ME 331

Magnetic Levitation Control Report

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Contents

1 Abstract

The Magnetic Levitation (MagLev) system project represents an innovative application of control engineering principles. The purpose of this experiment was to employ electromagnetic fields to levitate a metal ball in a controlled manner using a system driven by both hardware and software controllers. Through the use of a PID (Proportional-Integral-Derivative) controller, the system aimed to achieve stable levitation and precise control of the ball's height.
The experiment showed that the designed PID controller was successful in maintaining stable levitation of the metal ball under various input conditions, including height control, sinusoidal waves, square waves, and random patterns. Among these inputs, the sinewave height control demonstrated the most effective results due to its gradual change in height over time. We were able to increase the sine wave amplitude up to 4, while maintaining stability. We could only increase the square wave to an amplitude of 0.5 before the system would become unstable and the metal ball would stop levitating.

2 Introduction and Theory

The purpose of the magnetic levitation lab is to use control engineering in a real world system. The system is set up with a magnet at the top of the device with two voltage sensors on either side. These voltage sensors were used in the tuning of the system as the goal was to obtain a voltage reading of zero, which would indicate a system in which the ball can levitate because it is neither being pulled towards the magnet or pushed away from it. A picture of the experimental setup is displayed in the figure below.

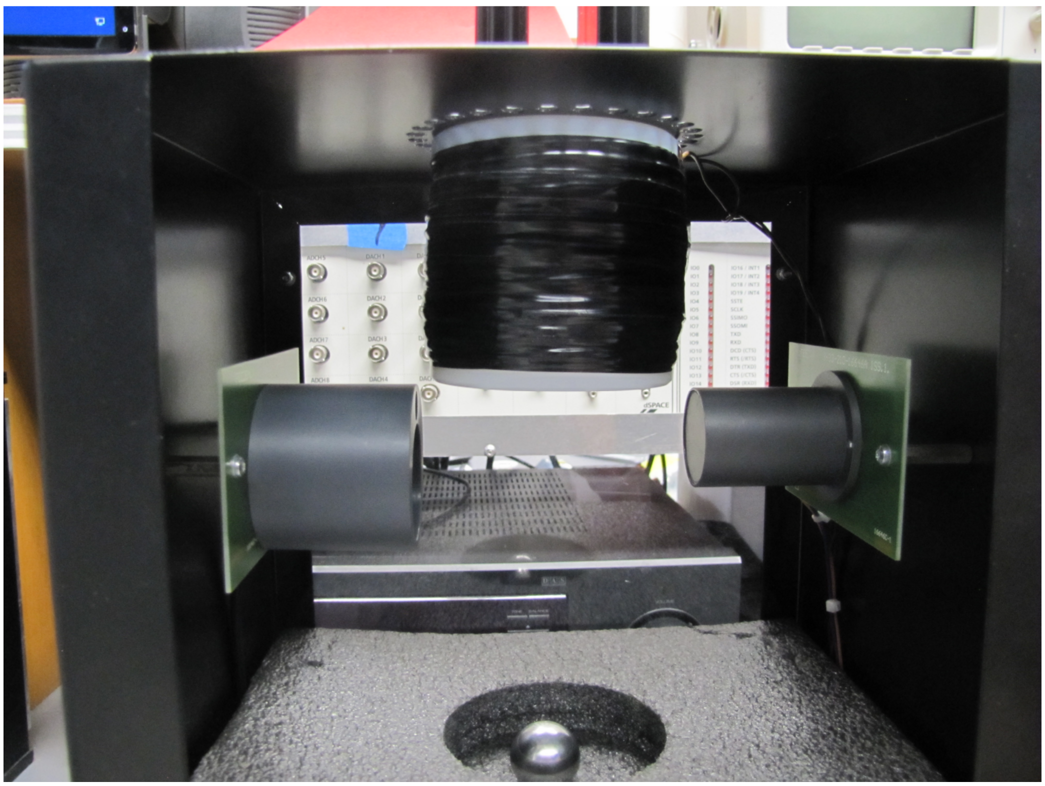

Figure 1: Experimental Set-Up

2.1 System Schematics and Block Diagram

In order to tune the system to get the metal ball to levitate, it is important to understand how the system operates. This is where the schematic of the system and the theoretical block diagram helped. It analyzes how the system comes together and what components (specifically the PID controller are important in getting the system to function correctly. The majority of our work focused on figuring out how to configure the PID so that it would operate the magnet correctly and acheive the proper attraction without it being too strong. However, it was important to understand how the whole system worked so that the proper VI could be assembled.

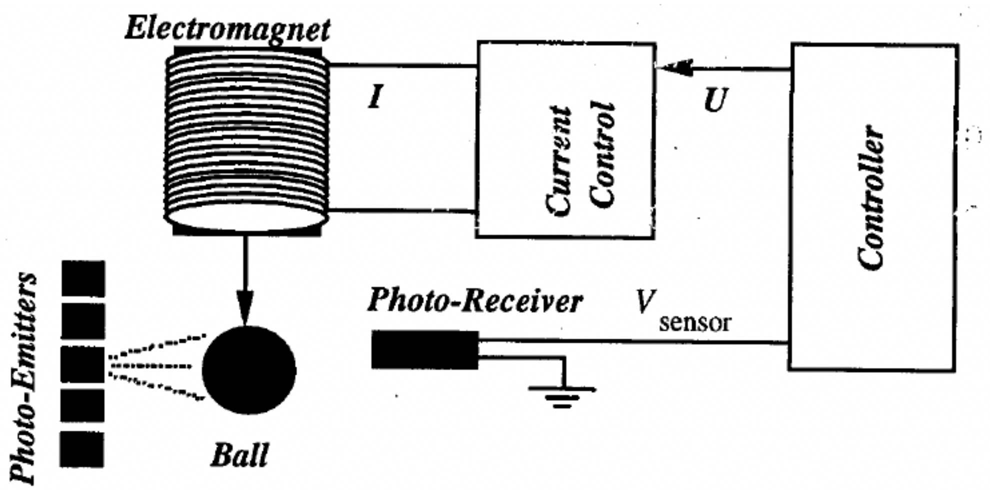

Figure 2: Schematic of System (Source 1)

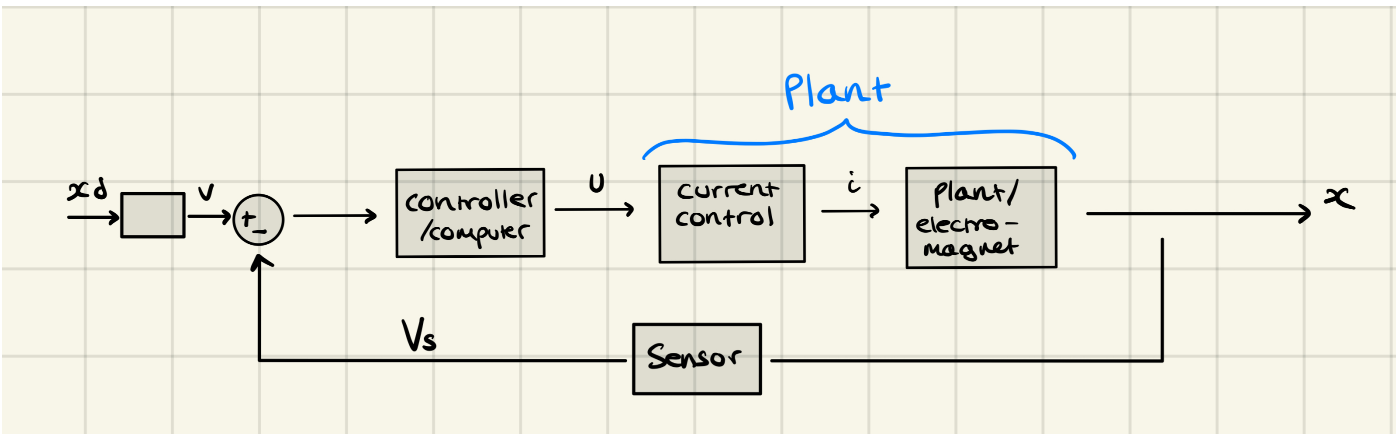

Figure 3: Theoretical Block Diagram of System

2.2 MagLev System and its Operation

The Magnetic Levitation (MagLev) system utilized in this project represents a cutting-edge application of control engineering principles. This system employs electromagnetic fields to levitate a metal ball in a controlled manner. The MagLev system operates on the principle of electromagnetic induction, whereby magnetic fields are generated to counteract gravitational forces, thereby suspending the metal ball in mid-air.

The system consists of two controllers, a lead compensation controller and a controller driven by the software. The photo-sensor measured the balls position and provides a measurement of the distance of the ball from the electromagnet by providing a voltage V_{sensor}, which operates according to equation 1.

$$V_{sensor} = -\gamma(x - x_o) \qquad \gamma > 0 \tag{1}$$

where x_o is the nominal operating point.

The current through the electromagnet is controlled by an inner-loop and is related to the voltage controller output U by equation 2.

$$I = 0.15U + i_o \tag{2}$$

where i_o is the nominal current corresponding to the nominal operating ball position x_o.

Finally, the displacement of the ball is governed by equation 3, where m is the mass of the ball, g is gravity, x is the distance of the ball from the electromagnet, i is the current through the electromagnet and k is a coefficient.

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

This system of equations can be linearized to approximate the system to second order. This process is as follows,

$$x = x_o + \delta_x \qquad\qquad i = i_o + \delta_x \tag{4}$$

$$m(\delta\ddot{x}) = mg - k\frac{i_o^2 + 2i_o\delta_i + \delta_i^2}{x_o^2 + 2x_o\delta_x + \delta_x^2} \tag{5}$$

$$m(\delta\ddot{x}) = mg - k\frac{i_o^2 + 2i_o\delta_i + \delta_i^2}{x_o^2 + 2x_o\delta_x + \delta_x^2} \tag{6}$$

$$(x_o^2 + 2x_o\delta_x + \delta_x^2)(m\delta\ddot{x} - mg) = -k(i_o^2 + 2i_o\delta_i + \delta_i^2) \tag{7}$$

This can be subdivided into the different orders as follows,

$$O(1) \qquad\qquad -mgx_o^2 = -ki_o^2 k = mg\frac{x_o^2}{i_o^2} \tag{8}$$

$$O(\epsilon) \qquad\qquad mx_o^2\delta\ddot{x} - 2mgx_o\delta_x = -2ki_o\delta_i\delta\ddot{x} = \frac{2g}{x_o}\delta_x - \frac{2ki_o}{mx_o^2}\delta_i \tag{9}$$

By integration of equation 1 and 2 into the above equations, we can deduce the transfer fucntion $G(s) = \frac{V_s(s)}{U(s)}$ as follows,

$$V_s(s)\left(\frac{2g}{x_o\gamma} - \frac{s^2}{\gamma}\right) = \frac{-0.3ki_o}{mX_o^2}U(s) \tag{10}$$

$$\frac{V_s(s)}{U(s)} = \frac{0.3ki_o}{mx_o^2\left(\frac{s^2}{\gamma} - \frac{2g}{x_o\gamma}\right)} = \frac{0.3g\gamma}{i_o\left(s^2 - \frac{2g}{x_o}\right)} \tag{11}$$

$$\tag{12}$$

where k $= \frac{mgx_o^2}{i_o^2}$ from the equilibrium conditions around x_o and i_o. From this we can also say that $\eta = \frac{0.3g\gamma}{i_o}$ and $\omega_o^2 = \frac{2g}{x_o}$. The constants x_o and i_o are calculated below in section 3.1.

These were our governing equations before diving into the experimental component of the device.

3 Procedures and Design Process

3.1 Determination of Constants (Io, Xo, gamma)

To find the value of gamma, we evaluated the voltage readings at set heights within the electromagnet. We learned very quickly that the ball had to remain in the same position in laterally as variations in the x and y positions would also cause variations in the voltage reading, and we only wanted to measure the variation with respect to the z-axis (height). In order to ensure that the ball remained centered throughout all the readings, we designed a test stand with an indent for the ball with stack-able additions. The test stand fit within the circular cutout in the foam base of the electromagnet, as this ensured it was positioned in the same place every time. This design allowed for us to also accurately measure the variable height, as the test stand and each stacking block was of a known height. The height was consistently measured from the foam base of the maglev machine. This gave us several data points which we plotted and then found a line of best fit. The slope of this line was our value for gamma, γ. Our data collected is shown below in the figure, which produced a γ of -0.226.

The value of x_o was found using equation 1 above, and the value of the position when the voltage is zero.

$$V_{sensor} = -\gamma(x - x_o) \tag{13}$$

$$\text{when } V_{sensor} = 0, \quad 0 = -\gamma(x - x_o) \text{ therefore } x = x_o \tag{14}$$

From Figure 4 and the equation of the slope, we determined that the x-intercept, and therefore the value of x_o was 81.42mm.

$$V = -0.226x + 18.4 \tag{15}$$
$$0 = -0.226x_o + 18.4 \tag{16}$$
$$0.226x_o = 18.4 \tag{17}$$
$$x_o = 81.42\ mm \tag{18}$$

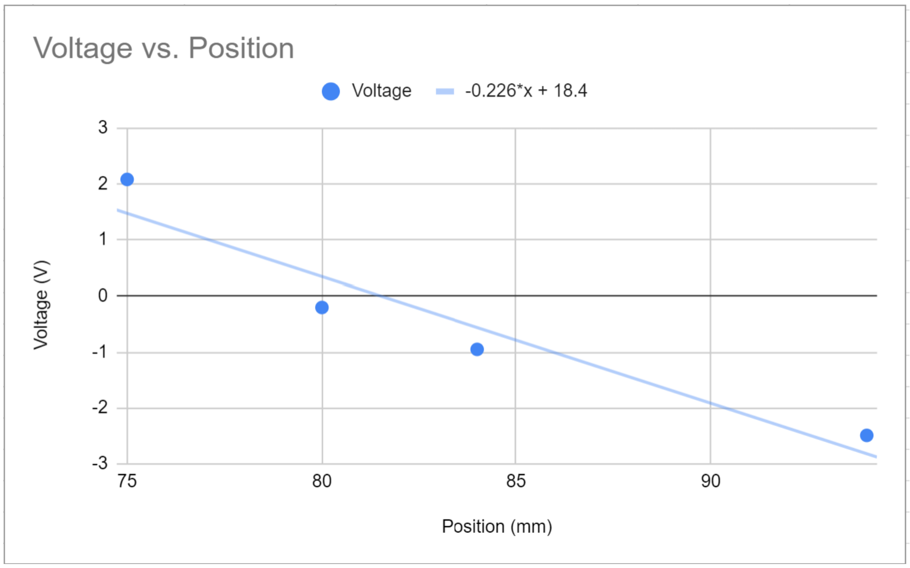

Figure 4: Voltage Readings to Determine γ

The value of i_o can be determined from the voltage across the electromagnet, V_{i_o} and the resistance of the electromagnet. In the lab manual, it states that V_{i_o} is in the range 13.4 to 14 V. It also gives the resistance of the electromagnet as 22 $\Omega. Therefore, to calculate i_o$ we took the average value of the range of values for voltage, and used Ohms law.

$$V_{i_o} = i_o R \tag{19}$$
$$i_o = \frac{V_{i_o}}{R} = \frac{13.7}{22} = 0.623A \tag{20}$$

3.2 Controller Type Selection and Tuning Process

The choice of controller type was based on the desired closed-loop dynamic response, taking into account factors such as transient response, steady-state error, and stability. The PID (Proportional-Integral-Derivative) controller was selected as the primary control mechanism due to its simplicity and effectiveness in a wide range of applications. In addition, by having an integral and derivative component, the controller was able to make the ball follow closely to the desired input, as the integral component helps to reduce teh steady state error and the derivative component helps to reduce the overshoot.

Variable	**Symbol**	**Value**
Proportional Gain	K_p	1
Integral Time	T_i	0.001665
Derivative time	T_d	0.0004166

Table 1: PID Controller Values

We first had the PID controller with a proportional gain, K_p, of 1 and an integral time, T_i, and derivative time, T_d, of zero. After inputting out gamma value into our controller, we noticed that the ball was close to being stable. There was a height where the ball would almost remain stationary with a slight pressure, however after releasing this pressure it would start to oscillate. To fine-tune the PID controller, we found the time period of these oscillations and input them into the calculator used in the turntable lab which inputs the gain and time period, and gives a value for the Integral and derivative time. The calculator gave values of 0.001665 and 0.0004166 for T_i and T_d respectively. When we input these values into the PID controller, the ball was able to float within the maglev device without any support.

4 Results

4.1 Test Inputs

After getting the ball to successfully float within the Maglev device, we then conducted experiments to see how effective the controller was with the different 4 inputs - height, sinewave, square wave and random. We tested the maximum and minimum point the ball was able to remain stable within the Maglev machine. This helped us to know the boundaries the ball could move between and therefore the correct offset for each input, as well as the constraints on the amplitude. We then ran each input, gradually adjusting the values to see at what point they all failed.

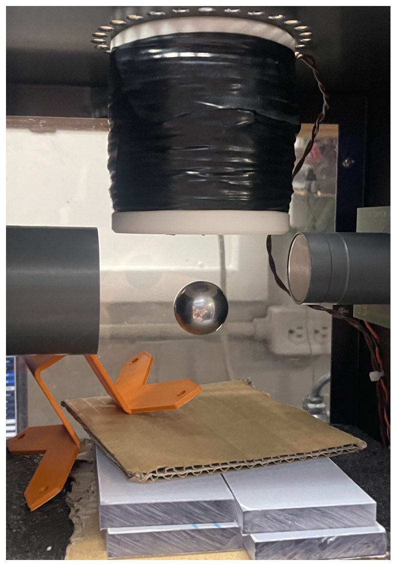

Figure 5: Stable Floating Ball

4.1.1 Height Control

The controller we designed was immediately extremely effective in adjusting the height of the ball when given an input. The stable point of the ball was considered to be zero, and when inputting a height of 1mm the ball would instantaneously jump up 1 mm. We were able to get the ball to a maximum height of -2 mm and a minimum drop of 2 mm from the equilibrium point 0 mm) while increasing the height in 1 mm intervals. We noticed that the ball would drop and the controller would fail if the height jumped more than 1 mm at a time, even at a height it was shown to be able to reach.

4.1.2 Sine Wave

The sine wave height control was extremely effective as the height of the ball would transition gradually and therefore there was not the issue of the sharp changes in height causing the ball to drop as in the height control.

We were able to achieve a sine wave with a maximum amplitude of 4 when the offset zero was set to 2. The offset zero point was important to achieve this amplitude as if the ball fell too low the magnetic force would not be strong enough the keep the ball floating. In addition, we generally set the frequency of the sine wave to 3 as this was fast enough to be able to see the height changes without the height fluctuating too fast and causing the ball to drop.

4.1.3 Square Wave

The square wave input was harder to achieve, as by the nature of the square wave, the adjustments in height are very sharp. This meant we were able to achieve the ball moving in a square wave patterns but only with much smaller amplitudes than the sinewave. The maximum amplitude of the square wave we were able to achieve was 0.5 with an offset point of 2.

4.1.4 Random

Much like the square wave input, the random input was harder to achieve due to the abrupt nature of the height adjustments. However, we were also able to achieve the random input with an amplitude of 0.5 and offset point of 2.

4.2 Oral Presentation

In our oral presentation, we successfully demonstrated how the control panel can modify voltage input to ensure stable levitation at the desired position. This was exemplified during the demonstration and elaborated on within the block diagram. Furthermore, we showcased our ability to accurately calculate gamma through position calculation and voltage intake. Overall, our presentation highlighted our comprehensive understanding of the Maglev Lab and its application of PID controllers to real-world scenarios.

5 Conclusions

The Magnetic Levitation (MagLev) system project effectively demonstrates the application of control engineering principles, particularly PID control, for achieving stable levitation of a metal ball. The experiments conducted provided insights into the system's performance under various inputs and showcased the ability of the designed PID controller to maintain stable levitation and control of the ball's height. We were able to successfully achieve a control system that was able to adjust the ball's height within the device using all 4 inputs. The sine wave input gave the most effective results due to the gradual change in height over time.

Given more time, conducting more experiments to fine-tune the PID controller further could improve the stability and responsiveness of the MagLev system. Exploring advanced control methods such as model predictive control (MPC) or adaptive control may offer additional benefits in managing the system's non-linearities and uncertainties. Improved precision and accuracy of the photo-sensor and other measurement tools could lead to better control and response.

Further testing with more complex input scenarios and environmental conditions, such as temperature and air resistance, would provide a deeper understanding of the system's robustness and adaptability. Additionally, investigating nonlinear control approaches, like sliding mode control, may offer improvements in performance and stability.

Overall, this project lays a solid foundation for future exploration in control engineering, offering a pathway for further advancements in similar PID control applications.

A Sources

1. Gustafson, Lipp, Stach, et al. (2023). *MagLev Final_s24_rev1* [Lab Maglev]. Retrieved from Duke University Engineering Department.

B Appendix

Date	Time Spent	Activity Description	Members Involved
Wed 4/3	2 hrs	Initial Review of the Equipment and Preliminary Questions	All members
Thur 4/4	1 hr	Initial Experimentation with computing gamma	All members
4/9	3 hrs	Designing Block Diagram and Achieving a floating ball	All members
4/10	2 hrs	PID gain fine tuning and experimenting with test inputs	All members
4/10	1 hr	Starting Lab report write up	Izzy Dudlyke
4/12	1 hr	Adding and refining lab report write up	Carly Fowler
4/13	1 hr	Editing and refining lab report write up	Elsie Gothman
4/15	2 hrs	Finalising Lab Report write up	All members
4/17	1 hr	Maglev Presentation	All members

Table 2: Activity Log

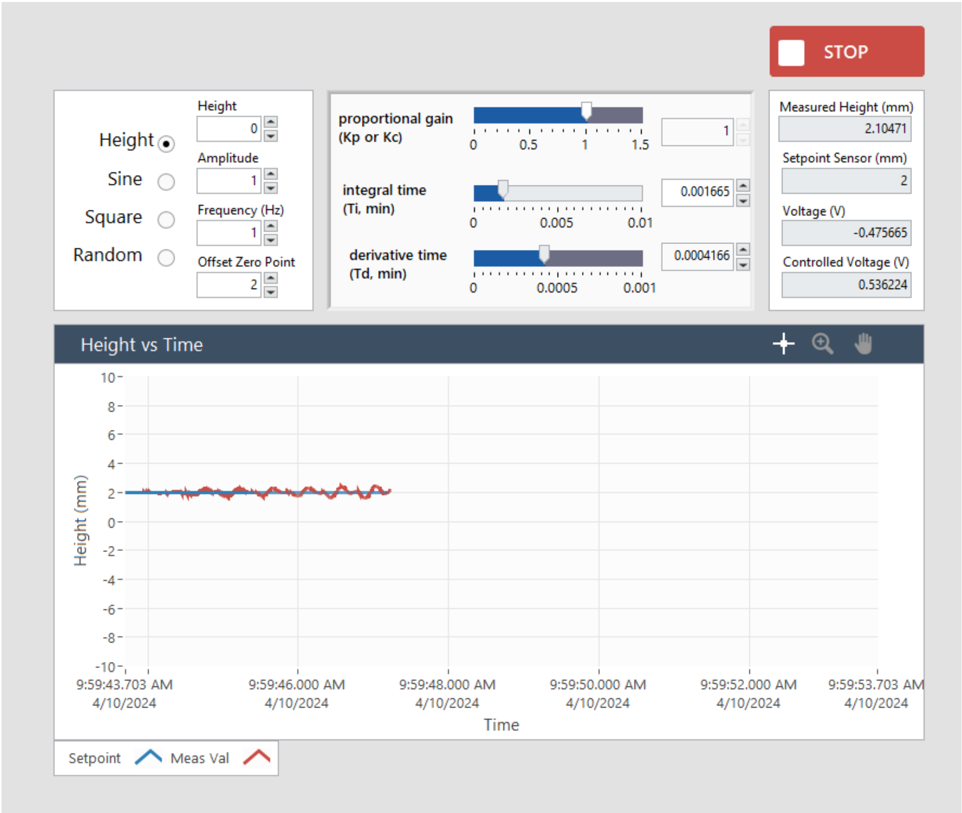

Figure 6: Control Panel

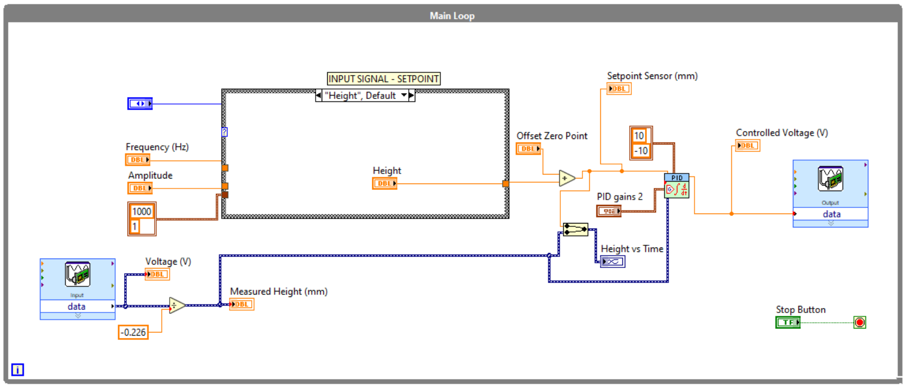

Figure 7: Block Diagram