

Closed Loop Magnetic Levitation Control of a Rotary Inductrack System

Senior Project Proposal

Students:

Austin Collins

Corey West

Advisors:

Dr. Winfred Anakwa

Mr. Steven Gutschlag

Date:

December 18, 2013

Abstract

Magnetic levitation train (Maglev) is becoming a preferred way of travel in many foreign countries. This is because the Maglev system can minimize drag force, increasing efficiency. This document contains information about implementing a controller on an FPGA board to control a Maglev system. The work to be completed for implementing the controller will use previous year's work for the motor model and controller design. A complete system block diagram and its subsystems will show how the system is modeled. A controller will be implemented on an FPGA board to control levitation height of the Halbach array. The FPGA implementation of the controller will result in a stand-alone system with the FPGA mounted on a PCB.

Table of Contents:

Project Summary..... 3

Background..... 3-5

Project Description..... 5-6

Modeling and Controller Design..... 7-10

Functional Requirements and Performance Specifications. 10-11

Preliminary Work..... 11-13

Patents..... 14

Schedule..... 15

Parts List..... 15

References..... 16

Project Summary

The Halbach array and the inductrack system developed by senior ECE students in previous years currently functions in open-loop mode. The next step is to make the system operate using closed-loop control. The first goal of this project is to choose a controller platform that will allow the system to control levitation height with a standalone system. An FPGA board will be the platform used for closed loop control. In the open-loop mode, the motor is driven by a manually controlled voltage input. Therefore, the second goal of this project is the implementation of a control algorithm to drive the motor using a PWM signal capable of adjusting the motor's rotational velocity, thereby controlling the levitation height directly from the FPGA. If all these tasks are completed the safety enclosure will be improved, and the FPGA will be mounted on a PCB.

Background:

Magnetic levitation technology (Maglev) is changing the way people travel. Maglev trains are lifted off the track and propelled forward, eliminating friction and allowing the train to travel at higher speeds than normal trains.

Maglev works by creating magnetic repulsion between the train car and the track. The train car has a special arrangement of magnets that minimizes the magnetic field above the Halbach array and creates a stronger magnetic field below the array. This arrangement of magnets is called a Halbach Array. Figure 1 below shows the polarity of each magnet and illustrates how the Halbach array intensifies the magnetic field below the array. Since this arrangement of magnets results in a more powerful magnetic field than a magnetic pole arrangement with all the poles aligned, the Halbach array is much more useful for large scale projects. Note also that reduced magnetic field above the the Halbach array would virtually eliminate the need for magnetic shielding to protect electronic storage equipment and people with pacemakers in maglev rail applications.

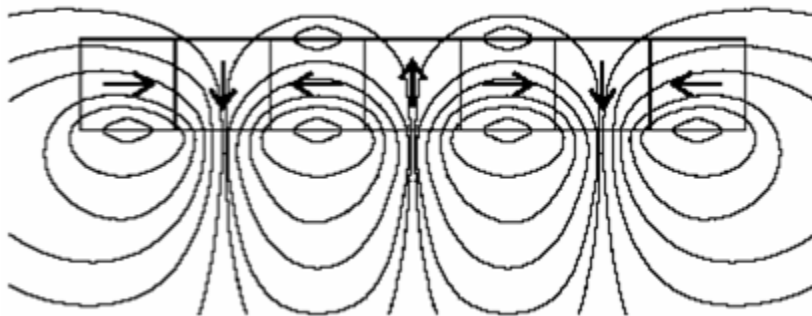


Fig. 1 Halbach Array of Magnets

It is well known that alternating current produces a magnetic field, and a changing magnetic field can induce currents in nearby conductors. As the Halbach array moves across a conductor in the track, it changes the magnetic field around the conductor and induces a current in the conductor. At the same time the induced current will be changing, creating another magnetic field. Figures 2 and 3 show the Halbach array device and its associated magnetic field in blue and red. The pink and light blue magnetic fields representations are created by an induced current in the inductrack. At low velocities the magnetic fields will not align. However, once the linear velocity increases above a critical level, the

induced current begins to lag, and the magnetic fields will align. The magnetic field will then produce lift forces, resulting in levitation of the train car above the track. However, a drag force is also generated, and the desired operating point is at a condition that maximizes lift forces and minimizes drag forces.

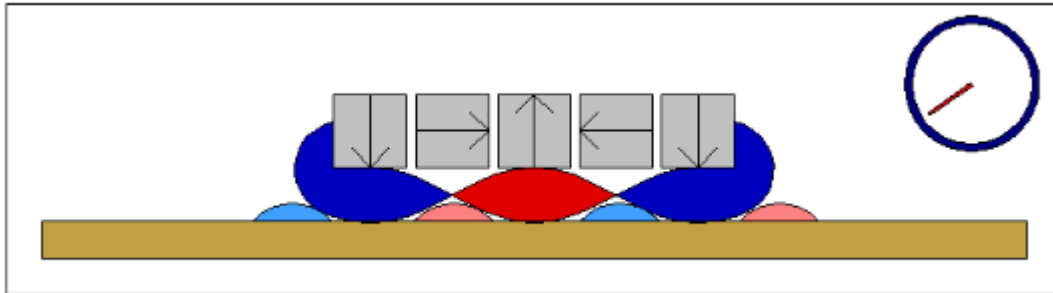


Fig. 2 Inductrack and Halbach Array Interaction at Low Velocity

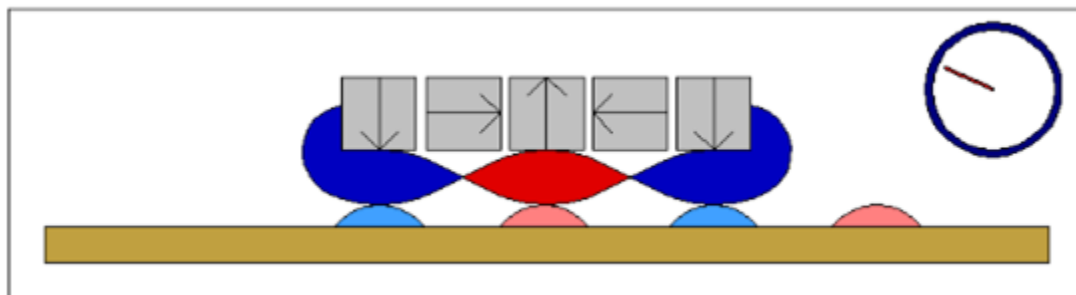


Fig. 3 Inductrack and Halbach Array Interaction at High Velocity

Figure 4 below shows the Halbach array and inductrack system that was designed by previous ECE senior project students. This is the system that will be controlled by the FPGA to produce a desired levitation height. The Halbach array will be the stationary part of the project and the inductrack will be the moving part. The copper inductrack will act as a conductor in this project.

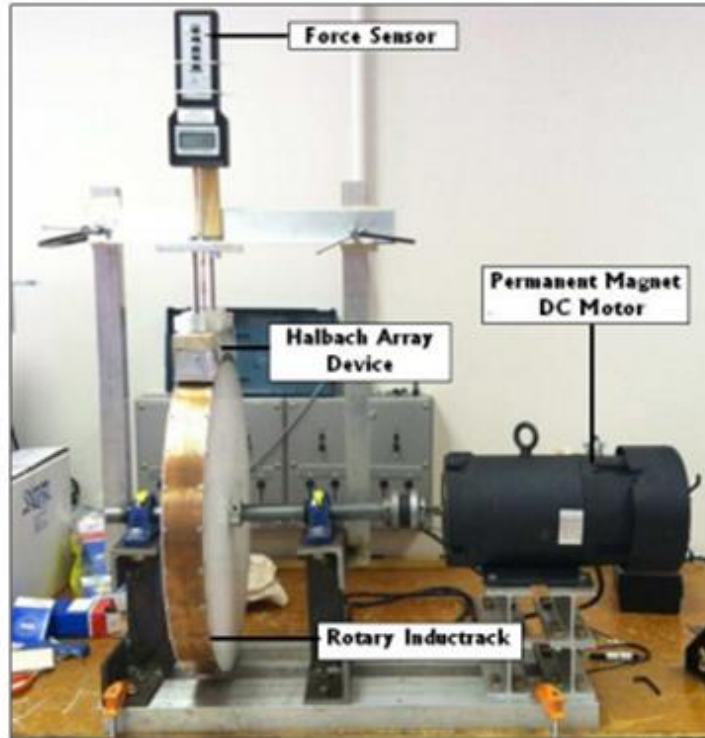


Fig. 4 Laboratory Model of Halbach Array Magnetic Levitation System

Project Description:

This project will modify the existing Halbach array magnetic levitation system by adding electronics to make the system a closed-loop levitation height control system. The primary focus of the project will be to choose a platform and design a controller that can process a user's input, and convert it into a PWM signal to drive the the Maglev system DC motor. The overall system is represented by the block diagram shown below in figure 5.

Initially, the controller design will use a lookup table to specify the angular velocity required for a desired levitation height and a classical digital control law to generate the PWM signal required to drive the motor at that velocity. Classical digital control law design uses root locus and bode methods instead of state variable feedback control theory. The initial input will be entered in millimeters and then converted to the desired velocity. Separately, an optical encoder will produce a frequency, which will be converted to velocity as the feedback signal. The controller will then generate the PWM signal based on the velocity error found by subtracting the current velocity from the desired velocity. This process is shown in figure 6 below. However, if time permits a displacement sensor will be used to generate a direct feedback signal representing the instantaneous levitation height. Both options are represented in figure 5 below.

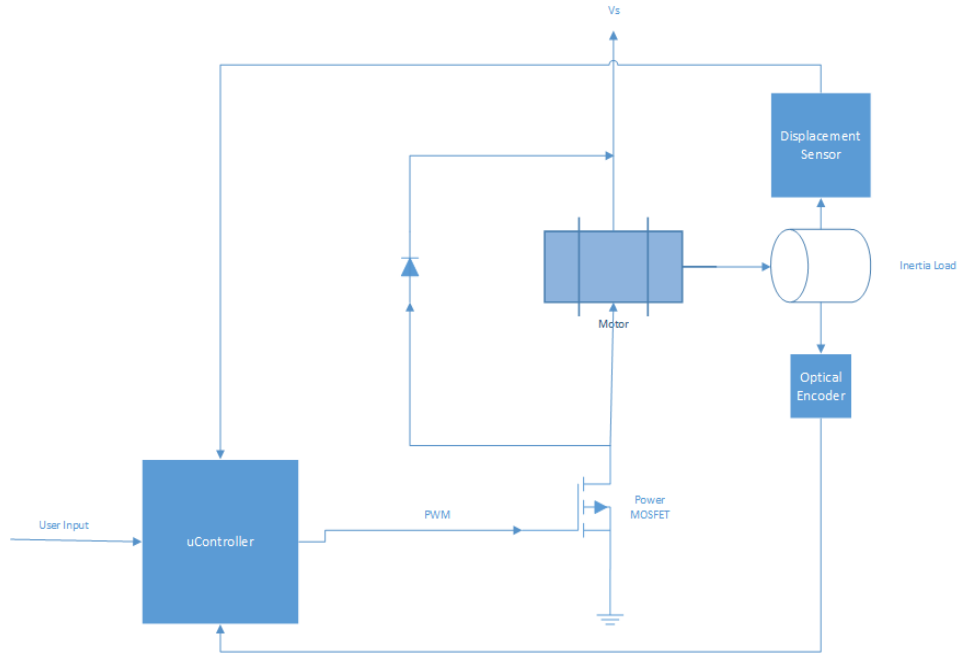


Fig. 5 High level Block Diagram of MLS

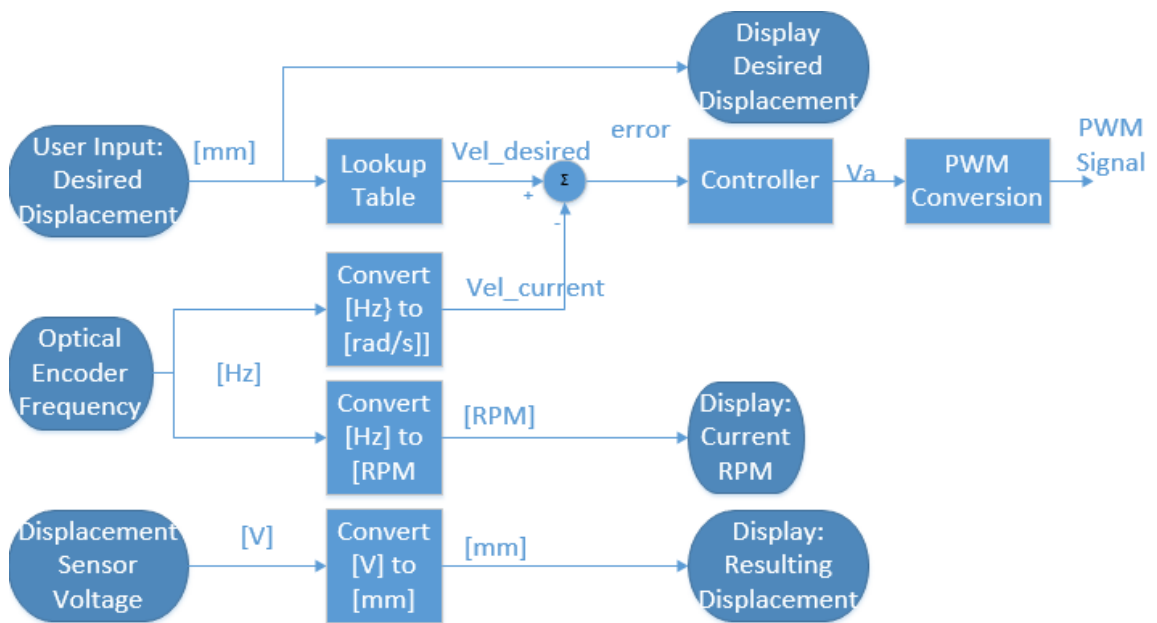


Fig. 6 Block Diagram of Controller

Modeling and Controller Design:

Figure 7 below is a common DC Motor Schematic that is similar to that used to model the Maglev system. Table 1 below defines the variables from the schematic shown in figure 7 that are measurable quantities determined by last year's ECE senior Maglev project group.

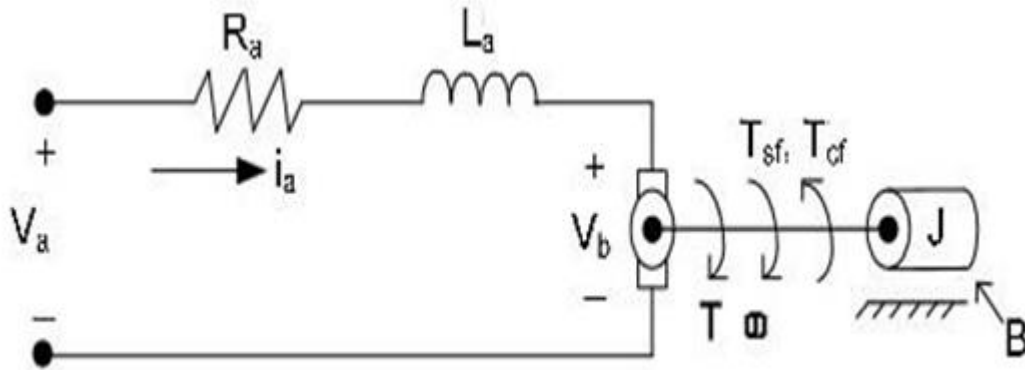


Fig 7. Common Dc Motor Schematic

Measurable Quantities:

ω_m – machine rotational speed i – armature current
 V_a – source voltage

Parameters to determine:

R_a – armature resistance L_a – armature inductance
 k_v – motor torque constant k_T – back emf constant
 B – motor viscous friction T_{cf} – coulombic friction
 J – moment of inertia

Table 1. Variables Used to Determine Motor Model

After determining the values defined above, the motor model was created using Simulink, and is shown in figure 9 below.

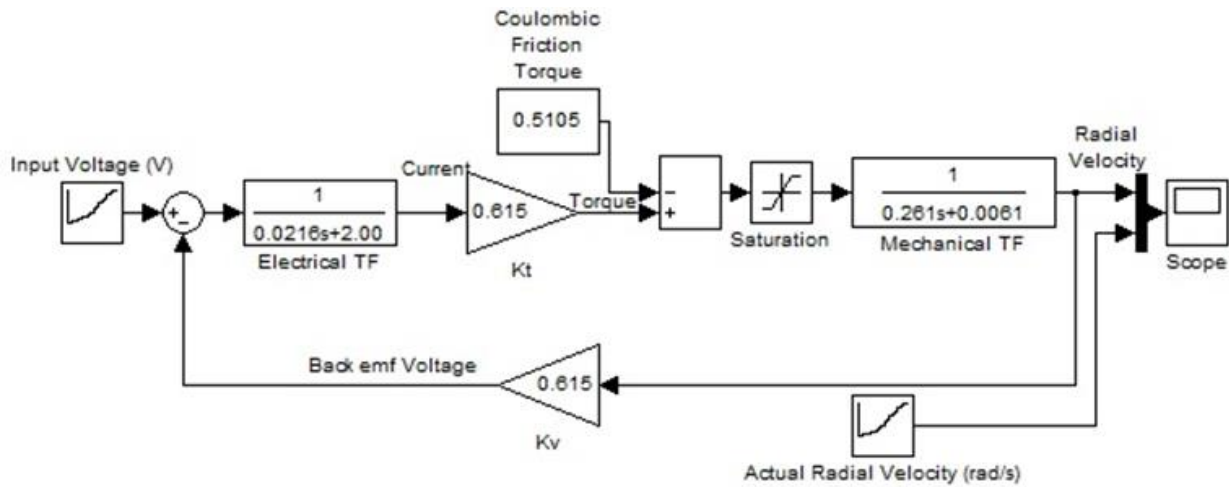


Fig. 9 Motor Model

Simulation results for the motor model are shown below in figure 10. The green plot is the steady-state response for a particular applied input voltage. The plot appears to contain ideal step responses because voltage points were manually entered, causing an instant jump to the next angular velocity value and then a constant line until the next voltage value is applied to the input. The blue response is the transient simulation response.

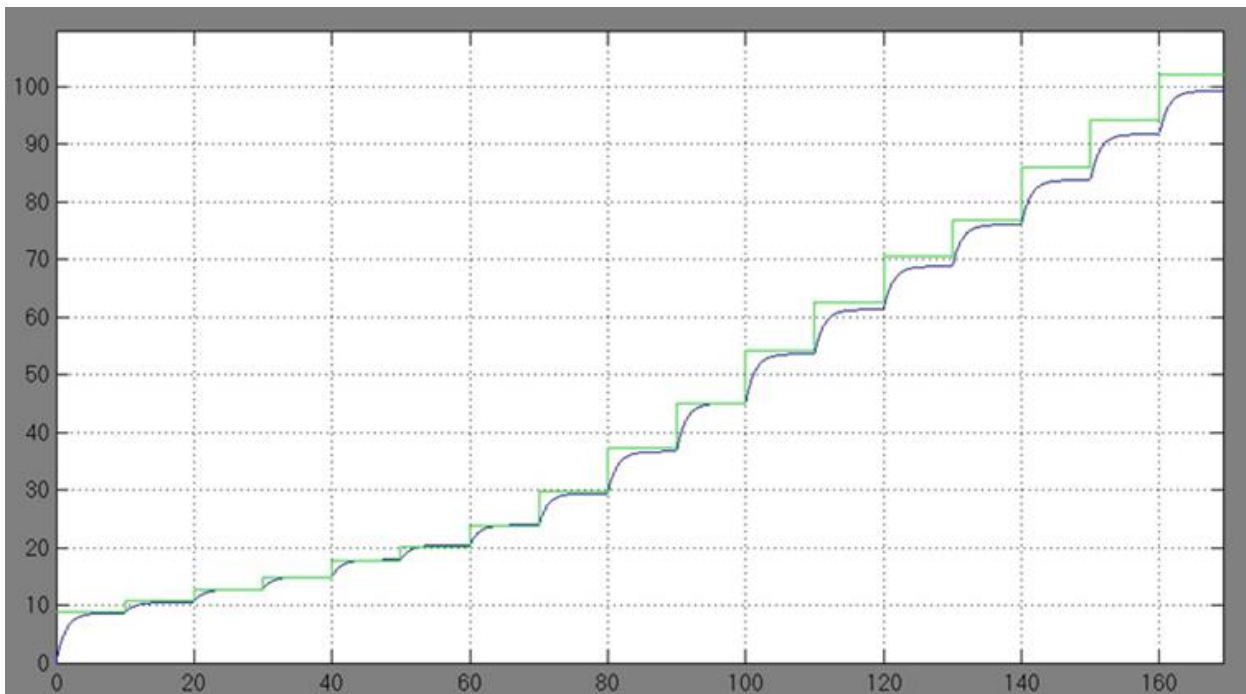


Fig. 10 Simulation Results for Motor Model

The transfer function $G(s)$ in equation 1 below that converts input voltage to motor angular velocity was determined experimentally by the previous groups who worked on the magnetic levitation system.

$$G(s) = 109.09 \frac{1}{s^2 + 92.62s + 69.25} \quad (1)$$

The previous group also designed a continuous time controller using Matlab.

$$C(s) = 75.71 \frac{s+1.56}{s(s+76.92)} \quad (2)$$

The open loop system and closed loop systems are simulated in figure 11 below.

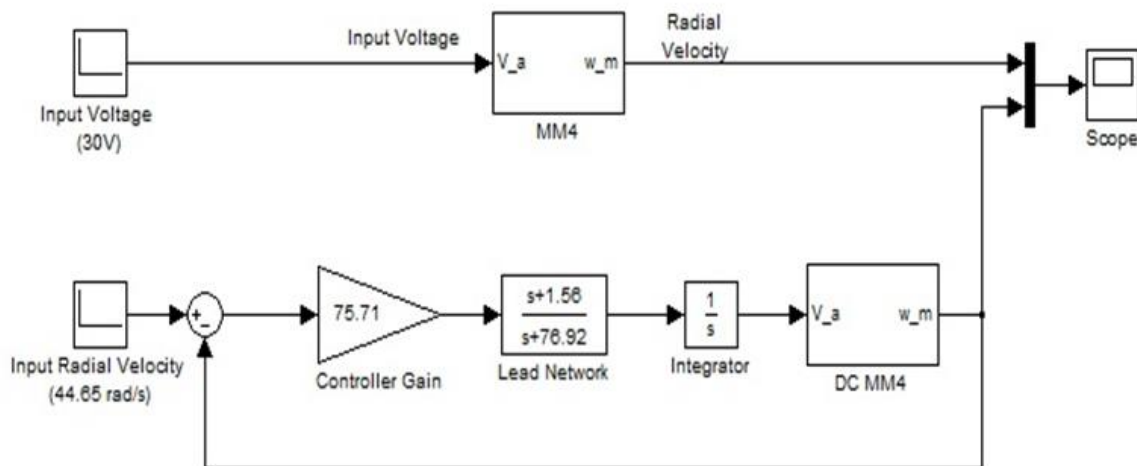


Fig. 11 Open and Closed Loop Systems

Figure 12 below shows the simulation results from the simulink model presented in figure 11. The curve that overshoots 44.65 rad/s and then comes back down is the closed loop response. The curve that goes right up to 44.65 rad/s is the open loop response.

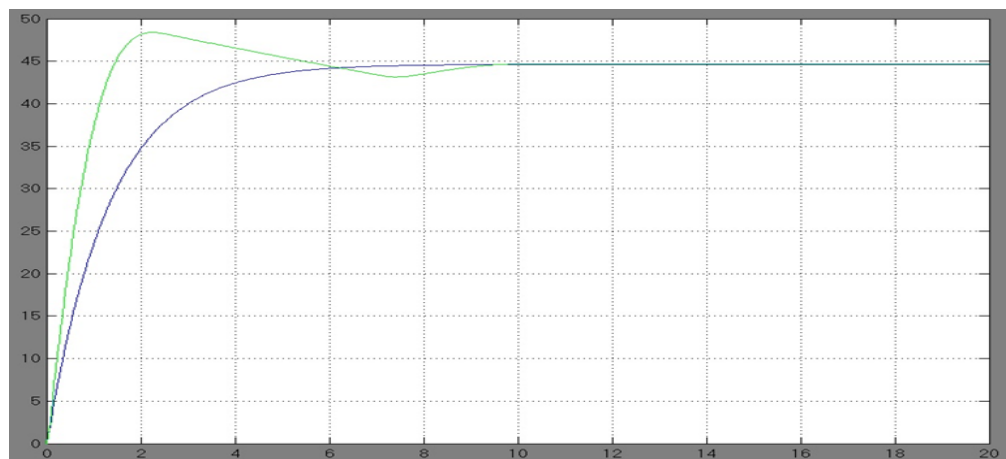


Fig. 12 Simulation Results for Open and Closed Loop System

Digital Controller:

The continuous time controller was converted to a discrete time controller using the “C2D” function in MATLAB using sampling interval of 10ms. The discrete controller transfer function can be written as:

$$C(z) = \frac{0.5453 - 0.5369z^{-1}}{1 - 1.463z^{-1} + 0.4634z^{-2}} \quad (3)$$

This transfer function was re-written in the form of a difference equation to allow implementation on an FPGA board.

$$y(k) - 1.463 y(k - 1) - 0.4634 y(k - 2) = 0.5453 x(k) - 0.5369 x(k - 1) \quad (4)$$

Functional Requirements and Performance Specifications:

FPGA Design:

- The digital controller selected is a Spartan 3E FPGA board.
- The Analog-to-Digital (ADC) chip has 12-bits of resolution, and is adequate to represent changes of 0.0002[V] in displacement sensor voltage.
- The FPGA shall accept an input for desired levitation height
- The FPGA shall digitally implement the controller model.
- The FPGA shall sample displacement every 50 [ms].
- The FPGA shall calculate and update the PWM control signal in less than 1 [ms].

Controller Design Specifications:

- The maximum overshoot of the system shall be less than 10%.
- The steady state error shall be less than 0.02 mm.
- The settling time shall be less than 6s.

Displacement Sensor Specifications

- The MTL002n3000b5c Linear Position Transducer shall be used to measure displacement produced by the Halbach array model.
- The range shall be 0-7 mm.
- The sensor shall produce a voltage that is linearly related to displacement and accurate to within 0.1%.
- The sensor shall have infinite resolution.

Optical Encoder:

- The EE-SG3 Omron optical encoder shall be used to measure the angular velocity of the system.
- The optical encoder shall read the system at a rate of 4 cycles per rotation.
- The PWM frequency shall be 1 kHz

Power Electronics:

- Gate Drive from FPGA to mosfet.
- Mosfet to motor.
- Protective circuit.
- Supply voltage of 90v to the motor.

Preliminary Work:

The first thing done with the FPGA was to generate a PWM signal. This was done in VHDL using a count variable. While this count variable is less than the percentage of duty cycle to be obtained it outputs a high signal. After the count variable is higher than the percentage of duty cycle to be obtained a low signal is outputted until the count variable reaches 100. After reaching 100 the count variable will reset and wait for a new duty cycle. Fig. 13 below is a picture of the oscilloscope showing an example duty cycle of 80%. This means the signal is high for 80% and low for the other 20%.

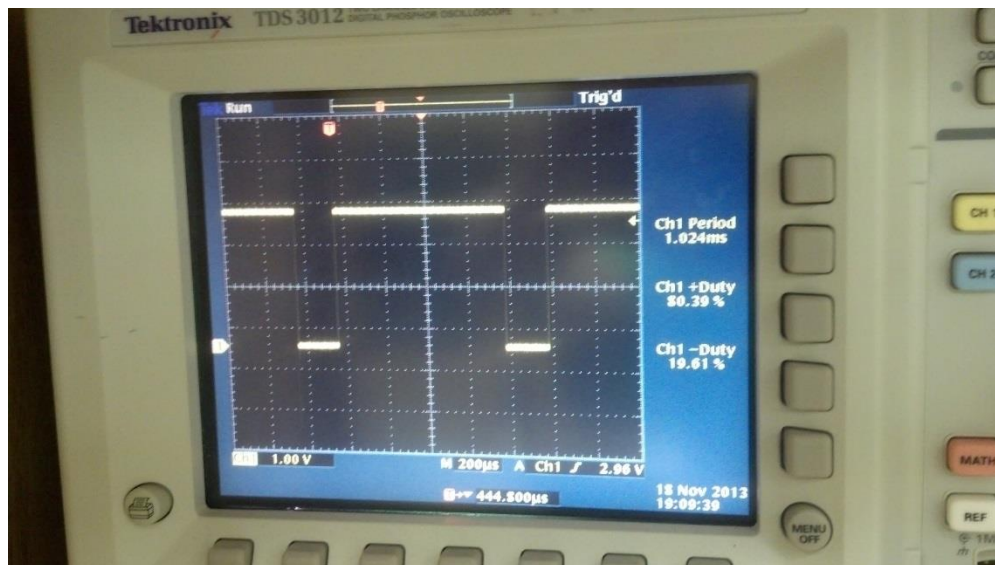


Fig. 13 simulation results for 80% duty cycle

After completing the PWM signal, work was done on the ADC and DAC. The first thing done with the ADC was to make a test bench to simulate results from the ADC chip. Figure 14 below shows the simulation results from the test bench created. The results show that the sdata keeps increasing until the value of FFF is obtained.

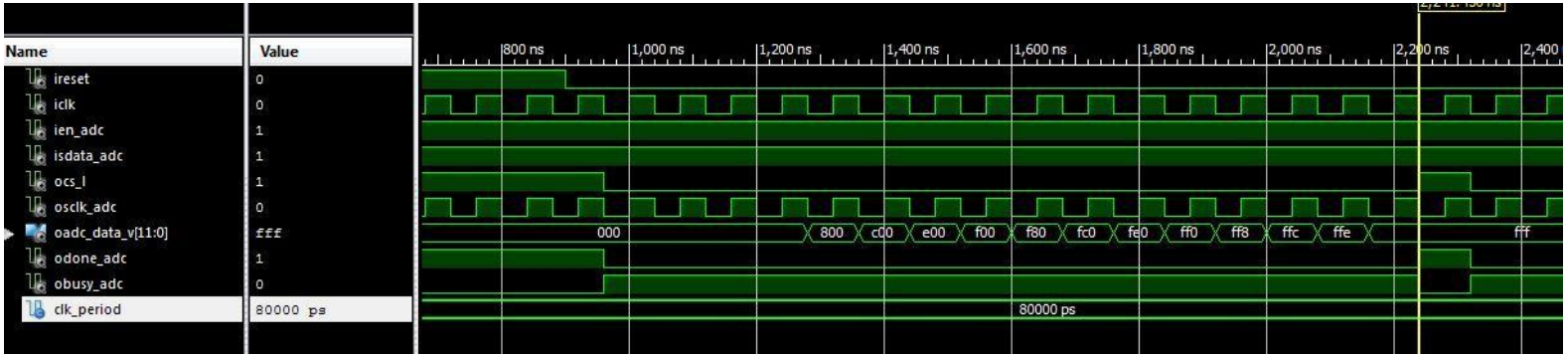


Fig. 14 Test bench simulation

After creating the test bench VHDL code was done to output a hex number of the voltage to the LCD display. The hex number for 1 volt is 4D9 and the results in figure 15 below show the number the ADC thinks we are getting in. 4D6 is very close to 4D9 so it is acceptable to use.



Fig. 15 Results shown from LCD display

The last thing completed for the ADC is completing code for the DAC to show that the output voltage from the ADC is the same as the input voltage to the ADC. Figure 16 below shows that this is the case, so the ADC is acceptable. Results are shown in Figure 16 below. Ch1 is the input voltage and Ch2 is the output from the DAC.

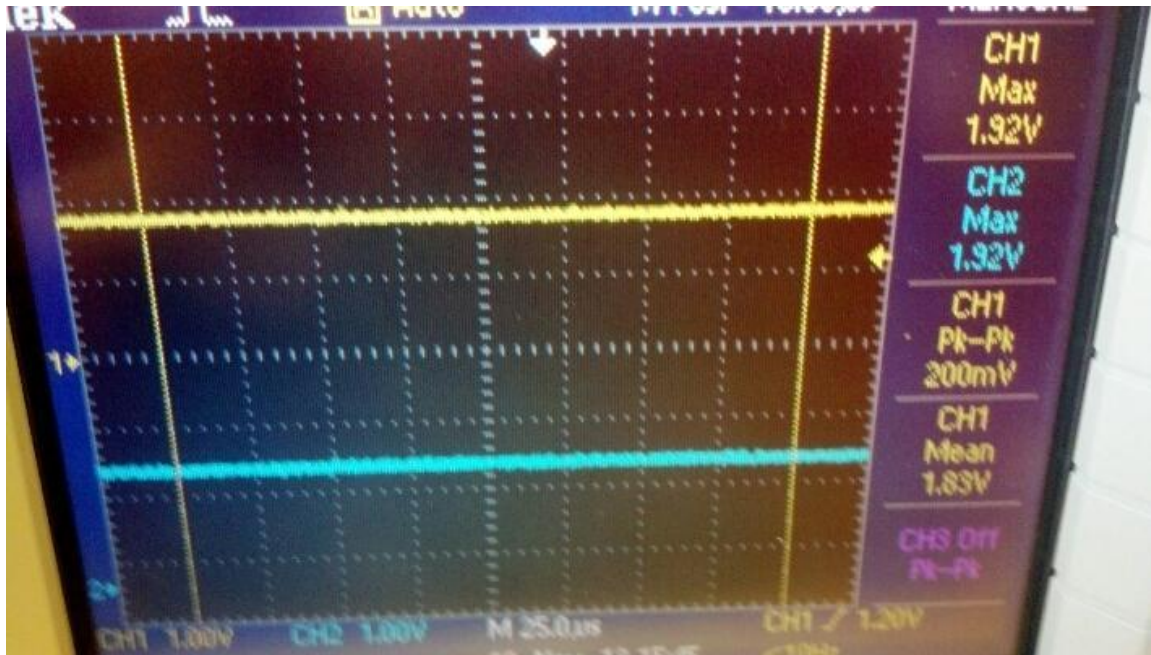


Fig. 16 Input voltage vs Output voltage for ADC

Patents:

- Richard F. Post
Magnetic Levitation System for Moving Objects
U.S. Patent 5,722,326
March 3, 1998
- Richard F. Post
Inductrack Magnet Configuration
U.S. Patent 6,633,217 B2
October 14, 2003
- Richard F. Post
Inductrack Configuration
U.S. Patent 6,295,503 B2
October 7, 2003
- Richard F. Post
Laminated Track Design for Inductrack Maglev System
U.S. Patent Pending US 2003/0112105 A1
June 19, 2003
- Coffey; Howard T.
• Coffey; Howard T.
Propulsion and stabilization for magnetically levitated vehicles
U.S. Patent 5,222,436
June 29, 2003
- Coffey; Howard T.
Magnetic Levitation configuration incorporating levitation, guidance and linear synchronous motor
U.S. Patent 5,253,592
October 19, 1993
- Levi; Enrico; Zabar; Zivan
Air cored, linear induction motor for magnetically levitated systems
U.S. Patent 5,270,593
November 10, 1992
- Lamb; Karl J. ; Merrill; Toby Gossage; Scott D. ; Sparks; Michael T. ; Barrett; Michael S.
U.S. Patent 6,510,799
January 28, 2003

Schedule for This Semester:

- 11/26 – Work on project proposal and project website
- 12/3-12/10 – Start coding rotary encoder and figure out power electronics

Schedule for Next Semester:

- 1/28-2/4 – Combine rotary encoder with PWM code to vary duty cycle
- 2/11-2/18 – Create lookup table to convert user input to PWM duty cycle
- 2/25-3/4 – Design a circuit to power motor and build
- 3/11 – Test circuit
- 3/25-4/1 – Implement controller design on FPGA
- 4/8-4/15 – Make system stand-alone and mount FPGA on a PCB
- 4/22-5/6 – Prepare for final presentation

Parts List:

- Xilinx SDK
- Spartan 3E Starter Kit
- 0-120v DC power supply
- 0-20v DC power supply
- ADCS7476
- DAC121S101
- Gate Driver
- Protective circuit

References:

[1] Dr. Lu for help with VHDL

[2] Kyle Gavelek, Victor Panek, Christopher Smith. Senior Project. "Closed Loop Control of Halbach Array Magnetic Levitation System Height". Final Report, May 2013.

[3] Dirk DeDecker, Jesse VanIseghem. Senior Project. "Development of a Halbach Array Magnetic Levitation System". Final Report, May 2012.

[4] Glenn Zomchek. Senior Project. "Redesign of a Rotary Inductrack for Magnetic Levitation Train Demonstration". Final Report, May 2007.

[5] Paul Friend. Senior Project. Magnetic Levitation Technology 1. Final Report, May 2004.

[6] Post, Richard F., Ryutov, Dmitri D., "The Inductrack Approach to Magnetic Levitation," Lawrence Livermore National Laboratory.