FPGA Implementation of Multiple Controllers for a Magnetic Suspension System

Final Report

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Abstract

System modeling and dynamics of the magnetic suspension system are interesting and challenging due to the nonlinear nature of the system. A nonlinear plant model has been studied and linearized. Different controllers have been designed and implemented on various hardware platforms including xPC Target Box and Motorola ColdFire microcontroller using Simulink and real-time workshop. Considering the very costly price ranges of such hardware, this project's original objective was to implement multiple controllers for the magnetic suspension system using a low-cost Field Programmable Gate Array board. However, only one previously designed controller was implemented. FPGA has advantages in design flexibility and functional enhancement. A system has been designed and implemented to demonstrate the controller for the magnetic suspension system. The system includes Spartan3E FPGA, digital-to-analog (D/A) converter, analog-to-digital (A/D) converter, and conditioning circuitry. The previous controller has been simulated using Xilinx system generator, a design tool for FPGA fixed-point implementation. In addition, the controller has been programmed in VHDL for FPGA implementation. This study shows that the Xilinx system generator is an efficient design tool for adjusting finite word-length, and FPGA is a viable platform for controller implementation.

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Introduction

System modeling and dynamics of the magnetic suspension system are interesting and challenging due to the nonlinear nature of the system. A linear plant model has been studied and different controllers have been designed and implemented on various hardware platforms including xPC target box and Motorola ColdFire microcontroller using Simulink and Real-time workshop [1, 2]. Field Programmable Gate Array (FPGA) has been widely used in embedded applications. It has advantages in design flexibility and functional enhancement. In this project, an FPGA is used to implement a controller for a magnetic suspension system. The motivation for this project is mainly to reduce costs. In addition, this project proves that an FPGA board can be used for controller implementation. This has not been done before in the ECE Department of Bradley University. Figure 1 shows the Spartan3E FPGA Board used in this project.

Figure 1 - Spartan3E FPGA Board

Background

Magnetic suspension systems are progressively used in industrial rotating machinery applications. They offer a number of practical advantages such as capacity for linear displacement, can operate at extreme temperatures with a longer lifespan, high rotational speeds, and low energy consumption. The problem of lubrication is eliminated by the absence of mechanical contacts that are present. The magnetic suspension system uses an electromagnetic force to suspend a hollow metal ball [3].

A schematic diagram of the magnetic suspension system is shown in Figure 2.

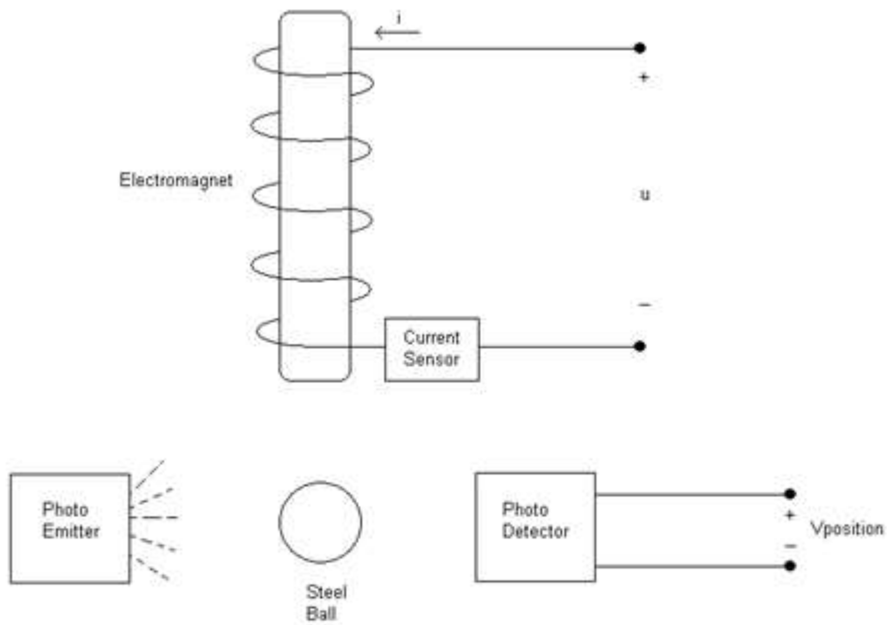

Figure 2 - Schematic Diagram of a Magnetic Suspension System [1]

Many controller design methods may be used to design controllers to satisfy performance goals. The controller design method used in this case relies heavily on a detailed mathematical model of the plant. The general nonlinear mathematical model of the magnetic suspension system is

$$\dot{x}_1 = x_2 \tag{1}$$

$$\dot{x}_2 = g - \frac{k}{m}\left(\frac{x_3}{x_1}\right)^2 \tag{2}$$

$$\dot{x}_3 = -\frac{R}{L}x_3 + \frac{2k}{L}\left(\frac{x_2 x_3}{x_1^2}\right) + \frac{u}{L} \tag{3}$$

where R is the resistance of the coil, L is the inductance of the coil, m is the mass of the steel ball, k is the force constant, x_1 is the distance of the steel ball from the electromagnet, x_2 is the velocity of the steel ball and x_3 is the coil current [1]. The model given in Eq. (3) assumes that the coil current is generated by the control voltage u directly.

Figure 3 shows the Feedback Incorporated Magnetic Suspension System.

Figure 3 - Magnetic Suspension System

However, the schematic diagram of the magnetic suspension system developed by Feedback Incorporated, shown in Figure 4, uses an active coil driver circuit to generate the coil current, and the force constant *k* cannot be easily measured. For these reasons a linear mathematical model was obtained experimentally in a previous student project.

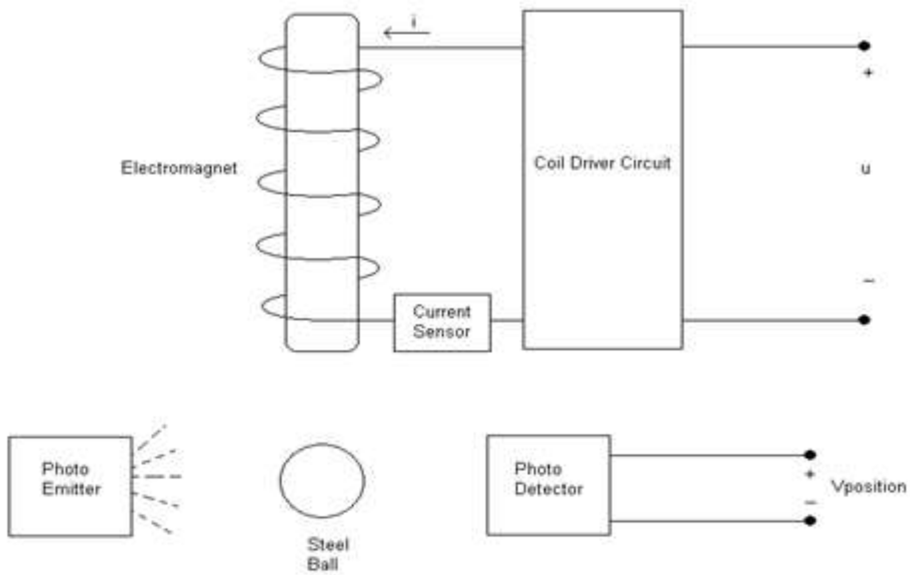

Figure 4 - A Schematic Diagram of Feedback Incorporated Model 33-210 Magnetic Suspension System [1]

The method of choice for this project is the Internal Model Principle, which was developed by B.A. Francis and W.M. Wonham [4]. The theory behind the Internal Model Principle is that the controller should include the model of the disturbance so that it can be rejected.

The Internal Model Principle is a mathematical approach to controller design. The actual model that is created using this method is a polynomial consisting of the least common factors of the unstable denominator roots of both the reference input signal and the disturbance to be rejected. In this project the reference input was considered to be a step function. The continuous transfer function was converted to a discrete transfer function using a "zero-order hold" method in MATLAB with a sample time of 1ms. A table of discrete transfer function denominators and their associated models appear in Table 1.

Functions	Continuous	Discrete	Model
Step	$\frac{1}{s}$	$z-1$	$z-1$
Ramp	$\frac{1}{s^2}$	z^2-2z+1	z^2-2z+1
Sinusoidal	$\frac{a}{s^2+a^2}$	$z^2-2z\cos(.001*a)+1$	$(z^2-2z\cos(.001*a)+1)(z-1)$

Table 1 - Table of Models for Specific Disturbance Classes

Once the model has been created, the model is inserted into the denominator of the controller to be designed. Figure 5 shows the proper placement of the model, P(z), in the denominator of the controller B(z)/A(z).

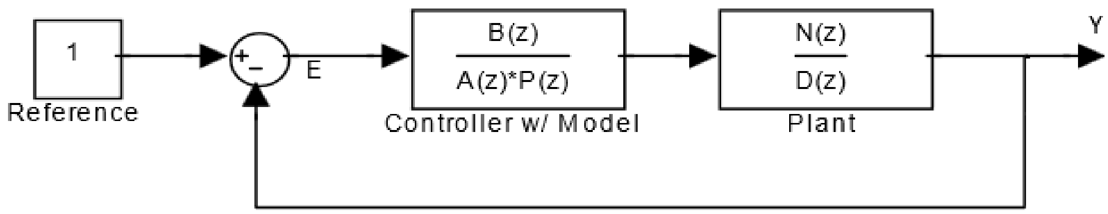

Figure 5 - Block Diagram Showing Location of Model and Controller Polynomials

The denominator of the closed loop system in Figure 5 is found to be D(z)P(z)A(z)+B(z)N(z). In this equation, N, D and P are known polynomials from the plant and the model. This leaves A(z) and B(z) to be found.

Solving a Diophantine equation of the form

$$D(z)P(z)A(z)+B(z)N(z) = F(z) \qquad (4)$$

both A(z) and B(z) can be determined assuming D(z) and N(z) of the plant are co-prime. The polynomial F(z) is a performance polynomial with roots at desired locations in the unit circle in the z-plane. These roots are placed at locations to achieve low percent overshoot, fast settling time and a minimal control signal.

The order of F(z) is dependent upon the order of the desired controller, the order of the plant and the order of the disturbance model. For example, the plant used has an N(z) of order 1 and a D(z) of order 2. The P(z) model for the ramp input disturbance from Table 1-1 is of order 2. Combining D(z) and P(z) gives order 4. Let the controller have a B(z) of order 3 and an A(z) of order 1 so that the actual controller, which includes the P(z) will have a denominator and numerator both of order 3. In the Diophantine equation, D(z), P(z) and A(z) combine to form a polynomial of order 5. Therefore, the order of F(z) will be 5 in order to solve Eq. (4). [2]

Project Goals

- ☐ Prove that FPGA is a viable solution for the magnetic suspension system.
- ☐ Design and implement a stand-alone system which includes FPGA, ADC, DAC, and conditioning circuitry.
- ☐ Utilize Xilinx System Generator simulation to determine computation precision of FPGA implementation.
- ☐ Design the system using VHDL
- ☐ Compare FPGA implementation results with those from other platforms such as xPC Target Box and Motorola ColdFire microcontroller

Previous Work

The Plant Model shown in Eq. (4) and Eq. (5) is the result after the reduction of the general nonlinear mathematical model of the magnetic suspension system. The plant model shows the relationship between the input control voltage *u* and the coil current x_3. [1]

$$\dot{x}_1 = x_2 \qquad (4)$$

$$\dot{x}_2 = g - \frac{k}{m}\left(\frac{f(u)}{x_1}\right)^2 \qquad (5)$$

Where x_1 is the displacement of the steel ball, x_2 is the velocity of the steel ball, *k* is the force constant, *u* is the control voltage, and *m* is the mass of the steel ball.

These equations were then linearized about an equilibrium point to obtain the continuous-time transfer function shown in Eq. (6).

$$H(s) = \frac{7.67}{\frac{s^2}{961} - 1} \qquad (6)$$

A sampling interval of 1ms was used to convert Eq. (6) to the discrete-time transfer function shown in Eq. (7). [1]

$$H(z) = \frac{6.6343e^{-4}\,z + 6.6343e^{-4}}{z^2 - 2.001\,z + 1} \qquad (7)$$

The experimentally determined discrete-time transfer function can then be used in Simulink and Xilinx System Generator along with the previously designed controller by Jon Dunlap, shown in Figure 6, was utilized in this project.

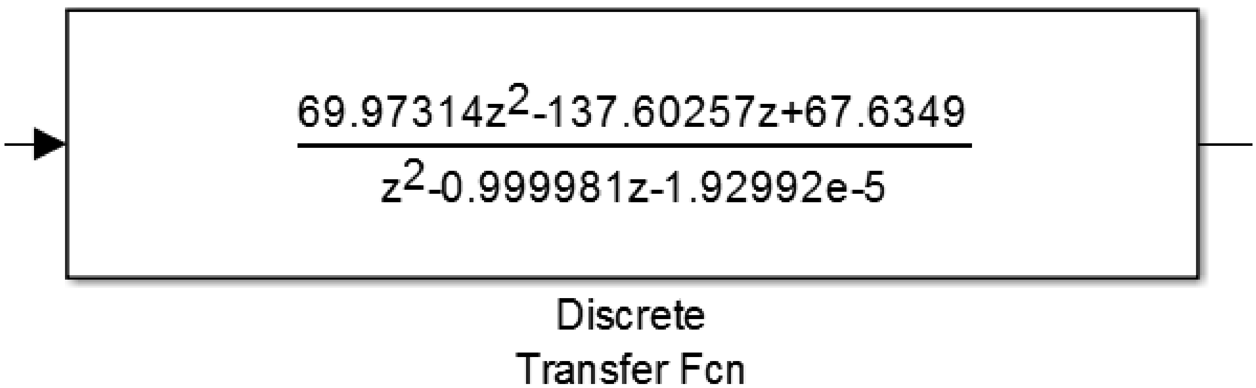

Figure 6 - Dunlap's Classical Controller [2]

This controller was utilized throughout the project to demonstrate that the implementation of a FPGA-based controller is possible.

Functional Description

The high-level block diagram for the overall system, shown in Figure 7, is comprise of three subsystems.

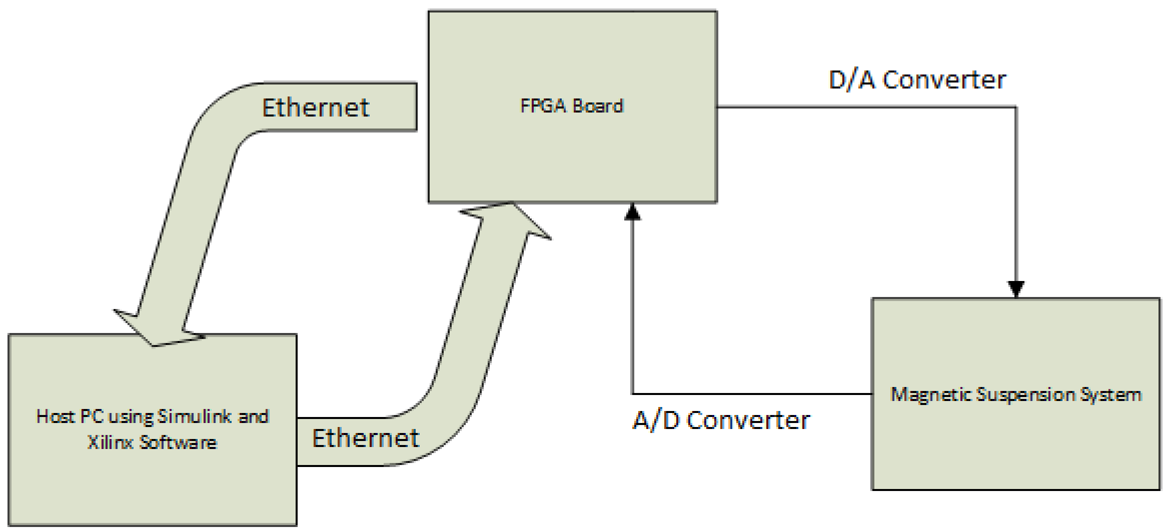

Figure 7 - High-level Functional Diagram

Host PC using Simulink and Xilinx Software

The PC uses Simulink and Xilinx software to compile VHDL code for the Simulink block diagrams and transfer functions. The controller model is then uploaded to the FPGA board using an Ethernet connection.

FPGA Board

The FPGA board holds the mathematical model of the controller model is used to stabilize and control the Magnetic Suspension System. The FPGA board is controlled by the host via Ethernet, which dictates run/stop functionality and also transfer data back to the host. The FPGA board has built in analog to digital and digital to analog converters, which allow data to be sampled from the Magnetic Suspension System as well as allowing control signals to be applied to the system.

Magnetic Suspension System

The magnetic suspension system uses a magnetic force to suspend a hollow metal ball. There are four inputs to the system, a set point, a reference input, a ball position feedback signal, and the disturbance input signal. The set point serves the purpose of giving the system a known location at which the ball should be stabilized. The reference input signal is used when the ball has to track a specific input signal. A sinusoidal reference input waveform, for example, will cause the ball to move in a sinusoidal fashion tracking the input waveform. The third input comes from the photo sensor which converts the ball position to a voltage signal which is fed back to the controller. The fourth input to the system is a disturbance, which will be rejected by the controller in the FPGA board. The output of the magnetic suspension system is a physical position of the ball.

Figure 8 represents the control block diagram for the system. The inputs and outputs of the system combine to form an error signal, which is composed of the reference, set point, and the position signal. This error signal then enters the FPGA board, which acts as the controller, and generates a correction signal for the plant. The correction signal and the disturbance drive the magnetic suspension system.

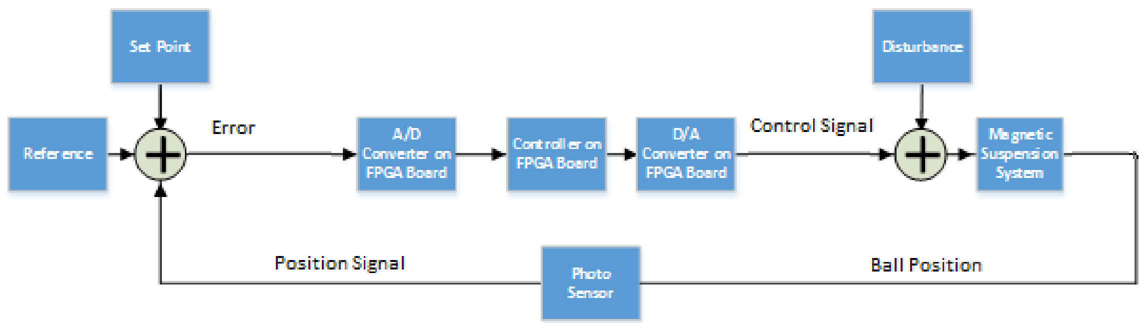

Figure 8 - Control Block Diagram

The magnetic suspension system driver model is shown more clearly in the upper portion of Figure 4. The control signal, “u”, across the Coil Driver Circuit is actually “u” from the controller combine with the disturbance signal, assuming that there is one. The Coil Driver Circuit converts the voltage to a current, which in turn generates a magnetic field around the Electromagnet. This magnetic field is what attracts and ultimately suspends the ball at equilibrium. The current sensor is a one ohm resistor in series with the Electromagnet Coil. Having the current sensor at this location allows experimental data to be taken to verify accuracy. As the ball passes through the photo emitter’s path of radiation, it breaks the light that the photo detector should be seeing. This process is illustrated in the lower portion of Figure 4. This detector converts the broken beam into a voltage representative of the position of the ball.

System Block Diagram

Figure 9 shows the overall system block diagram, which includes the three inputs and the external output. Not shown are the internal signals, which are required to control the system. A further expansion of this system has been shown already in Figure 8.

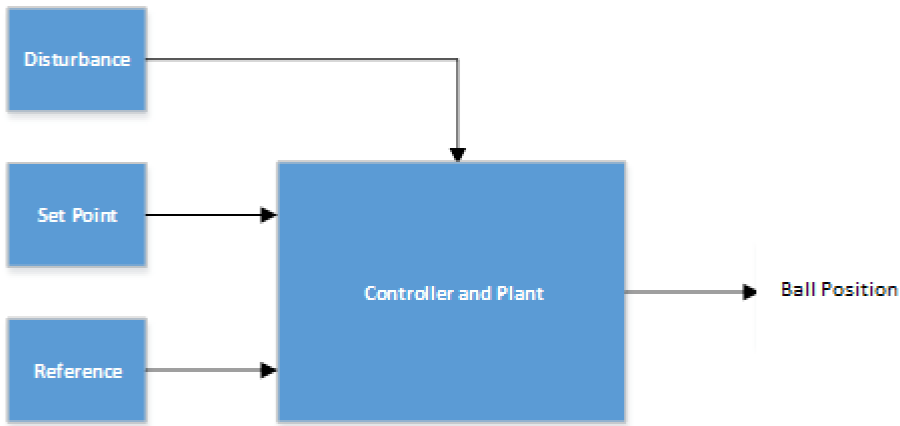

Figure 9 - Overall System Block Diagram

Figure 10 represents the block diagram for the magnetic suspension system. The control signal is summed with the disturbance and this drives the coil driver which converts a voltage to a current. This current induces a magnetic field about the coil, which attracts the ball. The ball then prohibits light from being cast into the photo sensor at a specific level indicative of the location of the ball. This location is converted to the position signal in the form of a voltage.

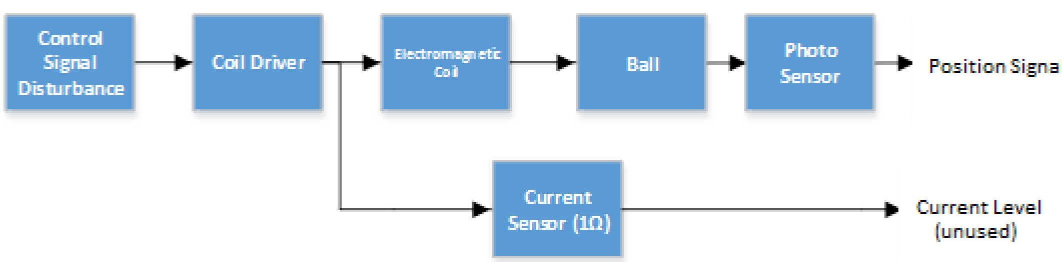

Figure 10 - Block Diagram of Magnetic Suspension System

Figure 11 shows a block diagram of the main components of the system: inputs, feedback signals, A/D converter, control system, D/A converter, plant, photo sensor, and current sensor. The inputs are set point, a point at which the ball should be suspended and the reference signal or a signal which the ball should track about the set point. The feedback signal is position. A/D converter allows use of a digital controller, the FPGA board. The D/A converter will send the control signal to the plant converting a digital representation to analog voltage. The plant is the Magnetic suspension system.

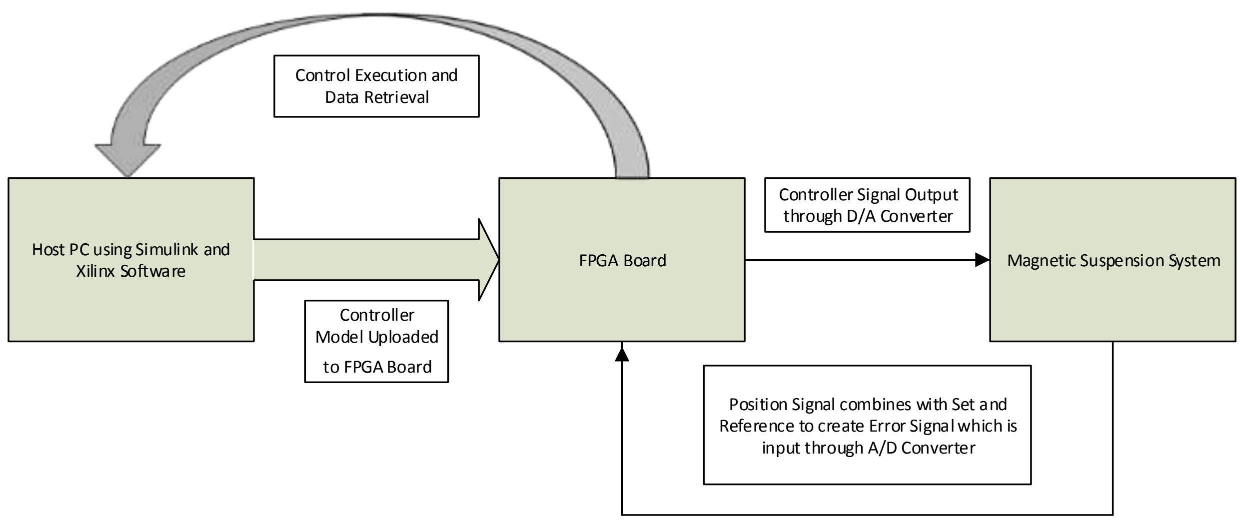

Figure 11 - Controller Block Diagram

Specifications

The specifications of this project were similar to the previous projects that utilized the magnetic suspension system. Using a square wave input with 0.25V amplitude and 0.5Hz frequency, the metal ball shall reach zero steady-state error with approximately 0.41 seconds settling time and 24% overshoot.

The A/D and D/A converters inside the FPGA board will receive the error signal from the plant and send the control signal to the plant. Set point and gain parameters will be user selectable along with a possible disturbance input.

The Xilinx software on the FPGA board will perform all the necessary conversions and calculations to implement the controller. This includes discrete sampling via timers, user input, and output signal to the magnetic suspension plant.

Equipment

- Magnetic Suspension System
- Spartan 3E FPGA board
- Breadboard
- Wires
- Resistors/Capacitors
- Host PC
- Oscilloscope (Tektronix TDS-3012)
- Function Generator (HP E3630A)
- LMC6482 Op-Amps
- +9V Battery and -9V Battery
- LM2940 and LM2990 Voltage Regulators

Simulink and Xilinx System Generator

In order to prove that FPGA is a viable solution for the magnetic suspension system, it becomes essential to demonstrate a virtual working system first. A successful project will always begin with design and simulations. One of the goals of the project was to utilize Xilinx System Generator simulation to determine computation precision of FPGA implementation. Figure 12 shows the Simulink model that was created in order to prove that FPGA implementation is possible for a controls project.

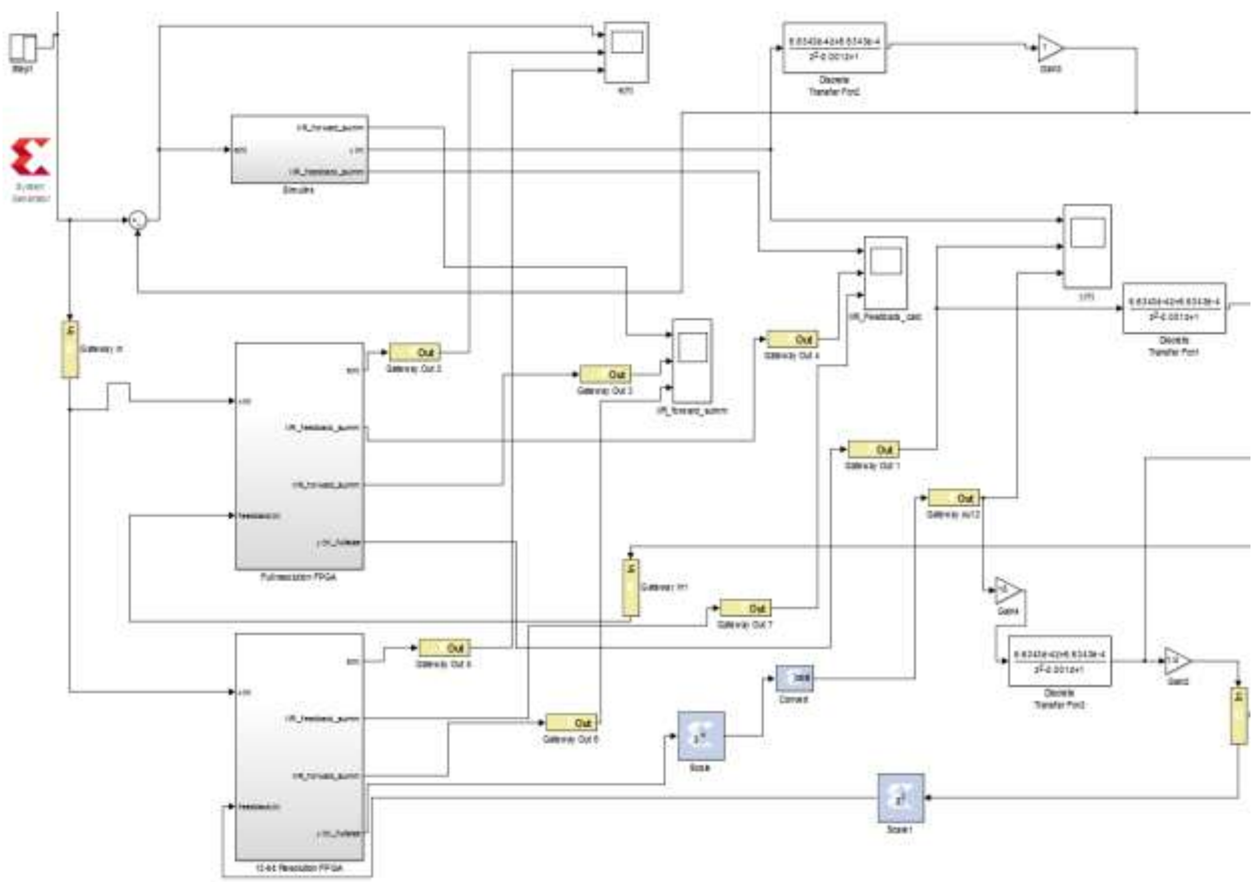

Figure 12 - Simulink, Full-length FPGA, Reduced-length FPGA Modules

The first system is the Simulink module which contains Dunlap's original controller that was given in Figure 6. The next two systems are FPGA design modules that utilized the Xilinx System Generator. The second system is the full-length resolution module that consists of roughly 64 bits. The third system is shown in more detail and is shown in Figure 13 and contains the reduced-length resolution module which is condensed down to approximately 12 bits.

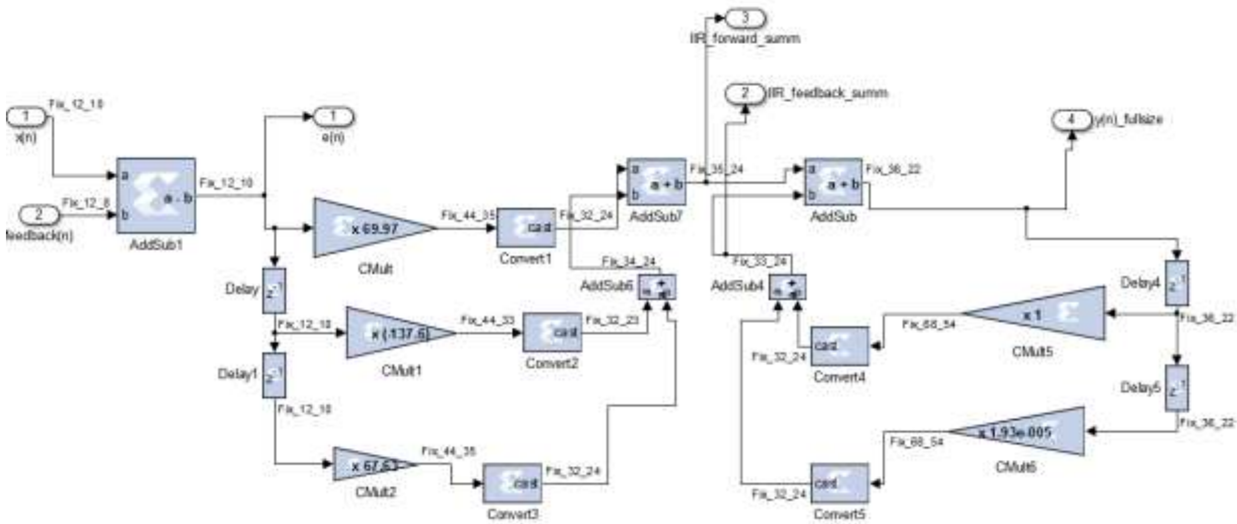

Figure 13 - Details of reduced-length FPGA design module

The condensed module was created through vigorous trial-and-error methods. The goal of this module was to ensure that FPGA implementation of the magnetics suspension system was not only possible, but efficient as well. A FPGA-based controller would be useless if this module showed heavily altered results from the originally designed controller.

The simulations of the entire system are shown below in Figure 14.

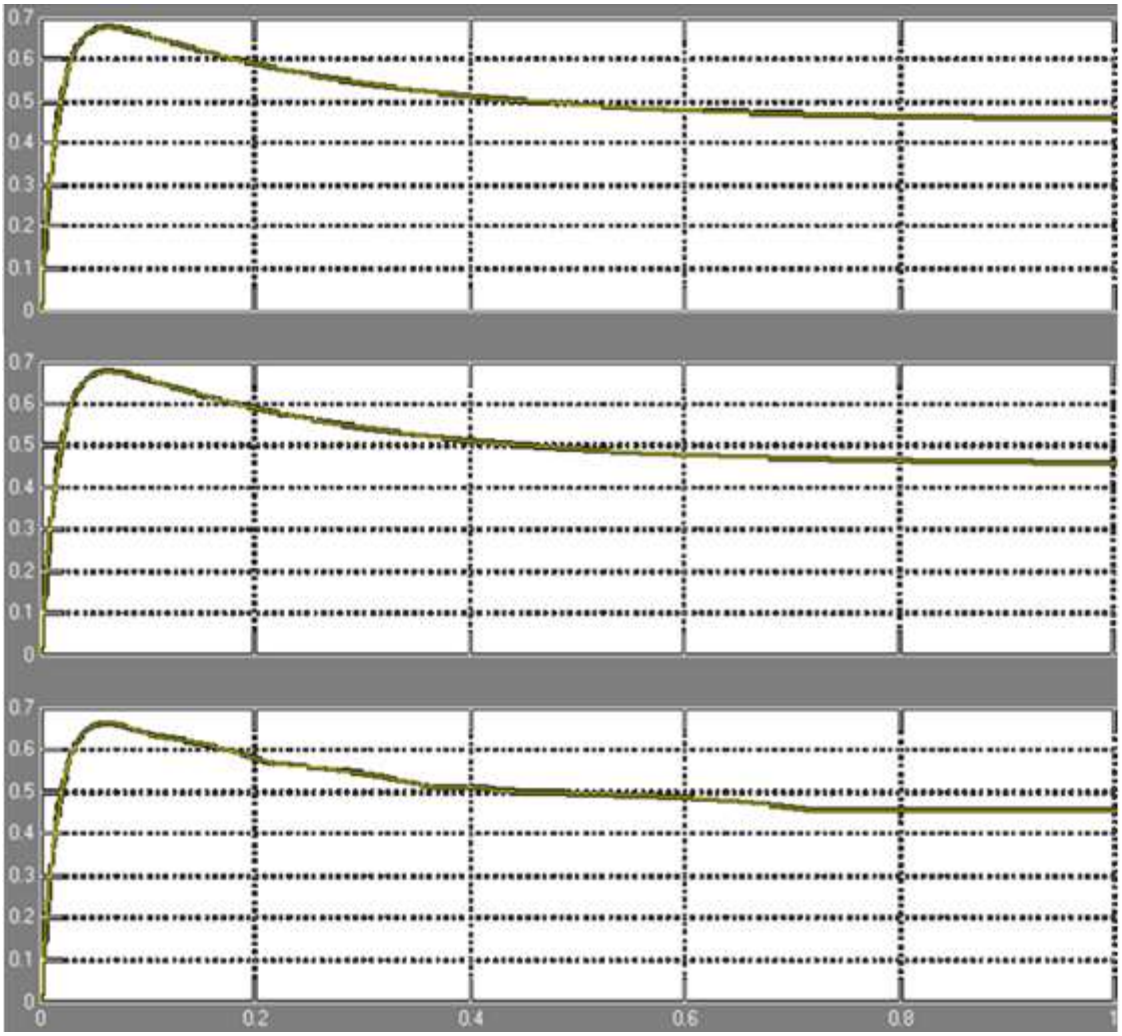

Figure 14 - Simulation of Simulink, Full-length FPGA, Reduced-length FPGA Modules

These simulations help show the transformation from Dunlap's original classical controller to a FPGA-based controller. The goal of these simulations is to condense the FPGA module as much as possible that would create an efficient FPGA-based controller that would have very similar results. The first simulation is the Simulink module which contains Dunlap's original controller that was given in Figure 13. The next two simulations are FPGA design modules that utilized the Xilinx System Generator. As shown in Figure 16, the disparities between Dunlap's original classical controller and the full-length resolution FPGA system are almost non-existent. However, the disparity between Dunlap's original controller and the reduced-length resolution FPGA system is quite more evident. The effect of condensing the FPGA resolution to the desired computational precision is shown clearly but also proves that the effect is only minimal. The third simulation shows only slight fluctuation between the other two simulations and therefore proves that an FPGA-based controller should work well enough with the magnetic suspension system.

VHDL Design

Another one of the goals of this project was to design the system using VHDL. Figure 15 and Figure 16 show the result of the FPGA-based controller being implemented using VHDL code.

Figure 15 - VHDL ISim Simulation Results

The clock is set to the predetermined sampling rate of 1ms as shown in Figure 15. The input is *x_in* which represents the bit value and is based off of a step input, *u(n)*. The original output is labeled *test_y_delay0_resize* with the more accurate bias output labeled as *y_out*. Figure 16 shows the VHDL and Simulink code being run and plotted in MATLAB.

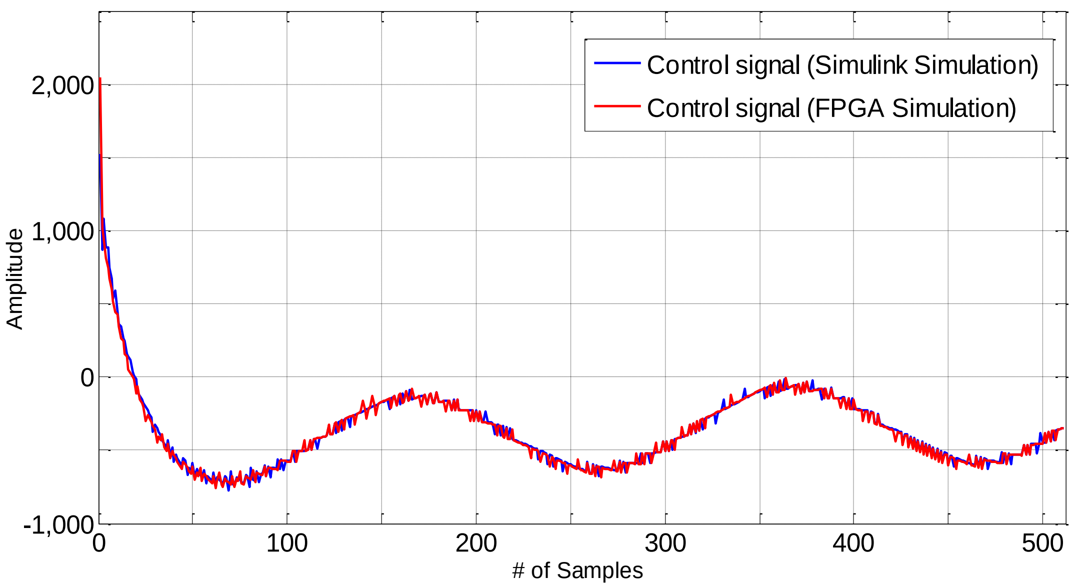

Figure 16 – Comparison of Simulink and FPGA Simulation Results

The blue line shows the control signal for the Simulink simulation which contains Dunlap's controller. The red line shows the control signal for the FPGA-based controller VHDL simulation results. The comparison of Simulink and FPGA simulation results show that both control signals are very similar to one another and thus help prove that FPGA is a viable solution to the magnetic suspension system.

Interfacing

The error and control signals from the magnetic suspension system are bipolar signals but the FPGA works with unipolar signals. In order to connect these systems, conditioning circuitry was built to interface unipolar A/D and D/A converters. In order to determine the range of voltages, testing of the previous controllers was needed to find the worst case range. The testing results are shown in Table 2.

Controllers	**Voltage Range**
Dunlap's [2]	[-3V to +3V]
Boline's #1 [3]	[-2V to +2V]
Boline's #2 [3]	[-3V to +3V]

Table 2 – Tested Voltage Ranges of Multiple Controllers

The worst case range was found to be [-3V to +3V].

Conditioning Circuitry

The circuits shown in Figure 17 and Figure 19 utilize a LMC6482 Op-Amp and necessary resistors and capacitors for the system to work properly and safely. The following circuit shifts the [-3V to +3V] bipolar signal to a [0V to +3V] unipolar signal.

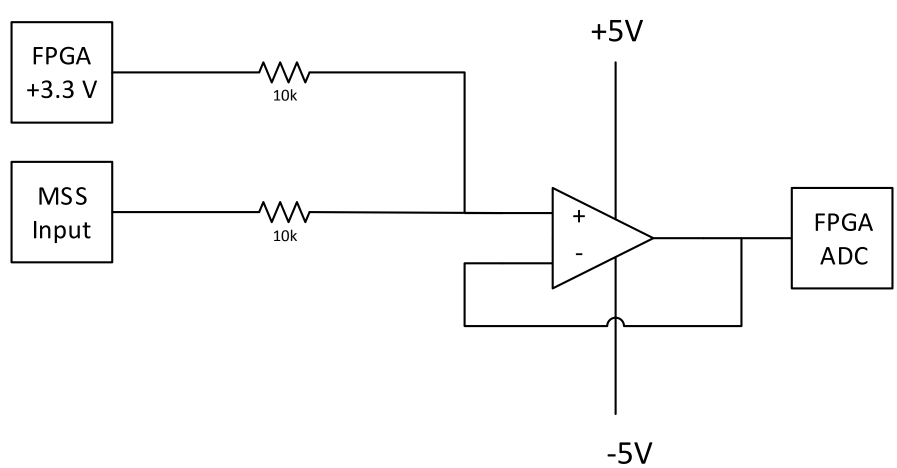

Figure 17 – Circuit #1 Bipolar to Unipolar

The input to the first op-amp circuit includes the magnetic suspension system as well as the FPGA +3.3V that drives the circuit. The output of the op-amp then travels to the FPGA A/D converter which connects directly to the FPGA board. Figure 18 shows the oscilloscope results of the circuit.

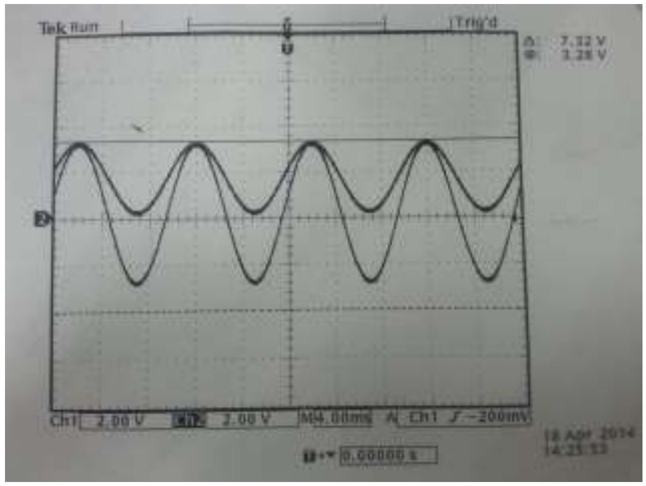

Figure 18 – Circuit #1 Oscilloscope Results

The oscilloscope results show a [-3V to +3V] sine waveform (Ch1) being manipulated into a [0V to +3V] sine waveform (Ch2).

Figure 19 shows the second circuit which shifts the [-3V to +3V] unipolar signal to a [0V to +3V] bipolar signal.

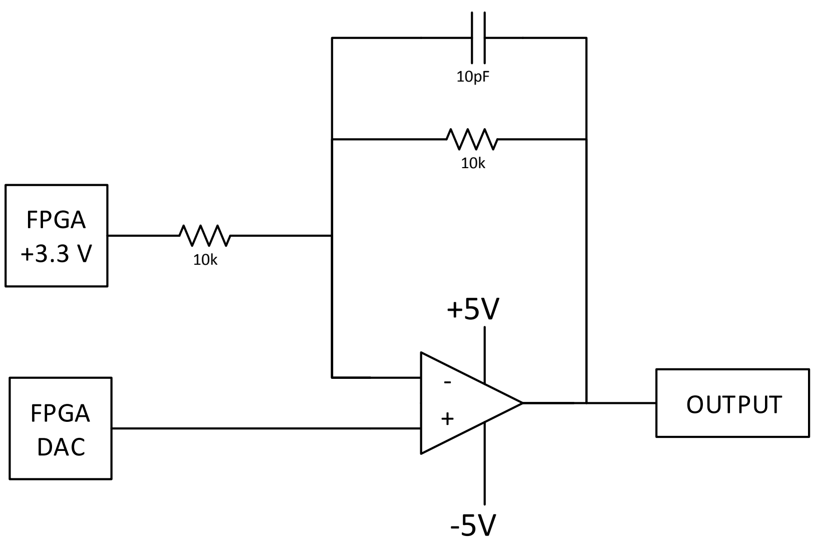

Figure 19 – Circuit #2 Unipolar to Bipolar

The input of the second op-amp circuit includes the FPGA D/A converter output as well as the FPGA +3.3V that drives the circuit. The output is the overall system output. Figure 20 shows the oscilloscope results of the circuit

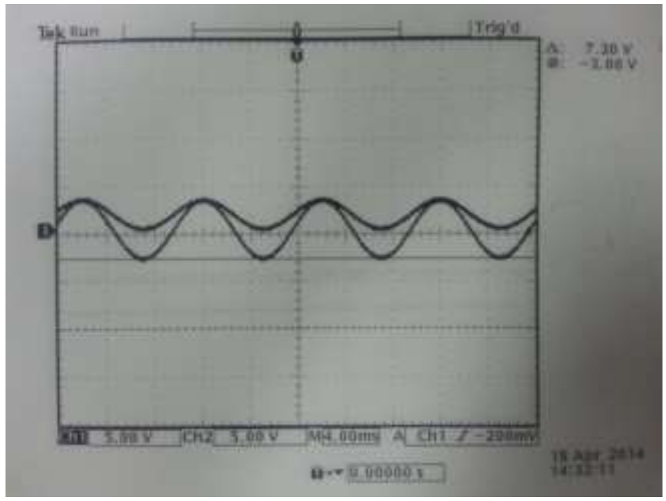

Figure 20 – Circuit #2 Oscilloscope Results

The oscilloscope results show a [0V to +3V] sine waveform (Ch1) being manipulated into a [-3V to +3V] sine waveform (Ch2).

Voltage Regulators

One of the goals of the project was to implement a stand-alone system. In order to do so, a battery would be needed to replace a power supply generator. A +9V battery and -9V battery were experimented with to try and accomplish this task. A LM2940 and LM2990 voltage regulators are shown in Figure 21 and Figure 23 and were then used to convert these ranges to the necessary voltage ranges that the FPGA board and conditioning circuitry required.

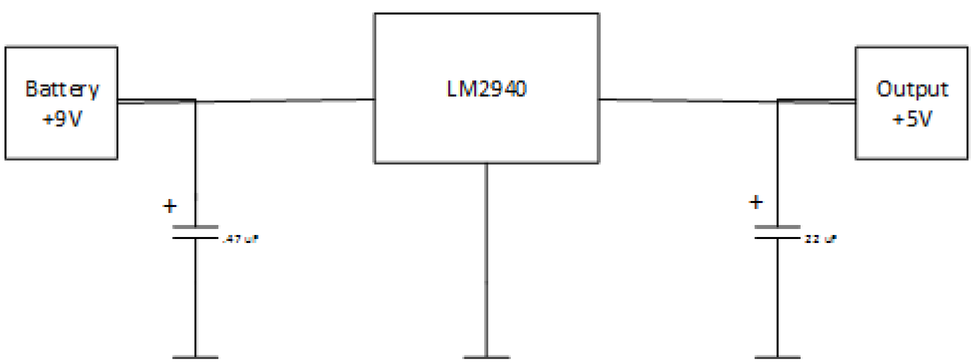

Figure 21 – LM2940 Voltage Regulator

The input to the LM2940 circuit is simply the +9V battery and the output is +5V which could then be used to drive the system. Figure 22 shows the oscilloscope results of the circuit.

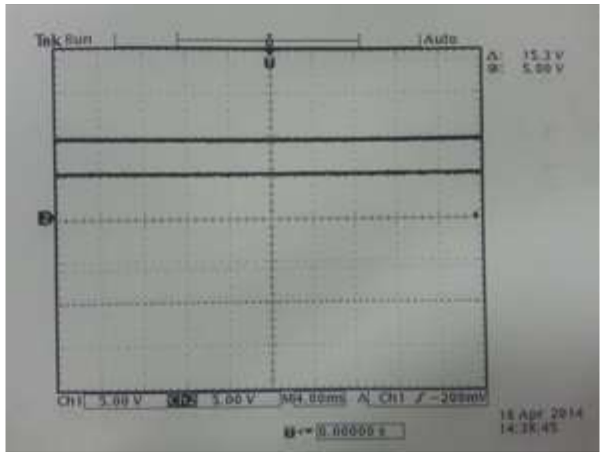

Figure 22– LM2940 Voltage Regulator Oscilloscope Results

The oscilloscope results show a +9V DC waveform (Ch1) being manipulated into a +5V DC waveform (Ch2).

The LM2990 voltage regulator is shown below in Figure 23.

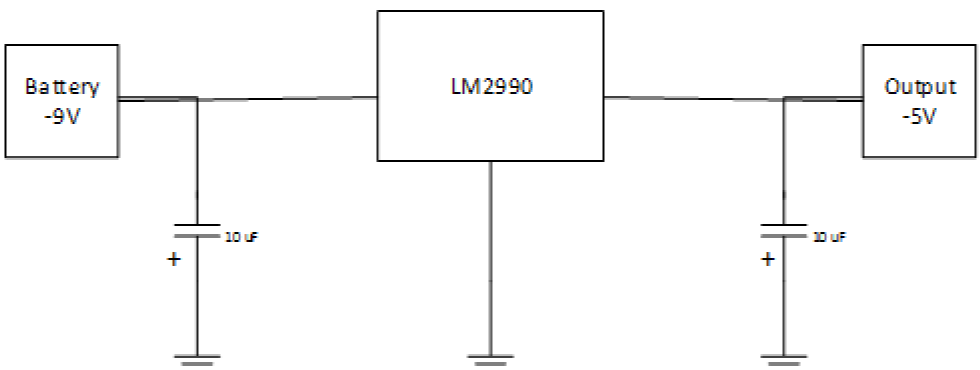

Figure 23 – LM2990 Voltage Regulator

The input to the LM2990 circuit is simply the -9V battery and the output is -5V which could then be used to drive the system. Figure 24 shows the oscilloscope results of the circuit.

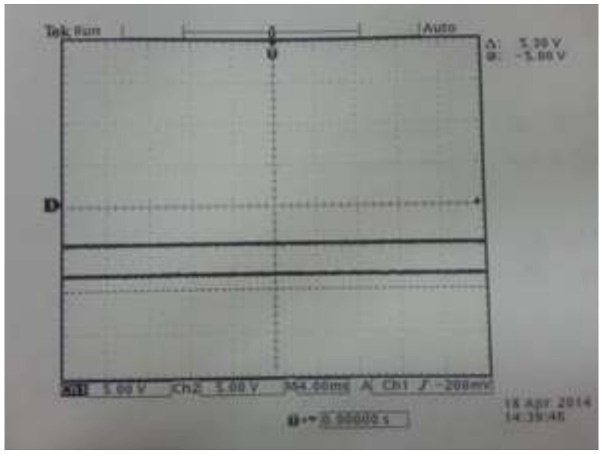

Figure 24 – LM2990 Voltage Regulator Oscilloscope Results

The oscilloscope results show a -9V DC waveform (Ch1) being manipulated into a -5V DC waveform (Ch2).

One of the biggest problems faced with the project included the use of the batteries. One of the project goals determined in the beginning of the semester was to design and implement a **stand-alone** system which includes FPGA, ADC, DAC, and conditioning circuitry. Unfortunately due to time constraints and unforeseen problems, the batteries were not utilized and a power supply was instead used. A working system was demonstrated with the power supply, however, when the power supply was replaced with the voltage regulator circuits and batteries, the system malfunctioned. Hours and hours were spent trying to debug the system but the problem was unable to be solved in time. The initial plan to use batteries was then aborted and resolved by using a power supply instead.

Operating Procedure

Follow these steps to run the controller on the FPGA:

1. Attach A/D input and Vcc from FPGA to conditioning circuitry shown in Figure 20.
2. Attach D/A output and Vcc from FPGA to conditioning circuitry shown in Figure 22.
3. Attach function generator to reference input on the magnetic suspension system.
4. Attach the magnetic suspension system input to conditioning circuitry shown in Figure 20.
5. Turn on all power supplies (+3.3V, -3.3V).
6. Turn on FPGA board.
7. Turn on function generator.
8. Now turn on the Magnetic Suspension system and place the steel ball on the holder and place it under the electromagnet.
9. The ball should be suspended. Lower the ball holder to verify.
10. Choose a desired waveform and amplitude on function generator to fluctuate the ball and to begin tracking.

System Setup

The overall system setup is shown below in Figure 24. The entire system is shown including the FPGA board, A/D and D/A Converters, breadboard with conditioning circuitry and magnetic suspension system. The photograph also shows the function generator which acts as the reference input, the power supply, and the oscilloscope to display results.

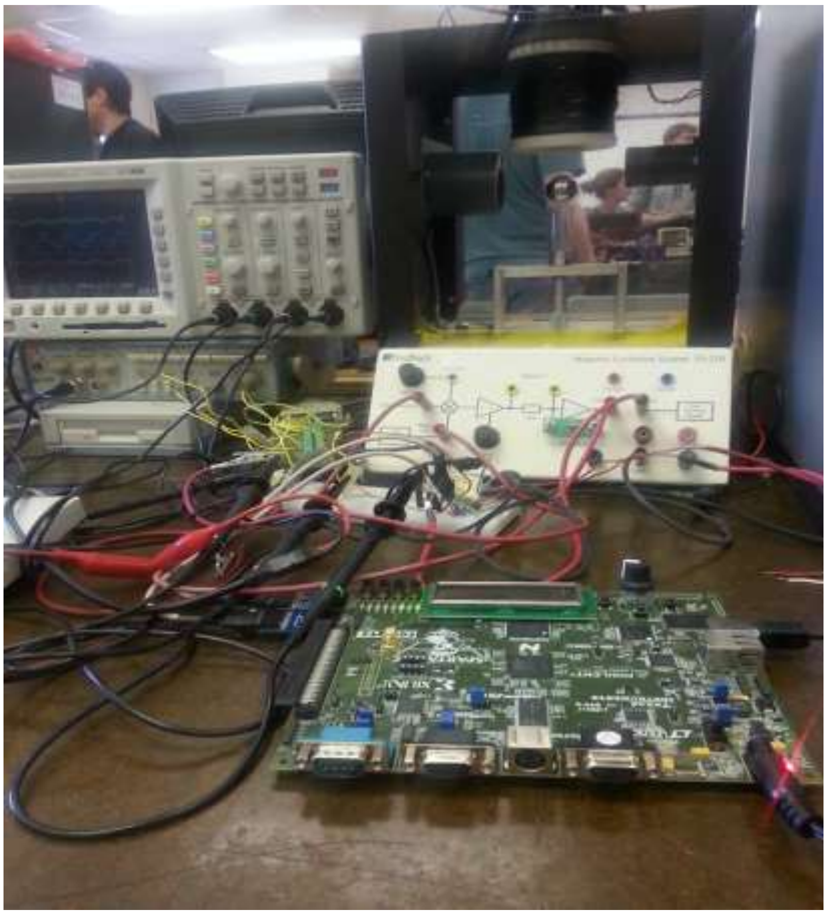

Figure 25– System Setup

Hardware and Implementation Results

The comparison of the FPGA implementation results with those from other platforms such as xPC Target Box are shown below. Unfortunately, solid FPGA results were not found due to time constraints and unforeseen problems. On the process of switching the system from a power supply generated system to a stand-alone system, there were many problems. When attempting to switch the systems back towards the end of the project, something went wrong and the system was unable to get back up and running again. The xPC Target Box results were using a square wave input of 0.25V amplitude and 0.5Hz frequency.

	Overshoot	**Settling Time**	**Steady State Error**
xPC Target Box	24%	0.41 sec	Zero
FPGA	TBD	TBD	TBD

Table 3 – Comparative Results

Although comparative results were not found, an oscilloscope result of the system when it was working most efficiently is shown below in Figure 26.

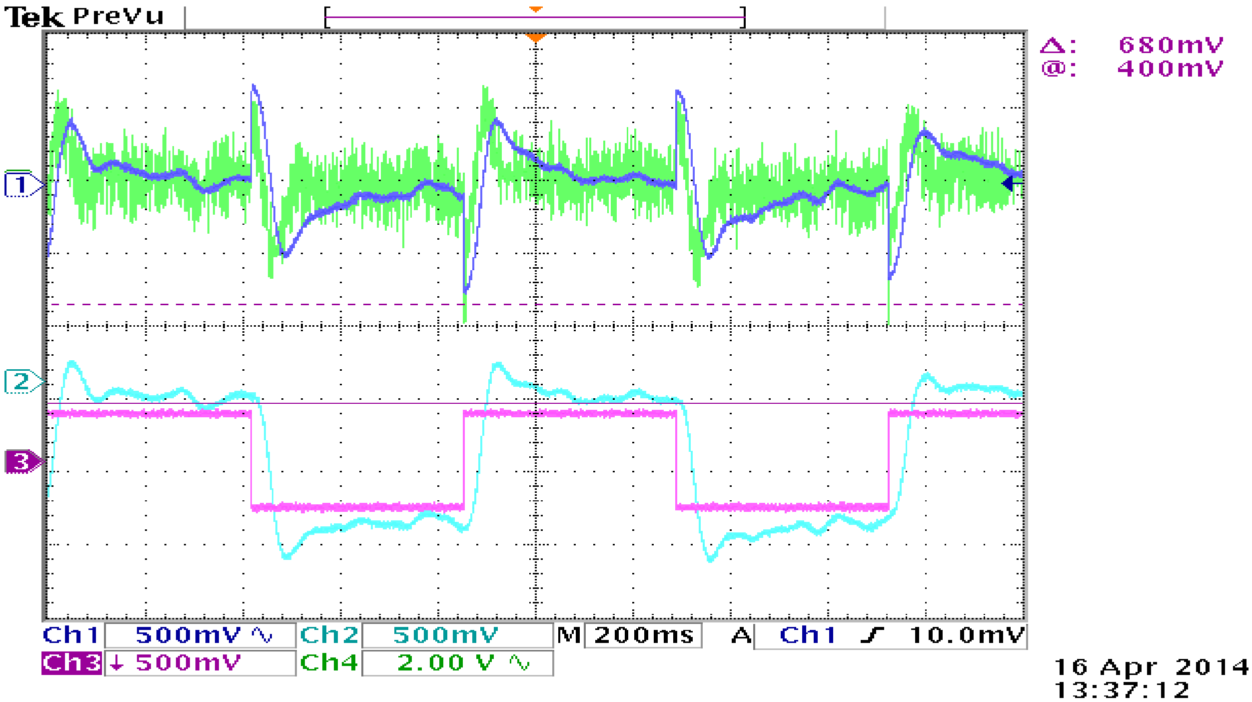

Figure 26 – Oscilloscope Results of Entire System

The top of the oscilloscope result shows the error signal (green) and control signal (dark blue). Towards the bottom of the oscilloscope result shows the reference signal (pink) and position signal (teal). With these results, the FPGA-based controller is working as the ball is clearly being tracked. The percent error on the results, however, indicate more problems with the manipulation than previously anticipated.

Recommendations for Future Work

There are numerous different paths that can be taken for continual project work. Obviously the main one is to finish up what this project was unable to finish. Find and test the design and get the entire system working efficiently would be a big step in deciding whether or not FPGA is truly a viable solution for a controls project.

Designing the hardware of the magnetic suspension system from the bottom up so that current feedback could become a viable controller design is another example. Currently, the overall performance and stability of the system is being affected by frequencies that are well above the crossover frequency. Adding an anti-aliasing filter could possibly remove all unwanted frequencies, thus improving stability and performance. Organization of the code was not taken into consideration and some time could be spent modularizing it. Once a route has been chosen for a design, realistic specifications should be included. [2-3]

Also, continued experiments using the Internal Model Principle should be considered. There are several different disturbances classes that were not considered in this and previous projects. Designing future controllers to reject multiple classes simultaneously also exists as well. If a sinusoidal disturbance class controller can be combined with the existing ramp controller in some fashion, then three classes of disturbances can be rejected at the same time. [2-3]

Conclusion

In this project, an FPGA-based controller for magnetic suspension system has been successfully implemented using Xilinx tools. Further comparative analysis and measurements are needed. Nevertheless, this study shows that FPGA is a viable solution for control application. System generator has been proven to be an efficient design tool of adjusting finite word-length for digital designs.

There are many things to be learned from this project. The main thing being the complexity that is required of any system. Even the smallest of sub-systems that were necessary to complete this project required hours and hours of work as well as hours and hours of additional work to completely understand. To understand the basics of something is nothing compared to understanding every bit of information necessary to be competent. Problems in any project are going to occur indefinitely and there should be time slotted away previously to ensure that deadlines are reached. The hours debugging even the smallest problems could take hours, days, and even weeks to fix.

Another key skill taught in this project was communication. Communication with your peers and employers is essential! Small miscommunications can add up to be a gigantic problem that could affect the entire project. Work done by your peers or employers should be thoroughly dissected to ensure everyone is on the same page with every little thing in the entire project.

Overall, this project taught a great deal about the overall process of engineering and what the workforce is going to be like. The whole point of the senior project is to instill upon the undergraduate the necessary skills that are going to be needed to excel and survive in the workplace. Undergraduates are still young, incompetent at times, and even arrogant to some degree. This experience has pushed all undergraduates a great deal and has given them a feel of what is going to be necessary to not only compete for jobs, but to keep jobs and advance further and further into sustaining a successful career.

References

[1] Jose A. Lopez and Winfred K.N. Anakwa, “Identification and Control of a Magnetic Suspension System using Simulink and dSPACE Tools”, Proceedings of the ASEE Illinois/Indiana 2003 Sectional Conference, March 27, 2004, Peoria, Illinois, U.S.A.

[2] Jon Dunlap, “Design of Disturbance Rejection Controllers for a Magnetic Suspension System”, Bradley University, IEEE Department, May 8, 2006, Peoria, Illinois, U.S.A.

[3] Gary Boline and Andrew Michalets, “Magnetic Suspension System Control Using Position and Current Feedback”, Bradley University Department of Electrical and Computer Engineering, May 17, 2007, Peoria, Illinois, U.S.A

[4] B.A. Francis and W.M. Wonham, “The Internal Model Principle of Control Theory,” *Automatica*. Vol. 12, pp 457-465, 1976.

Appendix

Poster along with a flash drive containing all programs and datasheets will be left in room Jobst 254 next to the magnetic suspension system.