Design, Fabrication, and Control of a Single Actuator Magnetic Levitation System

By

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Abstract

This thesis describes the design procedure, analysis, and control of a single actuator magnetic levitation system. First the details of the system design and construction are presented, followed by an analysis of the relevant sub-systems and controller theory. Experimental levitation data is collected and compared to the theory. Utilizing a lead-lag controller, the maglev system is made stable for the levitation of a steel ball. Despite the simplicity and low cost of the position sensing system, it is able to detect the ball position to a resolution of 45 µm. The successful operation of this system made of relatively low cost, low precision components reveals that compact, cheap, integrated magnetic levitation systems are becoming more feasible for a variety of applications with the increasing availability of new materials and faster, cheaper computer processing power.
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Chapter 1 – Introduction

Levitation is a magical sort of phenomenon that has long fascinated people. In our age of advanced materials and cheap, high-speed computing we have the ability to make levitation a commonplace and integral part of modern life. This phenomenon is typically accomplished using actively controlled electromagnets. Magnetic actuation has the potential for numerous other applications. In addition to supporting loads (levitation), it can dampen vibration, apply precision force, and move objects precise distances all with no contact between surfaces and essentially no friction. This type of actuation can be used in harsh environments (corrosive, vacuum, etc.) where traditional mechanical or hydraulic actuators might not survive. A magnetic actuator can operate in ultra clean environments without the hazard of producing contaminants from its use. The main hindrance to the widespread application of magnetic levitation and other magnetically actuated systems is the complexity of the involved physics and the need for cheap and effective control systems to operate the system and maintain stability.

The objective of this senior undergraduate honors thesis is to design, build, and control a magnetic levitation test bed. This test bed will be capable of levitating a small steel ball at some stable steady-state position. The intent is to construct this system using relatively low cost, low precision components and still be able to levitate the ball with high precision.

The basic framework for the design follows from the system laid out by Trumper [1990]. In his thesis he describes his single actuator magnetic levitation system and his approach in making the system stable.

In this paper I will first present the physical design aspects of this maglev system. This will involve design details for each of the various system components and sub-systems. Next I will model the dynamics of each relevant sub-system and use these to create a simulated maglev system. The simulation will then be used to construct a controller for stabilizing the maglev system. This controller will be implemented into the constructed maglev test bed to create a stable levitation of a steel ball. Last, the results from the simulation and experiment will be compared.
Chapter 2 – Design

2.1 System Introduction

The magnetic levitation system serves to hold a small steel ball in stable levitation at some steady-state operating position. It does this by using an electromagnet to produce forces to support the ball’s weight. The electromagnetic forces are related to the electrical current passing through the electromagnet coil. A control system, implemented by a PC installed controller board, regulates the coil current. The controller makes decisions on the required current based on a position sensor. This position sensor indicates the ball’s vertical position.

The system consists essentially of a platform test bed and a PC with a DSP controller board. The test bed contains the electromagnet actuator, optical position sensor, electromagnet PWM power amplifier, and 2 DC power supplies. Figure 1 shows the basic system setup with physical sub-system interfaces.

Figure 1: Magnetic Levitation System Diagram
Figure 2 shows the test bed. The system separates into two main sub-systems. These are the force actuation sub-system and position sensing sub-system. The next two sections will describe the design aspects of these two sub-systems. These will be followed by a description of the mechanical design aspects of the test bed.

2.2 Force Actuation Sub-System Design

Force actuation is accomplished through a system consisting of an electromagnet coil, a PWM amplifier, and a 24 V DC power supply. These systems are joined using AWG #16 shielded wire. The coil interfaces with the amplifier using the AWG #21 wire that forms the coil. Figure 3 below shows the electrical diagram for this sub-system.
24 V DC power is supplied to the PWM amplifier at connection points P2-5 and P2-4. The control signal from the controller board is allowed to vary from 0 V to 10 V and is connected to points P1-4 and P1-2. The electromagnet coil receives the amplified controller signal through points P2-1 and P2-2. The amplifier is set to operate in current mode where the output current is linearly proportional to the input control voltage.

The nominal coil dimensions are shown in Figure 4. A powered iron rod is used as the high permeability core for the electromagnet coil.

![Figure 4: Electromagnet Coil Drawings](image)

Table 1 lists the individual force actuation components and their general specifications (see Appendix B for detailed component specifications).

<table>
<thead>
<tr>
<th>Component</th>
<th>Brand</th>
<th>Part #</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Input Linear DC Power Supply</td>
<td>Lambda Electronics</td>
<td>HSN 24-4.8</td>
<td>Output: 24 V, 4.8 A max</td>
</tr>
</tbody>
</table>
| PWM Servo Amplifier            | Advanced Motion Controls | 25A – 12A8| Input: 20 – 80 V
                                    |                      |            | Output: ±12 A peak, ±6 A contin.    |
| Electromagnet Coil             | Wirewinders          | -          | AWG #21 magnetic wire ~ 3100 wire turns |
| Electromagnet Core             | Allstar Magnetics    | R33-050-400| High Permeability Powdered Iron Rod |

### 2.3 Position Sensor Sub-System Design

The position sensor sub-system consists of a photocell based sensor, incandescent light source, and 15 V DC power supply. Figure 5 shows the main components of the position sensor sub-system in their basic positions relative to one another.
For position sensing of the levitated ball, a photocell is used in conjunction with an incandescent light bulb. The vertical displacement of the ball is measured by this sensor configuration through gradual shielding and exposing of the photocell to light. To ensure that ambient light does not affect the sensor measurements, a tube is placed around the photocell. The tube is completely closed to external light except for a vertical slit located along the tube end near the ball and opposite the photocell (Figure 6).

The slit allows for the photocell to be exposed to the bulb light as a function of the ball position. The variable light exposure on the photocell results in a change of its electrical resistance. To use the variable resistor photocell as a position sensing device, it is configured in the electrical circuit shown in Figure 7.
A 15 V DC power supply runs the sensor. For the computer controller board interface, it is important that the $V_{\text{Sensor}}$ range between 0 V and 10 V. To maintain this range, the constant resistor is chosen to compliment the $R_{\text{Photocell}}$ variation range according to (1).

$$V_{\text{Sensor}} = \frac{15R}{R_{\text{Photocell}} + R}.$$  \hspace{1cm} (1)

The photocell resistance varies from 16 kΩ (10 lux) to 1 MΩ (dark) according to the specification. The constant resistance value is therefore chosen as 26.5 kΩ. Two light shields are placed around the sensor opening and light bulb to help prevent ambient light conditions from affecting the sensor readings. Figure 8 shows the sub-system.
The electrical connections are made with AWG #16 shielded wire. The 15 V DC power supply provides 15 V connections to both the sensor assembly and the incandescent bulb. Table 2 below lists individual sub-system components and their general specifications (see Appendix A for detailed component specifications).

Table 2: Position Sensor Sub-System Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Brand</th>
<th>Part #</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoconductive Cell (Photocell)</td>
<td>PerkinElmer Optoelectronics</td>
<td>VT50N3</td>
<td>Resistance: 16 kΩ – 1 MΩ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max Voltage: 300 V</td>
</tr>
<tr>
<td>Incandescent Light Bulb (mini-bayonet)</td>
<td>-</td>
<td>-</td>
<td>Voltage: 14 V</td>
</tr>
<tr>
<td>AC Input Linear DC Power Supply</td>
<td>Lambda Electronics</td>
<td>HDC 15</td>
<td>Output: 15 V (2), 3 A max</td>
</tr>
</tbody>
</table>

Testing of the position sensor revealed significant high frequency noise within the sensor signal. A simple low pass filter is added to the sensor output signal to attenuate the noise. The filter consists of a 19.8 kΩ resistor and 20 nF capacitor. The cutoff frequency for the filter is 400.5 Hz. Figure 9 shows the filtered and unfiltered sensor reading.

![Figure 9: Position Sensor Reading Before and After Filtering](image)

Despite the simplicity and low cost of this position sensor, it is capable of measuring object positions to a 45 µm resolution. Figure 10 shows the signal while detecting the position of a fixed object at the steady-state position.
2.3 Mechanical Design

The mechanical design of this system involves the structural design of the rig used to hold the various systems and the miscellaneous physical electrical connections. It is important that this rig is fairly rigid to vibrations and easily adjustable for the positions of the sub-system components. These components will require fine tuning of their positions during their calibration procedure. Figure 11 shows a scale drawing of the test rig. Dimensioned components of the rig can be seen in Appendix C.
The rig base is constructed of two ¾” boards stacked and joined to create a 1 ½” thick base. Eight through holes are placed into the base for the attachment of eight 3/8” diameter all-thread rods. These rods are used to mount the photocell assembly, electromagnet, and light source. Using the all-thread as a supporting rod allows for precise vertical positioning of these components.

The photocell sensor assembly (Figure 12), consisting of the photocell, light shield tube, and light shield plate, is strapped to the sensor platform. It is important that this assembly and the mounting platform are rigidly fixed in their position. Any movement of these items can alter the position sensor calibration.

![Figure 12: Photocell Sensor Assembly on Mounting Platform](image)

The electromagnet is attached to the supporting rods using rubber coated clamps (Figure 13). The electromagnet core is held within the coil using annular shims. The top and bottom faces of the coil are protected by plastic sheets epoxied into place.

![Figure 13: Electromagnet Coil on Mounting Rods](image)
The sensor light source is attached to a platform that is mounted using the all-thread rods. This platform also holds the other light shield plate (Figure 14).

![Figure 14: Light Source Platform on Mounting Rods](image)

In addition to the components attached by all-thread rod, the electromagnet power amplifier, and two DC power supplies are mounted to the test rig base. Two sets of terminal blocks are attached to the base plate to provide a physical connection point for the various electrical connections required by the system. Figures 15 and 16 show these connection specifications.

![Figure 15: Physical Electrical Interface for Terminal Block #1](image)

![Figure 16: Physical Electrical Interface for Terminal Block #2](image)
Chapter 3 – Modeling

3.1 Introduction

For this chapter, the dynamics and controls aspects of the magnetic levitation system are discussed. First I look at the theoretical background to this problem using the underlying physics. Then I develop models for the force actuator, plant, and sensor subsystem. A high level block diagram of these sub-systems is shown in Figure 17 below.

![Figure 17: Magnetic Levitation System Schematic](image)

Using these models and several performance requirements for the stable system, a suitable control system is designed in simulation that will satisfy these requirements. The system controller is then implemented within the hardware and tested to confirm the simulation predicted behavior.

3.2 Theoretical Background

This section covers the theoretical analysis of the magnetic levitation system. First, the system is described according to the dominant physical phenomena. This analysis is used to construct a non-linear force actuator and plant model.
Figure 18 shows the basic setup of the magnetic levitation system. The system actuator consists of an electromagnet formed by wrapping a powdered iron core of high permeability with an electrically conducting wire. The actuator creates a magnetic field when an electrical current is passed through the wires. This magnetic field creates an upward attractive force on any magnetic object placed below. A position sensor detects the vertical position of the object and passes this information to the controller. The controller then adjusts the current to the electromagnet actuator based on the object position to create a stable levitation.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>$i$</td>
<td>Electrical current through the electromagnet</td>
<td>[A]</td>
</tr>
<tr>
<td>$\hat{i}$</td>
<td>Perturbation current</td>
<td>[A]</td>
</tr>
<tr>
<td>$I$</td>
<td>Steady-state position current</td>
<td>[A]</td>
</tr>
<tr>
<td>$y$</td>
<td>Vertical displacement of object from electromagnet</td>
<td>[m]</td>
</tr>
<tr>
<td>$\hat{y}$</td>
<td>Perturbation displacement</td>
<td>[m]</td>
</tr>
<tr>
<td>$Y$</td>
<td>Steady-state displacement</td>
<td>[m]</td>
</tr>
<tr>
<td>$L$</td>
<td>Electromagnet inductance</td>
<td>[H]</td>
</tr>
<tr>
<td>$L_0$</td>
<td>Electromagnet inductance constant</td>
<td>[H]</td>
</tr>
<tr>
<td>$L_1$</td>
<td>Electromagnet inductance constant</td>
<td>[H]</td>
</tr>
<tr>
<td>$a$</td>
<td>Constant</td>
<td>[m]</td>
</tr>
<tr>
<td>$f^e$</td>
<td>Electromagnet force</td>
<td>[N]</td>
</tr>
</tbody>
</table>
3.2.1 Assumptions

1. The electromagnet inductance is assumed to have the form of (2) [Woodson, 1968]. Figure 19 shows a plot of this form.

![Figure 19: Inductance Behavior of Electromagnet [Woodson, 1968]](image)

\[ L(y) = L_1 + \frac{L_0}{1 + \frac{y}{a}} \]  

(2)

2. The inductance constants are assumed to have the relationship shown in (3).

\[ L_1 \gg L_0 \]  

(3)

3.2.2 Model

The first task for creating a magnetic levitation system is to model the maglev plant. A useful plant model for this situation would yield the levitated object position as a function of the input current.

The electromagnetic force on the levitated object is found using the concept of coenergy. The coenergy \( W' \) is defined as

\[ W'(i, y) = \frac{1}{2} i^2 L(y). \]  

(4)

The electromagnetic force \( f^e \) is defined as the derivative of coenergy. Substituting the electromagnet inductance and coenergy into the force equation yields a relation for the electromagnetic force in terms of current and displacement (5).
The next step is to define the equation of motion for the levitated object. Figure 20 shows the forces on the body in their defined direction.

\[
f^e(i, y) = \frac{\partial W'}{\partial y} = -\frac{L_0i^2}{2a(1 + \frac{y}{a})^2} \tag{5}\]

The next step is to define the equation of motion for the levitated object. Figure 20 shows the forces on the body in their defined direction.

![Figure 20: External Forces on Levitated Body](image)

The equation of motion is shown below (6).

\[
m\ddot{y} = mg + f^e \tag{6}\]

Substituting the electromagnetic force term into (6) gives the non-linear equation of motion as

\[
m\ddot{y} = mg - \frac{L_0i^2}{2a(1 + \frac{y}{a})^2}. \tag{7}\]

At static equilibrium, it follows that

\[
mg = \frac{L_0I^2}{2a(1 + \frac{y}{a})^2}. \tag{8}\]

Equation (8) shows that for a given steady-state current (I), the equilibrium position of the levitated object (Y) is determined. It is convenient to have (8) rearranged into the form

\[
I = \left(1 + \frac{Y}{a}\right)\sqrt{\frac{2mga}{L_0}}. \tag{9}\]

With the non-linear equation of motion determined (7), a Taylor series expansion can be used to create a linearized form of the equation of motion. The first few Taylor series terms are

\[
f^e(\hat{i}, \hat{y}) = f^e(I, Y) + \frac{\partial f^e(I, Y)}{\partial y} \hat{y} + \frac{\partial f^e(I, Y)}{\partial i} \hat{i} \tag{10}\]
where the perturbation quantities are defined as

\[
\hat{y} = y - Y \\
\hat{i} = i - I.
\] (11)

Substituting force equations into (10) produces the following:

\[
f^e(\hat{i}, \hat{y}) = \frac{-L_0 I^2}{2a(1 + \frac{r}{a})^2} + \frac{L_0 I^2}{a^2(1 + \frac{r}{a})^3} \hat{y} - \frac{L_0 I}{a(1 + \frac{r}{a})^2} \hat{i}.
\] (12)

The basic linearized equation of motion is

\[
m\ddot{y} = mg + f^e(\hat{i}, \hat{y}).
\] (13)

Substituting (12) into (13) and simplifying yields a linearized system equation of motion (14).

\[
m\ddot{y} = \frac{L_0 I^2}{a^2(1 + \frac{r}{a})^3} \hat{y} - \frac{L_0 I}{a(1 + \frac{r}{a})^2} \hat{i}.
\] (14)

Equation (14) is capable of being simplified further by multiplying both terms on the right by

\[
\frac{2mga(1 + \frac{r}{a})^2}{L_0 I^2} = 1.
\] (15)

The resulting equation (16) is left in terms of the perturbed current, perturbed displacement, gravity, steady-state displacement, and steady-state current. This is the considered the open-loop system model.

\[
\ddot{y} - \left(\frac{2g}{a + Y}\right)\dot{y} + \left(\frac{2g}{I}\right)\dot{i} = 0.
\] (16)

### 3.2.2 Transfer Function

The open-loop system model can now be used to determine the plant transfer function. Finding the transfer function consists of taking the Laplace transform of the equation of motion and rearranging the equation to be a ratio of the system output to the system input. Equation (16) shows the Laplace transform of the equation of motion.

\[
s^2 \cdot \hat{Y}(s) - \left(\frac{2g}{a + Y}\right)\hat{Y}(s) + \left(\frac{2g}{I}\right)\hat{i} = 0.
\] (17)

Rearranging this equation yields the plant transfer function
\[
\frac{\dot{Y}(s)}{I(s)} = \frac{-1}{As^2 - B} \left[ \frac{m}{A} \right]
\]  

(18)

where

\[
A = \frac{I}{2g} \left[ \frac{As^2}{m} \right], \\
B = \frac{I}{a + Y} \left[ \frac{A}{m} \right].
\]  

(19)

3.3 Plant Model

For the maglev system, the plant consists only of the steel ball to be levitated. The current configuration uses an 8.6 g ball that is 12.7 mm (0.5 in) in diameter. Equation (20) shows the time domain model of the plant

\[
F = m\dot{y}
\]  

(20)

Taking the Laplace transform and rearranging the equation provides the plant transfer function (21).

\[
\frac{Y(s)}{F(s)} = \frac{1}{ms^2}
\]  

(21)

3.4 Sensor Model

To develop the sensor model, the position sensor sub-system must be tested and calibrated according to the particular ball in use. This calibration is accomplished by incrementing a light shield that corresponds to the ball’s size in the y direction and recording the sensor output voltage (Figure 21). The data is given as displacement from the bottom of the electromagnet coil down to the top of the ball (positive is down). In this configuration, the sensor is placed so as to detect the bottom edge of the levitated ball.
Over a travel range of approximately 3 mm the sensor output is near linear. Within this range the sensor output is \(-1934\) V/m. Since the control system requires the sensor signal to be in the form of a position instead of a voltage, a sensor calibration is needed. This is simply the sensor model equation (Figure 21) plotted with voltage as the independent variable (Figure 22).
The calibration shows there to be a –0.5088 mm/V relationship. Since the system is to be operated at some constant position and treated as linear, the intercept of the sensor calibration is adjusted so as to show a zero voltage signal when the ball is located at the steady-state linearized position.

Using the results from the sensor model and calibration, the two sensor blocks from Figure 17 are created (Figures 23 and 24).

### 3.5 Actuator Model

The actuator model is generated by experimentally measuring the force on the ball at the steady-state position while varying the current through the coil. The force readings are determined by a load cell sensor. Figure 25 shows this experimental force versus current relationship for the steady-state position of y = 0.005 m. The force values are negative because the electromagnet attracts upward and the positive y direction is defined downward. The horizontal line represents the weight of the ball to be levitated.
Since the force actuation sub-system will be controlled via a voltage control signal to the power amplifier, the calibration of the amplifier must also be specified. Figure 26 shows this calibration.
To create a model for the entire force actuation system, the electromagnet model and power amplifier model are combined to form the force actuation block (Figure 27) from the system block diagram (Figure 17). This yields force from the electromagnet coil as a function of the input control signal voltage.

Figure 27: Force Actuator Block
Chapter 4 – Dynamics and Controls

4.1 Simulation Analysis and Controller Design

Using the sub-system models determined in the previous chapter, a complete system block diagram can be constructed for simulation purposes. Using this simulation an appropriate controller can be developed to maintain the closed-loop maglev system in stable levitation. The controller has two main performance requirements which it must maintain. These are the transient response settling time and percent overshoot.

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<table>
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<tr>
<td><strong>Table 4: Transient Response Performance Requirements</strong></td>
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<tr>
<td>Settling Time (t_s)</td>
<td>≤ 1 s</td>
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<tr>
<td>Percent Overshoot (P.O.)</td>
<td>≤ 50 %</td>
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4.1.1 Open-Loop Analysis

The open-loop maglev system consists of the power amplifier, electromagnet coil, and steel ball. The linearized model corresponding to these components is shown below (Figure 28).

![Figure 28: Linearized Open Loop System Model](image)

A root locus analysis for the linearized open-loop system shows the system to be unstable. To create a stable system, the system must be placed within a closed-loop control system.

4.1.2 Closed-Loop Analysis

To achieve stability, the open-loop maglev system must be placed within a feedback control system. The position sensor provides this loop back of information. Since the sensor model and sensor calibration cancel each other out, these two blocks are left out of the system block diagram for the simulation analysis (Figure 29).
A lead-lag controller is used for stabilizing the system. It is of the form shown in Figure 30. The constants C and K are chosen to match the desired performance requirements.

\[ \sigma = \frac{4.6}{t_s} \]  \hspace{1cm} (22)

Any roots to the left of this line satisfy the maximum settling time requirement. The percent overshoot is represented on the s-plane as an angle from the negative real axis. The angle magnitude is the arccosine of the damping ratio, which is related to the percent overshoot through [Franklin & Powell]

\[ P.O. = 100e^{-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}} \]  \hspace{1cm} (23)

Any roots that fall within an angle smaller than the critical angle will have a lower percent overshoot. Figure 31 shows the system root locus plot for the closed-loop maglev system with the lead-lag controller. The thick bands on the right side of this figure represent the performance.
requirements of $t_s \leq 1$ s and P.O. $\leq 50\%$. Choosing the controller constants to be $C = 0.7$ rad/s and $K = -33,300$ V/m places the roots as shown by the small squares on Figure 31.

Figure 31: Closed-Loop Root Locus with Design Constraints

Figure 32 shows a zoom of the region near the origin on the root locus plot. This confirms that the near origin root satisfies the design requirements.

Figure 32: Closed-Loop Root Locus with Design Constraints (Near Origin)
The transient response of the closed-loop system to a unit step input is seen in Figure 33. This shows the settling time to be about 0.045 s and the percent overshoot to be about 28%.

![Figure 33: Closed Loop Maglev System Transient Response for Unit Step Input](image)

The loop transmission and closed-loop bode plots are shown in Figures 34 and 35, respectively. The loop transmission figure shows the system crossover frequency to be approximately 26 Hz. Beyond this frequency the system output attenuates significantly. The resulting phase margin is 51.5°.
Figure 34: Maglev System Loop Transmission Bode Plot

Figure 35: Maglev System Closed-Loop Bode Plot
4.2 Controller Hardware Implementation and Analysis

4.2.1 Implementation

With the controller designed and modeled, the control system can be integrated with the physical maglev hardware. Before doing this, the control system must be converted from a continuous transfer function to a discrete transfer function (Figure 36). This is done using the Matlab command “c2d”.

\[
\frac{-33300s^2 - 2.564 \times 10^6 s - 1.632 \times 10^7}{s^2 + 700.7 s + 490} \quad \leftrightarrow \quad \frac{-33300z^2 + 6.551 \times 10^4 z - 3.222 \times 10^4}{z^2 - 1.704 z + 0.7044}
\]

With the controller in the discrete domain, a block diagram is constructed for integration with the physical system (Figure 37). The diagram includes several items from simulated systems including the controller, desired position, and position sensor calibration. In addition to these items, there are several new blocks required for the system. One is the constant steady-state voltage added to the controller output signal. This addition is necessary because the control system is designed to compensate for disturbances from a linearized position. This constant additional voltage corresponds to what force is necessary to initially hold the ball in this steady-state linearized position. Another new block is the signal saturation. These are to used to limit the control system to what voltage ranges are possible and logical for the physical system. The last significant difference is the removal of the right half of the block diagram. In the simulations, this right side represents the plant to be controlled. For the physical implementation, the plant lies outside of the software. After the signal saturation, the signal is converted from a digital signal to an analog one and passed outside the computer.

![Figure 36: Continuous vs. Discrete Lead-Lag Controller](image)

![Figure 37: Maglev System Block Diagram](image)
To provide the control signals and receive the sensor output, a dSPACE, Inc. 1104 Controller Board is used (Figure 38) (Appendix D). To program this board, the Simulink block diagram in Figure 37 is compiled using dSPACE software.

![dSPACE, Inc. 1104 Controller Board](image)

Figure 38: dSPACE, Inc. 1104 Controller Board

With the control program running on the 1104 board, the dSPACE program “Control Desk” is used to view the system, interact with the system, and collect any desired data (Figure 39).

![dSPACE Control Desk](image)

Figure 39: dSPACE Control Desk
The implementation of control system using these hardware and software tools successfully produces stable levitation of the steel ball as seen in Figure 40.

Figure 40: Stable Levitation of Steel Ball

4.2.2 Steady-State Analysis

Using the current lead-lag controller, it is useful to know the steady-state position error that persists within the system as the ball levitates. Comparison of sensor readings for a fixed object with the levitated ball are used to observe this behavior. This comparison showed no appreciable steady-state error for the levitating ball. Any existing error is likely small enough to be masked by the sensor noise.

4.2.3 Transient Analysis

One way to verify the operation of the physical system is to create step changes to the desired position in order to observe the system’s transient behavior. The system is tested with increasing step inputs. The steps are 10 µm, 50 µm, and 100 µm. Due to the 60 Hz noise of the sensor readings, much of the system behavior is masked for these small steps. To help resolve the details, a 40 Hz low-pass Butterworth filter is applied to the collected experimental data. Figures 41 - 43 show the resulting system behavior compared with the theoretical system response.
Figure 41: Maglev Transient Response to 10 µm Step Input

Figure 42: Maglev Transient Response to 50 µm Step Input
These transient responses for the system show a percent overshoot of approximately 150%. The settling time seems to be approximately 0.6 s for all three cases.

4.2.4 System Limitations

One concern with linearized systems is the range of operation of the system before the linearization breaks down. For this maglev system, the ball is capable of sustaining a stable levitation $1.57 \text{ mm} \pm 0.02 \text{ mm}$ below the linearized steady-state position and $0.84 \text{ mm} \pm 0.02 \text{ mm}$ above the linearized steady-state position. This is a total travel range of $2.41 \text{ mm} \pm 0.02 \text{ mm}$. This value corresponds to the operating range of the position sensor. The linearized controller, power amplifier model, and electromagnet coil model hold up over this range without any noticeable degradation.

Another limitation of the system is the maximum mass that can be suspended. To prevent damage to the electromagnet coil, current passing through the coil must remain below some upper critical value. This value limits the force that the actuator can produce. The current position sensing configuration also has a limitation involving the shape of the object to be levitated. Currently the system detects the lower edge of the object for determining position. If the object were anything other than a sphere (symmetric about all 3 axes), any change in attitude of the object might confuse the sensor.
Chapter 5 – Summary and Conclusion

The main objective of this thesis research was to construct a magnetic levitation test bed using relatively low cost, low precision components and demonstrate high precision, stable levitation of a steel ball. The project began with designing and building a portable and versatile maglev system test bed. The design was to be easily adjustable for future changes to the configuration and capable of housing new and different systems. With the maglev test bed constructed, the sub-system components were characterized to allow theoretical analysis of the entire system and design of the closed-loop controller. The control system was then implemented into the maglev test bed using a dSPACE 1104 Controller board sampling at 2 kHz. This enabled the steel ball to levitate at a stable steady-state position. The experimental behavior was recorded, analyzed, and compared to the theoretical results.

The experimental results showed some large differences when compared to the theoretical results. Both the transient response settling time and percent overshoot exceed the predicted values, though the settling time still fell within the system performance requirement. One possible explanation for this is the noise within the position sensor signal. The limited position range of the maglev system forced the transient analysis step inputs to be relatively small compared to the sensor noise level. This low signal-to-noise ratio could confuse the controller or hide the behavior of the system within the noise. Another possibility is that the non-linearity of the actual system is causing some behavior differences compared to the linearized simulation. Also, these differences could be accounted for by including the dynamics the system electronics and other assumed negligible components.

The successful completion of this project demonstrates the feasibility of levitation for any number of diverse applications. The continued trend of smaller and cheaper semiconductor devices makes the possibility of integrating powerful control systems into any device more of a reality. These integrated control systems used in conjunction with low cost and low complexity maglev systems (like the one demonstrated in this thesis) can make magnetic actuation a sensible and cost effective means to eliminate friction, precisely position, support weight, etc. Maglev systems are currently in use for applications such as bearings, high speed trains, and manufacturing. With a streamlining of the high precision maglev system, many unanticipated applications will develop for the future.

This test bed provides a platform for future, advanced investigations into magnetic levitation systems. There are several improvements to the system that could enhance the current configuration or provide opportunities for new work. One of these is to improve the position sensor range of operation. Currently it is the limiting factor for the ball range of motion. Providing a more uniform and distributed light source could help the sensor dynamics. Another option is to try out completely different sensor techniques. Adding additional filtering to the sensor signal could help with future analysis of the system. If additional sensing range is achieved then implementation of a more advanced control method (i.e. nonlinear) could be useful.
Bibliography


Appendix A: Position Sensor Sub-System Component Specifications
Appendix B: Force Actuation Sub-System Component Specifications
Appendix C: Mechanical Design Component Drawings
Test Bed Base Plate
Electromagnet Coil

\[ \phi = 0.500 \]

\[ \phi = 2.000 \]

[Diagram of cylindrical object with dimensions labeled]
Sensor Plate

Dimensions:
- Length: 5.500
- Width: 2.500
- Hole diameter: 0.500
- Hole distance: 4.000
- Thickness: 0.500
Light Platform
Appendix D: dSPACE 1104 Controller Board Specification