Closed Loop Magnetic Levitation Control of a Rotary Inductrack System

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Presentation Outline

I. Introduction
  A. Background and Previous Work
  B. Original Goals
  C. System Block Diagram
II. Current Progress
  A. Analog Circuitry
  B. Controller
  C. Status of the Project
III. Conclusion
  A. Patents
  B. References
  C. Questions

Halbach Array of Magnets

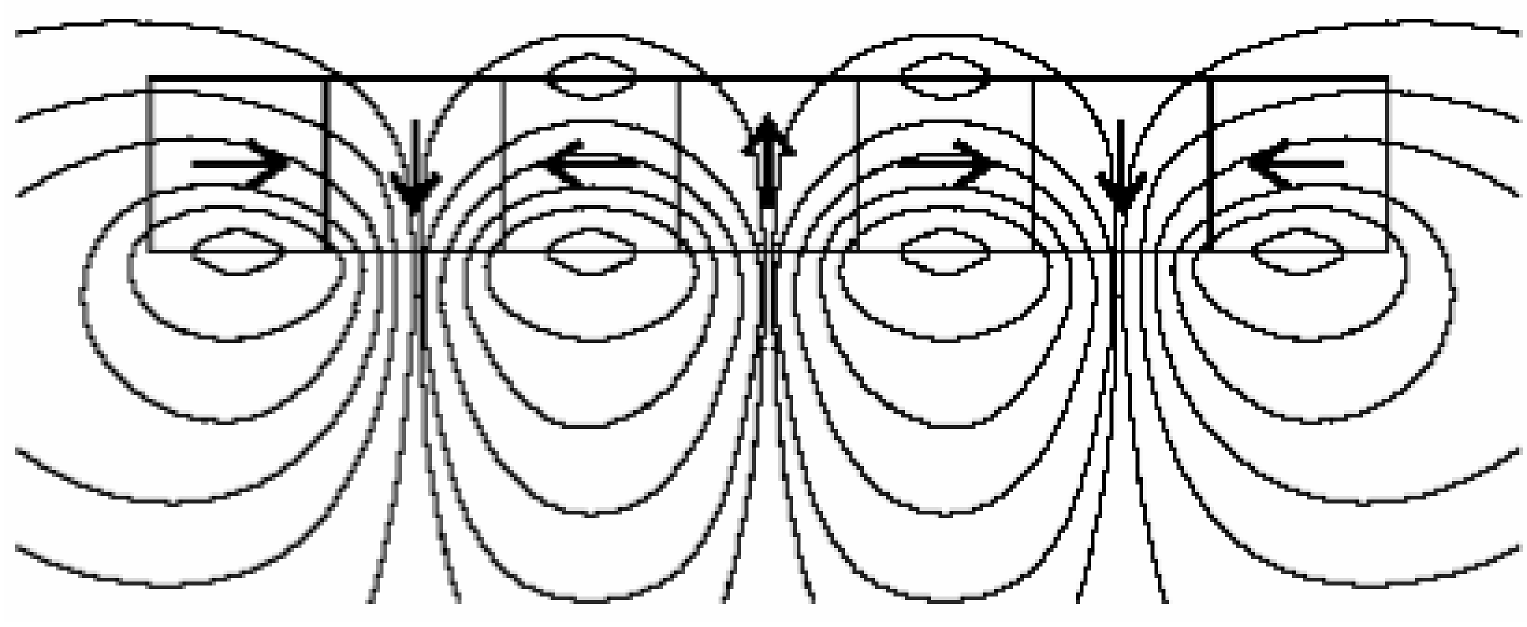


Figure 3-1

Halbach Array in an Actual Bullet Train

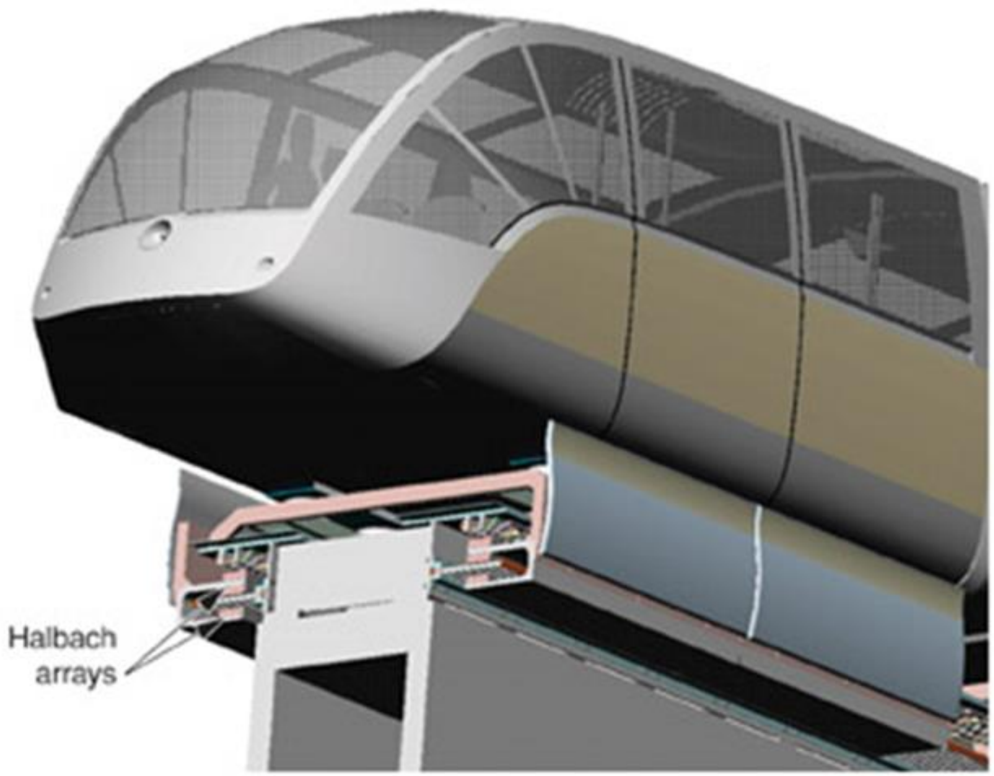


Figure 4-1

Inductrack System without and with Safety Enclosure

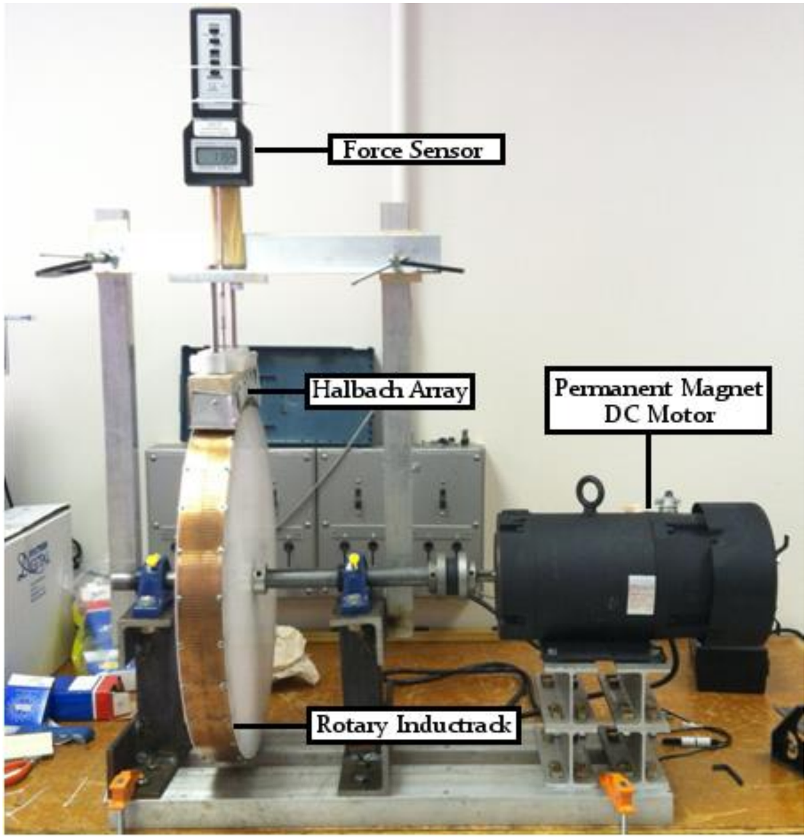


Figure 5-1

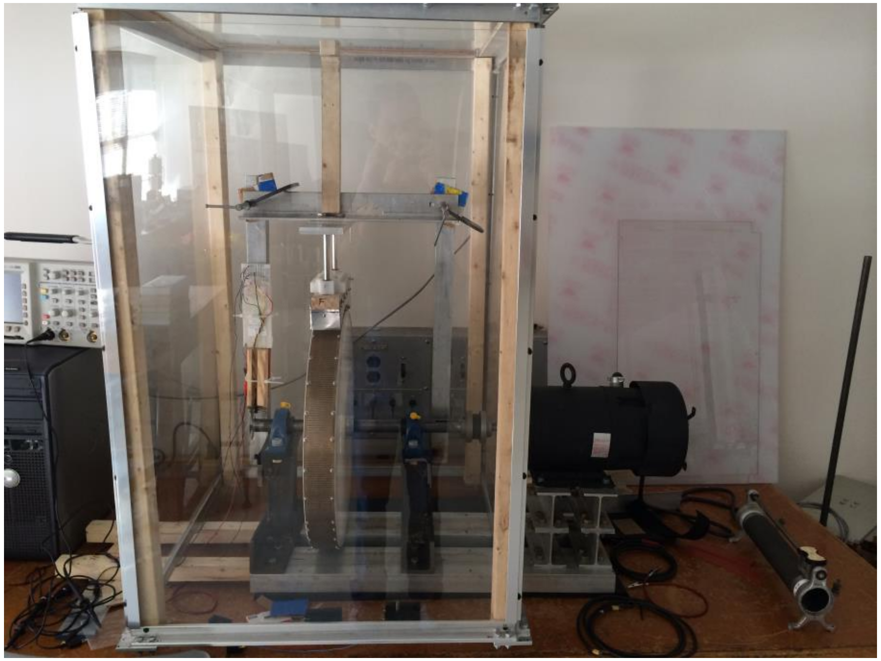


Figure 5-2

Copper Inductrack Rail

Figure 6-1

Magnetic Field Interaction

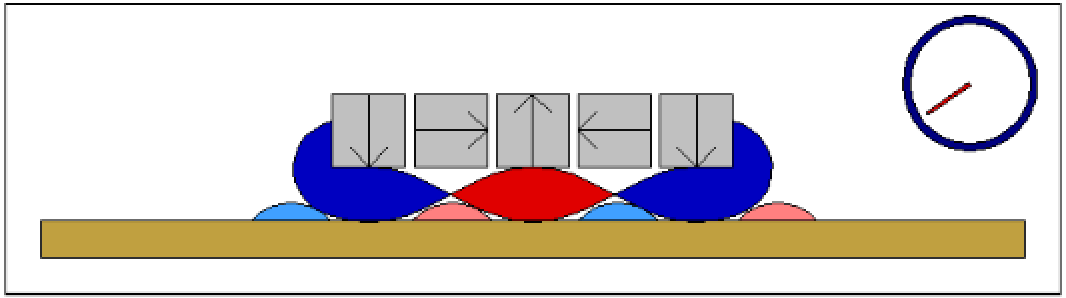


Figure 7-1

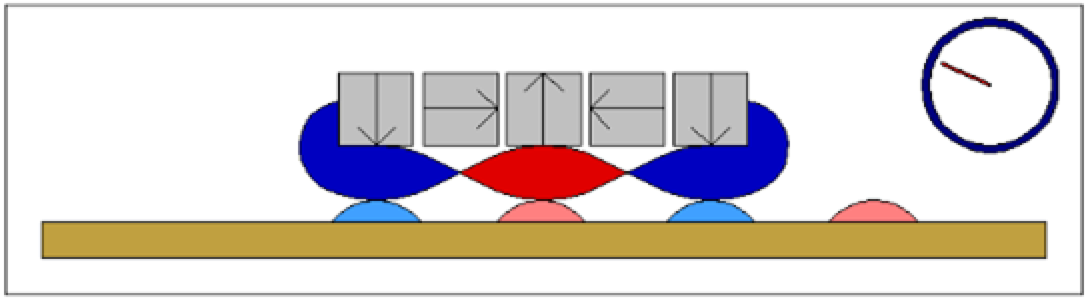


Figure 7-2

Relevant Equations

Vertical Force:

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

Equation 8-1

Drag Force:

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

Equation 8-2

Common DC Motor Circuit Schematic

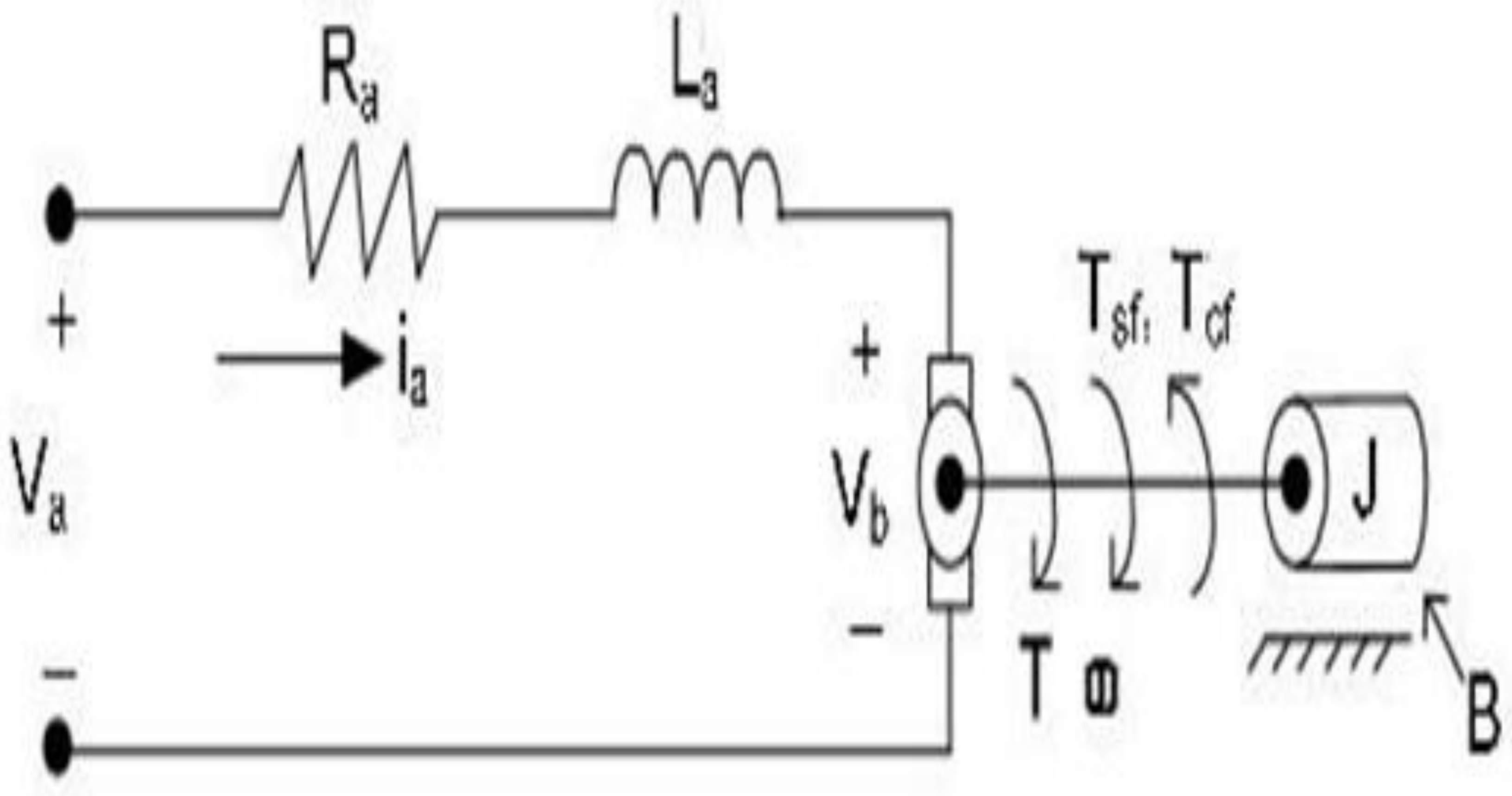


Figure 9-1

Experimental Values Used for Motor Model

$$R = 2.00\ \Omega \qquad L = 0.0216\ \text{H}$$

$$k_t = 0.615\ {}^{\text{Nm}}/_{\text{A}} \qquad k_v = 0.615\ {}^{\text{V}}/_{(\text{rad/s})}$$

$$T_{cf} = 0.5105\ \text{N m} \qquad B = 0.0061\ {}^{\text{Nm}}/_{(\text{rad/s})}$$

$$J = 0.216\ \text{kg m}^2$$

Motor Model

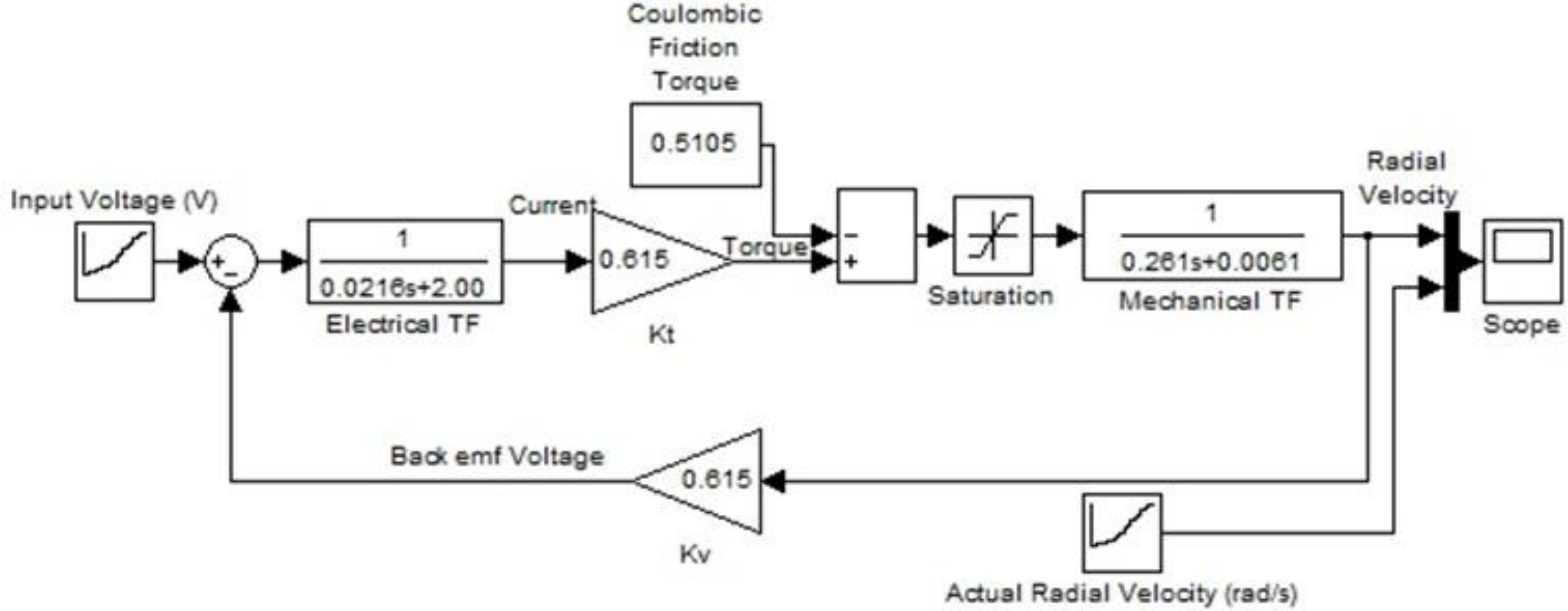


Figure 11-1

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 system to be autonomous.
- Selection and design of appropriate power electronics which will allow control of the PWM signal.

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

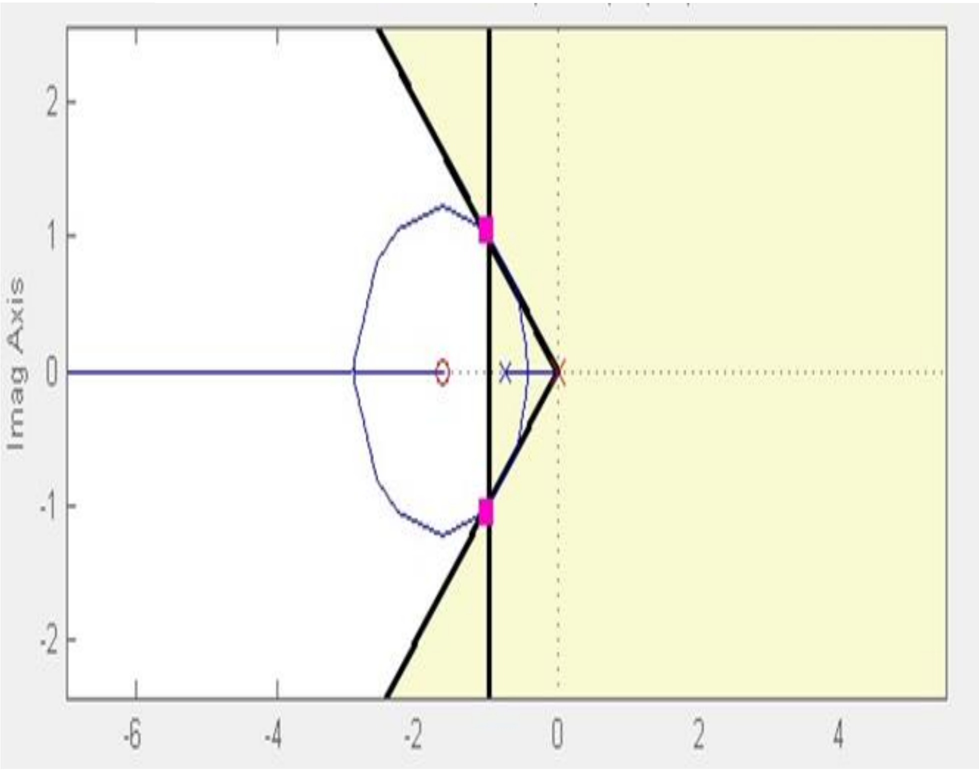


Figure 13-1

Converting Continuous Time Controller to Discrete Time

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

Equation 14-1

Discrete Time Controller:

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

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

Equation 14-1

Closed Loop Control Simulation

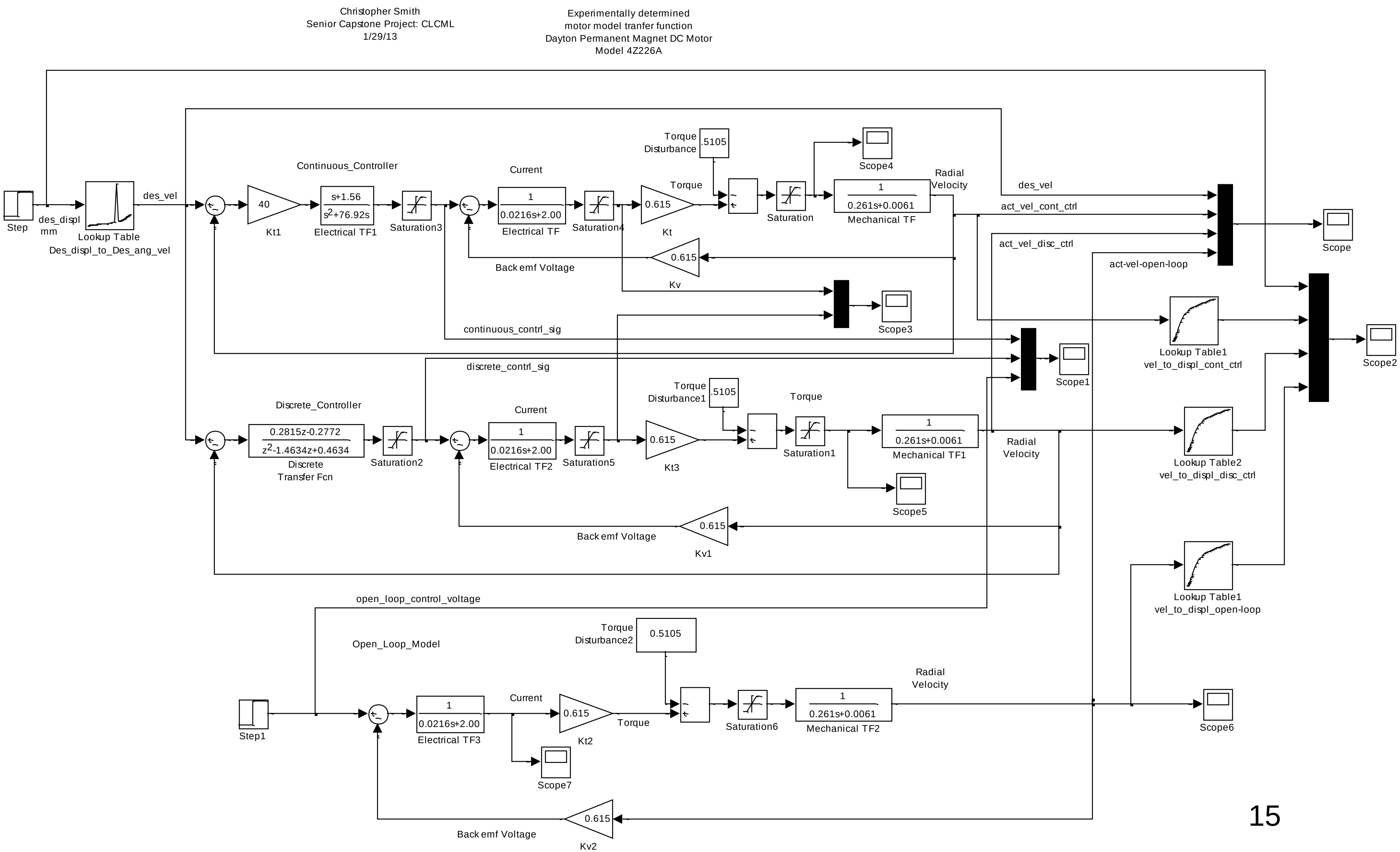


Figure 15-1

Displacement

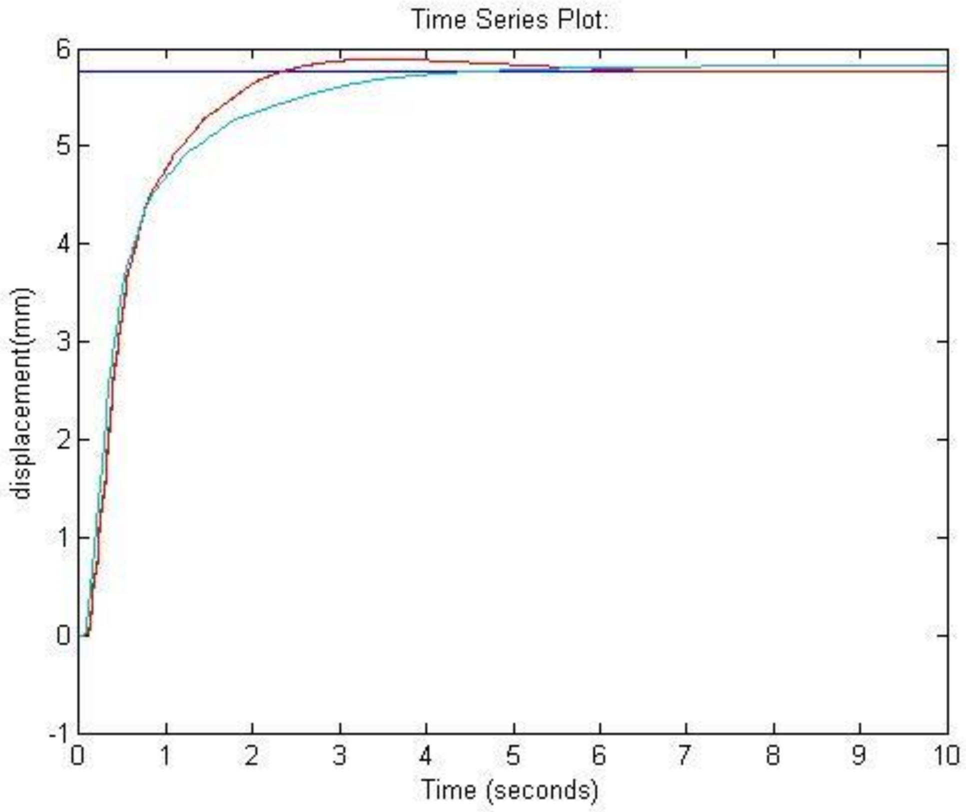


Figure 16-1

Angular Velocity

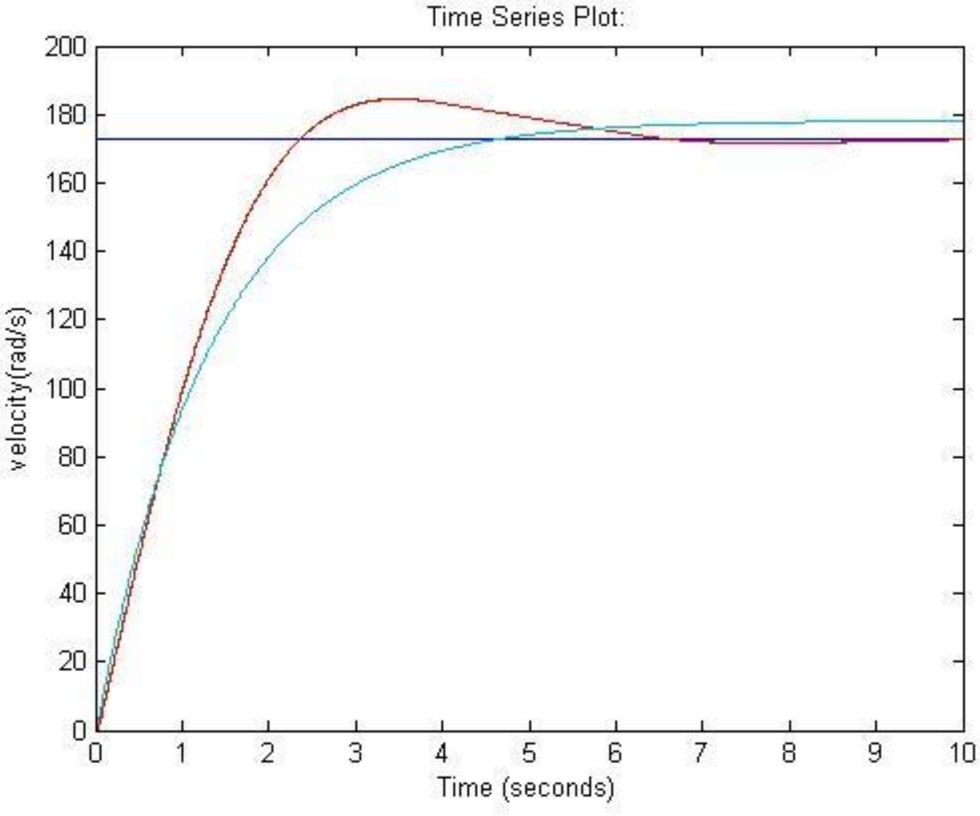


Figure 17-1

Control Voltage

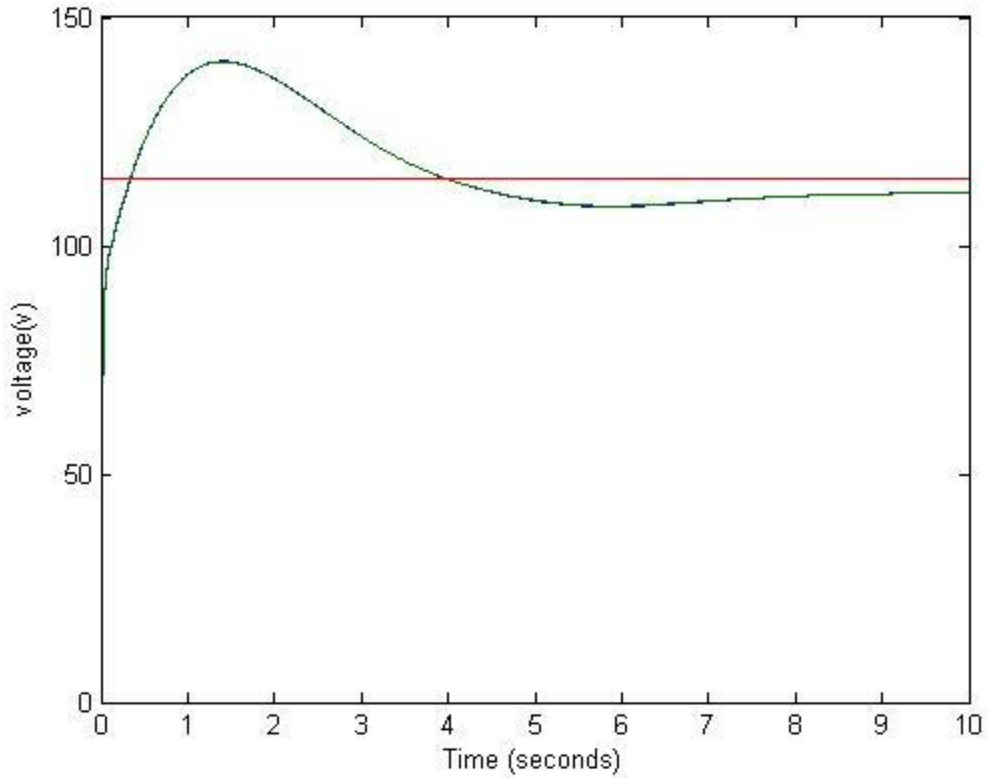


Figure 18-1

Discrete Time Controller

Discrete Time Controller:

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

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

Equation 19-1

Xilinx Blockset

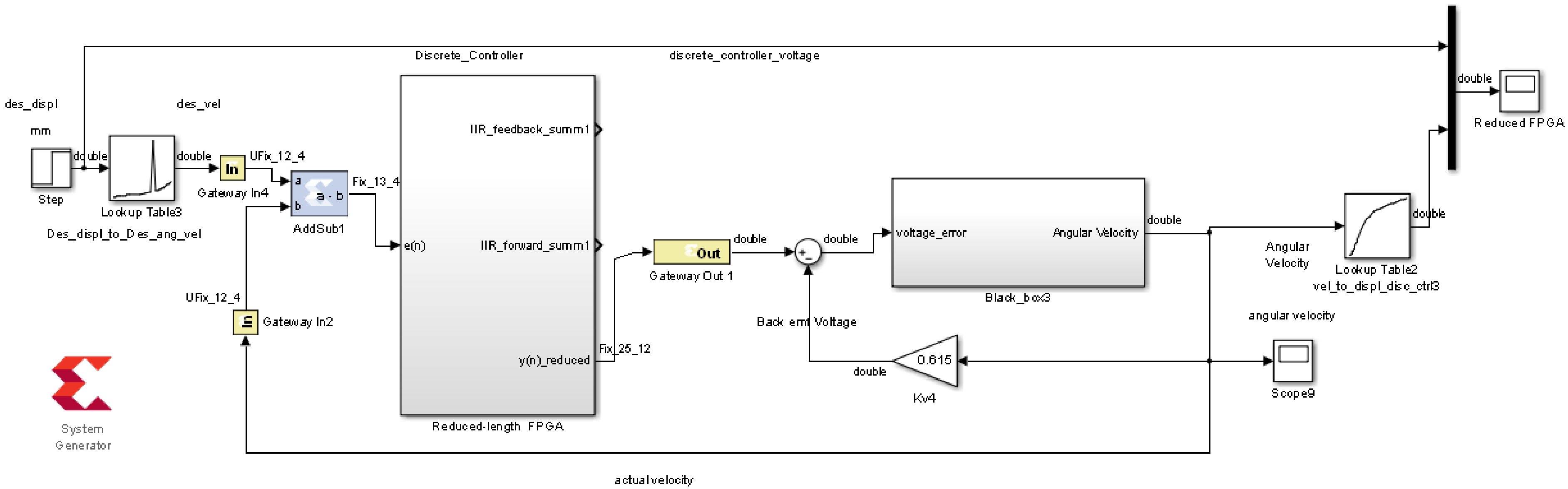


Figure 20-1

Xilinx Blockset

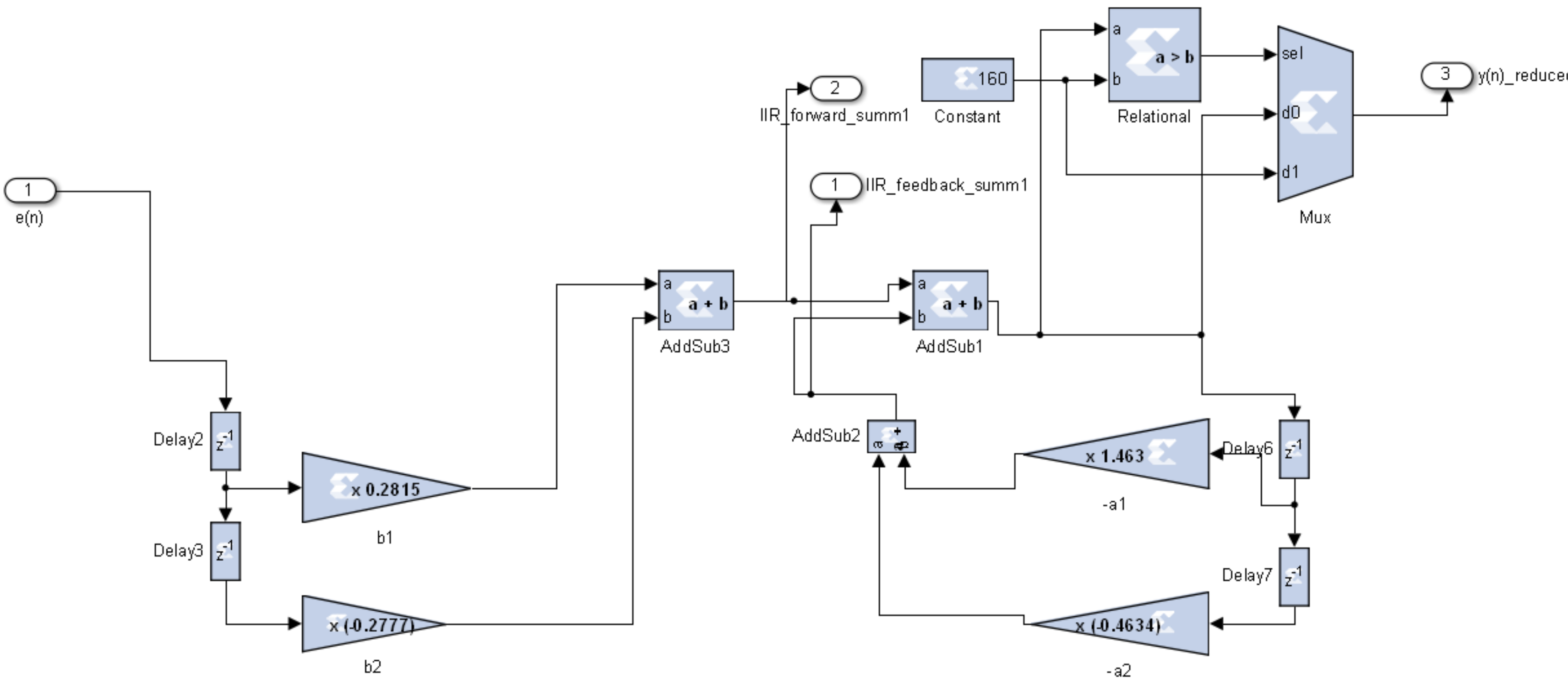


Figure 21-1

Xilinx Blockset Simulation

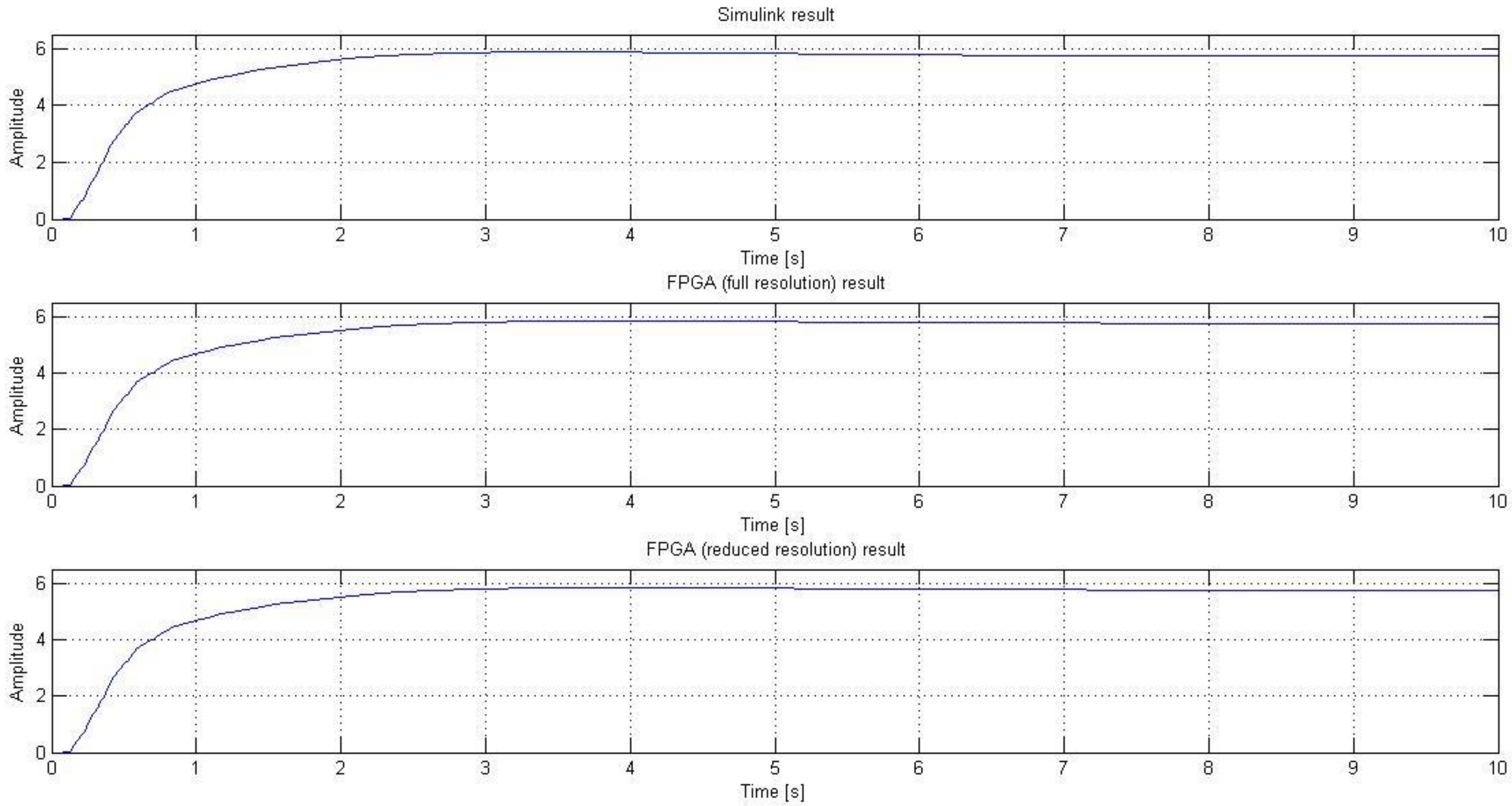


Figure 22-1

Xilinx Blockset Simulation

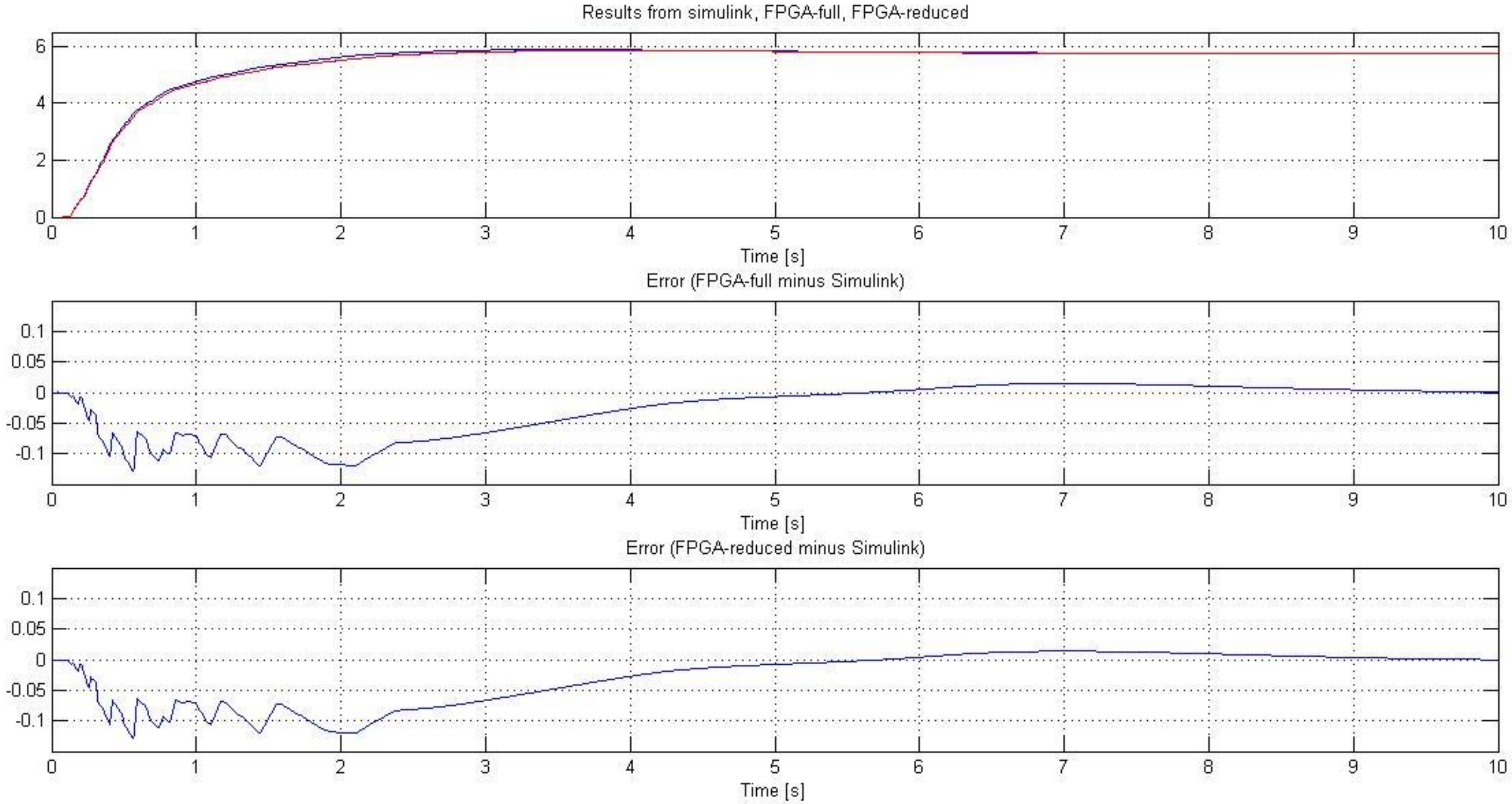


Figure 23-1

Xilinx Blockset Simulation

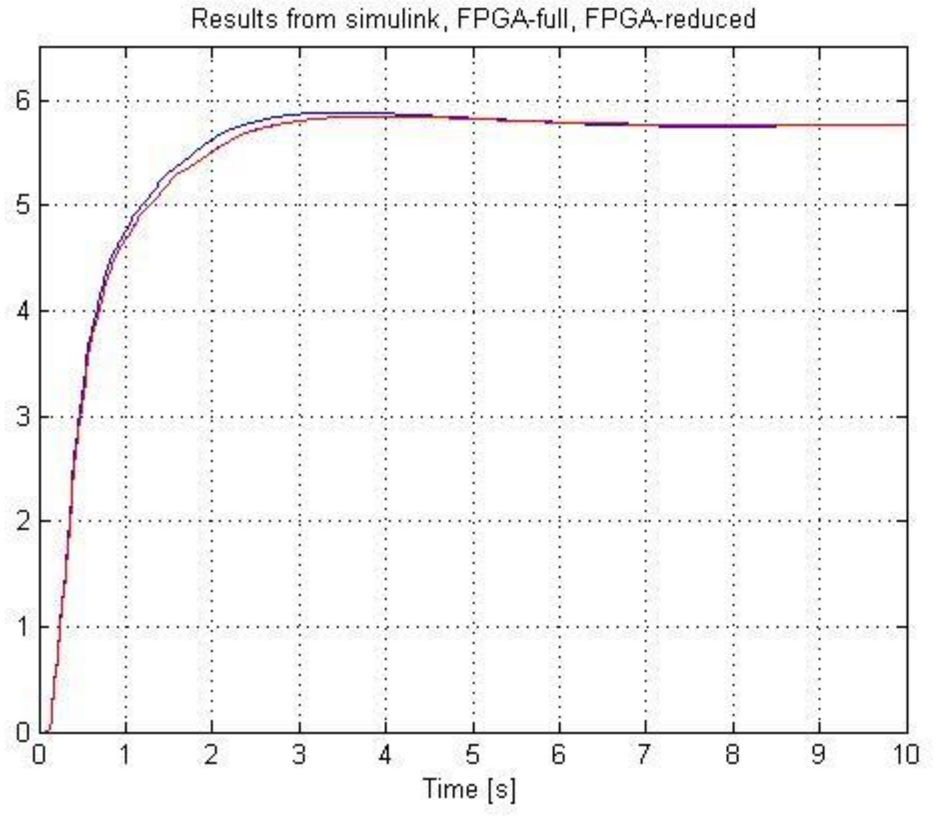


Figure 24-1

High Level Block Diagram

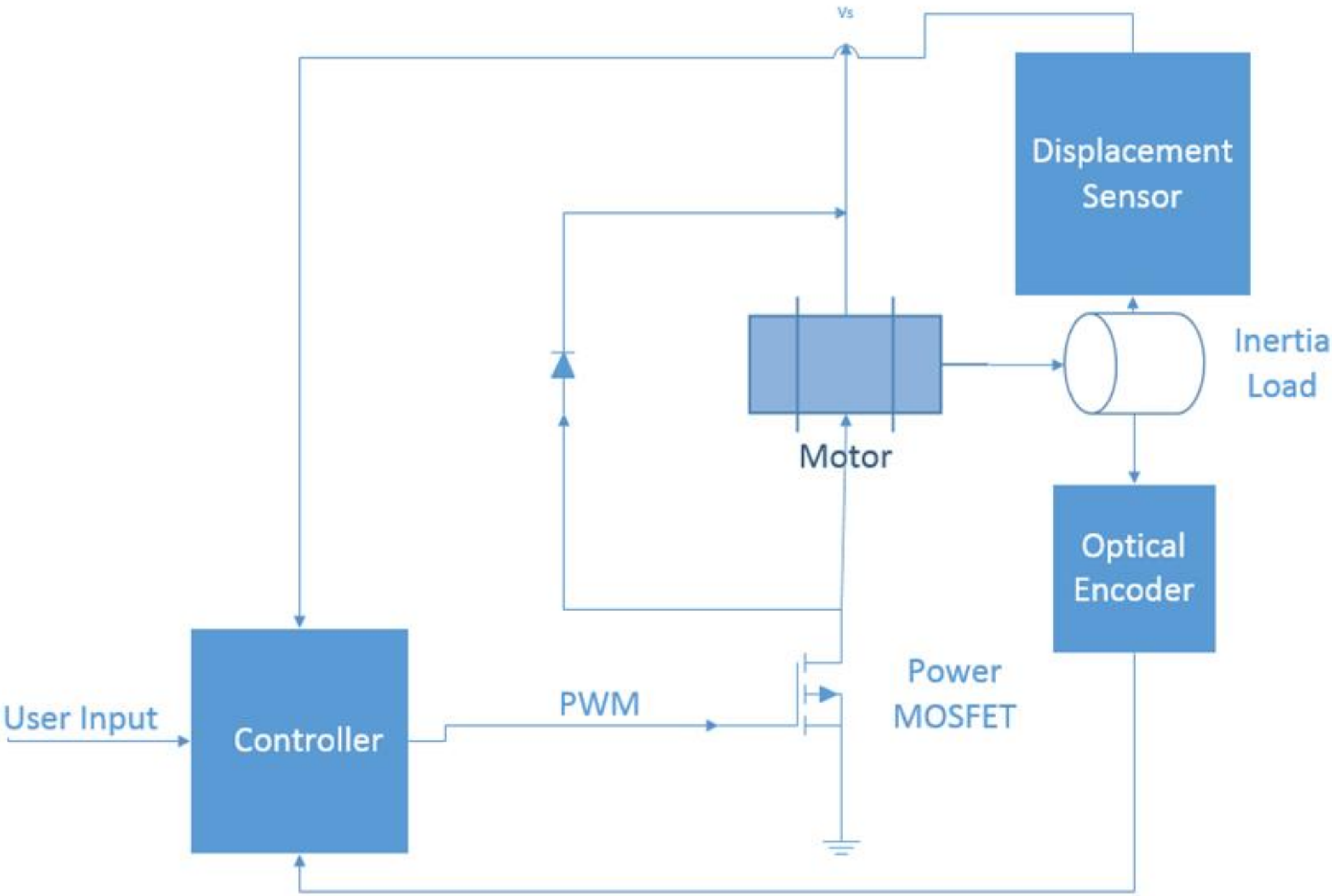


Figure 25-1

Controller Flowchart

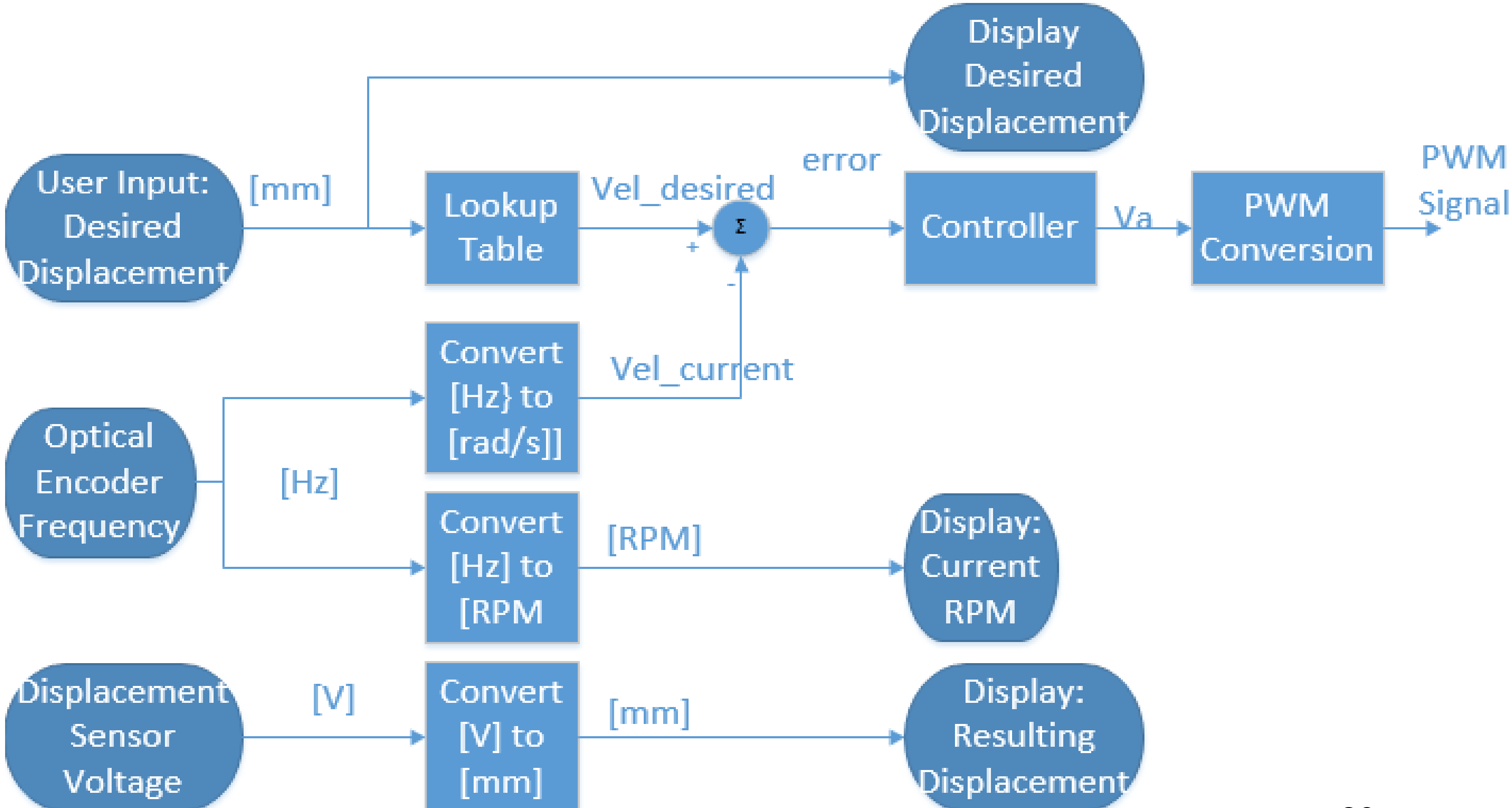


Figure 26-1

Performance Specifications for Controller

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

- The controller shall sample displacement at least every 10 ms.

- The controller shall generate PWM control signal within 10 ms.

Controller Simulation

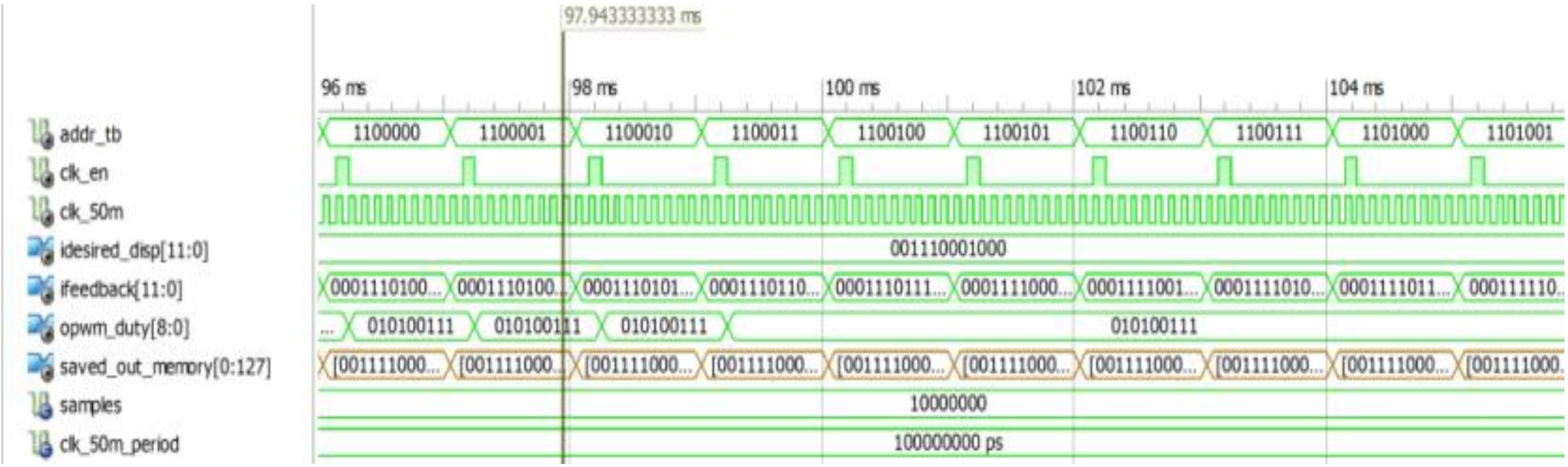


Figure 28-1

Experimental Data for Look-Up Table

Unit Conversion	
[RPM]=[Hz]*60[sec/min] / 4[pulses/rev]	
[rad/s]=[RPM]*2*pi[rad/rev] / 60[sec/min] (rotational velocity conversion)	
[m/s] = [rad/s]*0.2286[m]	
[rad/s] = [m/s]*224.4[m^{-1}] (electrtical frequency conversion)	

Figure 29-1

Input Voltage	Displacement Sensor Voltage	Encoder Frequency	Velocity			Height	Displacement	Electrical Frequency	Height
V_a [V]	[V]	F_{enc} [Hz]	v_{RPM} [rpm]	ω_m [rad/s]	v_t [m/s]	y [mm]	[mm]	ω_e [rad/s]	y [mm]
4.72	3.7290	2.10	31.5	3.3	0.8	7.000	0.000	169.21	-0.81
9.39	3.7280	5.60	84.0	8.8	2.0	7.010	0.010	451.24	3.52
10.25	3.7210	6.20	93.0	9.7	2.2	7.082	0.082	499.59	3.96
11.20	3.7110	6.90	103.5	10.8	2.5	7.184	0.184	555.99	4.43
12.18	3.7050	7.50	112.5	11.8	2.7	7.246	0.246	604.34	4.79
13.13	3.6950	8.40	126.0	13.2	3.0	7.348	0.348	676.86	5.27
14.12	3.6850	9.10	136.5	14.3	3.3	7.451	0.451	733.26	5.61
15.07	3.6730	9.80	147.0	15.4	3.5	7.574	0.574	789.67	5.92
17.06	3.6620	11.70	175.5	18.4	4.2	7.686	0.686	942.77	6.65
18.92	3.6440	13.10	196.5	20.6	4.7	7.871	0.871	1055.58	7.11
21.08	3.6110	15.00	225.0	23.6	5.4	8.209	1.209	1208.68	7.64
23.08	3.5950	16.60	249.0	26.1	6.0	8.373	1.373	1337.60	8.03
25.03	3.5770	18.50	277.5	29.1	6.6	8.557	1.557	1490.70	8.43
30.12	3.4740	25.00	375.0	39.3	9.0	9.612	2.612	2014.46	9.45
35.21	3.4200	31.00	465.0	48.7	11.1	10.166	3.166	2497.93	10.07
40.32	3.3690	36.00	540.0	56.5	12.9	10.688	3.688	2900.82	10.45
45.36	3.3410	42.00	630.0	66.0	15.1	10.975	3.975	3384.29	10.79

Figure 29-2

Converting Electrical Frequency to Displacement

$$y(\omega_e) = 0.002228 * ln(\frac{232.69}{1 + \frac{9.55*10^6}{\omega_e^2}}) \text{ m}$$

Equation 30-1

$$\omega_e = \sqrt{\frac{9.55 * 10^6}{-1 + 232.69e^{\frac{-y}{0.002228}}}} \text{ rad/s}$$

Equation 30-2

Preliminary PWM Flowchart

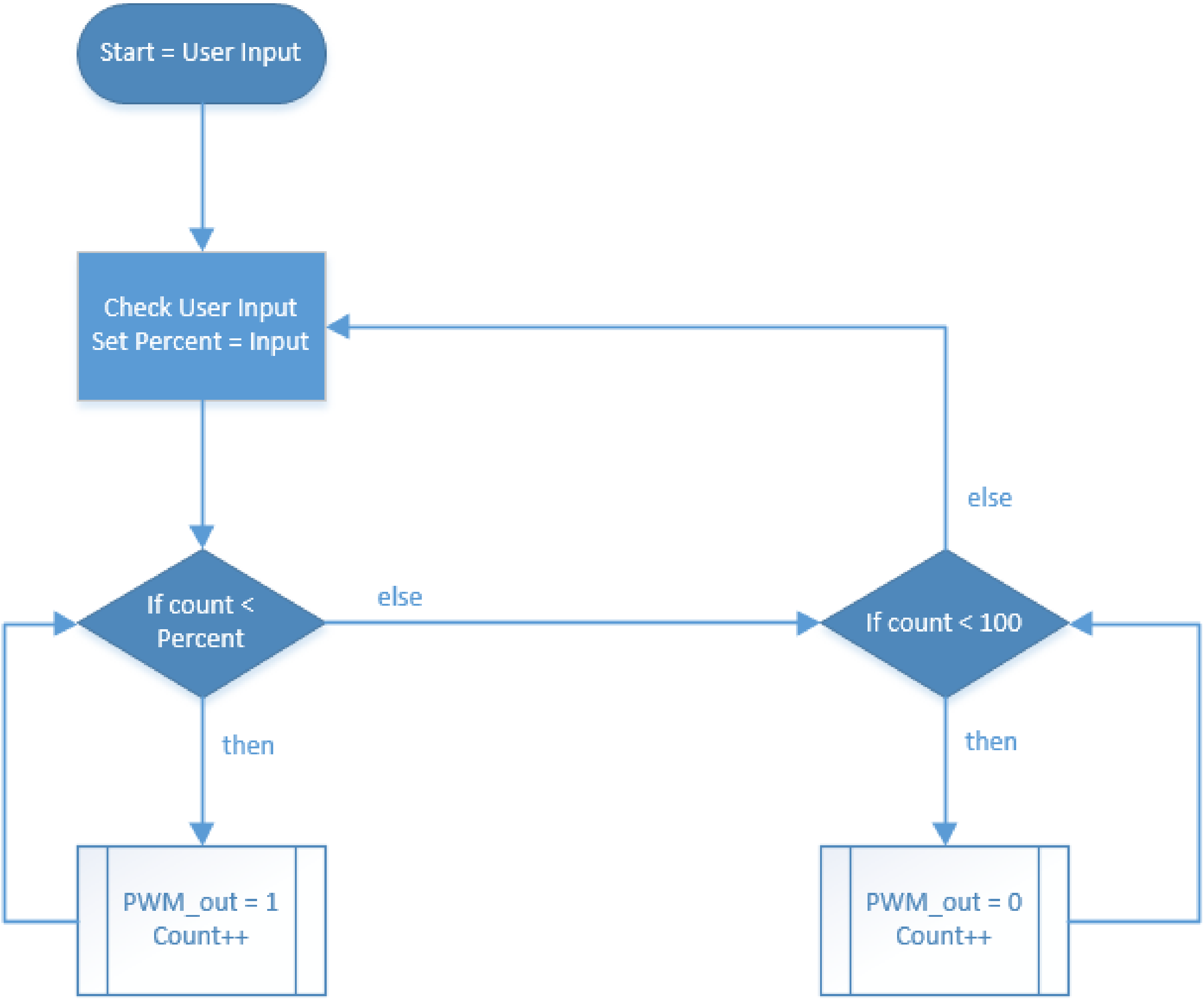


Figure 31-1

FPGA PWM Results

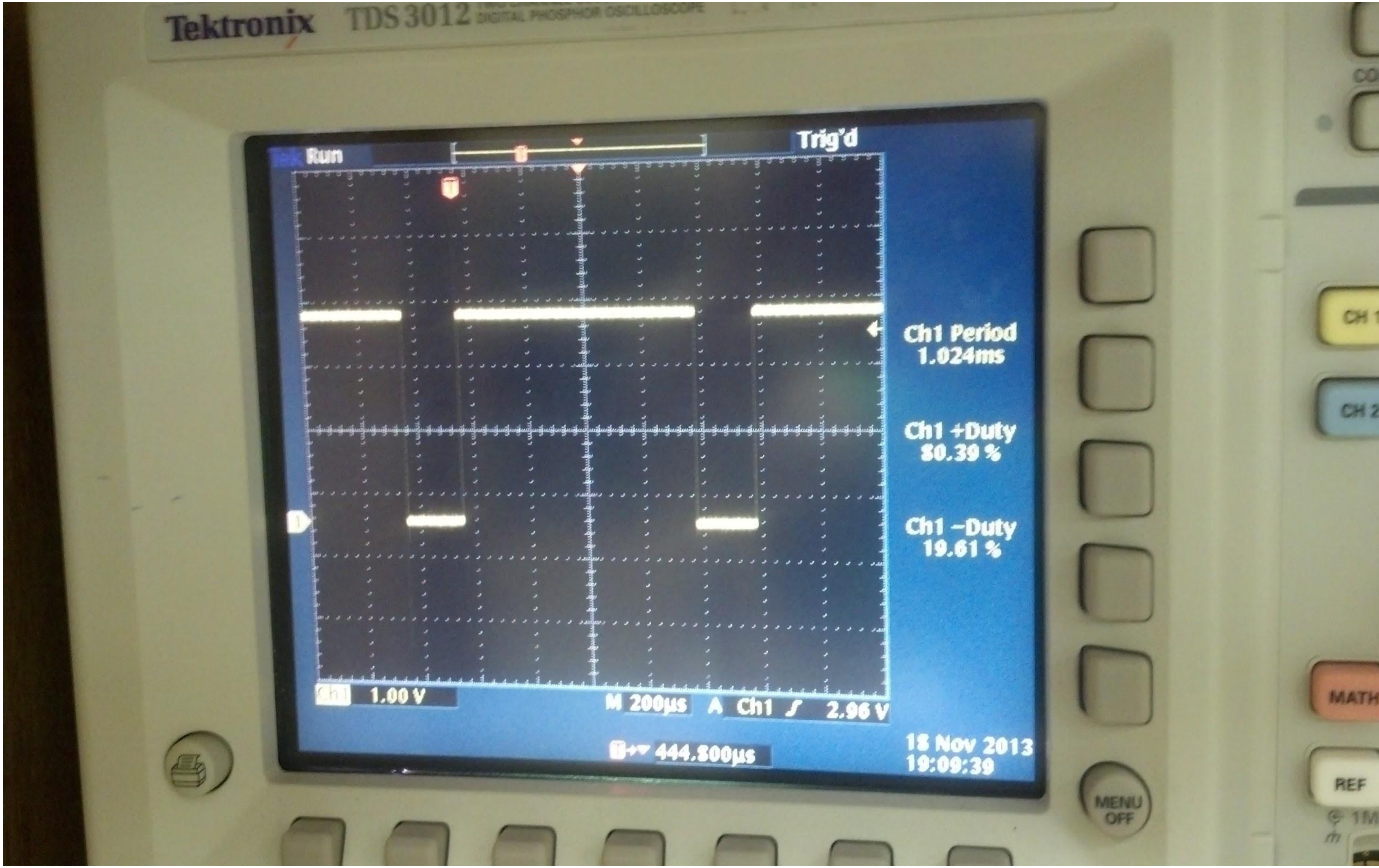


Figure 32-1

Analog Circuit Schematic

$$R_g = 3120_{vout}/3120_{Imax}$$
$$I_i = 3.3 - 1.1/R_i$$

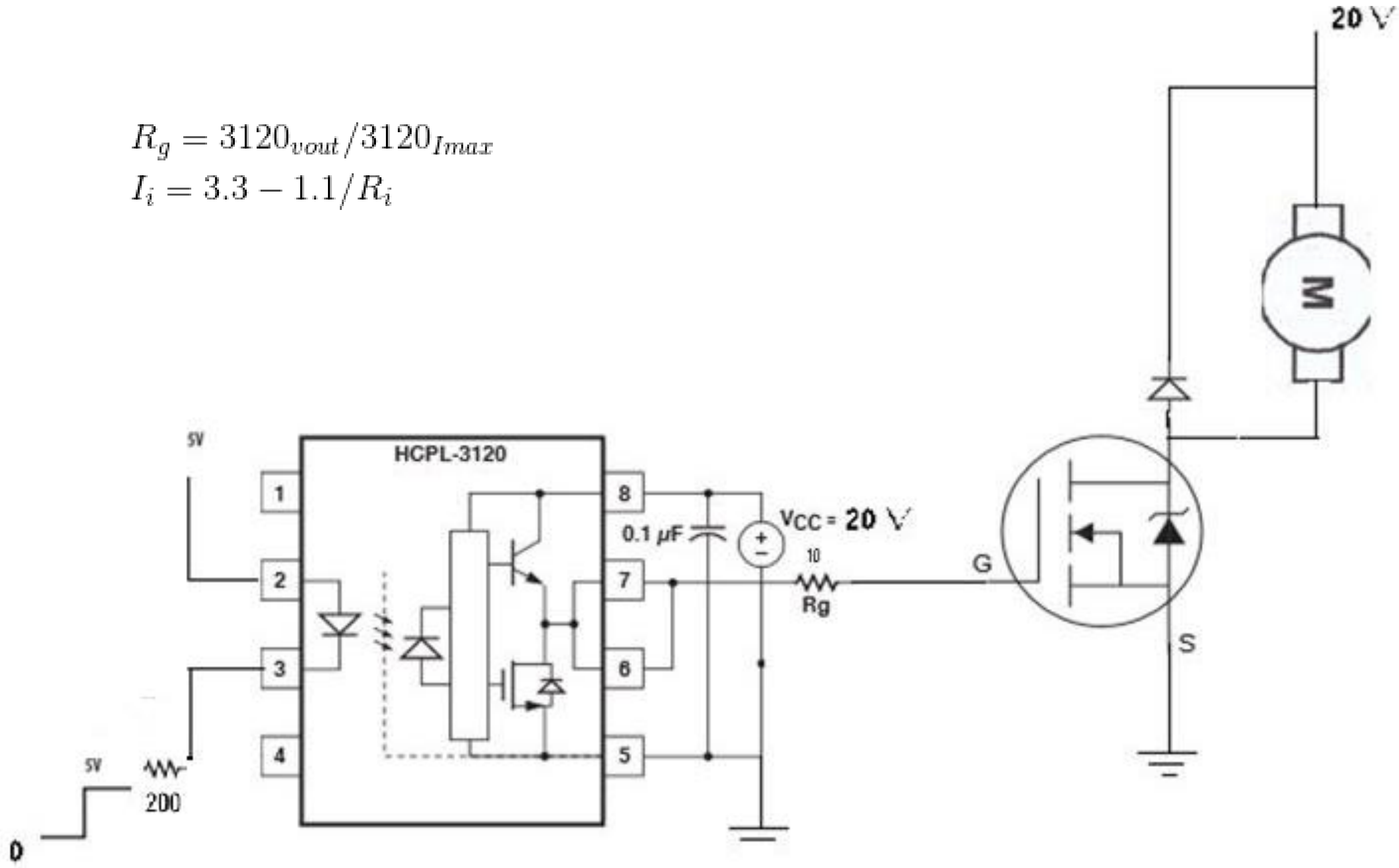


Figure 33-1

Application of Circuit with Pittman Motor

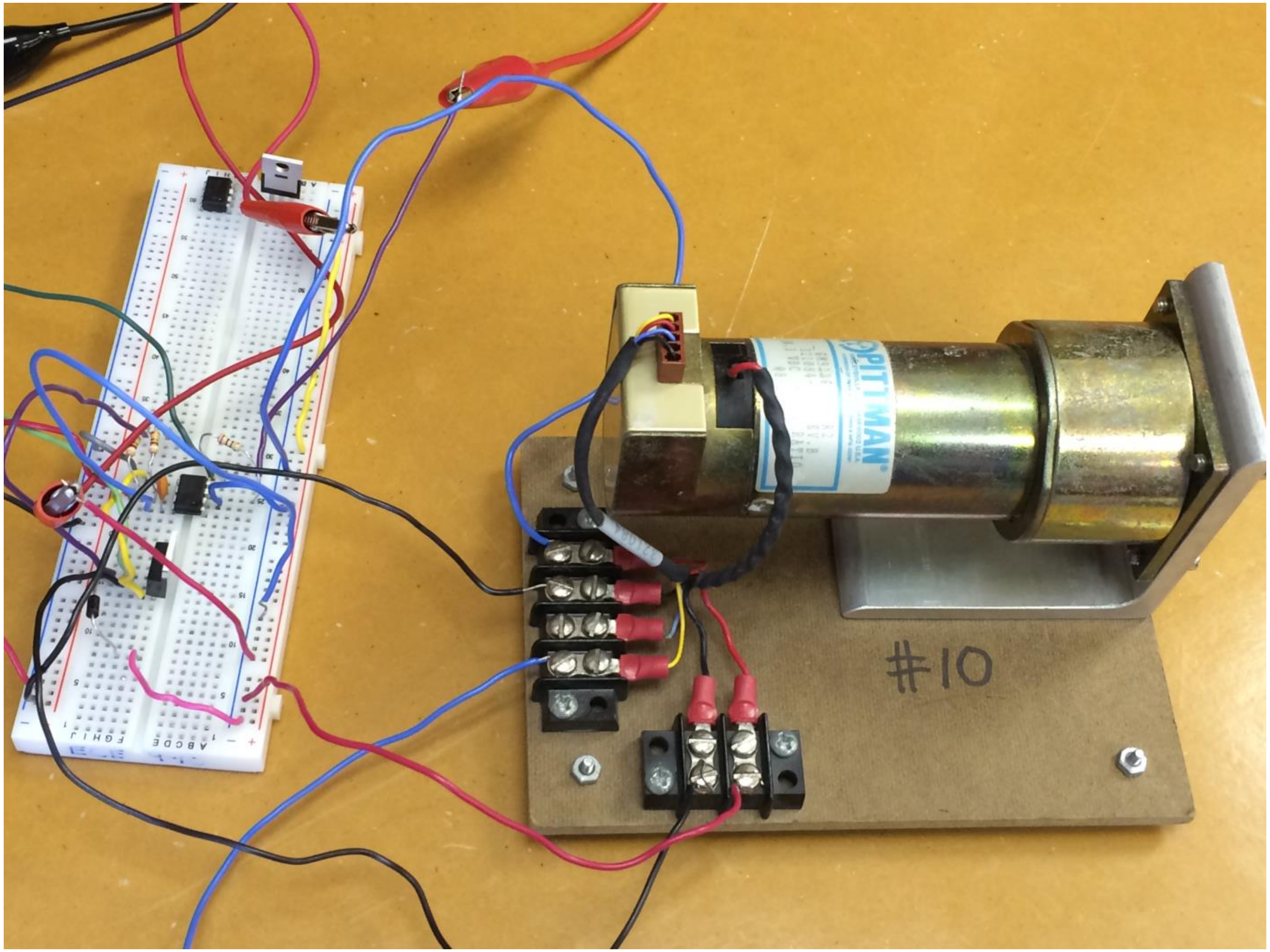


Figure 34-1

Analog Circuit Results

Figure 35-1

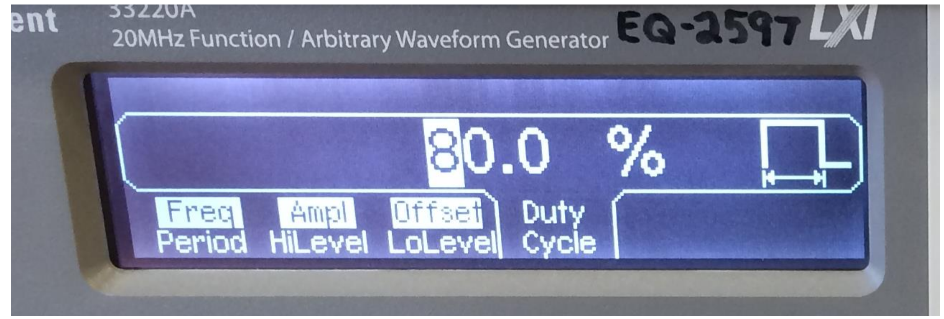
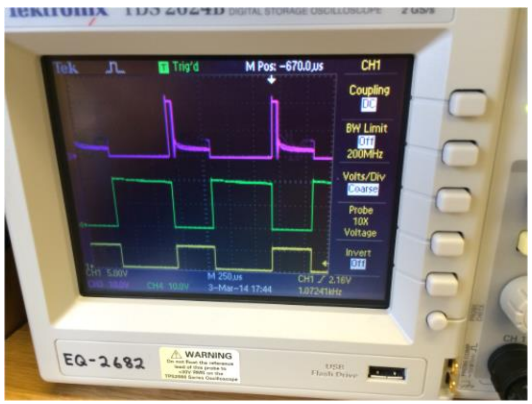


Figure 35-2



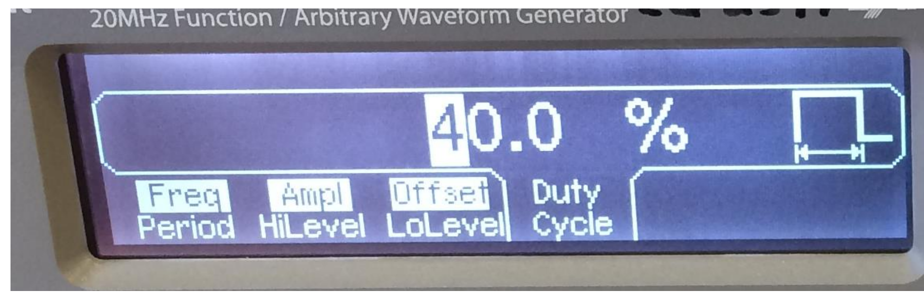
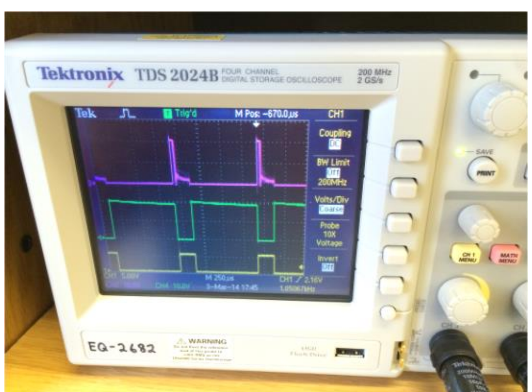
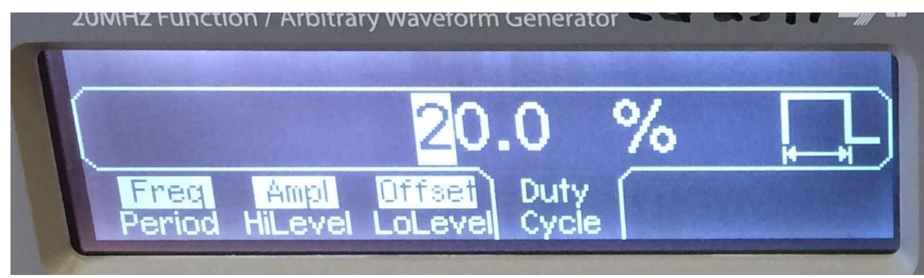


Figure 35-3





Status of the Project

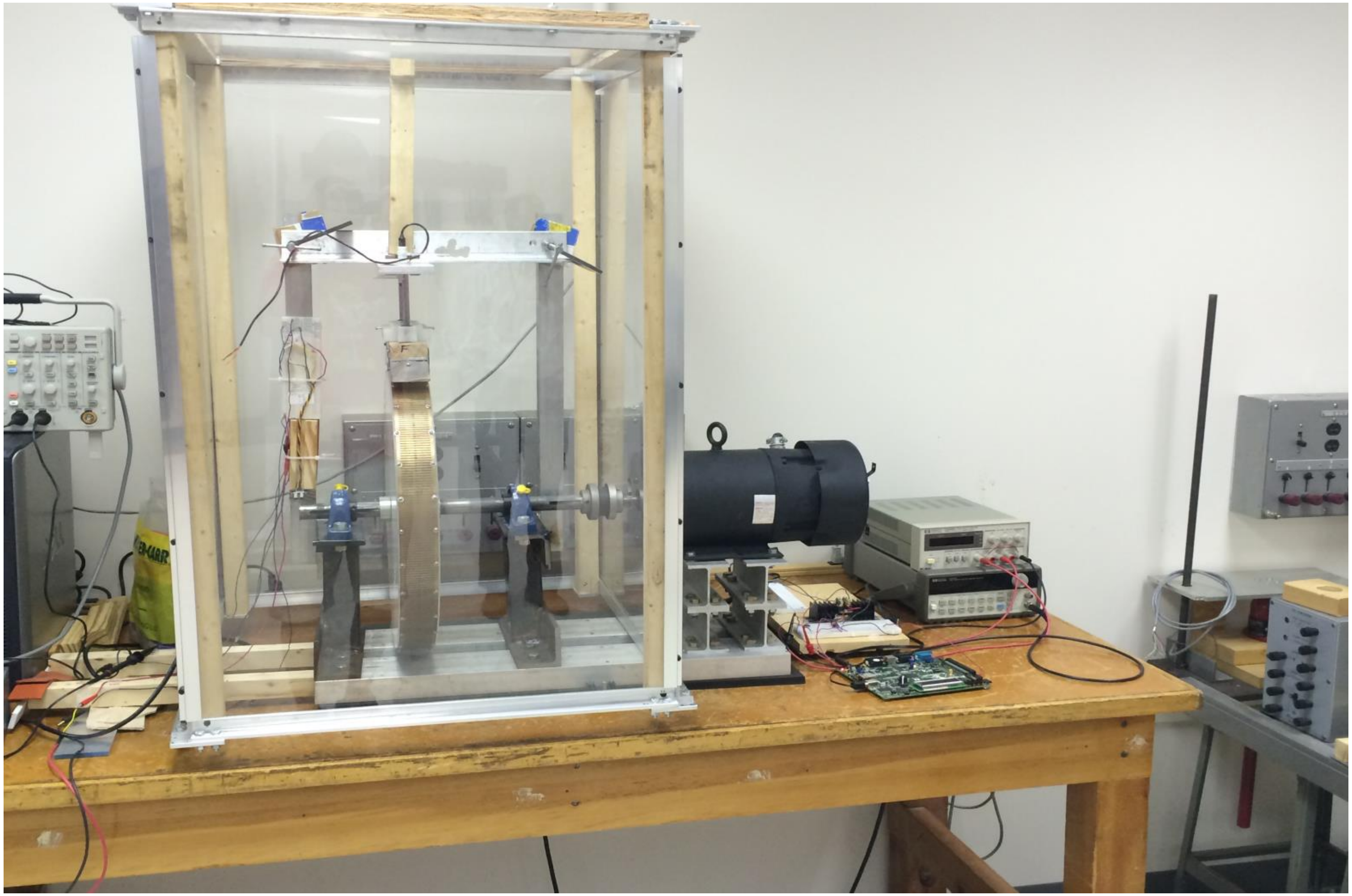


Figure 36-1

Status of the Project

- Analog Circuitry
- Controller
- VHDL Modules

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

- 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.