Closed Loop Magnetic Levitation Control of a Rotary Inductrack System

Students: Austin Collins
Corey West

Advisors: Dr. Winfred Anakwa
Mr. Steven Gutschlag

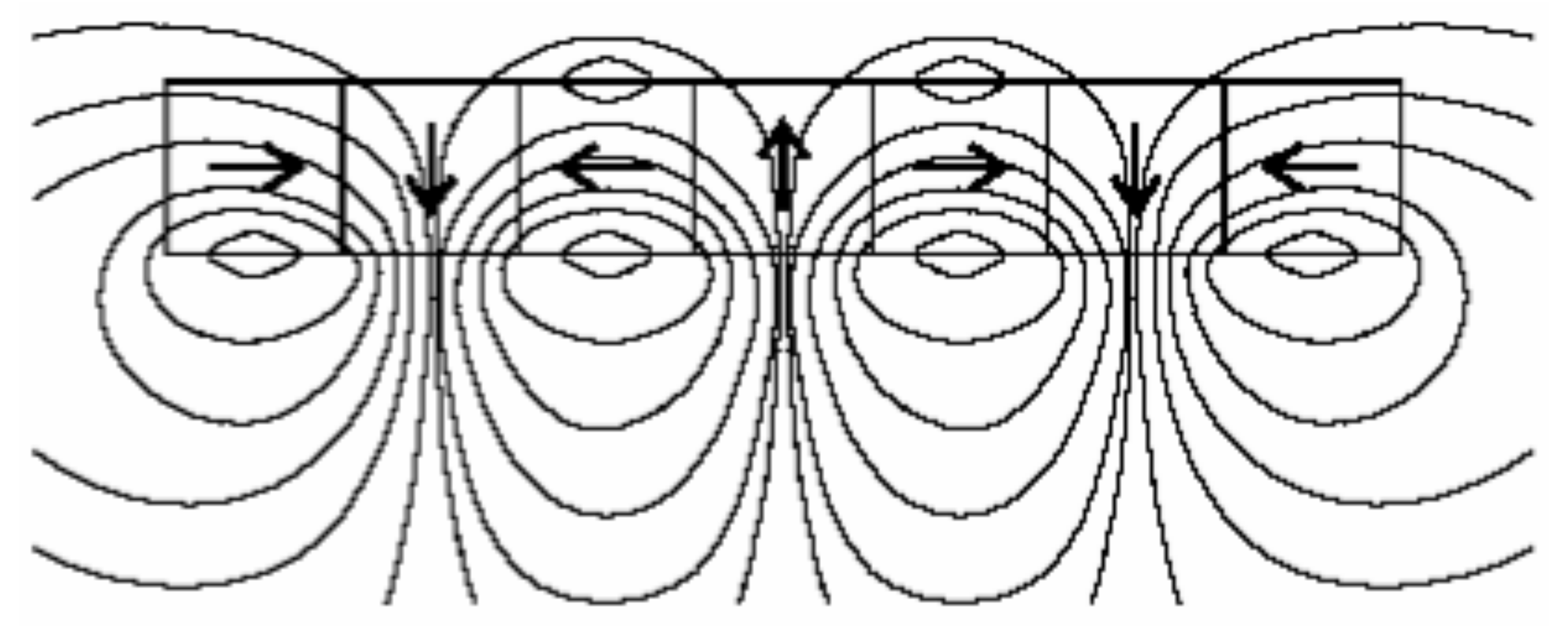
Presentation Outline

I. Introduction
  A. Background
  B. CLMLCRIS Project

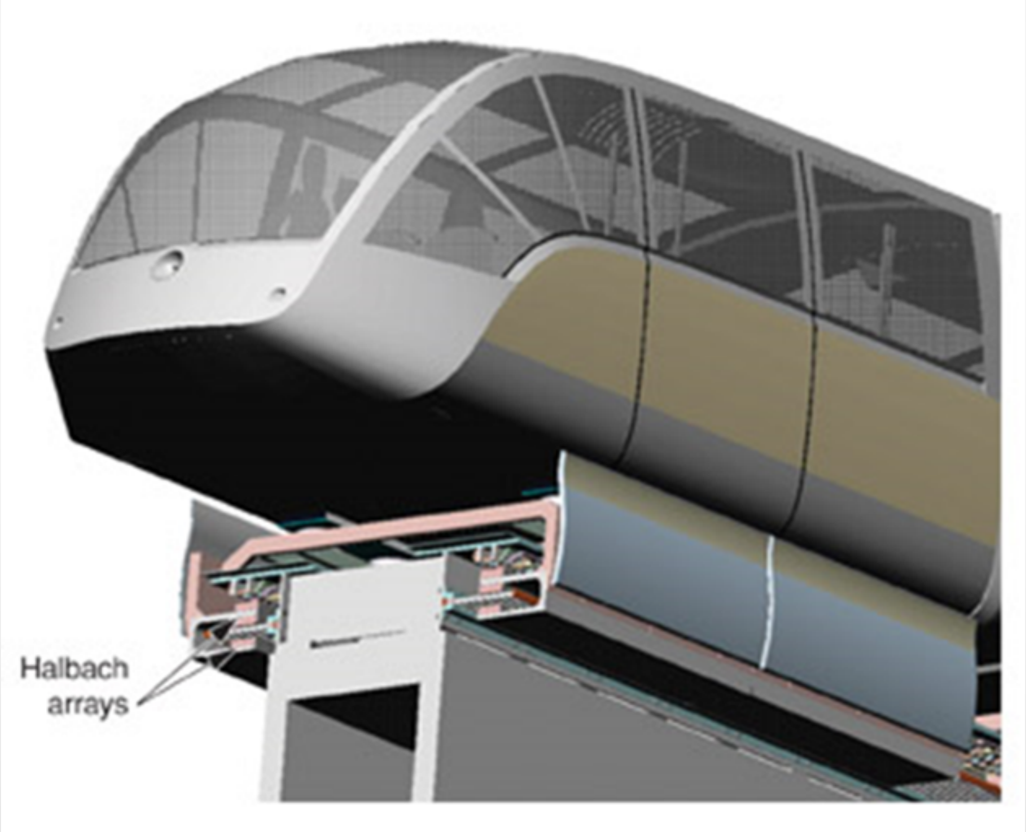
II. Development
  A. Motor Model
  B. Controller
  C. FPGA

III. Conclusion
  A. Work to be completed next semester
  B. Questions

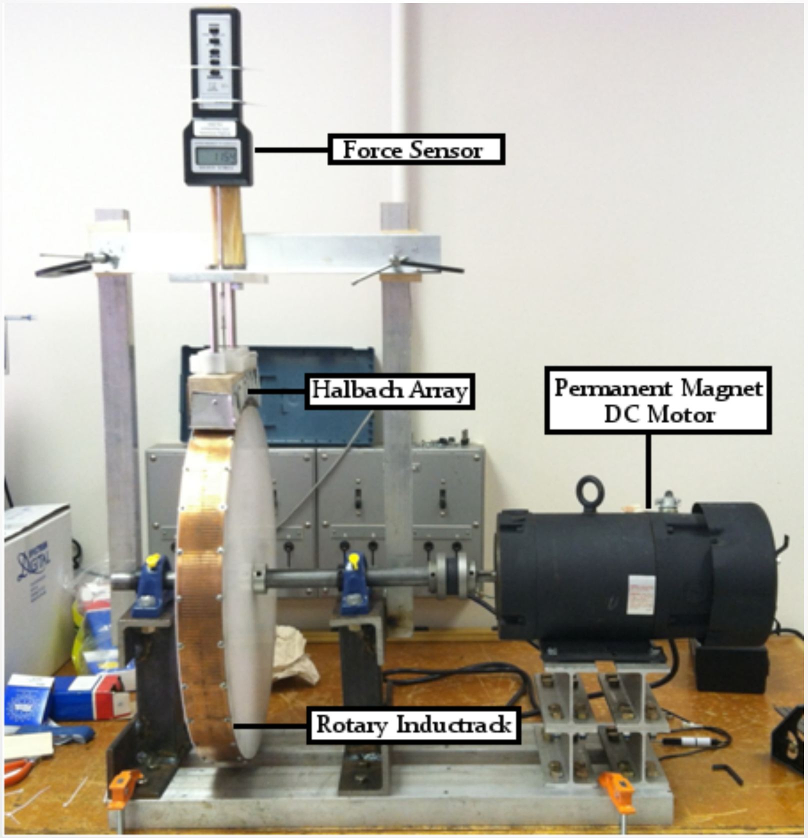
Halbach Array of Magnets



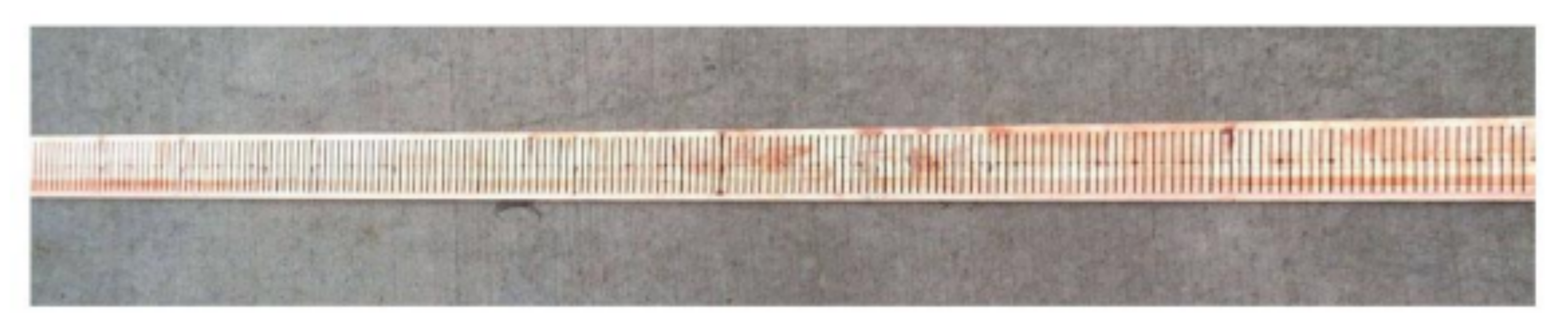
Halbach Array in an Actual Bullet Train



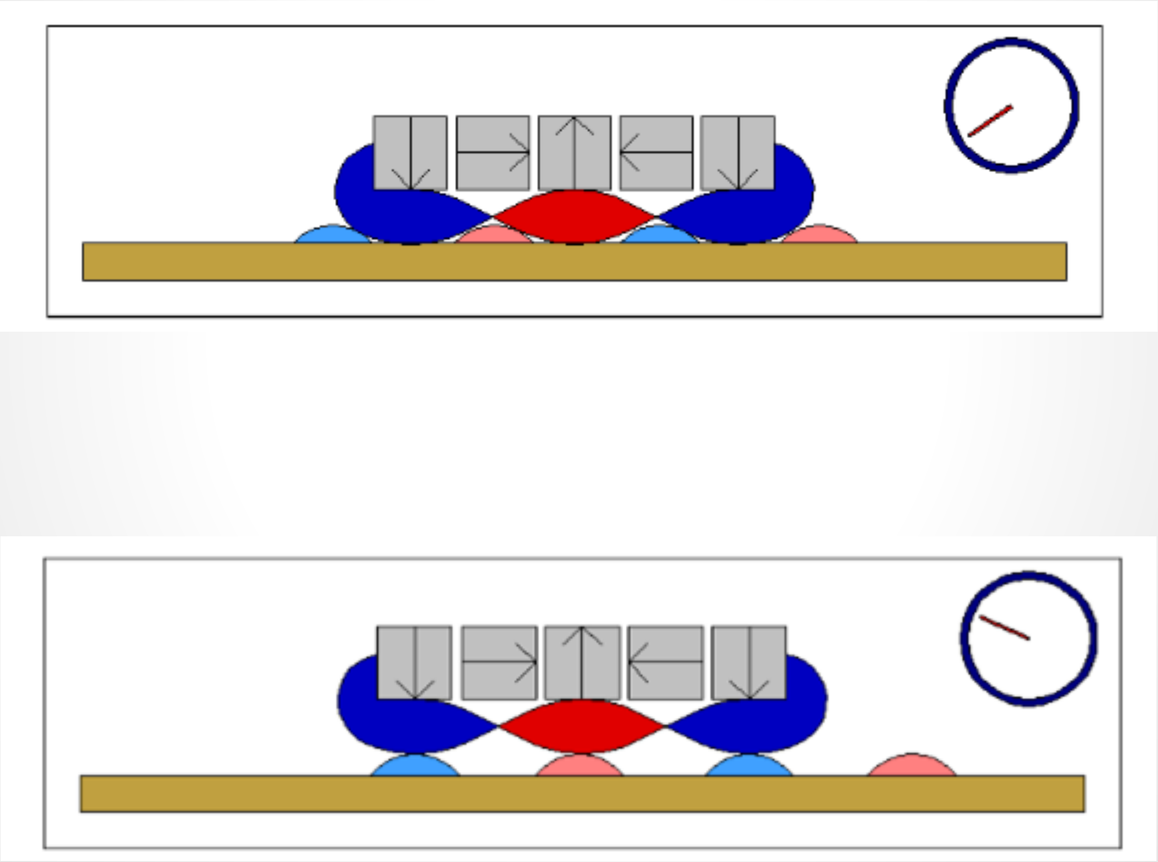
Our Inductrack System without Safety Enclosure

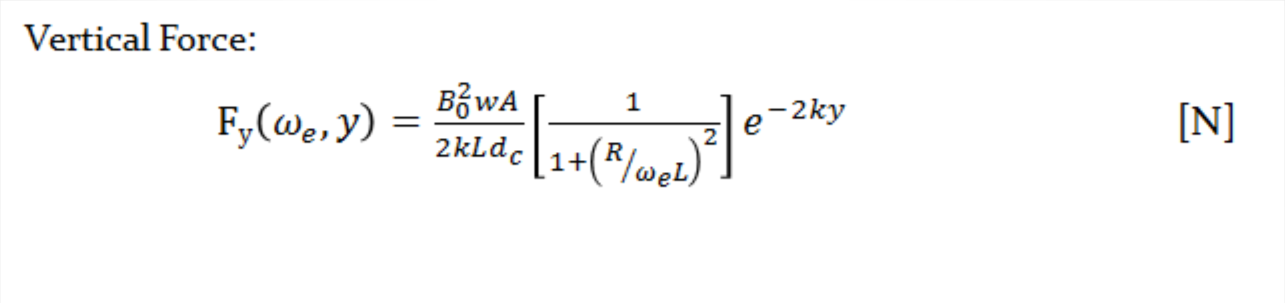


Copper Inductrack Rail



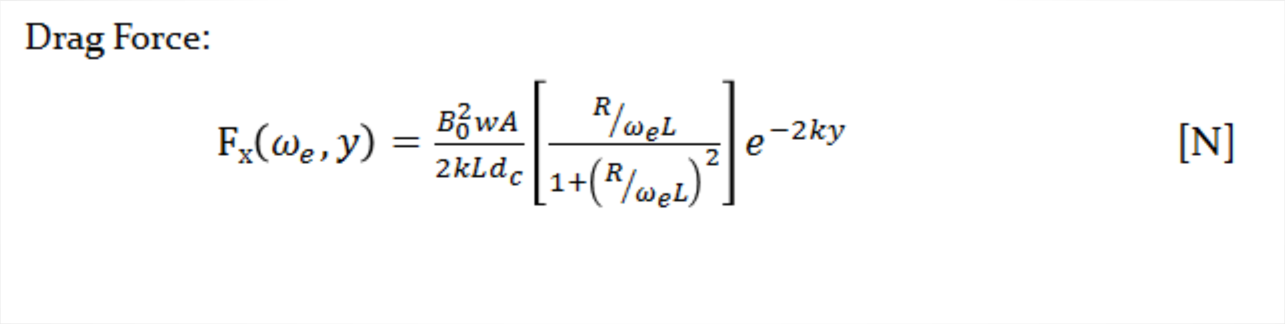
Magnetic Field Interaction





Vertical Force:

$$\mathrm{F_y}(\omega_e, y) = \frac{B_0^2 wA}{2kLd_c}\left[\frac{1}{1+\left({}^{R}\!/_{\omega_e L}\right)^2}\right]e^{-2ky} \qquad [\mathrm{N}]$$

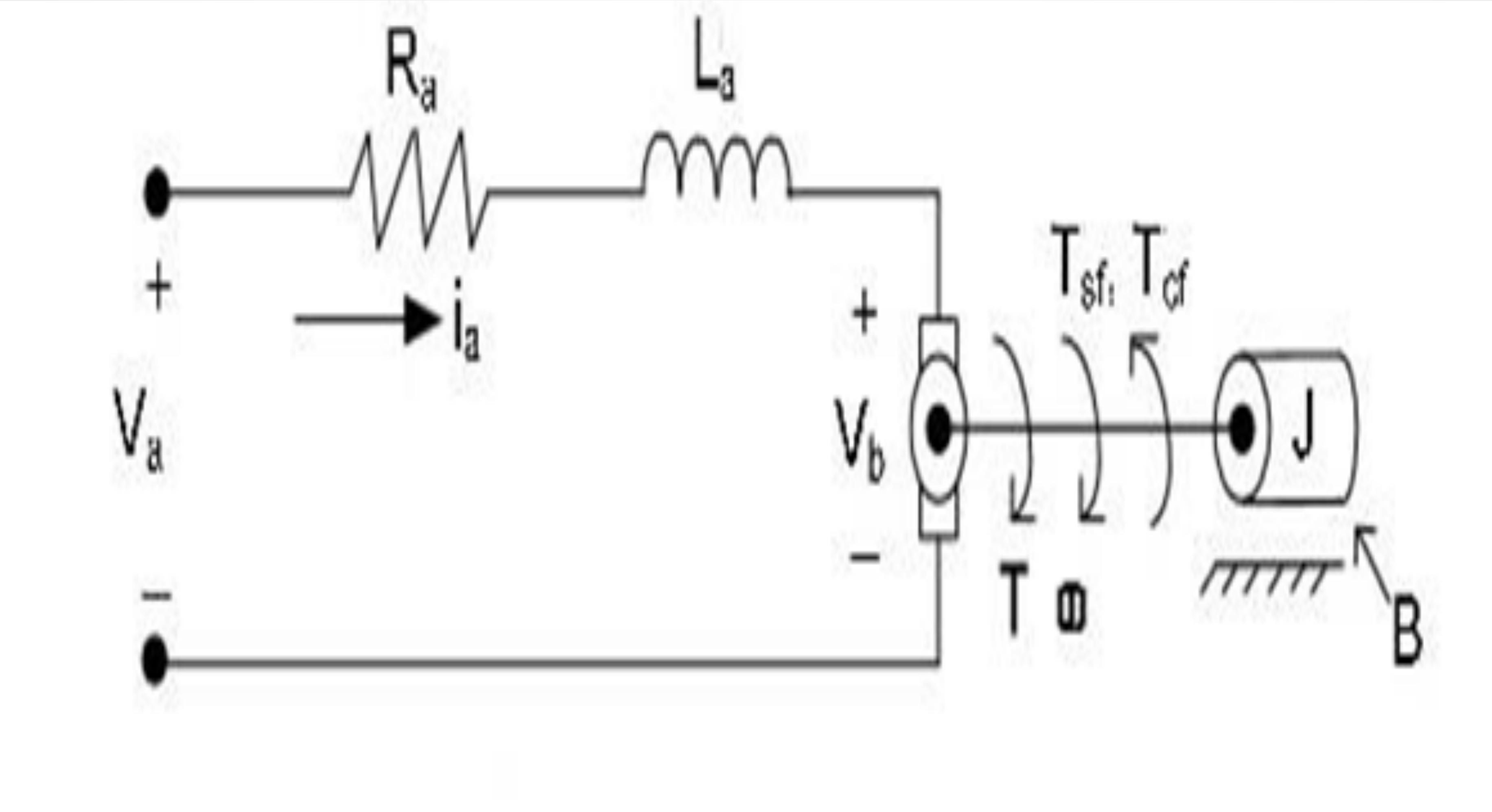


Drag Force:

$$\mathrm{F_x}(\omega_e, y) = \frac{B_0^2 wA}{2kLd_c}\left[\frac{{}^{R}\!/_{\omega_e L}}{1+\left({}^{R}\!/_{\omega_e L}\right)^2}\right]e^{-2ky} \qquad [\mathrm{N}]$$

Objectives

- Selection of suitable platform for controller implementation, which will allow a user to enter desired levitation height.
- Use of the selected platform to generate a PWM signal to drive the power electronics.
- Design controller implementation for system autonomy.
- Selection and design of appropriate power electronics which will allow control of the PWM signal.



Common Dc Motor Circuit Schematic

Measurable Quantities:

ω_m – machine rotational speed i – armature current

V_a – source voltage

Parameters to determine:

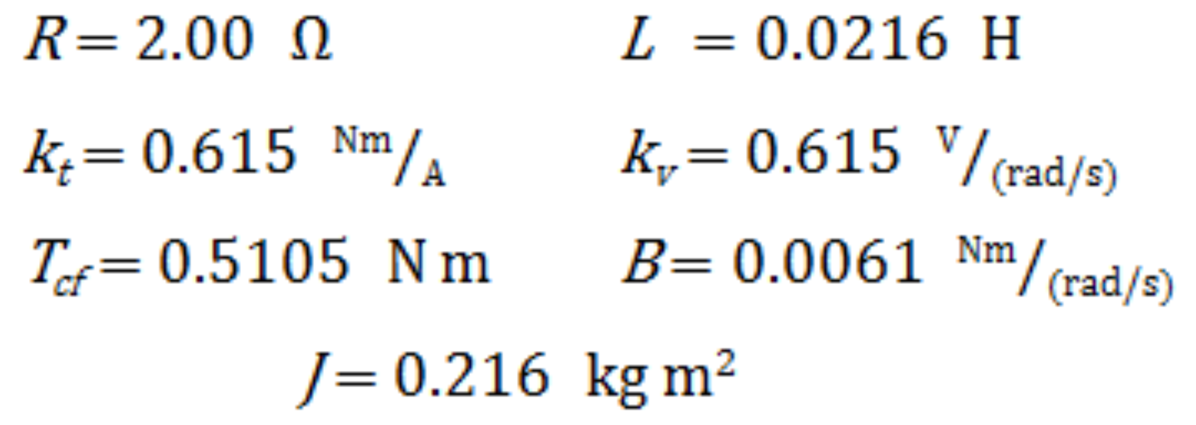
R_a – armature resistance L_a – armature inductance

k_v – motor torque constant k_T – back emf constant

B – motor viscous friction T_{cf} – coulombic friction

J – moment of inertia

Values Used for Motor Model



$R = 2.00\ \Omega$

$L = 0.0216\ \mathrm{H}$

$k_t = 0.615\ {}^{\mathrm{Nm}}/_{\mathrm{A}}$

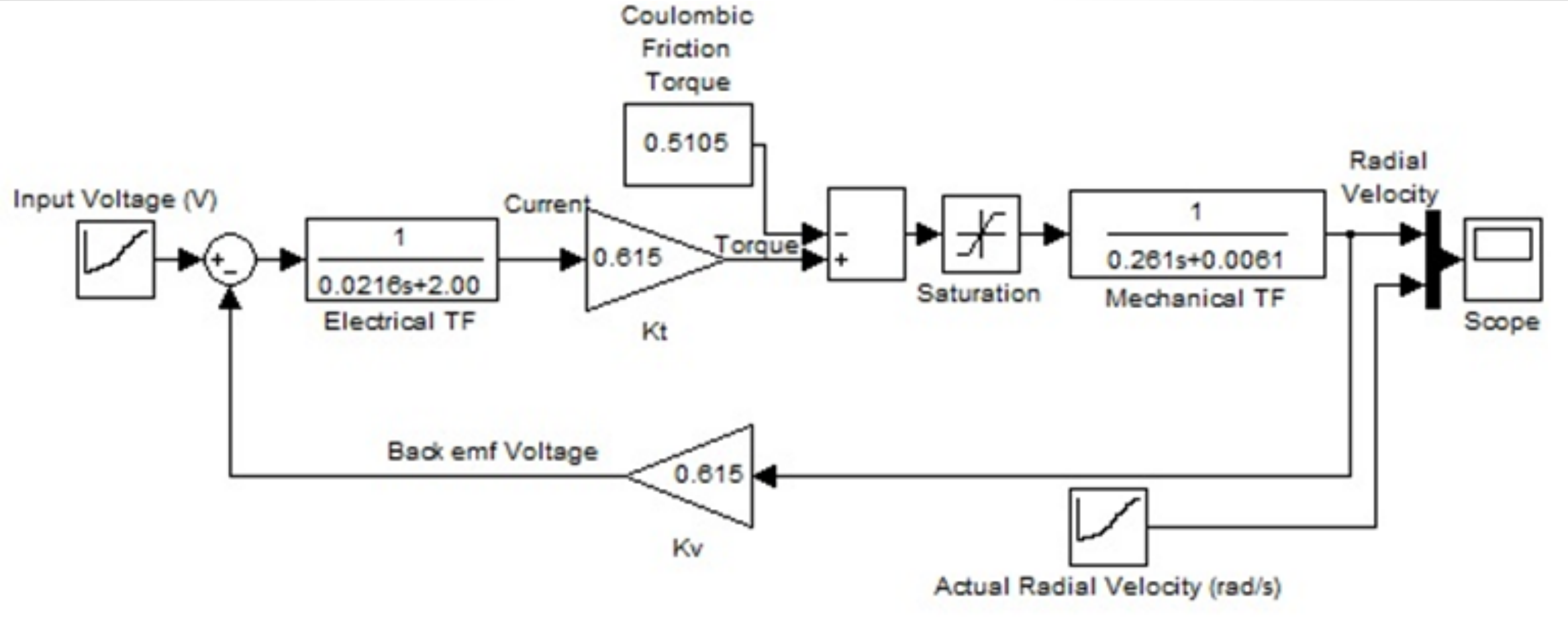
$k_v = 0.615\ {}^{\mathrm{V}}/_{(\mathrm{rad/s})}$

$T_{cf} = 0.5105\ \mathrm{N\,m}$

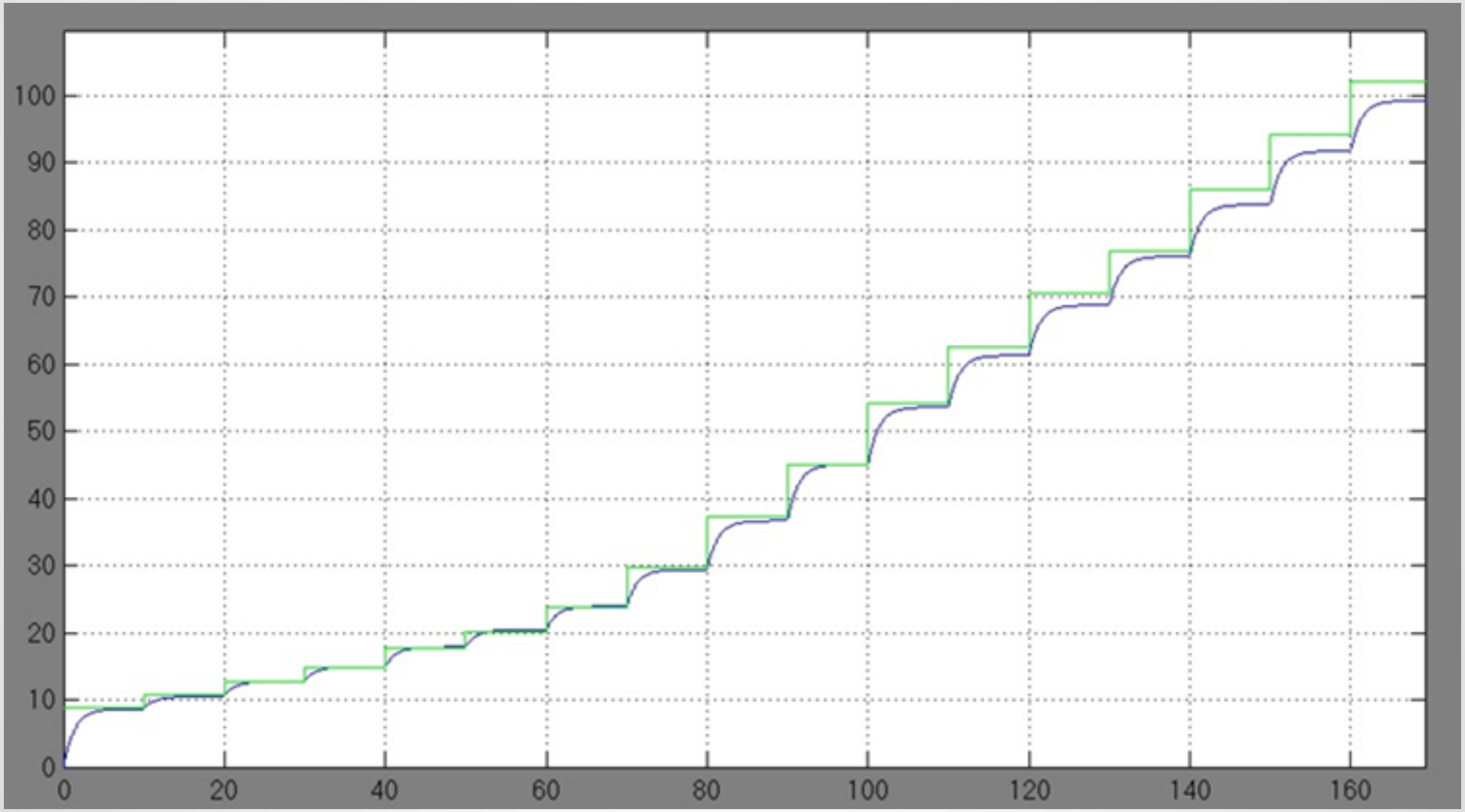
$B = 0.0061\ {}^{\mathrm{Nm}}/_{(\mathrm{rad/s})}$

$J = 0.216\ \mathrm{kg\,m^2}$

Motor Model


Coulombic Friction Torque
0.5105
Input Voltage (V)
+
–
1
0.0216s+2.00
Electrical TF
Current
0.615
Kt
Torque
–
+
Saturation
1
0.261s+0.0061
Mechanical TF
Radial Velocity
Scope
Back emf Voltage
0.615
Kv
Actual Radial Velocity (rad/s)

Green = Experimental Steady State Blue = Model Simulation



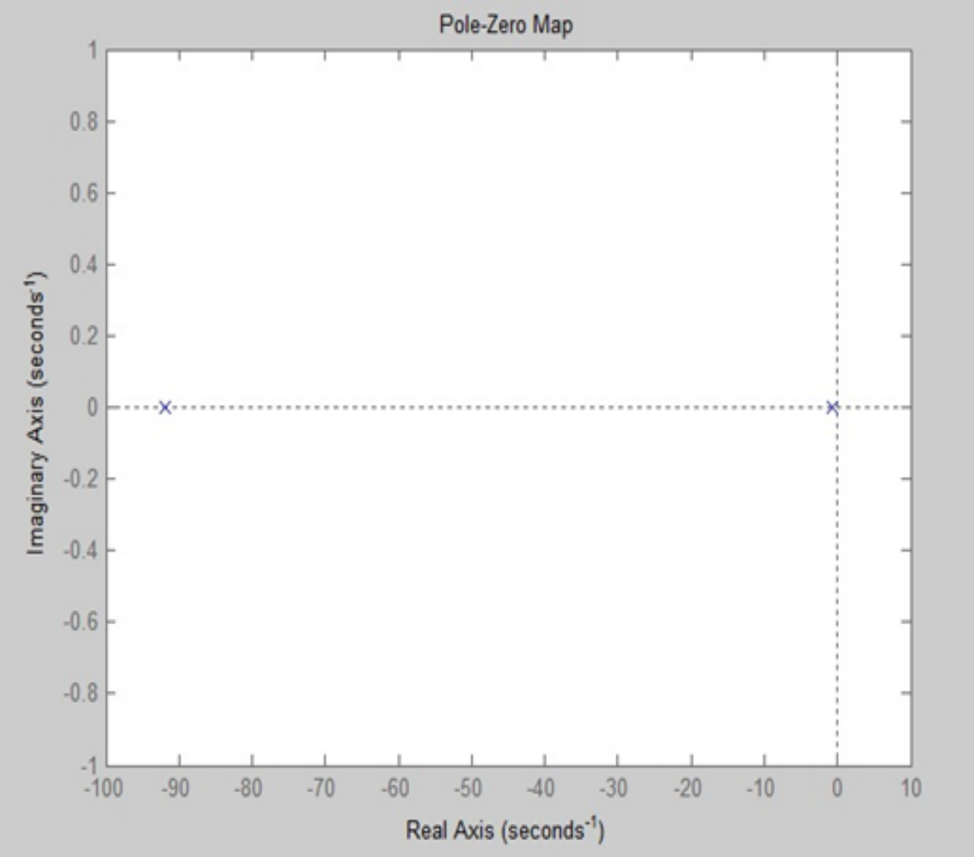
Voltage	Velocity	SIMULINK Model	% Error
V_a *(V)*	ω_m *(rad/s)*	ω_m *(rad/s)*	
7.15	8.792	8.643	1.69%
11.15	14.915	14.947	0.22%
13.00	17.741	17.861	0.68%
16.85	23.864	23.925	0.26%
20.34	29.830	29.421	1.37%
45.35	70.650	68.815	2.60%
49.96	76.930	76.077	1.11%
54.86	85.958	83.795	2.52%
64.70	102.050	99.295	2.70%

Plant for Closed Loop Control

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

$p_1 = -91.86$ [rad/s]

$p_2 = -0.75$ [rad/s]



Controller Transfer Function Using Matlab

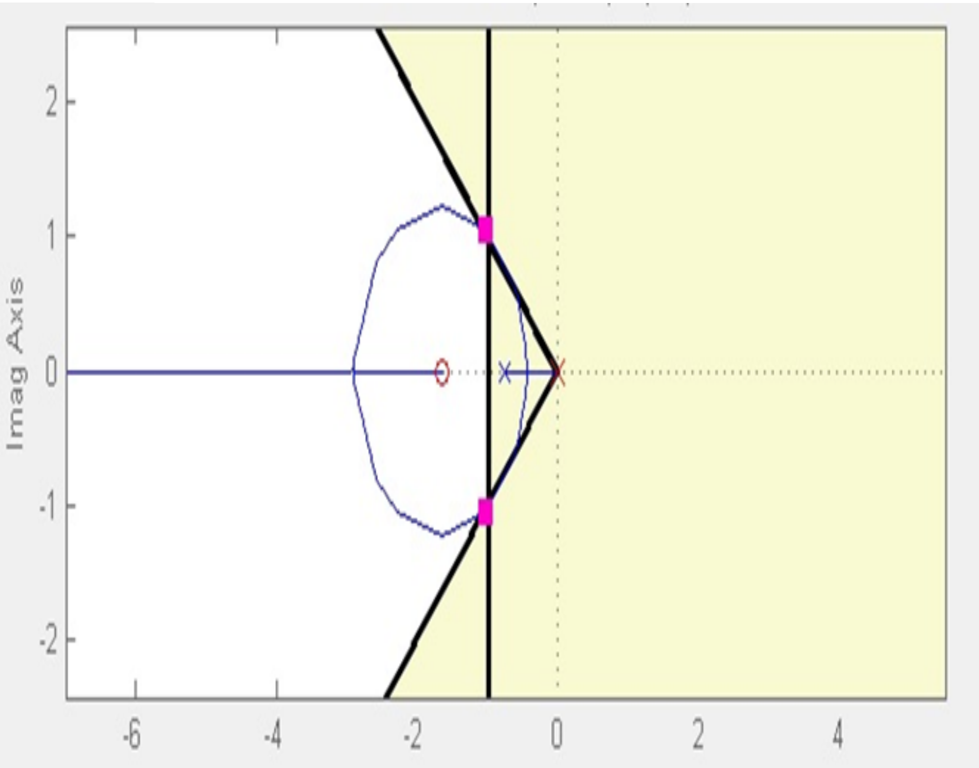
Controller Transfer Function:

$$C(s) = k_p \frac{s+z}{s}$$

A more realistic Transfer Function:

$$C(s) = k_p \frac{s+z}{s(s+p)}$$

A lead network with integral action



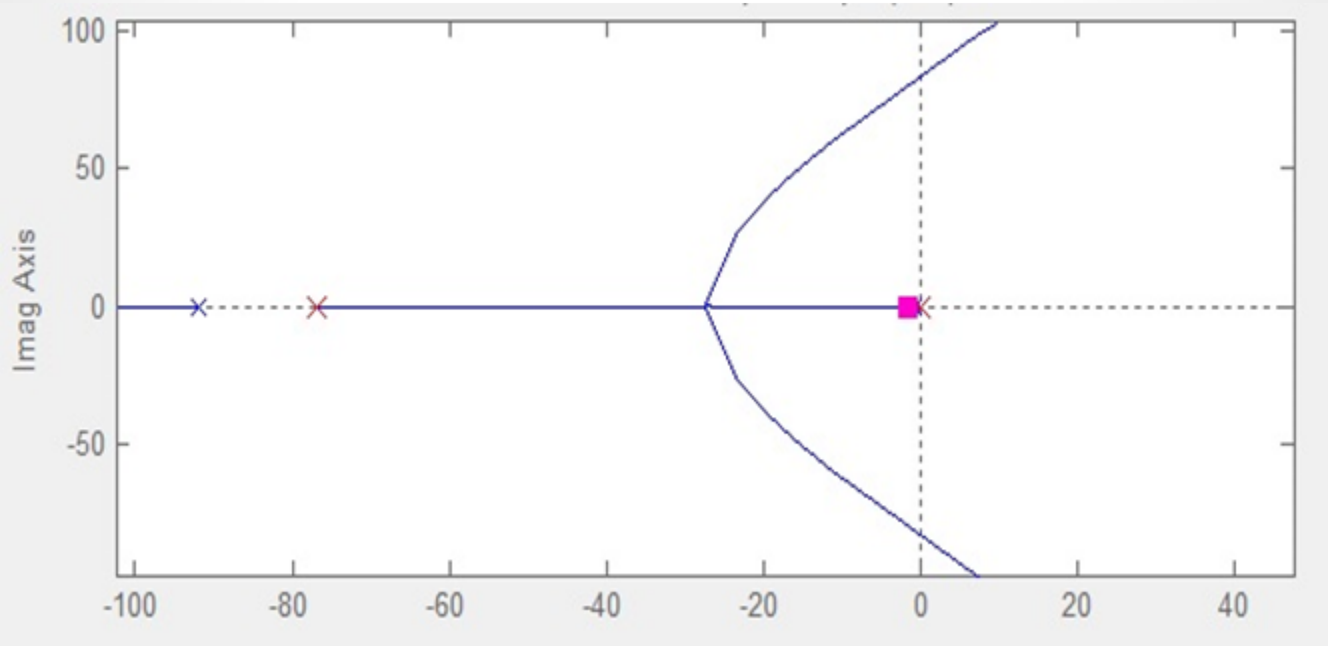
Design Specification 1: steady state error = 0

Design Specification 2: Less than 10% overshoot. $\zeta = 0.707$

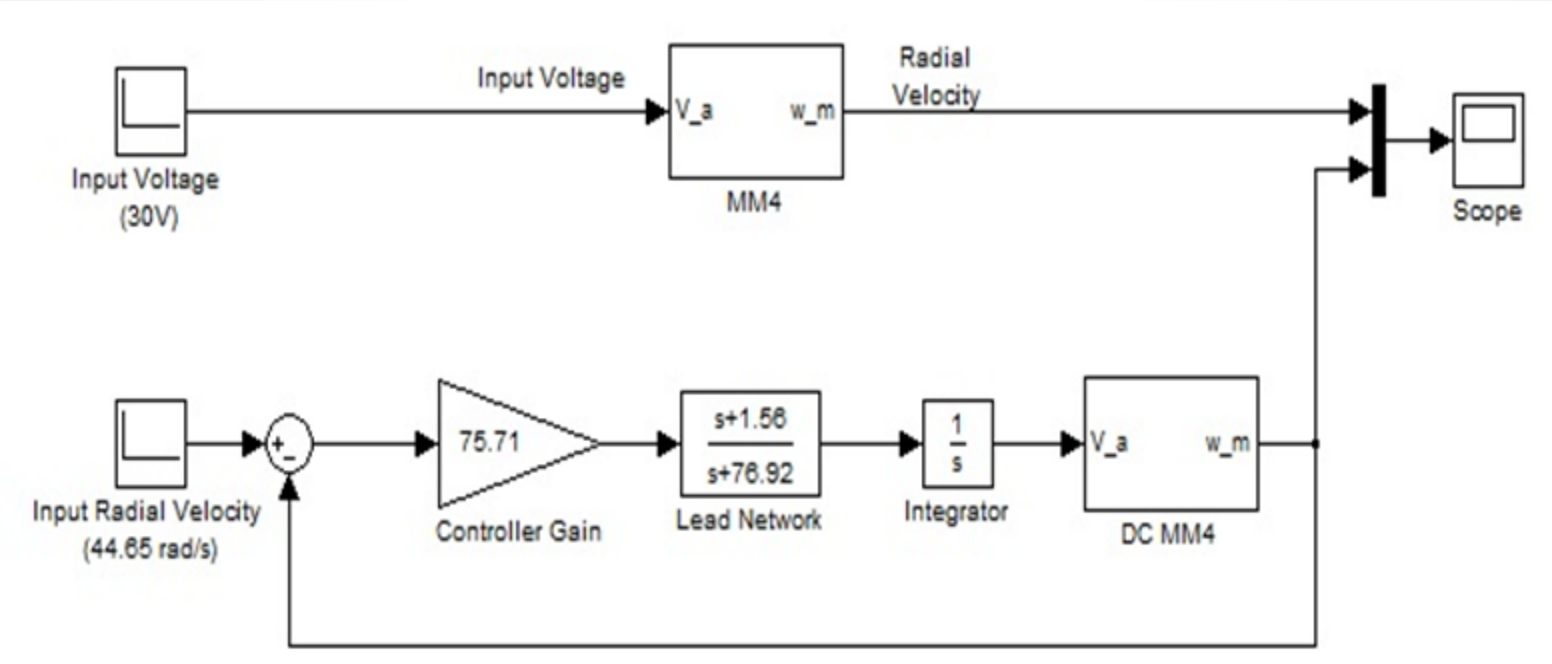
Design Specification 3: $t_s < 6$ seconds

Controller Transfer Function Using Matlab

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

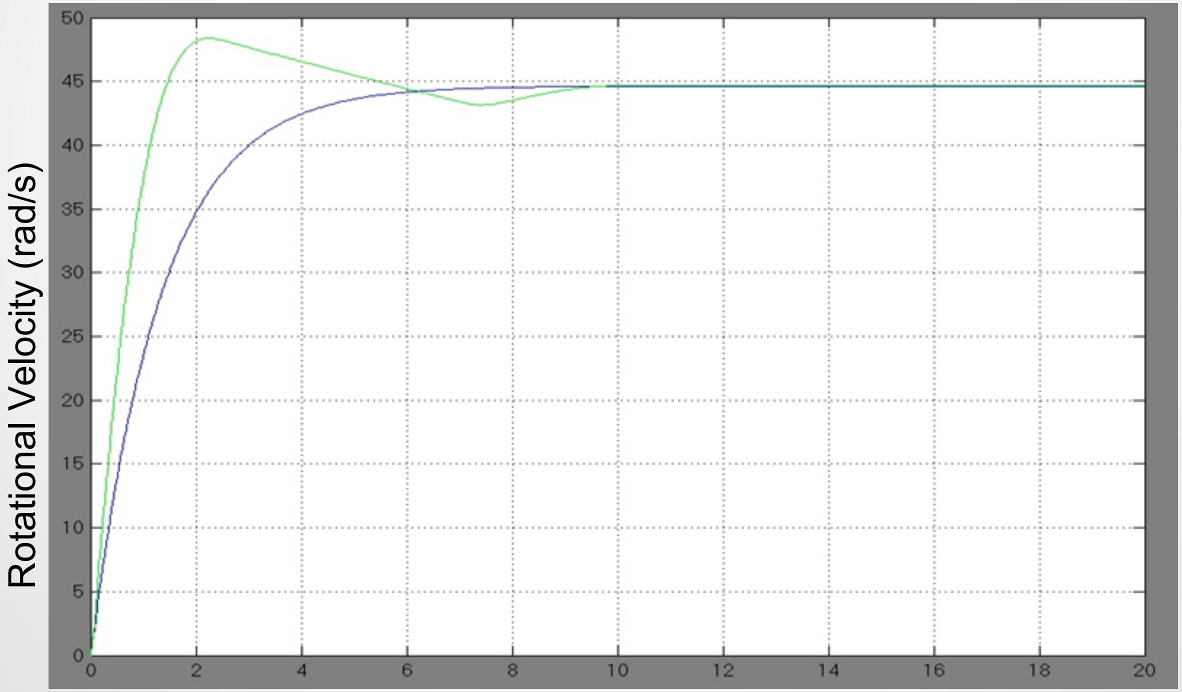


Open and Closed Loop System



Simulation Results for Open and Closed Loop System

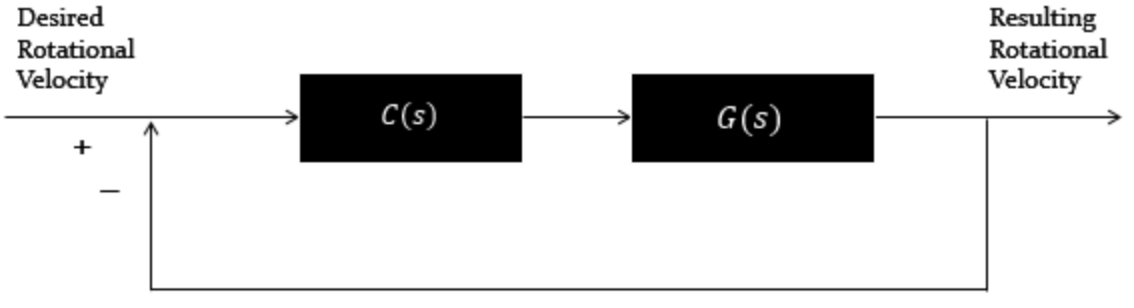
Green = Controller Blue = Uncontrolled



Determining Sampling Time

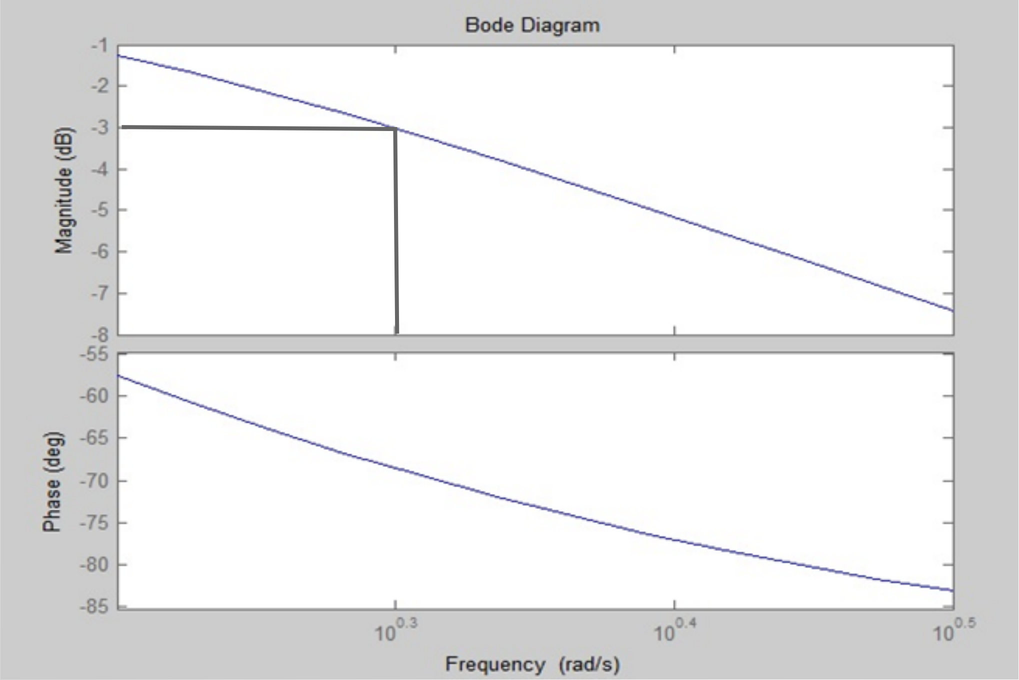
$$C(s) = 75.71\frac{s + 1.56}{s(s + 76.92)}$$

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



$$G_{cl}(s) = 1.42\frac{s + 1.56}{s^4 + 169.54s^3 + 7193.85s^2 + 13776.92s + 13207.69}$$

Determining Sampling Time



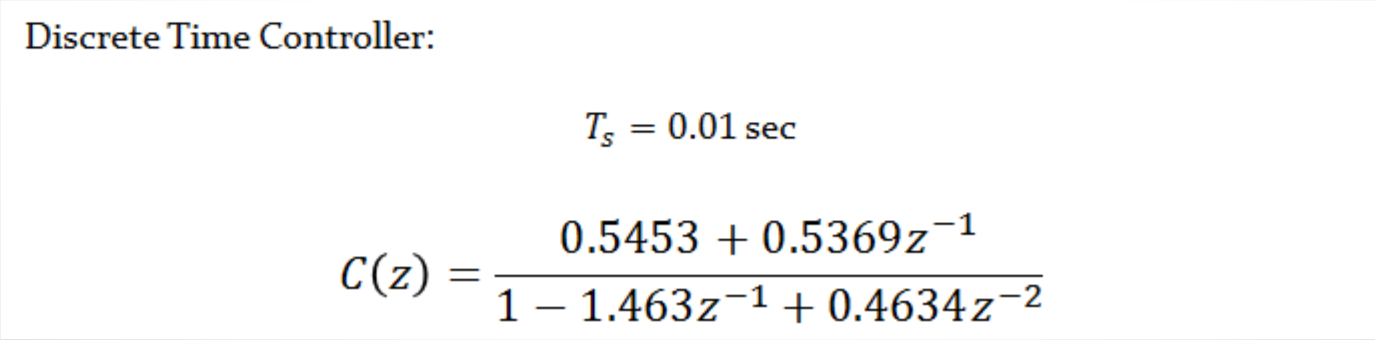
$$T_s < \frac{1}{40 \times BW}$$

$$T_s < \frac{1}{40 \times 10^{0.3}}$$

$$T_s < .0125 \text{ sec}$$

Converting continuous time to discrete time controller

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



Discrete Time Controller:

$$T_s = 0.01\,\text{sec}$$

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

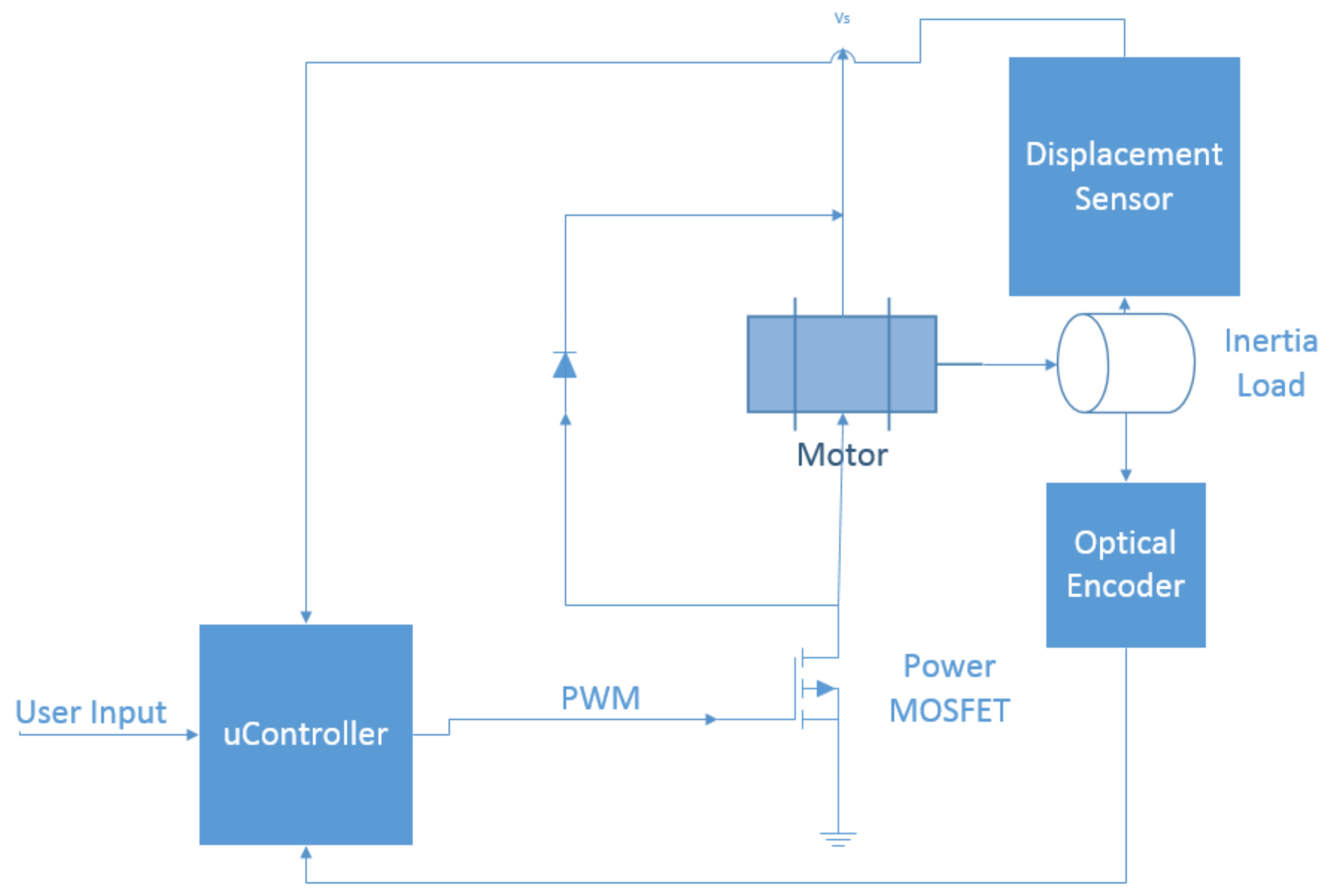
Performance Specifications for Controller

- The controller selected is a Spartan 3E FPGA board.

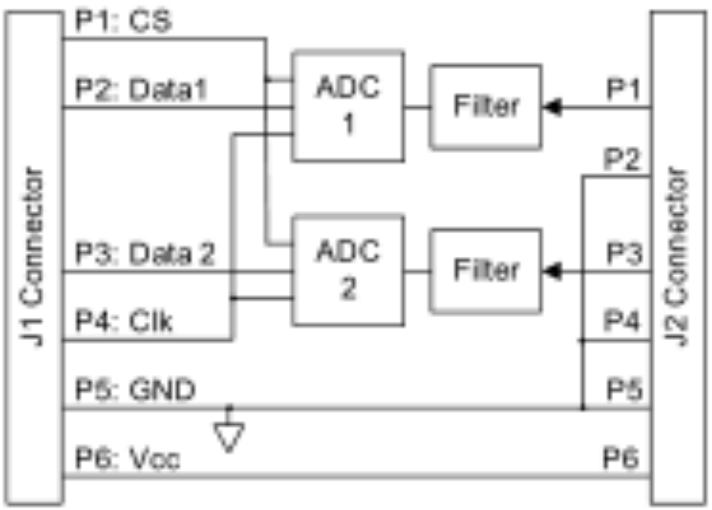
- The ADC chip has enough resolution to handle changes of .0002v in displacement sensor voltage.

- The controller shall sample displacement at least every 50 ms.

High Level Block Diagram



Datasheets



AD1 Circuit Diagram

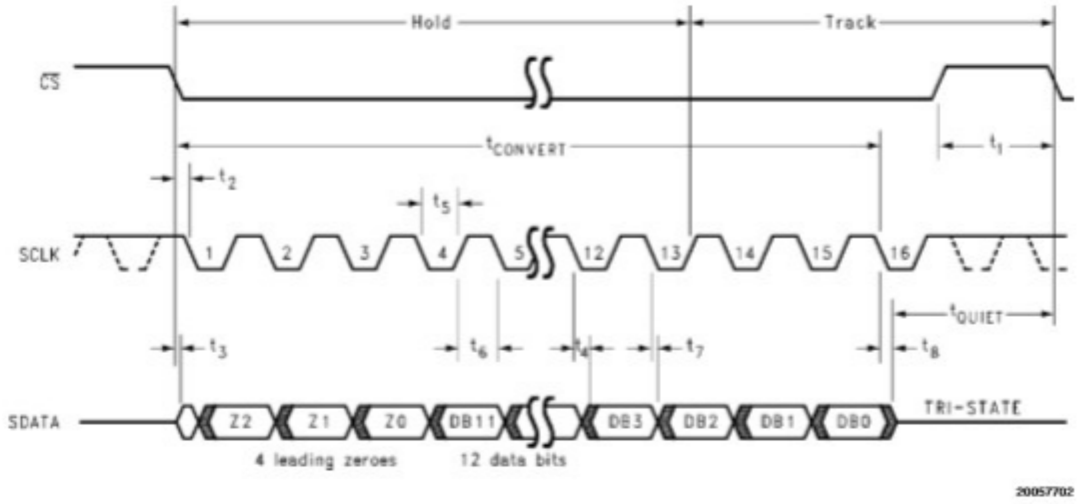
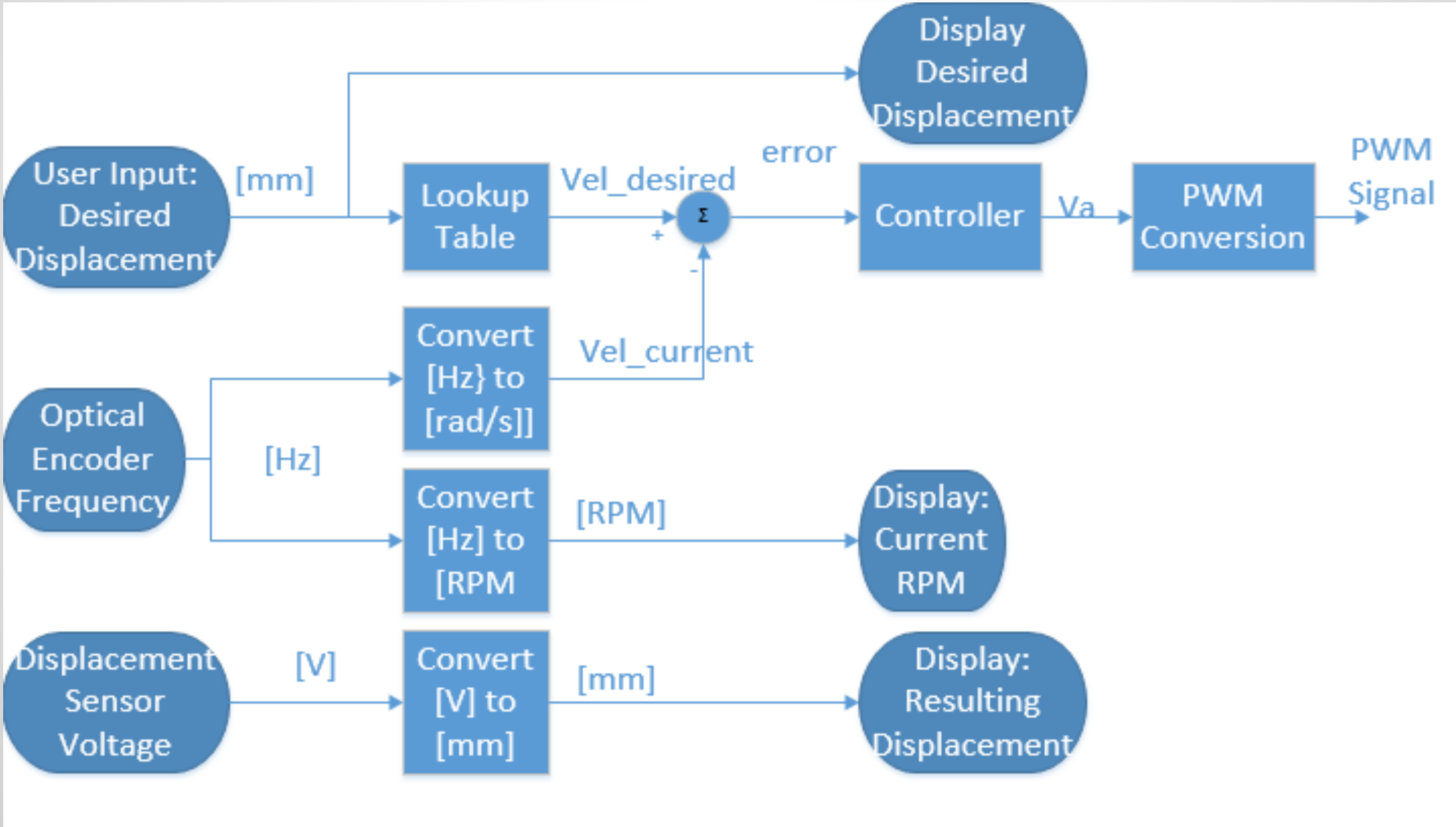


FIGURE 1. ADCS7476 Serial Interface Timing Diagram

Controller Flowchart



User Input: Desired Displacement

[mm]

Display Desired Displacement

Lookup Table

Vel_desired

+

Σ

-

error

Controller

Va

PWM Conversion

PWM Signal

Optical Encoder Frequency

[Hz]

Convert [Hz} to [rad/s]]

Vel_current

Convert [Hz] to [RPM

[RPM]

Display: Current RPM

Displacement Sensor Voltage

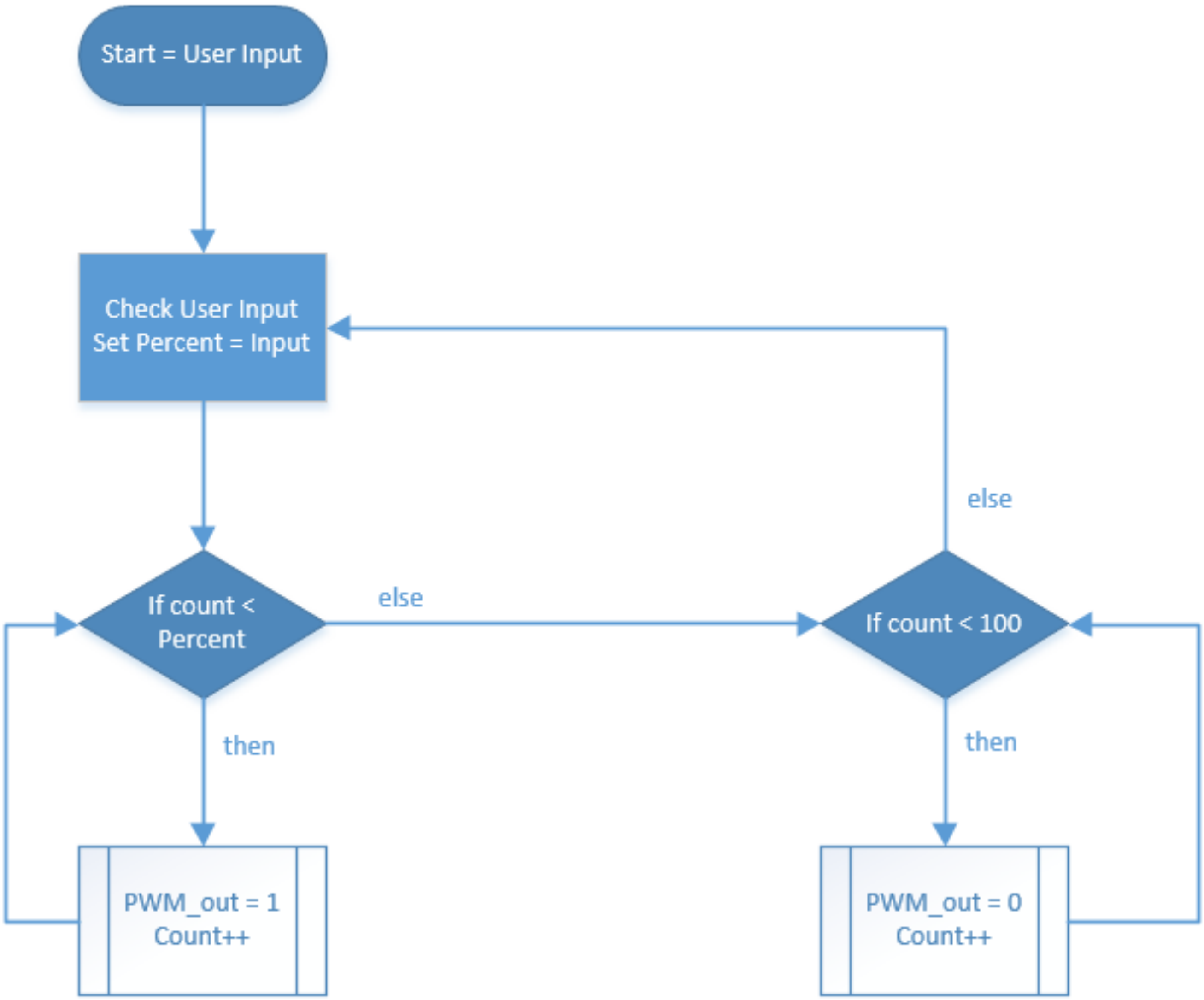
[V]

Convert [V] to [mm]

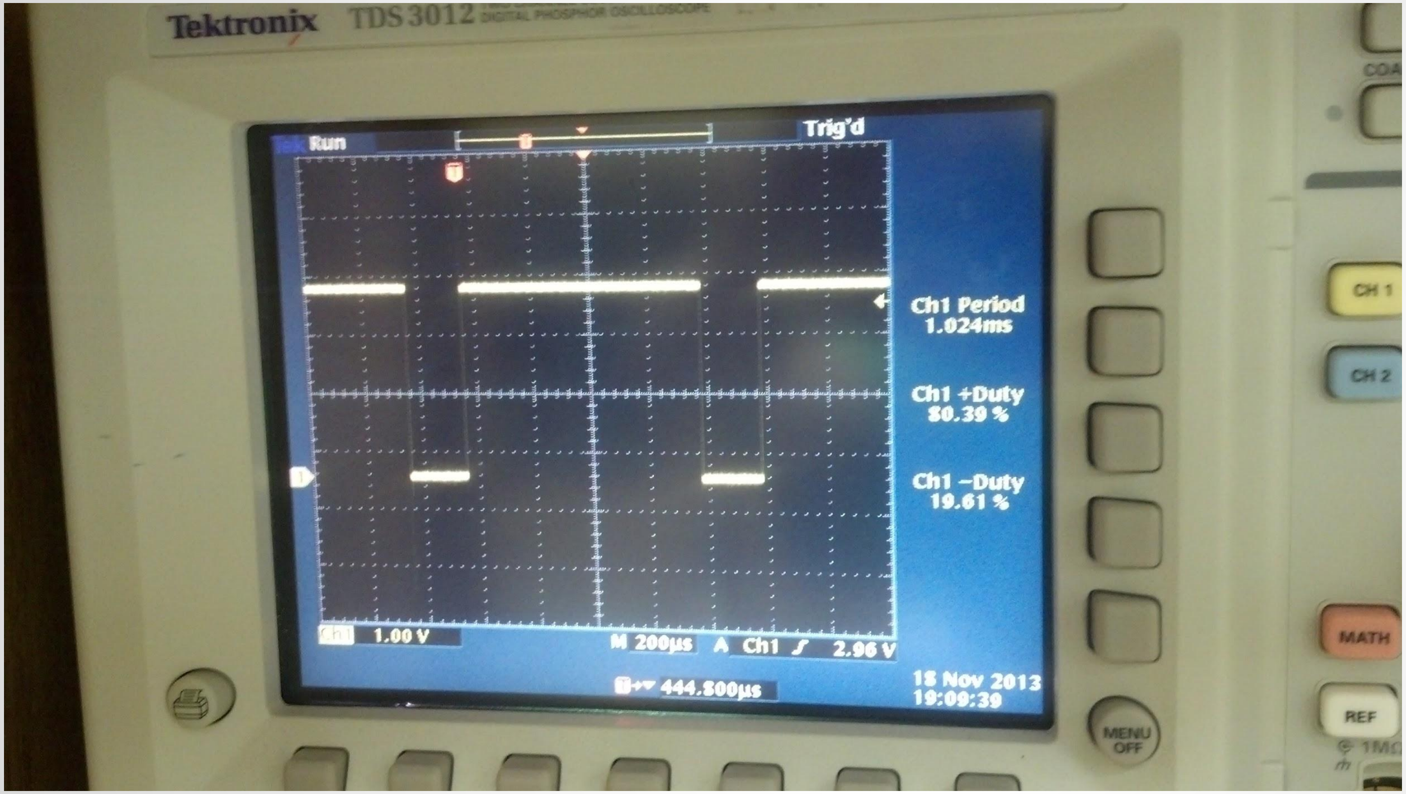
[mm]

Display: Resulting Displacement

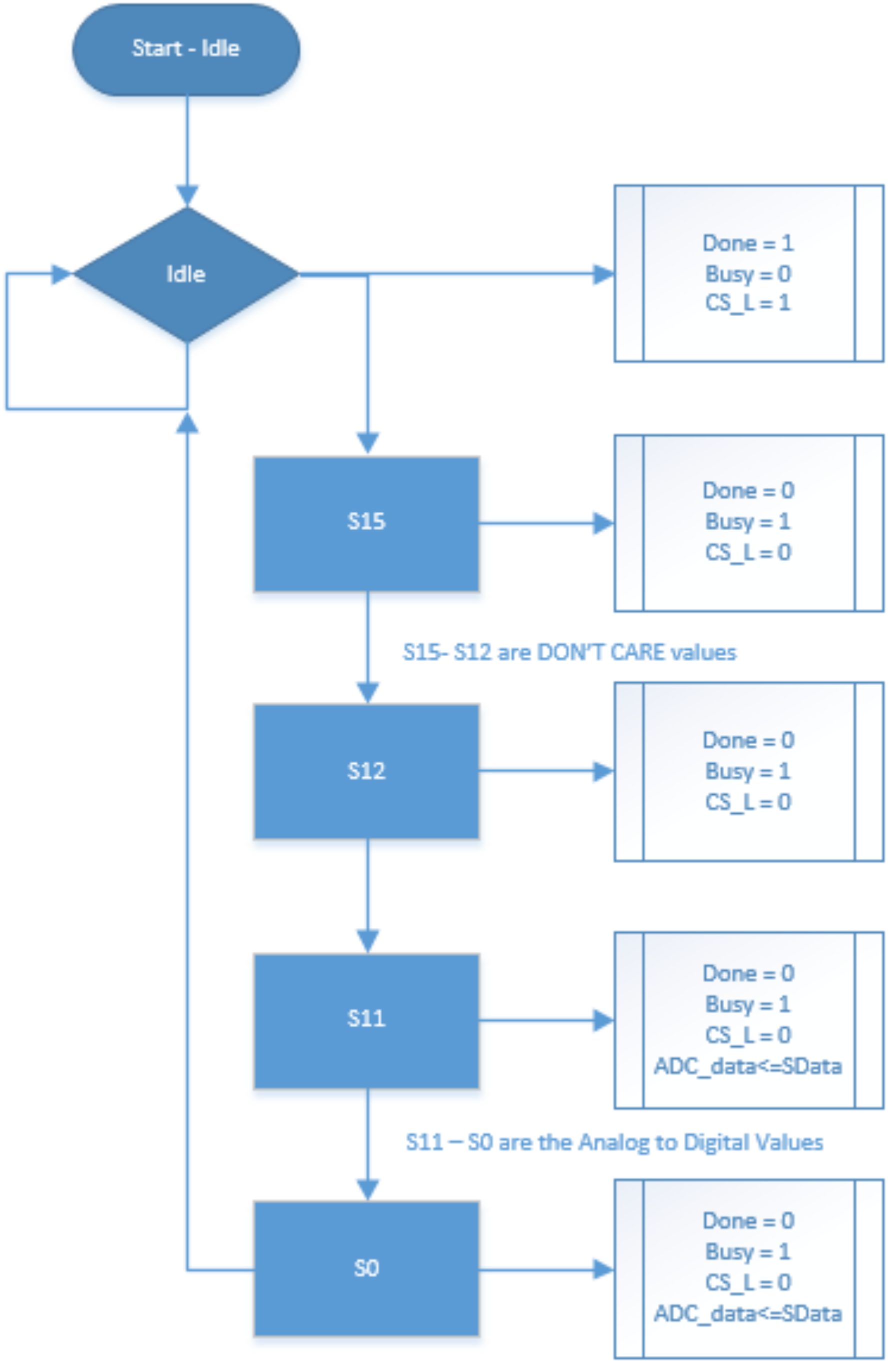
PWM Flowchart



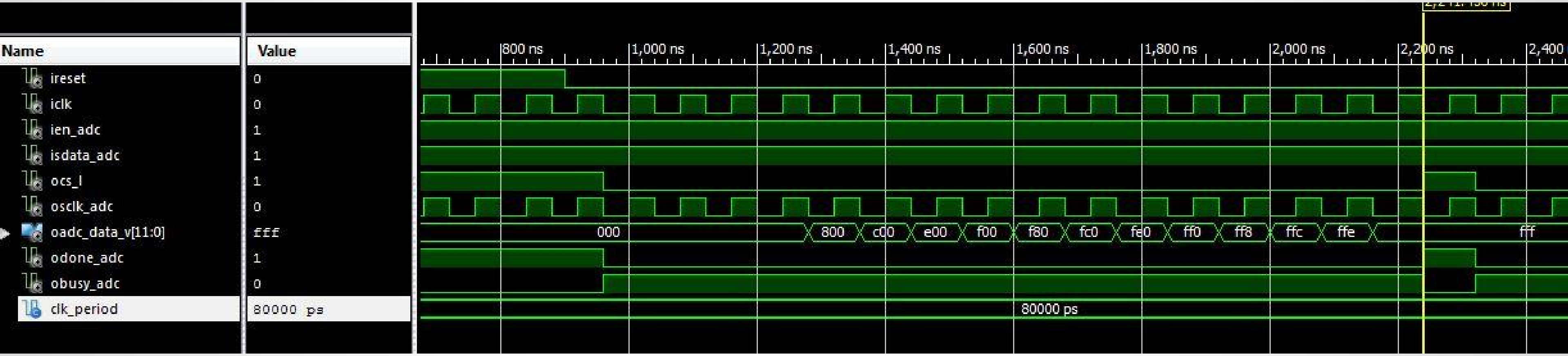
PWM Oscilloscope Results



ADC Flowchart

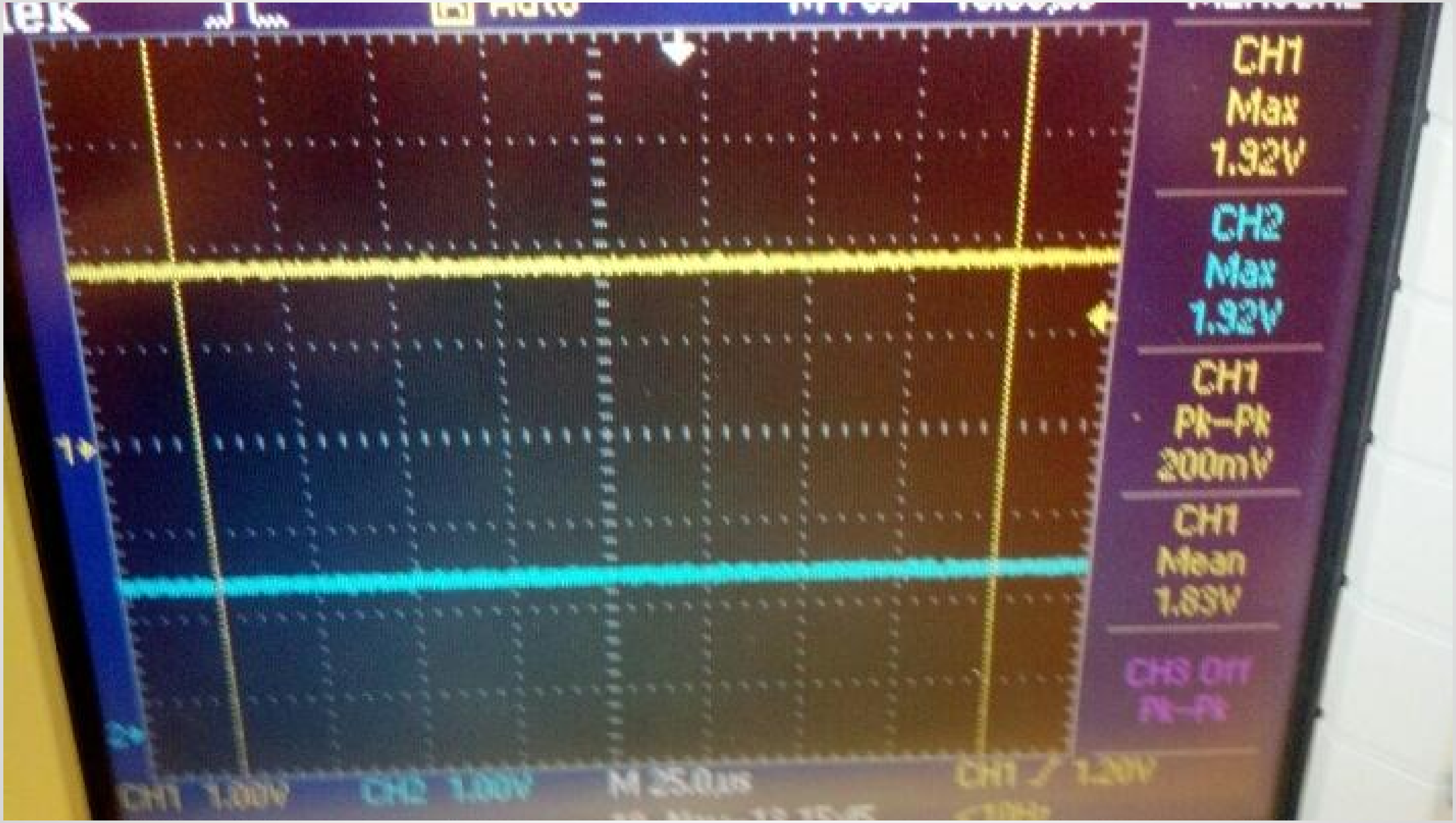


ADC Simulation Results



ADC Input Results

Input Voltage and Output Voltage



Equipment and Parts List

- Oscilloscope
- Spartan 3E starter kit
- ADC chip
- VHDL
- Maglev system in power lab

Schedule for This Semester

- 11/26-12/10 Code rotary encoder

Schedule for Next Semester

- 1/28-2/4 Combine rotary encoder with PWM code to be able to vary duty cycle
- 2/11-2/18 Create lookup table to convert user input to PWM duty cycle
- 2/25-3/4 Select power electronics and design circuit to power motor

Schedule for Next Semester

- 3/11 Test power electronics
- 3/25-4/1 Implement controller design
- 4/8-4/15 Make system a stand-alone system and mount FPGA on a PCB
- 4/22-5/6 Prepare for final presentation

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 629,503 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.
  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

References

- Dr. Lu for help with VHDL coding
- Kyle Gavelek, Victor Panek, Christopher Smith. Senior Project. “Closed Loop Control of Halbach Array Magnetic Levitation System Height”. Final Report, May 2013.
- Dirk DeDecker, Jesse VanIseghem. Senior Project. “Development of a Halbach Array Magnetic Levitation System”. Final Report, May 2012.
- Glenn Zomchek. Senior Project. “Redesign of a Rotary Inductrack for Magnetic Levitation Train Demonstration”. Final Report, May 2007.
- Paul Friend. Senior Project. Magnetic Levitation Technology 1. Final Report, May 2004.
- Post, Richard F., Ryutov, Dmitri D., “The Inductrack Approach to Magnetic Levitation,” Lawrence Livermore National Laboratory.