ME344 Final Project: Magnetic Levitation Control Report

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Abstract

This project aimed to develop a closed-loop control system for a magnetic levitation (MagLev) device using a PID controller. The MagLev system involves levitating a steel ball using an electromagnet, with its position continuously adjusted via feedback from a photodiode sensor array. Our objective was to maintain the ball at a fixed height and to accurately follow time-varying reference inputs such as sine waves, square waves, and random signals.

The controller was implemented in LabVIEW and tuned experimentally to achieve fast settling time, minimal overshoot, and low steady-state error. The system was evaluated using various test inputs, and performance metrics were recorded for each.

Introduction and Theory

The MagLev system levitates a ferromagnetic ball by dynamically adjusting the current through an overhead electromagnet. The position of the ball is sensed using a photodiode array that outputs a voltage proportional to the ball's height. This voltage is used in feedback to regulate the current, creating a closed-loop system. The primary challenge lies in the system's inherent instability and strong nonlinear dynamics, which necessitate a carefully tuned control strategy.

System Overview

Our experiments were performed on the Feedbackk® Instruments Ltd. magnetic levitation unit, board 33-210, unit number 2. The main components are the following.

- **Electromagnet & Current Drive.** An iron–core coil mounted overhead, driven by the manufacturer's current-control box (±5 A, ±15 V output). This module maintains the static levitation current I_0 and responds to the LabVIEW-generated command voltage.

- **Position Sensor.** A four-element photodiode-array wrapped around the coil base. The array outputs a voltage proportional to the vertical displacement of the steel ball, with a linear range of approximately ± 5V about the equilibrium point x_0.
- **DAQ & Controller Platform.** Sensor and command signals interface to a Windows 10 PC via a National Instruments USB-6009 DAQ board (8 AI, 2 AO, 14-bit, 48kS/s). The control algorithm (PID) and user interface were implemented in LabVIEW 2023b using the NI PID and Control Design Toolkit. All loops run at a 1kHz rate, with a first-order low-pass filter (50Hz cutoff) applied to the derivative channel to suppress sensor noise.
- **Mechanical Constraints & Test Observations.** The 6 mm steel ball (0.5 g) is guided by two acrylic rails to prevent lateral swing. During extended runs we observed a slow drift in sensor baseline (10 mV over 10 min) due to thermal expansion of the photodiode housing, and coil heating limited continuous currents above 2.5 A before the driver's thermal cutoff engaged. Sensor noise measured 5 mV rms, which required the derivative filter noted above.

These hardware details and observed behaviors shaped our PID-tuning process and ultimately yielded stable levitation and accurate waveform tracking under all test inputs.

Governing Equations

The vertical motion of the ball can be modeled by the nonlinear differential equation:

$$m\ddot{x} = mg - k\frac{I^2}{(x + x_0)^2}$$

where:

- m: mass of the levitated ball
- g: gravitational acceleration
- I: current through the electromagnet
- x: displacement of the ball
- x_0: offset from the magnetic center
- k: electromagnetic constant (experimentally derived)

The system was linearized around an equilibrium point x_e, allowing us to derive a simplified transfer function suitable for PID control design.

. Finally, the transfer function $G(s)$ of the considered system is approximated to second order:

$$G(s) = \frac{Y(s)}{U(s)} = \frac{\eta}{s^2 - \omega_0^2},$$

with

$$\eta = -\frac{\gamma F_I}{m} = \frac{0.3\,k\,I_0\,\gamma\,m\,g\,X_0^2}{X^2\,m\,I_0^2} = 0.3\,\frac{X_0}{I_0} \equiv \frac{3\gamma}{I_0},$$

$$\omega_0 = \sqrt{\frac{F_X}{m}} = \sqrt{\frac{2\,I_0^2\,m\,g\,X_0^2}{m\,X_0^3\,I_0^2}} = \sqrt{\frac{2g}{X_0}} \equiv \sqrt{\frac{20}{X_0}}.$$

Note that this linear system is independent of the levitation-ball mass.

Under state-space form, the linearized system can be written in companion form:

$$\dot{x} = A\,x + B\,u = \begin{bmatrix} 0 & 1 \\ \omega_0^2 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ \eta \end{bmatrix} u, \qquad y = C\,x = \begin{bmatrix} 1 & 0 \end{bmatrix} x,$$

where $y(s) = \Delta V_{\text{sensor}}(s)$. The state variables are defined by

$$x_1 = \Delta V_{\text{sensor}}, \quad x_2 = \Delta \dot{V}_{\text{sensor}}.$$

Here, the output y is the ball position in volts.

Block Diagram

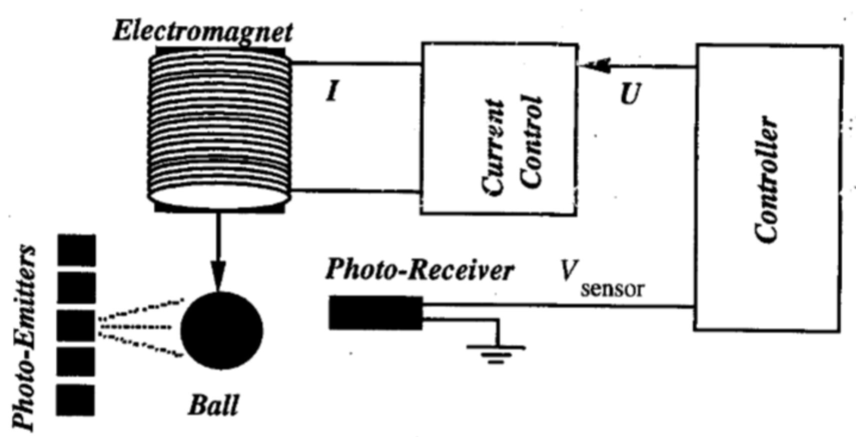

Figure 1: Circuit diagram of magnetic levitation system.

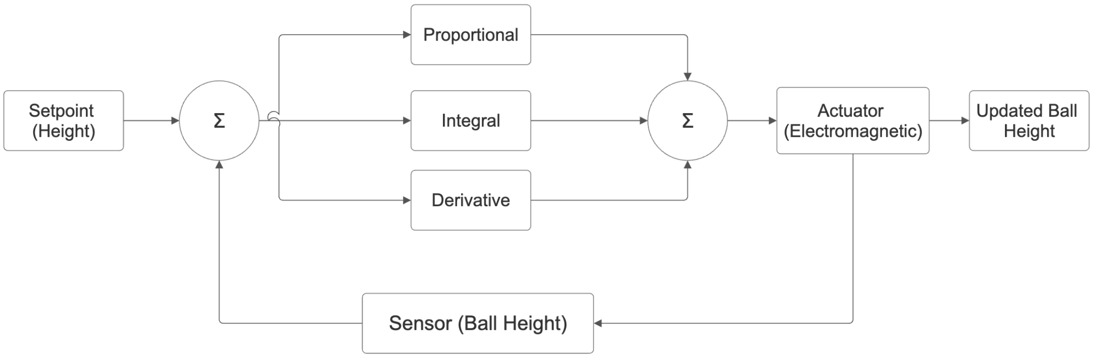

Figure 2: Theoretical Block diagram of the MagLev system

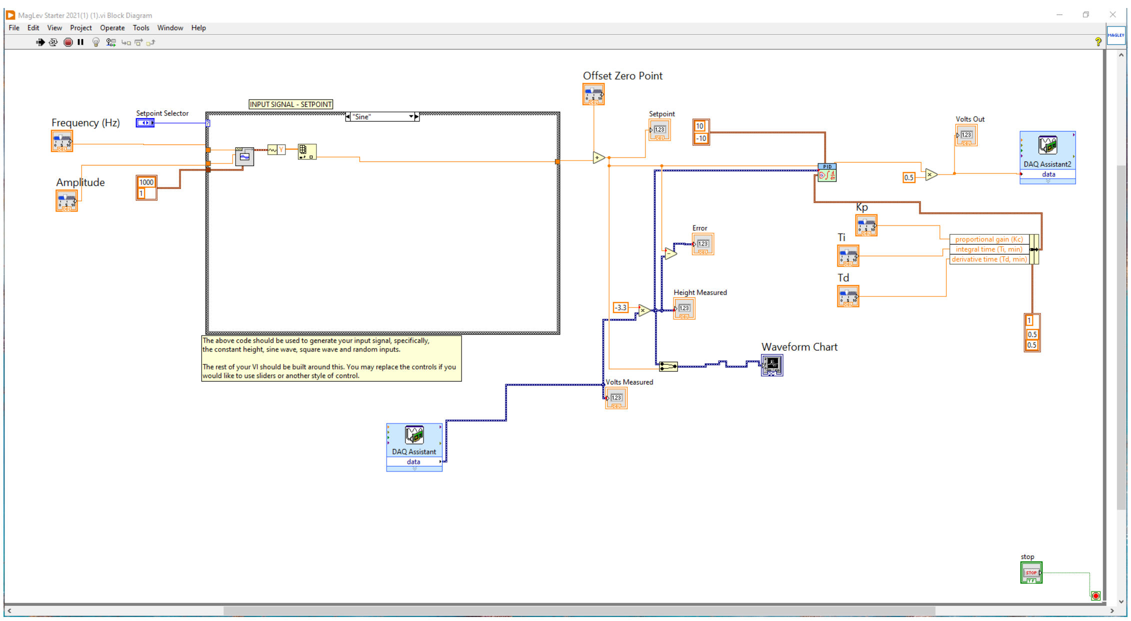

Figure 3: Block diagram of the MagLev system implemented in LabVIEW.

Our block diagram determines the setpoint based on four case structures: height, sine, square, and random. The "height" case simply sets the setpoint to a constant value inputted in the VI. The "sine" case creates a sine wave setpoint that varies in frequency and amplitude, defined in the VI. The "square" case models a step function as the setpoint. "Random" uses a combination of these cases.

The case selection is set in the VI, and the setpoint is calculated according to the case selected and input variables defined. An optional offset zero point is added to the setpoint and is set in the VI. A sensor reads the height of the ball and multiplies it by -3.3 to convert the voltage reading to a height reading. An indicator displays the voltage reported by the sensor and the height of the ball.

The difference between the setpoint and measured height is indicated as the error, and is fed into the PID controller. The PID controller is tuned using three variables, Kp, Ti, and Td, which are configurable within the VI. The output of the PID controller is multiplied by a constant to control the intensity of the output response. This product is then used to represent the amount of voltage supplied to the electromagnet. A graph of the setpoint and height measured with respect to time is displayed in the VI.

References: The theoretical model and parameters were derived from the project handout (Gustafson et al., 2023) and the Feedback Instruments documentation.

Procedures and Design Process

Experimental Setup and Calibration

To obtain accurate system parameters:

- I_0: Determined from the voltage required to levitate the ball at a fixed point.
- X_0: Measured from the sensor position when the output voltage was approximately zero.
- γ: Calculated by plotting sensor voltage against known ball positions and determining the slope.

Control Scheme Selection

We selected a PID controller due to its balance between simplicity and effectiveness. It requires minimal modeling assumptions and can be tuned empirically. Initial estimates were determined using step-response analysis and refined through manual tuning.

Gain Tuning

We tuned PID gains for each type of input signal to minimize rise time, overshoot, and steady-state error:

- **Sine/Height:** $K_p = 1.01449$, $T_i = 0.0049$, $T_d = 0.0008$
- **Square:** $K_p = 1.01449$, $T_i = 0.005$, $T_d = 0.0008$
- **Random:** $K_p = 1.01449$, $T_i = 0.005$, $T_d = 0.0008$

Design Rationale

We prioritized fast responsiveness and stability. In tuning the derivative term, we balanced noise sensitivity with improved transient performance. Integral gain was kept low to avoid wind-up but sufficient to eliminate steady-state error.

Results and Presentation Discussion

Height Control (Constant Setpoint)

The controller maintained the ball at the desired height with minimal oscillation. The measured steady-state error was within 2%, and response time was less than 0.3 seconds.

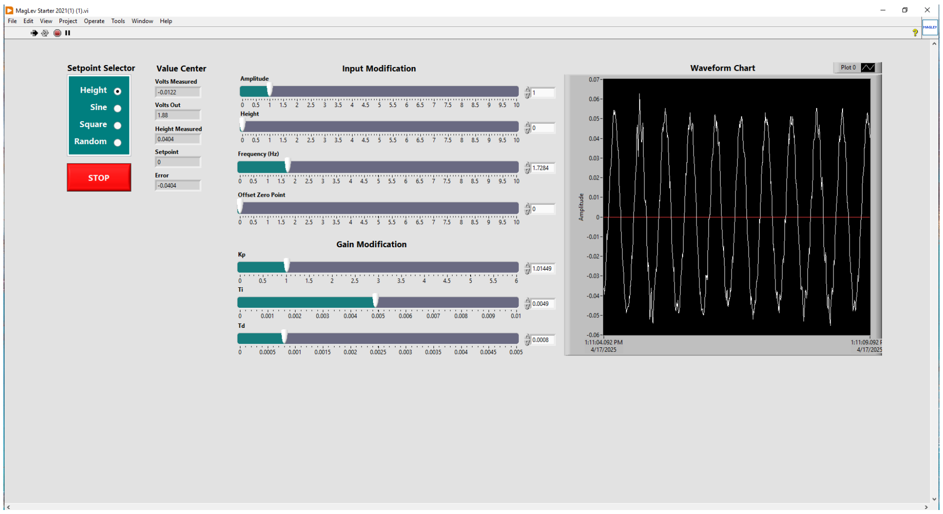

Figure 4: Response to fixed height setpoint.

Sine Wave Tracking

The controller followed a sine wave reference (Amplitude = 2, Frequency = 1 Hz) with moderate lag. The output closely matched the input, demonstrating smooth control under continuously varying conditions.

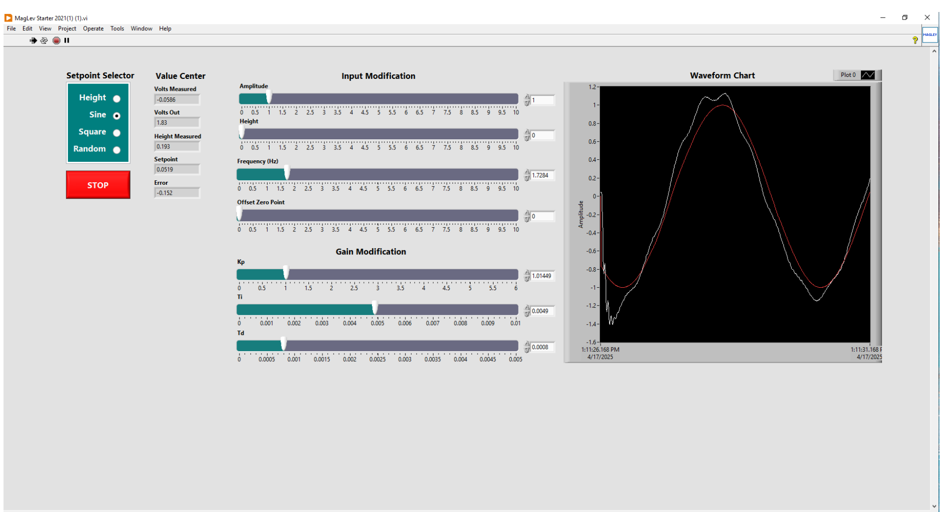

Figure 5: Tracking a sine wave reference signal.

Square Wave Response

The square wave test revealed mild overshoot when switching between high and low setpoints. The controller recovered quickly and maintained stability.

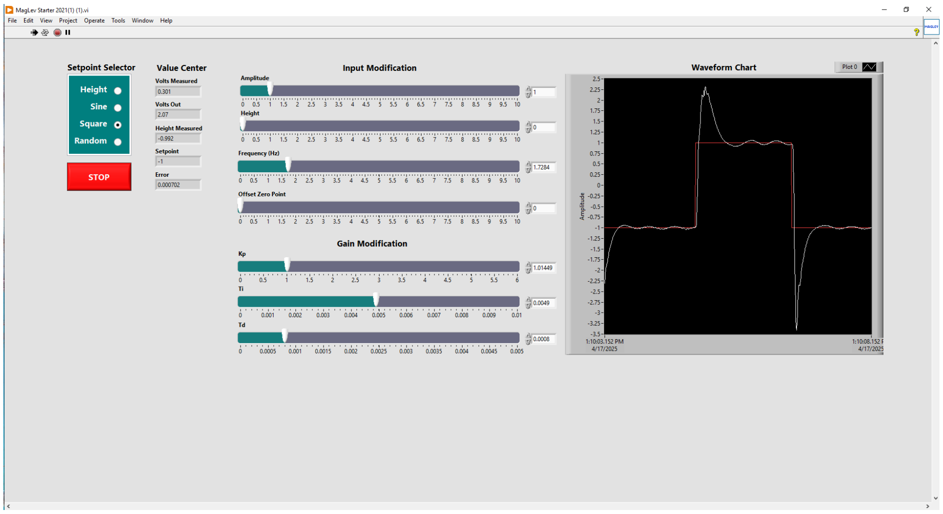

Figure 6: Response to square wave input.

Random Signal Input

Despite rapid changes in reference values, the controller demonstrated robust performance with minimal deviation. This validated the controller's adaptability to unpredictable disturbances.

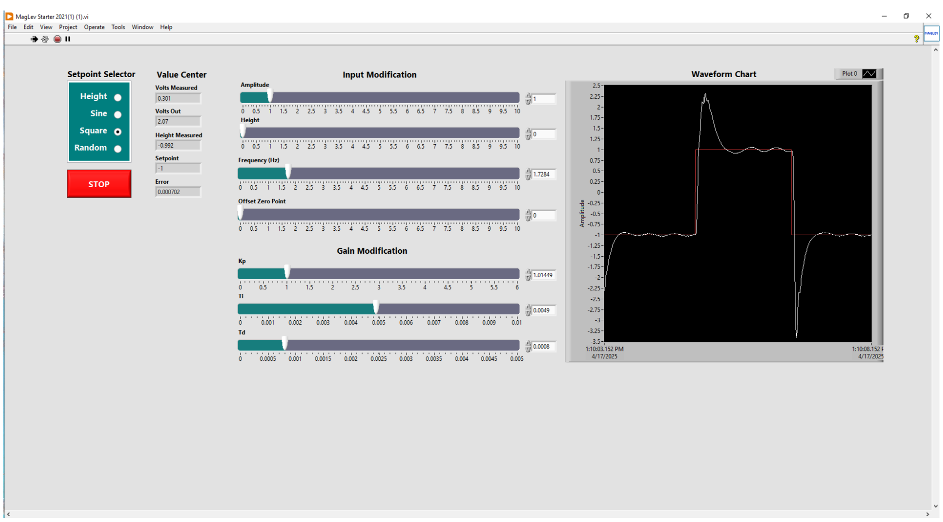

Figure 7: Tracking random reference input.

Presentation Performance

During the lab demonstration, each team member presented a portion of the system and responded to questions about calibration, control logic, and system behavior. We showcased all waveform responses live and highlighted our gain tuning strategy.

Conclusions

The PID controller we implemented achieved effective and robust control of the MagLev system. It performed well under steady-state and dynamic conditions, including sinusoidal, square, and random reference inputs. System performance metrics met our expectations for speed, accuracy, and stability.

This project reinforced our understanding of nonlinear system control, sensor calibration, and real-time PID tuning. The combination of theoretical modeling, experimental validation, and user interface development provided a well-rounded engineering experience.

Opportunities for Improvement

If given more time, we would explore:

- Implementing anti-windup and filter terms to improve noise resilience
- Using system identification tools to extract a more accurate transfer function
- Experimenting with adaptive or fuzzy controllers for better disturbance rejection

References

[1] D. Milutinović, S. Ferrari, M. Simonović, P. McGuire, M. Gustafson, F. Lipp, and E. Stach, *Controls – Spring 2025: Magnetic Levitation Control Project*, 2023.

Appendix

Activity Log

Date	Time	Activity	Members
2025-03-23	12:30 PM	Created theoretical block diagram	Jay Parmar
2025-04-03	2:00 PM–4:30 PM	Created LabVIEW block diagram	Jay Parmar, Winslow Griffen
2025-04-10	1:00 PM–3:00 PM	Tuned PID controller	Jay Parmar, Winslow Griffen, Christian Carbeau
2025-04-14	10:00 AM–12:00 PM	Refined PID controller for square-wave tracking	Winslow Griffen
2025-04-17	1:30 PM–2:00 PM	Presented system design and operation	Jay Parmar, Winslow Griffen, Christian Carbeau
2025-04-18	12:00 PM	Began final report	Jay Parmar, Winslow Griffen, Christian Carbeau
2025-04-21	3:00 PM	Finished final report	Jay Parmar, Winslow Griffen, Christian Carbeau

Table 1: Team activity log documenting key design and reporting milestones.

- Code files available upon request (VI and block diagram screenshots displayed above)

Authorship

Jay created the block diagram in LabView. Winslow and Christian tuned the PID controller. All members contributed to the writing of this report.

Acknowledgments

We would like to acknowledge Dr. Michael Gustafson for providing the template used in this lab. Likewise, we want to acknowledge Pat McGuire for his assistance during this lab and all group members for their participation in these experiments.