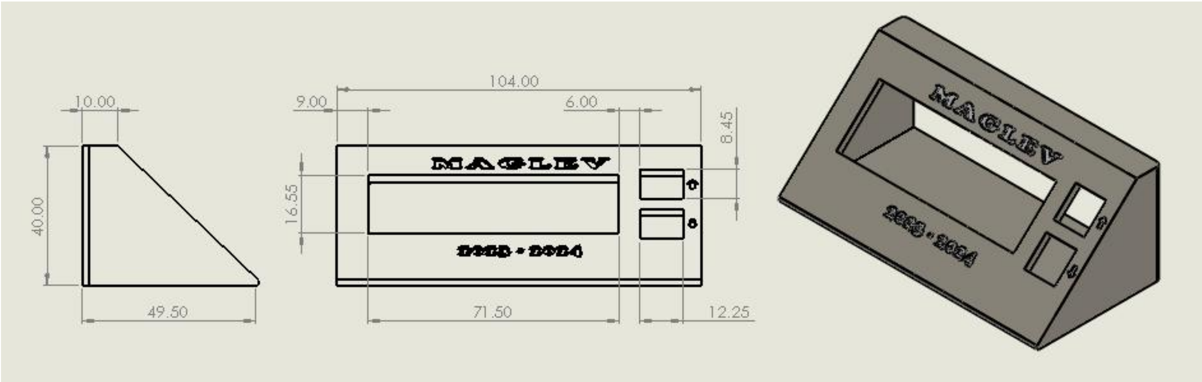


Figure 7: LCD structure.

Figure 8 shows the dimensions of the finalized machine design, which has a height of 220mm.

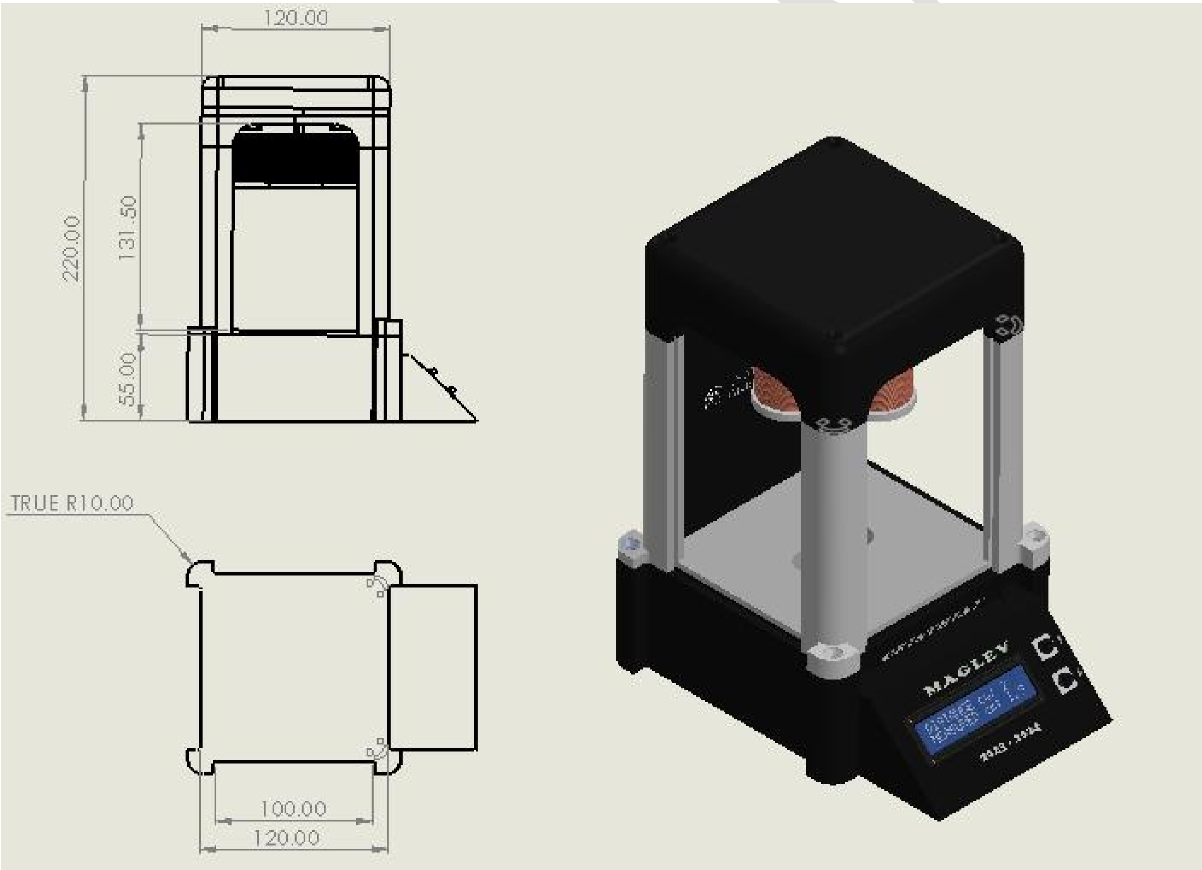


Figure 8: Final structure dimensions.

With all of the components in place, Figure 9 depicts the final render and machine.

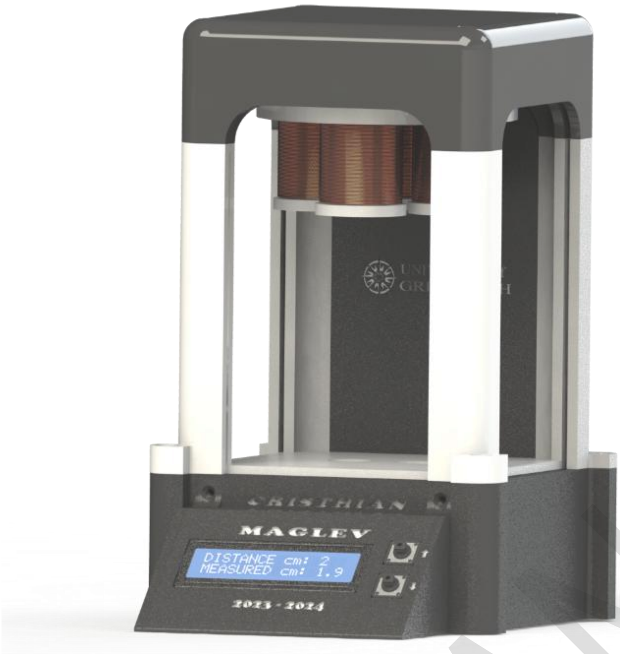


Figure 9: Final design.

Another important component of this project was the PCB, which controls everything in the system. As shown in Figure 10, various electronic components were used, and the circuit was divided into subsections to create a more organized schematic.

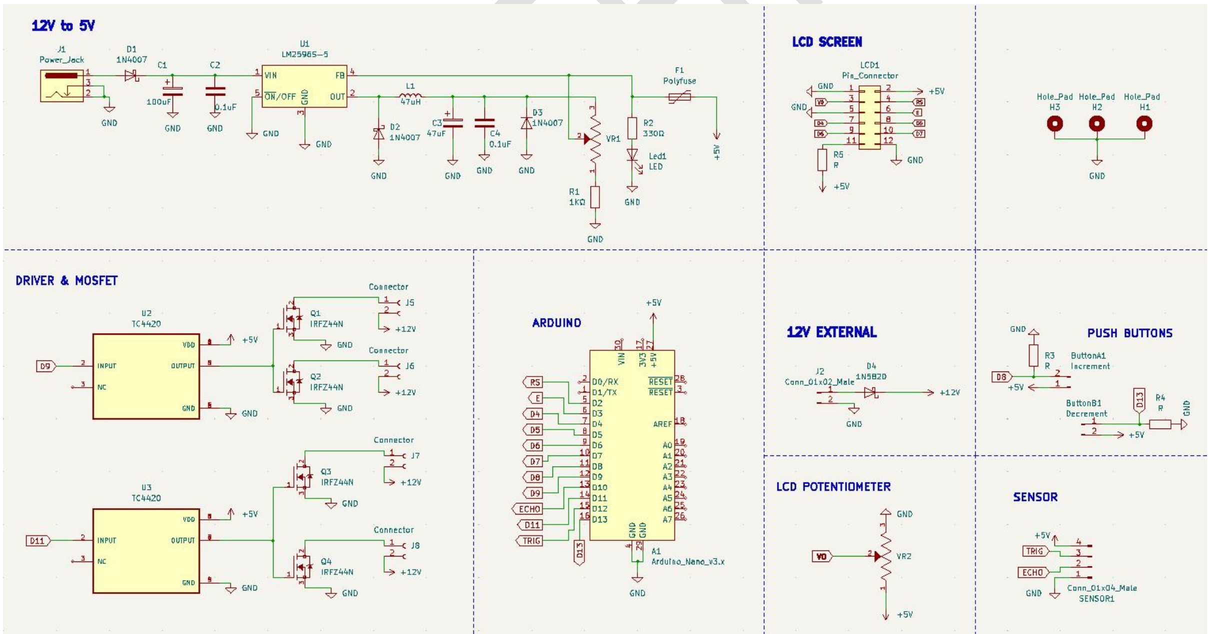


Figure 10: Circuit schematic diagram.

With all of the components chosen and the schematic circuit designed, it became possible to create the PCB layout, as shown in Figure 11.

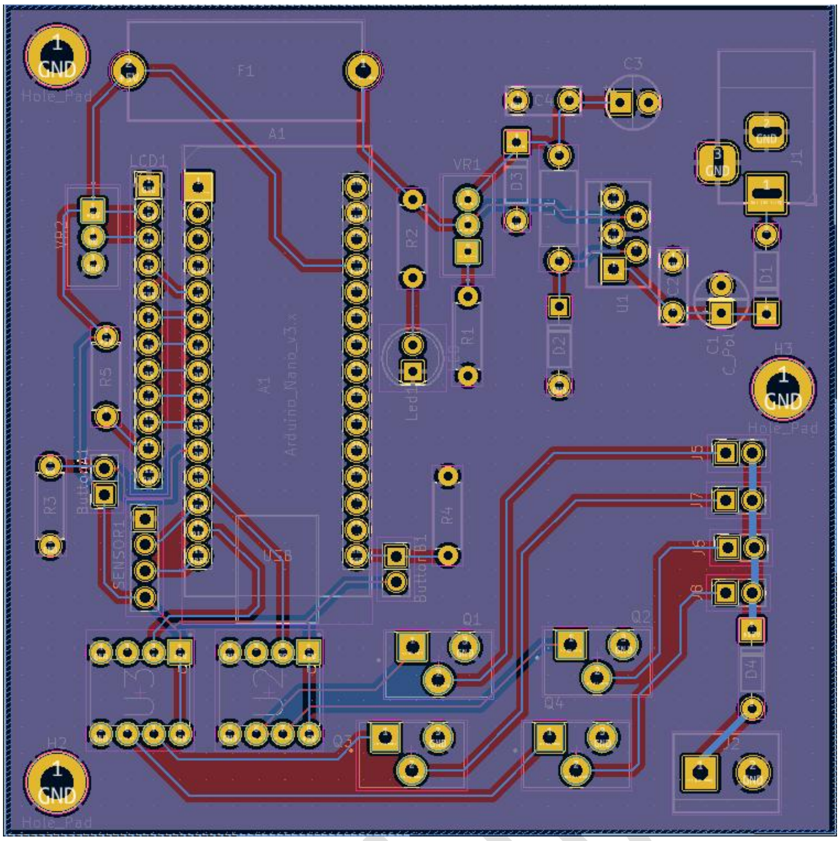


Figure 11: PCB layout.

Figure 12 illustrates how the PCB will appear after manufacturing, with all the components properly placed.

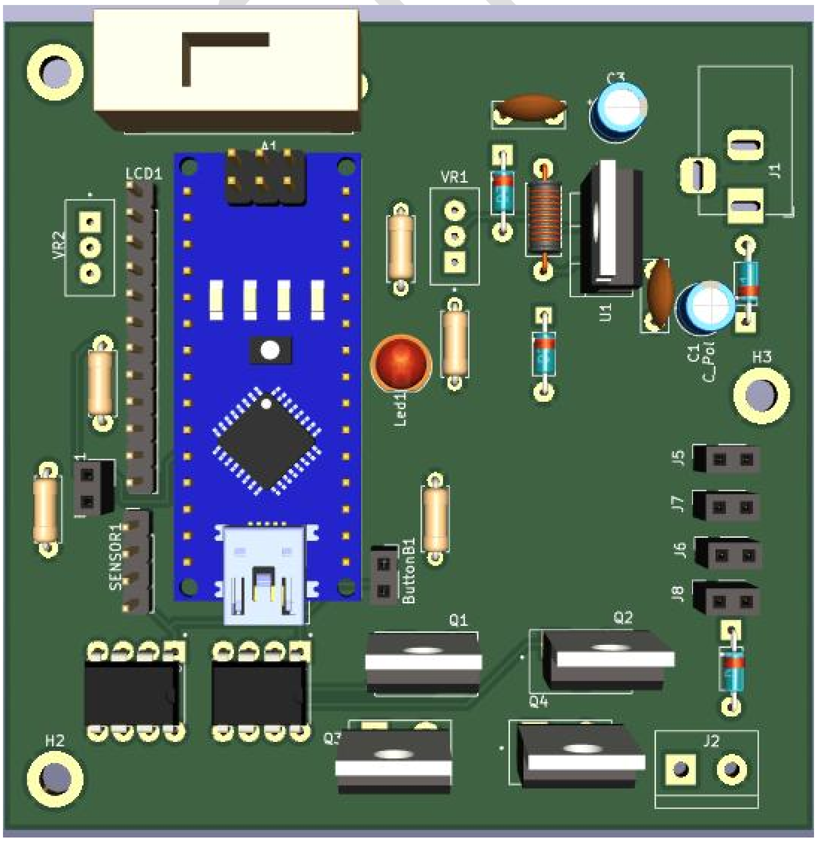


Figure 12: 3D vie of the PCB

3.4 Simulations

The following figures show sections of the code used for this project. Figure 13 shows the code that generates a dialogue box in MATLAB. This dialogue box allows the user to enter different parameters for the solenoids, making it easier to calculate values like current and inductance.

```
%% Dialogue box %%
dlgtitle = 'Matrix values';%% Name of the dialogue box
prompt={'Distance in cm','Number of Turns:','Radius of the Sol
dims=[1 30]; %% Dimensions of the text box
answer = inputdlg(prompt,dlgtitle,dims); %% user data

%% Convert from string to N %%
D = str2num(answer{1})/100; %% Value Distance
N = str2num(answer{2}); %% Value Number of Turns
RS = str2num(answer{3})/100; %% Value Radio of the Solenoid
LS = str2num(answer{4})/100; %% Value Length of the Solenoid
m = str2num(answer{5})/1000; %% Value Mass
```

Figure 13: Dialogue box code.

Figure 14 illustrates the code used to derive significant parameters such as the current and inductance of the solenoid with and without the core, as well as the total inductance of all solenoids.

```
%% Formulas
%% Solenoid Values
a=9.81; %% Gravity
U0=4*pi*10^-7; %% Permivitty
U=3.49*10^-6; %% Permivitty
A=(pi*RS^2) %% Area
top=2*m*a*D^2;
bot=4*A*U0*N^2;
I=sqrt(top/bot) %% Current equation
%% Constantant
K = 2*(A*U0*N^2)
%% Inductance 4 solenoids
L=(4*A*U0*N^2)/LS;
%% Inductance not core
Ln=(A*U0*N^2)/LS;
%% Inductance with core
Lc=(A*U*N^2)/LS;
```

Figure 14: Inductance and current equations.

Figure 15 shows the important constant obtained by using MATLAB, that will be used in future projects in Simulink.

```matlab
%% Force
topF=4*A*U0*(I^2)*(N^2);
botF=2*D^2;
F=topF/botF; %% Formula for force
%% Magnetic Filed
B=sqrt((2*U0*F)/A) %% magnetic field
%% CONSTANT
A1 = (-2*K*I)/(D^2) %% constant A1
A2 = (2*K*I^2)/(D^3) %% constant A2
R = 3.3 %% resistance of solenoid
%% TF of the system
%% Solenoid tf
STF = tf([1],[L R]) %% Solenoid transfer function
%% POSITION tf
PSTF = tf([-A1],[m 0 -A2])
ONE = tf(1)
```

Figure 15: Solenoid and constant transfer functions.

Figure 16 illustrates a section of code that demonstrates the integration of the PID controller in the closed loop. It also shows the code used to plot the system's step response as well as the root locus plot to distinguish between stable and unstable systems.

```matlab
% Create PID controller
PID = pid(Kp, Ki, Kd, N);
% Create closed-loop system with PID controller
ClosedLoop_PID = feedback(PID * TF1, ONE1);
% Plot the step response of the closed-loop system with PID controller
figure(1);
step(ClosedLoop_PID);
title('Step Response of Closed-Loop System with PID Controller');
figure(2);
rlocus(ClosedLoop_PID);
title('Root Locus of Closed-Loop System with PID Controller');
```

Figure 16: Code for the PID and plots.

3.5 Calculations

The following images show the calculations required to represent the system's behaviour in MATLAB and Simulink. Figure 17 depicts the initial equations, which aim to calculate the force produced by the solenoids. Figure 18 shows the final equation used to calculate the force generated by the solenoid for levitation based on the desired distance and current. Furthermore, Figure 19 and Figure 20 depict the equations used to derive the linear equation of force after applying Laplace, Taylor series, and Newton's laws.

Energy

$$U=\frac{1}{2}LI^2$$

Inductance

$$\mathcal{E} = -L\frac{di}{dt} = -N\frac{d\Phi}{dt}$$

$$-Li = -N\Phi \rightarrow LI = N\Phi$$

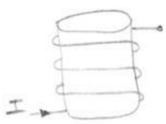
$$\boxed{\Phi = BA} \quad \boxed{B = \frac{\mu I N}{L}}$$ → Length

$$L = \frac{N\Phi}{I} \rightarrow L = \frac{NBA}{I}$$

$$L = \frac{N\cdot A\left(\frac{\mu I N}{l}\right)}{I} \rightarrow L = \frac{\frac{N^2\cdot A\cdot \mu I}{l}}{I}$$

$$\boxed{L=\frac{N^2 A\mu}{l}}$$ → Inductance.

Current



$$\oint \bar{B}\cdot d\bar{l} = \mu_0 I N$$

$$B\cdot l = \mu_0 I N$$

$$\boxed{\frac{B\cdot l}{\mu_0 N} = I}$$ → Current enclosed

$$U = \frac{1}{2}\cdot\left(\frac{N^2 A\mu}{l}\right)\left(\frac{B\, l}{\mu_0 N}\right)^2 \rightarrow \frac{1}{2}\left(\frac{N^2 A\mu}{l}\right)\left(\frac{B^2 l^2}{\mu^2 N^2}\right)$$

$$\frac{1}{2}\, A\cdot\frac{B^2}{\mu} \Rightarrow \boxed{\frac{AB^2 l}{2\mu}}$$ → Energy stored.

$$W = -\Delta U$$

$$F = \frac{dw}{dl} \rightarrow F = \frac{\frac{AB^2 l}{2\mu}}{l} \rightarrow \boxed{F_m = \frac{AB^2}{2\mu}}$$ → Force

Figure 17: Initial force equations.

Calculations II

• Magnetic flux.

$$\Phi = B \cdot A$$

• Self Inductance.

$$L = \frac{N \cdot \Phi H}{l}$$

• Magnetomotive Force.

$$f_{mm} = N \cdot I$$

$$f_{mm} = \Phi \, R \rightarrow \int \frac{dl}{\mu A}$$

• Magnetic field intensity.

$$H = \frac{NI}{L}$$

$$B = \mu \cdot H \rightarrow B = \mu (H + M)$$

Considerations

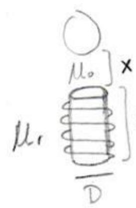
$N =$ 300 approximate

$I =$

Distance = 2cm to 10 cm

$m = 0.011 Kg \rightarrow 0.12 N$ minimum

$V = 9 - 12V$



1) $\Phi \rightarrow NI = \Phi R$

$$N \cdot I = \Phi \cdot \int \frac{dL}{\mu A}$$

$$N \cdot I = \Phi \cdot \left(\frac{L}{\mu_r A} + \frac{x}{\mu_0 A} \right)$$

→ Remove it "for Now)

$$N \cdot I = \Phi \rightarrow \frac{x}{\mu_0 A}$$

$$\frac{NI}{\frac{x}{\mu_0 A}} \rightarrow \frac{\mu_0 I \cdot N \cdot A}{x} = \Phi$$

2) $F = \frac{B^2 A}{2 \mu_0}$, $\Phi = B \cdot A$

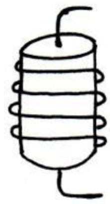
$$\Phi = B \cdot A \rightarrow B \cdot A = \frac{\mu_0 \cdot I \cdot N \cdot A}{x} \rightarrow B = \frac{\frac{\mu_0 I \cdot N \cdot A}{x}}{A} \rightarrow B = \frac{\mu_0 I N}{x}$$

$$F = \left(\frac{\left(\frac{\mu_0 I N}{x}\right)^2 A}{2 \mu_0} \right) \rightarrow F = \frac{\frac{\mu_0^2 I^2 N^2 A}{x^2}}{2 \mu_0} \rightarrow F = \frac{\mu_0^2 I^2 N^2 A}{2 \mu_0 x^2}$$

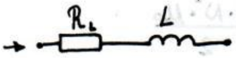
$$F = \frac{I^2 N^2 A \cdot \mu_0}{2 x^2} \rightarrow \boxed{F = \frac{N^2 A \cdot \mu_0}{2} \cdot \left(\frac{I}{x}\right)^2}$$

Figure 18: Force equation for the solenoids.

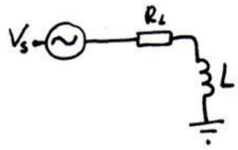
Laplace



→ Solenoid → EQUIVALENT CIRCUIT →



$*R_L$ = Resistance of solenoid



$$V_s = V_{RS} + V_{LS}$$

$$V_s = I_s \cdot R_s + L \cdot \frac{dI_o}{dt}$$

$*V_{RS}$ = Voltag in the Resistance of the solenoid connected with the V_s

$*V_{LS}$ = Inductance of the solenoid connected with the V_s

$$V_s(s) = I_s(s) \cdot R_s + Ls \cdot I(s)$$

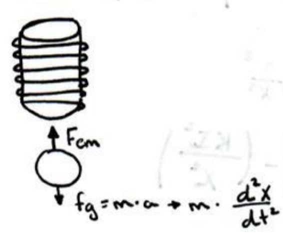
$$\frac{I(s)}{V(s)} = \frac{1}{R_s + Ls}$$

$$*K = \frac{1}{R_s}$$

$$*J = \frac{Ls}{R_s}$$

TF of Solenoid

$$\underbrace{\frac{1}{R_s + Ls}}$$



$$m \cdot \frac{d^2x}{dt^2} = -f_1$$

$*f_1$ • Obtained Before

$$m \cdot \frac{d^2x}{dt^2} = \underbrace{-\frac{2KI_o}{X_o^2}}_{A_1} \Delta I + \underbrace{\frac{2KI_o^2}{X_o^3}}_{A_2} \Delta X$$

A_1 and A_2 used to simplify the equations.

$$m \cdot \frac{d^2x}{dt^2} = -A_1 \Delta I + A_2 \Delta X$$

$$m \cdot S^2 X(s) = -A_1 I(s) + A_2 X(s)$$

$$(m \cdot s^2 - A_2) X(s) = -A_1 I(s)$$

$$\underbrace{\frac{X(s)}{I(s)} = \frac{-A_1}{mS^2 - A_2}}$$

from Laplace table

$$f'' = \frac{d^2x}{dt^2} = S^2 F(s)$$

$$f' = \Delta I \circ \Delta X = SF(s)$$

Figure 19: Laplace equations for the solenoids position.

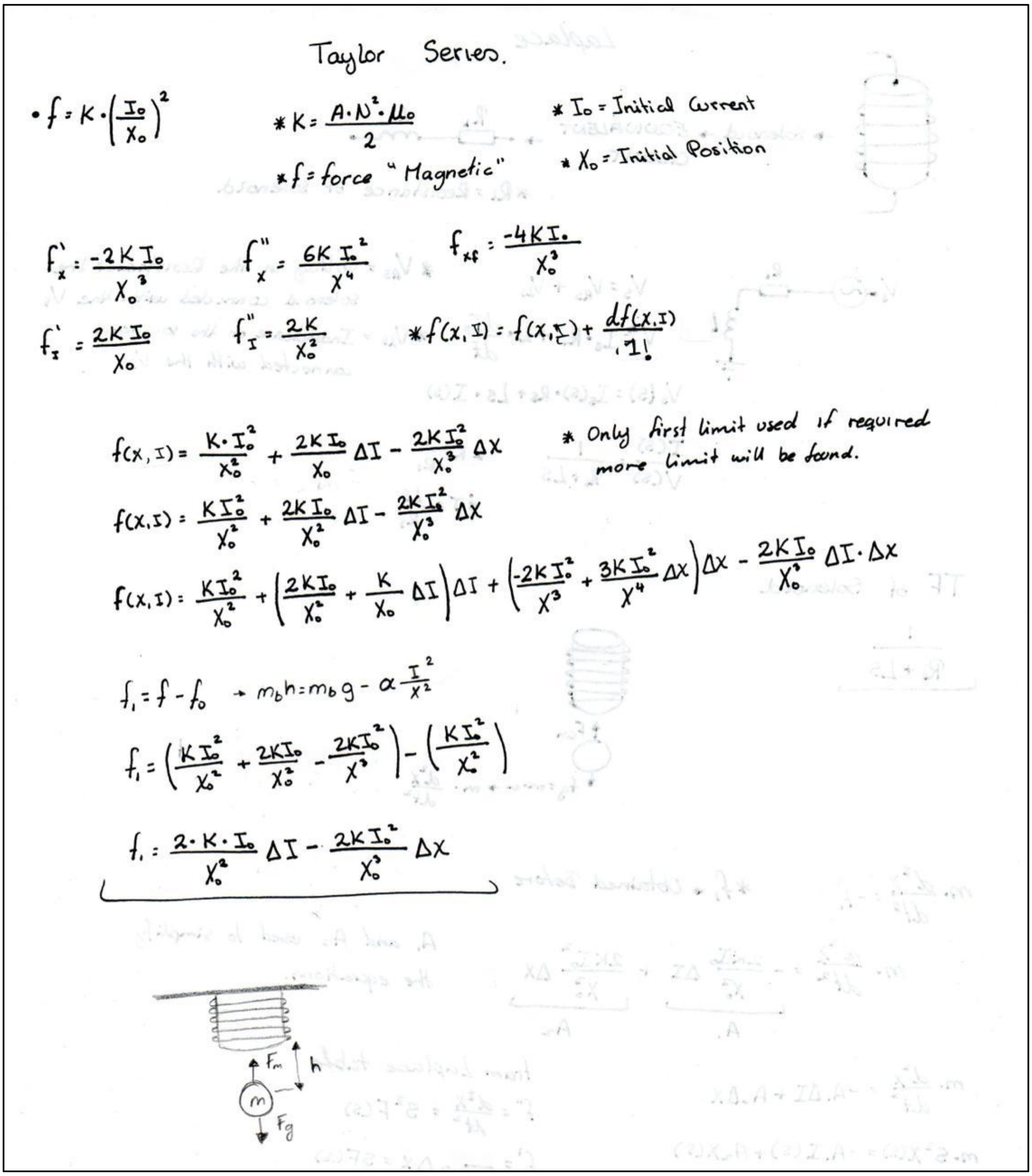


Figure 20: Taylor series equations.

4 SKILLS REFLECTION

Throughout the project, I was able to delve into a variety of topics that required the use of applied mathematical calculations, practical experimentation, and the acquisition of new technical skills. One area where I extensively used mathematical calculations was the design and optimization of the levitation system. Using concepts like Taylor series, I created equations to model the force produced by the solenoids as a function of distance and current (Figure 17-20). Using these mathematical tools, I was able to fine-tune the system's behaviour and gain precise control over the levitation process.

Furthermore, delving into the realm of hardware design, I took on the challenge of designing the PCB layout from scratch despite having no prior experience in this field. I managed to master PCB design software through self-learning and meticulous attention to detail, resulting in a layout that optimized electronic component placement and ensured efficient signal flow (Figure 10-12). This endeavour not only developed my technical skills but also gave me confidence in tackling complex engineering tasks.

In addition to theoretical calculations and design work, I conducted practical experiments to validate system performance and troubleshoot issues. I put electronic components through rigorous testing with oscilloscopes and other diagnostic tools to obtain the inductance of the solenoids or to verify the output voltage obtained from the voltage step down. This hands-on approach allowed me to gain invaluable insights into real-world engineering challenges while iteratively refining the system to achieve the desired results.

In essence, the project gave me a multifaceted learning experience that included applied mathematics, hardware design, and practical experimentation. Through these endeavours, I not only expanded my technical skill set but also developed a mindset of continuous learning and problem-solving, both of which are necessary for success in the field of engineering.