Final Report

Interfacing Motors of PUMA 560 Robot with a PC-based Controller

ECE4007 Senior Design Project

Section L01, Yellow PUMA Team

Josh Chao, Team Leader
Francis Fernandes
Denny Lie
Jackson Tanis

Submitted

May 1, 2009

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Unimation PUMA (Programmable Universal Machine for Assembly) 560 robot is a six-axis articulating arm robot. Applications such as welding, packaging, palletizing, and parts installation have been automated using such type of industrial robots for higher efficiency and productivity.

Georgia Tech's ME department has donated one such robot to the ECE department. The robot's controller was not functional, and the team tasks involved inspecting the mechanical aspects of the robot and replacing the robot's control system with a National Instruments controller. The next phase involved interfacing all of the components PC, controller, motor drivers, and motors. Once these components were functional, kinematic equations was to be programmed into the control system in order to make the end effectors of the robot move to a specified x, y, and z coordinate with a specified rotational direction. However, due to several problems that occurred during the semester and time constraints, the final objective was changed to control a single motor using feedback received from the encoders and potentiometer.

With six degrees of freedom and re-programming ability, the PUMA 560 robot is able to handle different types of tasks with changes only in the end effectors and software, thereby reducing production cost and increasing its potential in the market. With all the prices combined, the total cost was $8,460. With successful completion of the project, the functional system can be used as an automated measurement tool for research and groundwork for future ECE students' projects.

Interfacing Motors of PUMA 560 Robot with a PC-based Controller

1. INTRODUCTION

Many applications, such as welding, packaging, palletizing, and parts installation, have been automated using industrial robots for higher efficiency and productivity. In particular, the six-axis articulating arm robots are widely used for these applications due to their wide range of motion and reach [1].

Georgia Tech's ME department has donated a broken Unimation PUMA 560 robot, a six-axis articulating arm robot, to the ECE department. The team was able to inspect the mechanical aspects of the robot and replace the broken motors. In addition, the broken controller was replaced with National Instrument 7356 PCI controller card. The purpose of this project is to serve as groundwork for future ECE students' project, and the functional system can be used as an automated measurement tool for research projects.

1.1 Objective

Initially, the team's objective was to interface the PUMA 560 robot with a PC-based controller, so that given a single or series of input, the robot's end effectors shall move to the specified position in spatial coordinates. However, since the required control system was not available through the sponsor, the final objective was changed to controlling a single axis of the robot using received feedback signals with a PC-based controller. The immediate purpose of this project is to serve as groundwork for future ECE senior design project.

1.2 Motivation

Even though the PUMA 560 robot could be considered as an old technology, it is desirable to repair the robot because it can be used in different applications as previously mentioned. Moreover, the repair cost would be considerably lower than the purchase cost of a new six-axis articulating arm robot. In fact, the functional system can be used by Dr. Thomas Michaels, the project sponsor, as an automated measurement tool for research projects.

In addition, this project shall provide the team members with practical learning experience in robotic system including the system interface, the control system, and the robot's electrical design. This experience will prove useful for the team members in their future careers especially in robotic industry as articulating arm robots are widely used in manufacturing industries.

1.3 Background

Industrial Robots

Industrial robots are reshaping the manufacturing industries. Since 2003, North American manufacturing companies have spent up to $877 million for industrial robots [2]. Depending on the structures, industrial robots can be categorized into Selective Compliant Assembly Robot Arm (SCARA), Gantry (Cartesian coordinate robot), and Articulating Arm [3]. Specifically, articulating arm robots are widely used in manufacturing industries due to their wide range of motion and reach [4].

Depending on the end effectors, an articulating arm robot can perform different tasks, such as welding, assembly, painting, and packaging. Some of the commercial welding robots include Panasonic VR-006, Motoman UP6, Fanuc, and ABB IRB 1600 [1].

National Instruments PCI 735x Controller

National Instruments is a technology pioneer and leader in virtual instrumentation. On June 8th, 2004, NI introduced high-performance motion controller boards for PCI-based integrated motion data acquisition applications. The NI PCI-7350 series boards offer stepper and servo motion control, various axis configurations and general-purpose digital and analog I/O suitable for machine control applications such as semiconductor manufacturing or automated component testing [5].

In addition, the PCI controllers would provide a customizable control architecture which makes the changes in the robot's configuration easy for different applications. NI also provides flexibility in software choices to program the PCI controllers including NI Motion Assistant, LabVIEW, LabWindows/CVI, Measurement Studio for Microsoft Visual Basic, C and C++.

Other Related Research

A similar project, titled "Implementation of an open-architecture for PC-based control of PUMA 560", was undertaken by a former research student in National University of Singapore, Parasar Kodati [6]. Although the ServoToGo motion control card by IBM was used in this project, the project's report provided useful information about the PUMA 560 robot's technical specifications and the method of open architecture implementation for PC-based controller.

2. PROJECT DESCRIPTION AND GOALS

Mechanically, the PUMA 560 robot has been inspected, and two new motors have been purchased and properly tested to replace the broken motors. Electrically, the robot has not been interfaced with the controller because there was an issue with the sponsored Rockwell controller. On March 26th, 2009, the team discovered that the sponsored controller, CompactLogix L43, can only control up to four axes. CompactLogix L45, which can control up to eight axes, was requested, but the team was not able to receive good response from Rockwell Automation. As a result, National Instruments PCI 7356 controller was selected as it met the needs for this project.

Due to the above mentioned issue and time constraints, the team had set up new realistic goals to be achieved by the end of this project which includes:

- Establishing a system interface for the motor, the motor driver, and the NI controller
- Providing a GUI for end users to read in feedback signals from the motor
- Using the controller to control a single motor’s position and speed
- Establishing groundwork and proper documentation for future ECE students’ project

Upon completion of this project, the team will provide essential framework of the interface and control system and documentations of the robot, the motor driver, and the controller for the next senior design group to continue on this project.

3. TECHNICAL SPECIFICATIONS

Hardware

Motor Drivers

TA115 Motor Driver from Trust Automation was used. The manufacture specified specification and actual specification, used and measured, are listed in Table 1.

Table 1. Trust Automation TA115 Motor Driver Specification [6]

	Specified Values	**Actual Values Used**	**Actual Values Measured**
Supply Voltage (V)	15-48	24	N/A
Digital Signal I/O	TTL Level 1 or 0	Same	N/A
Command Input	±10V	Same	N/A
Current Mode Ratio (A_o/V_i)	0.2, 0.4,0.6, 0.8	N/A	0.2, 0.4,0.6, 0.8
Voltage Mode Ratio (V_o/V_i)	20	N/A	14

To minimize the number of power supplies used, the 24V power supply was used to power both the motor drivers and the brakes for Motors 1, 2 and 3. The actual voltage mode ratio differs from the manufacturer specifications. With voltage mode ratio of 14, the output voltage is in the range of ± 140V.

In addition, the motor driver supports opto-isolation, which connects the signal circuit to the power circuit with optical devices instead of hard wires. Opto-isolation protects the signal circuit from catastrophic disasters such as lightning strikes by stopping the flow of high voltage past the motor driver.

Motors

The motors in the arm robot were disassembled from the robot and were tested on the bench. Table 2 shows the results of the tests performed.

Table 2. Motor specification [7]

Parameter	**Motor 1-3 Specified**	**Motor 1-3 Measured**	**Motor 4-6 Specified**	**Motor 4-6 Measured**
Rated Current (A)	5.3	N/A	1.5	N/A
Rate Voltage (V)	40	Reached	32	Reached
Rated Power Output (W)	150	N/A	30	N/A
Rate Speed (RPM)	1200	Reached	2350	Reached
Torque Constant (kg*cm/A)	2.58	N/A	0.973	N/A
Voltage Constant (V/krpm)	26.5	28.0	10	8.81
Encoder Slots	250	250	250	250
Circular Potentiometer	Yes	Yes	Yes	Yes

Algorithm for determining the rated parameters could not be found. Parameters are marked ‘reached’ if the specified operating values does not cause sudden increase in temperature, jerk, or smoke when applied for a few seconds. Certain values were not tested so as to prevent the motors from damaging. Torque constants were not tested due to lack of proper equipment.

Voltage constants were tested by using the developed software and measuring the RPM corresponding to an incremental voltage. Matlab was used to approximate the value over the testing range and Figure 1 shows the generated plot. The Matlab script is posted in Appendix A.

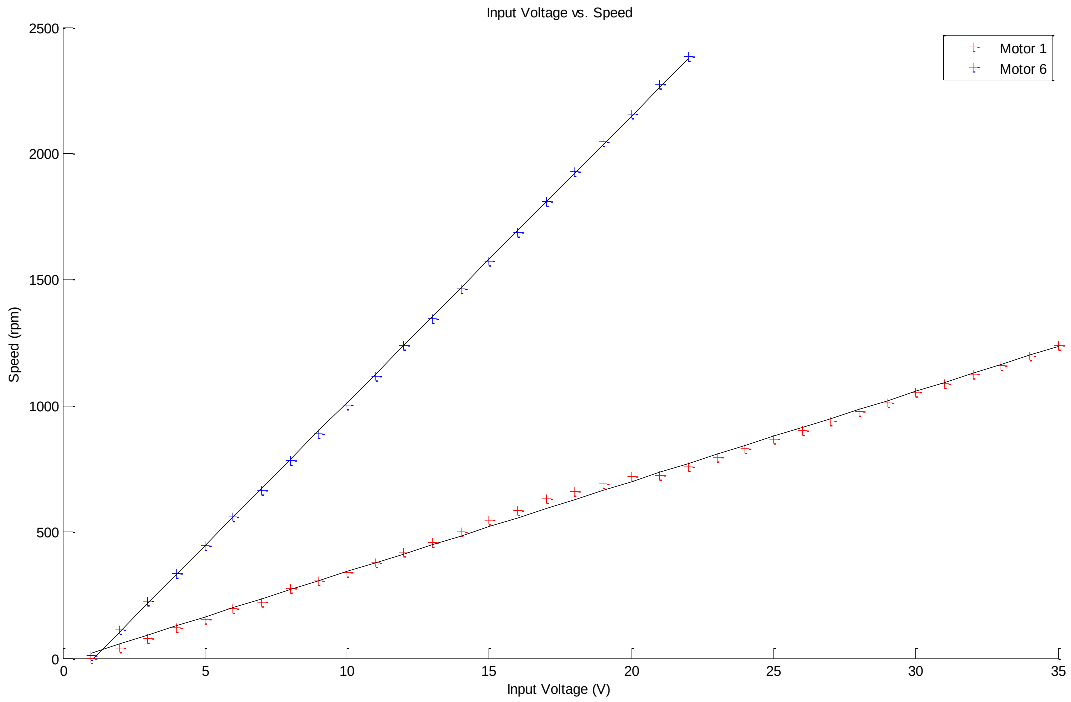


Figure 1. Input Voltage vs. Speed plot for Motors 1 and 6 generated using Matlab.

The quadrature encoders were tested by counting the ticks seen in LabVIEW per revolution. 1000 ticks were registered per revolution. Assuming the program uses both encoders, 90˚ out of phase from each other, and counts both rising and falling edge, 1000 ticks per resolution corresponds to 250 slots per encoder.

Circular potentiometer connects both extremes in the output voltage range together. The potentiometer output resets to zero when it reaches the input voltage, within the range of the output voltage from zero to the input voltage. The potentiometer is geared down from the motor shaft, but the gear ratio is not measured since it is not essential in completing the whole project.

Controller

During the project the controller was switched from Rockwell Automation to Nation Instruments PCI-7356, to fully support all six axes on the robot. Table 3 shows the I/O pins for the controller and the required pins for the project.

Table 3. NI PCI-7356 I/O Pins [8]

Pinout	Supports	Project Requirements	Use
Encoder	3	3	Encoder A, B, and I
Analog Input	1	1	Potentiometer
Analog Output	1	1	Motor Power
Digital Ports	8	2	Enable/Fault Signal to/from Motor Driver
Various Switches (Home, Limit, etc.)	3	0	Currently no Plan for Installation

Other Notes

More information on the robot and its specification is given in Appendix B, to understand the operation and limitation of the arm robot, when the arm robot is reassembled.

Software

Previously the project was intended to interface the PUMA 560 robot with a Rockwell Automation motion control system. However, the project's motion control system was changed from Rockwell Automation to National Instruments due to the unavailability of the CompactLogix L45 in a timely manner. Table 4 displays the proposed versus actual software specifications.

Table 4. Proposed vs. Actual Software Specifications

	Proposed	**Actual**
Motion Controller	Rockwell CompactLogix L45	NI PCI-7356
Programming Language	Rockwell RSLogix5000	NI LabView 8.5
Driver	Built-in	NI Motion 7.6

The software was intended to be able to read and display potentiometer and encoder signals from the six motors to the user, and to control the analog output voltage signal for the six motors using the NI PCI-7356 card. The software was also able to find and set the encoder index position as the motor home position, calculate the speed of rotation, and receive position input command (in number of revolutions). However, the current software can control only one axis, and the position command has an offset error of 80°. Table 5 displays a list of the proposed software objectives and compares it to the actual specifications that were achieved.

Table 5. Proposed vs. Actual Software Objectives

	Proposed	**Actual**
Number of Axes Controlled	6	1
Analog Input Reading (POT)	Yes	Yes
Analog Output Control	Yes	Yes
Encoder Reading	Yes	Yes
Speed Calculation	Yes	Yes
Home Calibration	Yes	Yes
Position Error	0°	~80°

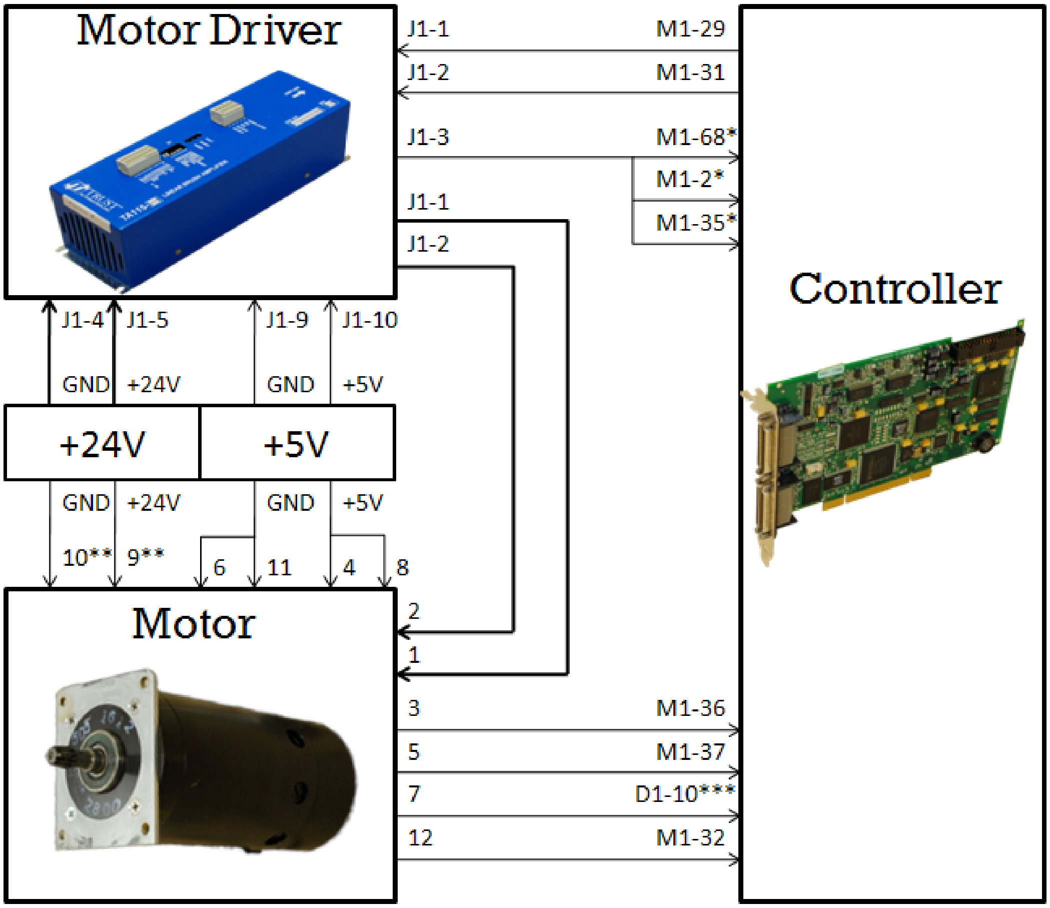
4. DESIGN APPROACH AND DETAILS

4.1 Design Approach

Hardware

Much time was spent on discovering the pinout diagrams for various parts in the robot and the control system. All the information collected on the pinout diagrams has been summarized in Appendix C.

Figure 2 shows the wiring diagram for one axis system with detailed connections. The wiring diagram shown in Figure 2 and the switch settings in Table C4 of Appendix C allows the controller to implement the control loop and sends the appropriate command input signals, which will be discussed further in the software section.



Note*: Shared ground for Analog Input, Digital Grounds for Motion and Digital connectors.

Note**: Only Motors 1-3 have brake, rated at 24V.

Note***: Use digital port for Index Encoder instead of designated Index Encoder pin. Please refer to Software section for the reason.

Note: Arrows indicate direction from output to input.

Note: Enable and Fault pins from the motor driver were not connected in this phase, to simplify wiring.

Note: M1 denotes Motion I/O Connector for Axis 1-4 and D1 denotes Digital I/O Connector for Axes 1-4.

Figure 2. Sample wiring for one axis.

Other Notes

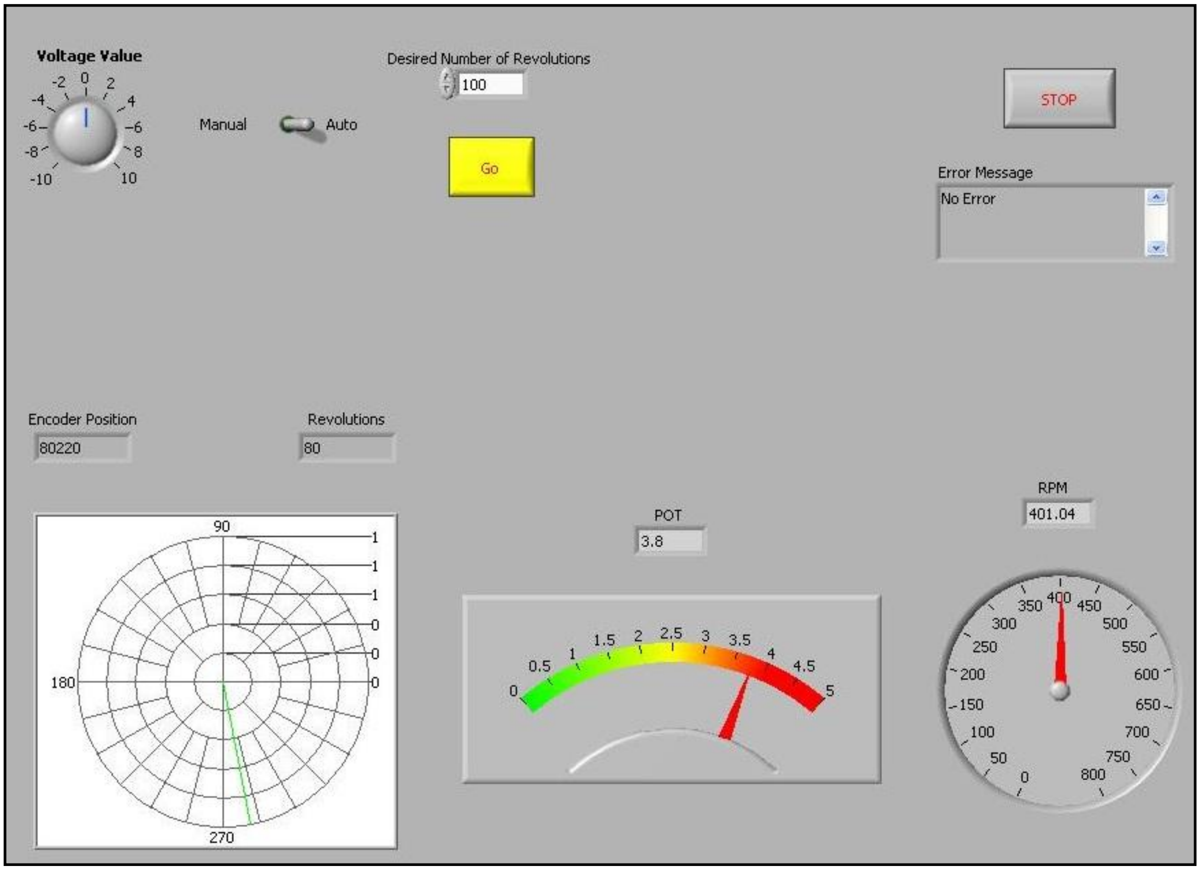
- Ensure the brakes on Motors 1-3 release before power is supplied to the motor to prevent any damages. A ‘clicking’ sound will occur when a brake is released.

- Index Encoder pulse width is very short. The optimal oscilloscope setting is 1V and 2ms for reading the encoders.

- A solid state relay is suggested in order to control the brakes from the software program. A solid state relay candidate information is listed below:
  - Input: Logic
  - Output: Up to 60 V DC and up to 3 A
  - Part No: Digi-Key CC1126-ND
  - Price: $18

Software

The main LabVIEW VI shown in Appendix D is used as a software interface to control the analog output port, and read the analog and digital input ports of the motion controller. The software is connected to Motor Axis 1. Therefore, the parameters used in the software are specific to Motor 1 only. In addition, the motor has no load mounted on it. The following features are implemented in the software GUI as shown in Figure 3.



Desired Number of Revolutions: 100

Error Message: No Error

Encoder Position: 80220

Revolutions: 80

POT: 3.8

RPM: 401.04

Figure 3. GUI displaying the manual and automated modes along the current encoder position, potentiometer value, and calculate RPM.

- **Home Calibration:** to set the encoder index position as the home position. This feature runs automatically when the software is turned on. It runs the motor at the minimum voltage required to move the motor.

- **Manual/Auto Switch:** to switch between the manual voltage control mode and the position input command mode. If the switch is set to manual, the motion of the motor is controlled by turning the voltage control knob. If the switch is set to automatic, the motion of the motor is controlled based on the input number of desired revolutions. The maximum voltage produced by the automatic mode is 2 V when running in current mode with a gain of 0.2. The speed of the running is approximately 780 RPM.

- **Voltage Control Knob:** to control the analog output voltage used to move the motor. The range of the output voltage is between -10 V to +10 V. The software has to be set to manual mode to enable the voltage knob.

- **Input Number of Revolutions:** to command the motor to move a certain number of revolutions. The software has to be set to automatic mode for the input command to work. The motion is divided into 3 parts: voltage incline (40% of distance), constant voltage (20% of distance), and voltage decline (40% of distance), as seen in Figure 4.

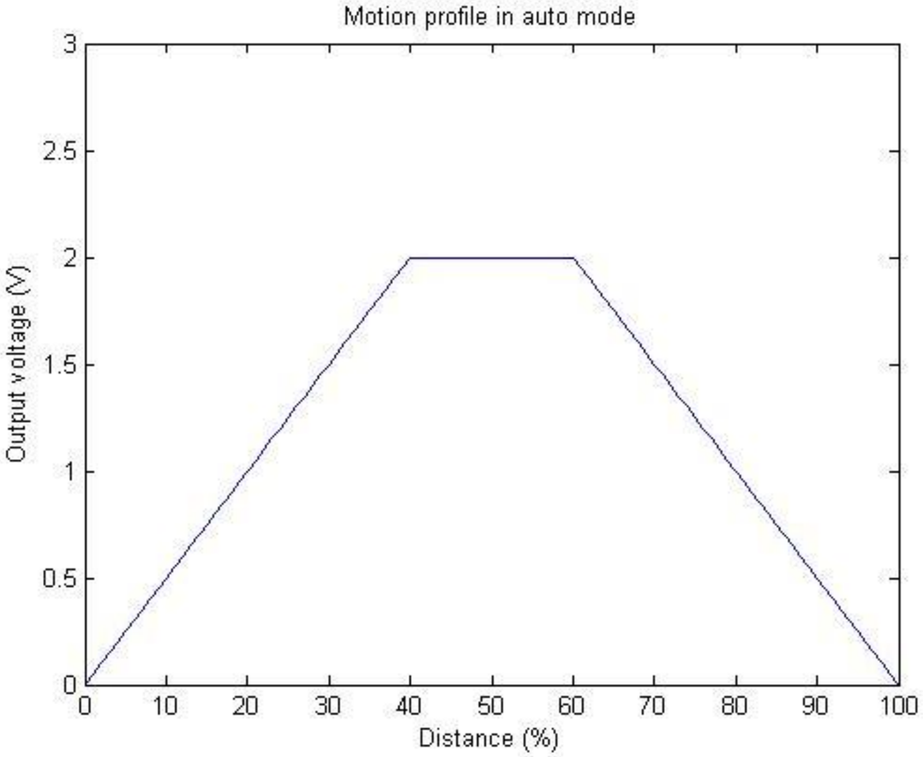


Figure 4. Motion profile in auto mode (for explanation purposes only, not measured data).

- **Encoder Display:** to display the current encoder position numerically and graphically. The numerical display shows the number of encoder ticks. One complete revolution is equal to 1000 encoder ticks.
- **POT Display:** to display the analog input voltage from the motor's potentiometer. The potentiometer is connected to a 5 V supply.
- **RPM display:** to show the speed of the motor rotation. The speed is calculated based on Δs/Δt, where Δt is 0.5 sec and Δs is the encoder ticks difference in 0.5 sec. The result is than converted into revolutions per minute.

The NI PCI-7356 has a built-in processor to read in the encoder signals. By default, it can read encoder data at a rate of up to 20MHz [8]. National Instruments also provides the NI Motion driver that includes LabVIEW VIs needed to read the encoder data from the motion controller memory. The low level communication procedure between the motion controller and the computer is handled within NI Motion.

The software flowchart is shown in Figure 5. The first step is to set the necessary parameters in order to run the motor. The software then moves to the home calibration algorithm. During this process, it also runs two other while loops simultaneously which is necessary for encoder display and RPM calculation. The RPM calculation while loop runs at a slower rate than the encoder while loop, because larger Δt leads to more accurate and stable results. After the home calibration is performed, the software enters the run mode, which can be either in manual mode or auto mode. In both modes, the software will run the third while loop necessary to control the analog output voltage. Refer to Appendix E for block diagrams and details on the software implementation.

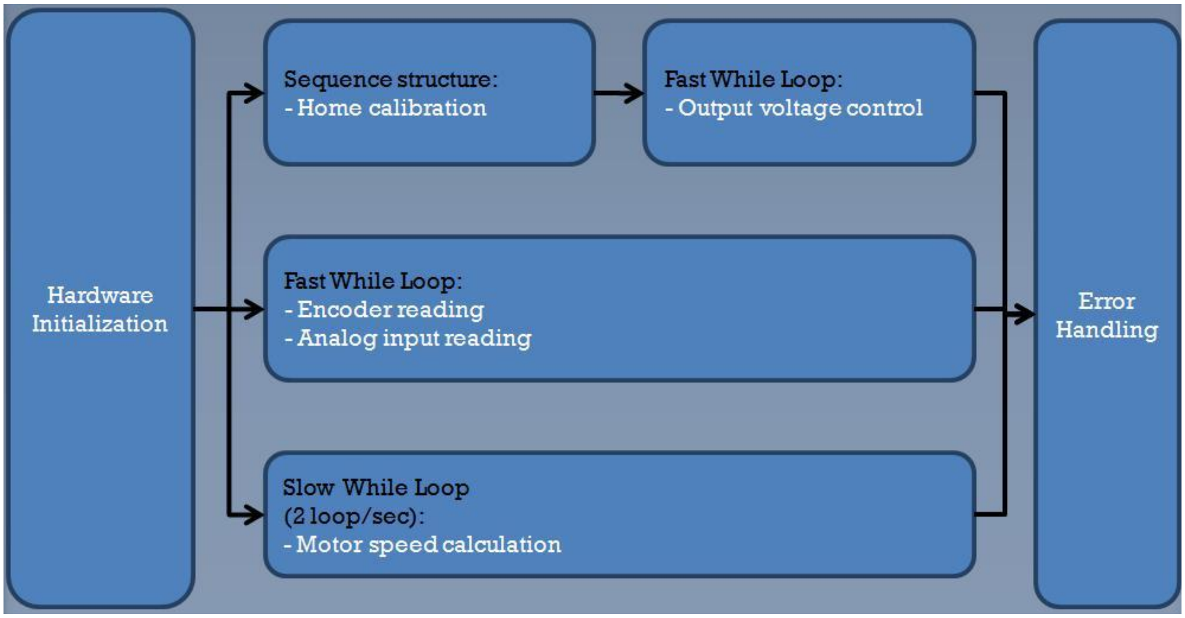


Figure 5. Software implementation flowchart.

The encoder signal from the motor is connected to encoder port on the motion controller. The motion controller is able to read the encoder signal at a rate of up to 20MHz [9], and stores the values in the memory. The value is obtained in the software using the Read Encoder Data VI. The encoder index signal is connected to the digital input port of the motion controller. The VI that is used to read the digital input port is the Read I/O VI. The potentiometer is connected to the analog input port, and the value is read using the Read ADCs VI. All the VIs are listed in Table 6.

The home calibration is done by moving the motor at a low speed while constantly reading the encoder index signal. Once the encoder index signal is found, the encoder value is reset to zero using the Reset Position VI, and the motor is stopped.

The automatic run mode is done by controlling the output voltage over the period of encoder distance. The motion consists of 40% voltage incline, 20% constant voltage, 40% voltage decline as shown in Figure 6. In the first 40% of the distance, starting with the minimum voltage of 1 V, the voltage is increased at a constant rate over the distance until the output voltage reaches 2 V. The motor will then move at a constant voltage of 2 V for the next 20% of the distance and start declining to the minimum voltage required to keep the motor moving at 0.75 V during the last 40% of the position. The implemented motion profile is shown in Figure 7. Encoder value is used to determine the necessary changes in output voltage. The distance for the incline, constant, decline voltage, and the rate of change of the output voltage are calculated in advance based on the given number of revolutions. These values are calculated after the run button is pressed, but before the motor starts spinning. The automatic run mode algorithm is written in a separate VI shown in Appendix F. This VI is called from the main software VI.

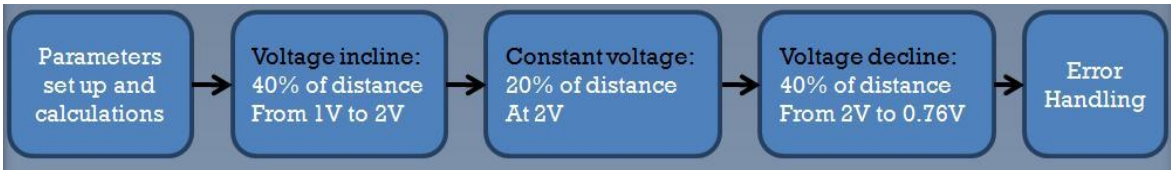


Figure 6. Flowchart of the RampFinal VI.

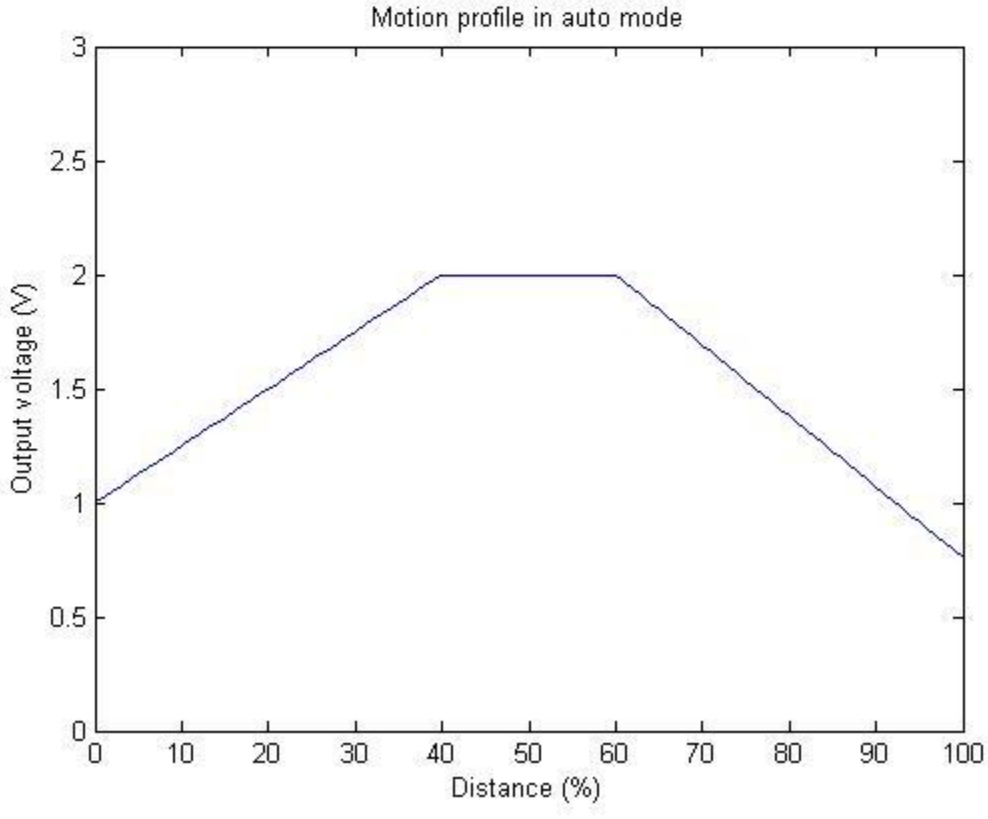
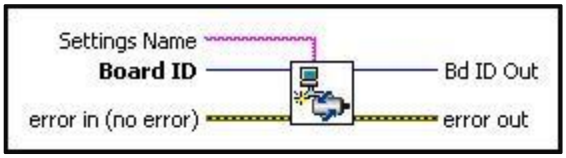
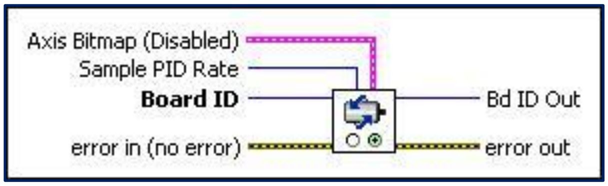
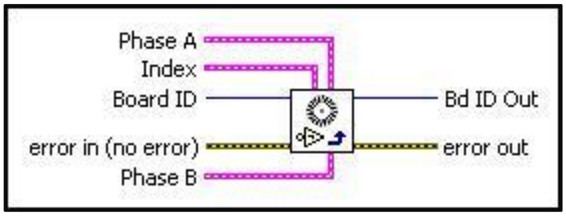
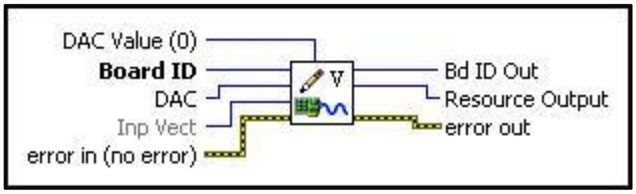
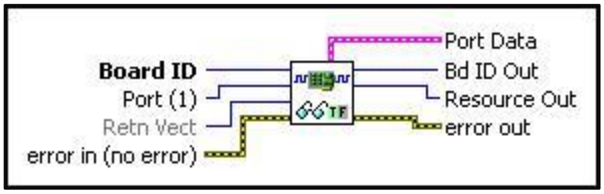


Figure 7. Implemented motion profile in auto mode (for explanation purposes only, not a measured data).

4.2 <u>Codes and Standards</u>

The NI Motion LabVIEW VIs that were used or explored in the development process of the software are listed in Table 6, based on NI Motion 7.7 and LabView 8.5. The initialization parameters needed are listed in Table 7. Table 8 shows the ADC conversion value range for the analog I/O port.

Table 6. NI Motion LabVIEW VIs Implemented [10]

Icon	Name	Description
	Initialize Controller	Initializes the motion controller.
	Enable Axes	Enables the operating axes and defines the PID and trajectory update rate.
	Configure Encoder Polarity	Configures the encoder **Phase A**, **Phase B**, and **Index** line polarities.
	Load DAC	Controls the output voltage.
	Read I/O Port	Reads the digital port for encoder index reading.

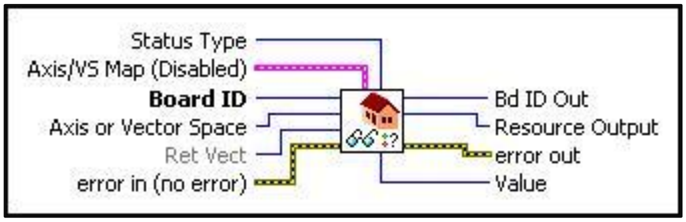
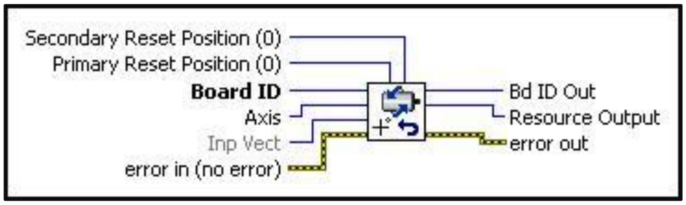
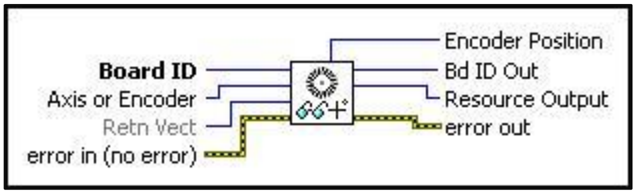
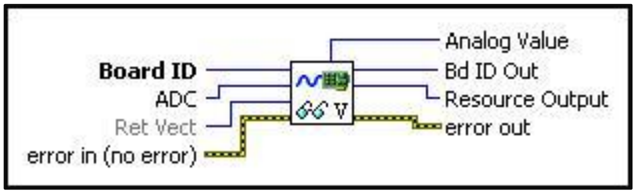
	Read Reference Status	Reads the encoder index port.
	Reset Position	Resets the encoder value to zero.
	Read Position	Reads the encoder position. One revolution is equal to 1000 encoder ticks.
	Read ADCs	Reads the converted value from an ADC input channel.

Table 7. Initialization Parameters for NI Motion LabVIEW VIs [10]

Parameter name	VI	Value	Description
Board ID	Initialize Controller	1	Number assigned and used by NI MAX to identify the PCI-7356.
Axis Bitmap	Enable Axes	True	The value true means the axis is enabled. There are 6 Axis Bitmap parameters.
Index	Configure Encoder Polarity	False	The value false means that the encoder index is active low.
Phase A	Configure Encoder Polarity	False	The value false means that the encoder A is active low.
Phase B	Configure Encoder Polarity	False	The value false means that the encoder B is active low.
DAC	Load DAC	DAC Channel 1	The analog output port to control. DAC Channel 1 means control the analog output channel 1.
ADC	Read ADCs	ADC Channel 1	The analog input port to read.
Axis	Reset Position	Axis 1	The encoder axis to reset the position.
Axis	Read Position	Axis 1	The encoder axis to read the position.

Table 8. Analog Value Range vs. LabVIEW Value Range [10]

Analog Value Range	LabVIEW Value Range
0 to 5	0 to +65,535
-5 to +5	-32,768 to +32,767
0 to 10	0 to +65,535
-10 to +10 (default)	-32,768 to +32,767

Two of the analog value ranges in Table 8 are used for communication between the NI PCI-7356 and the rest of the system. TA115 Motor Driver takes command voltage signal in the range of ± 10 V and the potentiometer gives analog output in the range of 0 V to 5 V.

The connection between the NI PCI card and the rest of the control system requires a VHDCI cable, which is proprietary to NI devices.

4.3 Constraints, Alternatives, and Tradeoffs

Hardware

Two power supplies, HP E3630A and Agilent E3634A, were provided by Dr. Thomas Michaels. The HP power supply does not have sufficient output power to power one or more motor driver. Hence the Agilent power supply was required to power the motor driver, and the HP power supply was used as the +5 V signal supply. The HP power supply with analog voltage output is less precise compared to the digital voltage output on the Agilent power supply.

During motor testing, broken brake and broken Encoder A were found inside of Motor 3 and Motor 4, respectively. To ensure a properly working system, both motors were replaced. New motors were purchased through Dr. Thomas Michaels and were made for the same type of robot to ensure matching mounting plate and specifications. However, because of the age of the arm robot, these specific motors were difficult to spot and were more expensive than the equivalent counterpart used in the newer arm robots.

Software

The software is developed in LabVIEW programming language rather than other languages like C or C++ because National Instruments provides NI Motion driver and LabVIEW VIs that handles all communication between the motion controller and LabVIEW. In addition, building a user interface in LabVIEW is a matter of drag and drop.

The encoder index from the motor is connected to the digital input port instead of the encoder index port in the motion controller, because running the Read Reference Status VI together with the Wait Reference VI in a while loop results in a lower encoder index sampling rate than running the Read I/O VI in the same while loop. The idea behind connecting the Read Reference Status VI with the Wait Reference VI was to wait for the encoder index signal to ensure that the controller catches the signal. However, the Wait Reference VI only has a maximum sampling rate of 1 reading/ms. The situation can be improved by removing the Wait Reference VI and using the while loop rate to sample the encoder index signal.

In the home calibration, the motor is moved by sending the lowest voltage necessary to move the motor. The reason is because the encoder index signal is too short. Running the motor faster than 200 RPM will result in an inconsistent encoder index reading i.e. the software fails to read all the encoder index signal occurrences. The 200 RPM value is not the border line for the misreading problem, the exact cutoff speed for the misreading problem is yet to be determined.

5 SCHEDULE, TASKS, AND MILESTONES

Table 9 displays the scheduled tasks, duration, start dates, end dates, level of difficulty, and the main person responsible for the task. January 12th marked the commencement of the project and April 28th was the end date. The proposed Gantt chart of the project is shown in Appendix G. However, due to several changes in project definition and time constraints, the proposed schedule was completely modified and the final Gantt chart is shown in Appendix H.

Table 9. Schedule, Tasks, and Milestones

Task Name	**Duration**	**Start Date**	**Finish Date**	**Difficulty Level**	**Main Person Responsible**
Project Definition	**23 days**	**1/12/2009**	**2/11/2009**		**Group**
Meet with Dr. Thomas E. Michaels to Define Goals and Objectives	10 days	1/12/2009	1/23/2009	Low	Chao
Define Project Scope	3 days	1/26/2009	1/28/2009	Low	Tanis
Research on Control System, Software, Motor Drives, and Motors	10 days	1/29/2009	2/11/2009	Low	Tanis
Robot Inspection and Testing	**32 days**	**2/12/2009**	**3/26/2009**		**Chao, Tanis**
Disassemble Motors	7 days	2/12/2009	2/20/2009	High	Chao
Pin Identification and Testing	2 days	2/23/2009	2/24/2009	Medium	Tanis
Test Motors Individually	7 days	2/25/2009	3/5/2009	Medium	Tanis
Motor Testing Complete	1 day	3/6/2009	3/6/2009	Milestone	Tanis
Order and Parts Delivery for 2 Motors	12 days	3/7/2009	3/23/2009	Low	Chao
Test New Motors	2 days	3/24/2009	3/25/2009	Medium	Chao
All Motors Working	1 day	3/26/2009	3/26/2009	Milestone	Chao
Rockwell Automation Controller	**18 days**	**3/4/2009**	**3/26/2009**		**Fernandes, Lie**
Setup Controller	5 days	3/4/2009	3/9/2009	Medium	Fernandes
Learn Ladder Logic	12 days	3/10/2009	3/25/2009	High	Fernandes
Switch to NI Controller	1 day	3/26/2009	3/26/2009	Milestone	Lie
Interface all Components	**23 days**	**3/9/2009**	**4/8/2009**		**Chao, Tanis**
Studying Servo Amplifier	3 days	3/9/2009	3/11/2009	Medium	Tanis
Build Wiring System	5 days	3/12/2009	3/18/2009	Medium	Chao
Order and Parts Delivery for 6 Servo Amplifiers	3 days	3/19/2009	3/23/2009	Low	Chao
Complete Wiring for Motor Driver and Motor	1 day	3/26/2009	3/26/2009	Milestone	Chao
Motor Driver Testing with Motor	3 days	3/27/2009	3/31/2009	Medium	Tanis
Interfaced Controller to	5 days	4/1/2009	4/7/2009	Medium	Chao

Motor Driver and Motor					
Communication of all Components Complete	1 day	4/8/2009	4/8/2009	Milestone	Chao
NI Controller Setup	**10 days**	**3/26/2009**	**4/8/2009**		**Fernandes, Lie**
Order and Parts Delivery for NI PCI-7356 Controller	3 days	3/26/2009	3/30/2009	Low	Lie
Setup Controller	2 days	3/31/2009	4/1/2009	Low	Lie
Order and Parts Delivery for Cables and Breakout Boards	4 days	4/2/2009	4/7/2009	Low	Fernandes
Controller Setup with Cables and Breakout Boards	1 day	4/8/2009	4/8/2009	Milestone	Fernandes
Software Implementation	**14 days**	**4/9/2009**	**4/28/2009**		**Fernandes, Lie**
Reading Encoders and Potentiometer	4 days	4/9/2009	4/14/2009	High	Lie
Home Position Calibration	5 days	4/16/2009	4/22/2009	High	Fernandes
Position Control	3 days	4/23/2009	4/27/2009	High	Lie
Final Demonstration	1 day	4/28/2009	4/28/2009	Milestone	Fernandes

6 PROJECT DEMONSTRATION

The project demonstration took place on April 28th 2009 at 12:00 pm in the Van Leer building Room 113. The goal of the demonstration was to show that the developed software could perform the following tasks.

- Read feedback information from encoder and potentiometer.
- Calculate the RPM of the motor.
- Regulate the output voltage to the motor manually.
- Tune the motor to start at the index pulse.

- Ramp up and down the voltage to the motor to the desired number of revolutions in forward and reverse mode.

The GUI shown in Figure 3 was divided into two controls, manual and automatic. The software is to calibrate to the home position and display the encoder position, potentiometer value, and the calculated RPM regardless of which control mode the software is executed. The demonstration involved three runs, one in manual mode and two in automatic mode.

- During the manual mode, the motor first rotated at 0.75 V (lowest voltage at which Motor 1 runs) and stopped until the index pulse was found. The voltage was then regulated manually between -2.00 V to +2.00 V to rotate the motor. Whenever the motor was in motion, the GUI displayed the current encoder position, the potentiometer value, and the calculated RPM of the motor numerically and graphically.
- A desired positive number of revolutions was entered for the automated run. Like the manual mode, the motor first performed the home position calibration. Once the GO button was clicked, the motor ramped up from 1.00 V to 2.00 V during the first 40% of the number of revolutions, stayed constant at 2.00 V for the next 20%, and then ramped down from 2.00 V to 0.75 V during the last 40% of the revolutions.
- For the last run, a negative number of desired revolutions was entered. After the home position calibration and once the GO button was clicked, the motor ramped up from -1.00 V to -2.00 V during the first 40% of the number of revolutions, stayed constant at -2.00 V for the next 20%, and then ramped down from -2.00 V to -0.75 V during the last 40% of the revolutions.

7 MARKETING AND COST ANALYSIS

7.1 Marketing Analysis

In 2004, approximately 5% to 15% of the industrial robots in injection molding industry were six-axis articulated robots [11], leaving a large market for PUMA 560 robots to grow. However, since the PUMA 560 robot was manufactured back in 1985 [12], it is not equipped with modern technology such as high speed microprocessor and zero-backlash mechanism such as the harmonic drive gearing [13]. Compared to the KUKA 5 sixx R850 [14], a modern arm robot in the same class, the PUMA 560 robot is inferior in many aspects such as speed, repeatability, and payload as shown in Table 10. Although the PUMA 560 robot does not excel in comparison, it is capable of completing any task where speed and accuracy are not critical.

Table 10. Comparison between PUMA 500 Robot and KUKA 5 sixx R850 Robot

Technical Specifications	**PUMA 560**	**KUKA 5 sixx R850**
Axes	6	6
Repeatability	± 0.1 mm	± 0.03mm
Maximum Static Load	2.5 kg	5 kg
Maximum Speed	0.508 m/s	7.6 m/s
Reach	914 mm	814 mm

Hand-held teach pendants such as the Motoman NXC100 teach pendant are commonly used to program the movements of articulating arm robots in the industry [15]. However, according to [16], PC-based controllers have recently become more popular as they provide an advantage of reduced cost, improved robustness, and open architecture platform. With six degrees of freedom and re-programming ability, the PUMA 560 robot will be able to handle different types of tasks with changes only in the end effectors and software, thereby reducing production cost and increasing its potential in the market.

7.2 Cost Analysis

Table 11. Lists of Parts and Labor Costs

Item	Description	Retail Value	Actual Value
Robotic Arm	PUMA Robot 560 Series	$5,000	FREE
150 W Motors (1)	Unimation Original Parts	$600	$600
30 W Motors (1)	Unimation Original Parts	$350	$350
Servo Drives (6)	TA115	$4,200	$4,200
PLC Controller	NI PCI 7356	$2,890	$2,890
PCI Cables (4)	68 Pin VHDCI M to MD68 M	$220	$220
Breakout Boards (4)	68 Pin F Vertical Breakout	$200	$200
Desktop	Dell GX260	$350	FREE
Miscellaneous	Tools, Wires, Connectors, Switches, Electrical Components	$100	FREE
Labor	600 hours x $50 / hour	$30,000	FREE
Total		**$43,910**	**$8,460**

Table 11 lists the parts and labor costs needed to work on the project. The total actual cost for this project ended up to be $8,460, which is higher than the estimated cost in the proposal, $5,150. The difference in the total cost was due to the purchase of NI PCI 7356 controller, which was sponsored by Dr. Michaels. All other items except for the PCI cables and the breakout boards were also sponsored by Dr. Michaels.

The PCI cables and the breakout boards, which cost $420 dollars, were purchased from Daqstuff, a company that replicates connector cables and breakout boards for NI controllers, using the team’s senior design fund.

Labor spent to work on the project was estimated to be 600 hours with typical market engineer’s salary of $50/hour, which results in $30,000 dollars. Table 12 shows the breakdown for the estimated labor hours for each team member.

Table 12. Estimated Labor Hours

Task	**J. Chao (Hr.)**	**J. Tanis (Hr.)**	**D. Lie (Hr.)**	**F. Fernandes (Hr.)**
Class Hours				
Lecture	26	26	26	26
Reports	27	24	24	30
Presentation	6	6	6	6
Website development	0	0	15	0
Project Hours				
Project Research and Definition	25	25	25	25
Robot Inspection and Testing	30	30	15	20
Motor Driver Setup	8	8	0	0
Interface Components	28	31	0	0
Code Implementation	0	0	31	35
Final Testing	0	0	8	8
Total per Person	**150**	**150**	**150**	**150**
Total Hours	**600**			

In order to achieve the original goal, which is to interface the whole PUMA 560 robot, the only additional parts that may have to be purchased are wires and connectors for the entire wiring system. For these parts, additional cost of $250 dollars is estimated. Additionally, the team estimated that four hundred labor hours are needed for the following tasks:

- Reassemble the motors back to the robot’s body
- Implement kinematic equations on the controller
- Implement the control PID loop for position and speed control
- Test the overall system and make necessary adjustments

8 SUMMARY AND CONCLUSIONS

The initially proposed design goal was to program kinematic equations into the control system to make the end effectors of the robot move to a specified x, y, and z coordinate with a specified rotational direction within an error of ± 1 cm and ± 3º, respectively. Due to several problems that occurred during the semester and time constraints, the goal was not met. However, the re-proposed goals of the project were successfully achieved.

- A system interface is established for the motor, the motor driver, and the NI controller
- A GUI is provided for end users to read in feedback signals from the motor
- The controller is able to control a single motor's position and speed
- Established groundwork and prepared documentation for future ECE students' project

Appendix I shows all the tasks that were completed during the semester and also provides a task list for future ECE senior design teams to achieve. Other helpful resources are also made available on the Yellow PUMA website and can be accessed at the following link.

http://www.ece.gatech.edu/academic/courses/ece4007/09spring/ece4007l01/ws5/index.htm

9 REFERENCES

[1] ATSI. (2008). Articulating Arm Robot [Online]. Available: http://www.atsi.cc/articulating-arm-robot.htm

[2] J.M. Pethokoukis. (2004, Mar. 7). Industrial robots are reshaping manufacturing. *U.S. News* [Online]. Available: http://www.usnews.com/usnews/biztech/articles/040315/15eerobots.htm

[3] ATSI. (2008). Robot Basics [Online]. Available: http://www.atsi.cc/robotbasics.htm

[4] RobotWorx. (2009). Industrial Arc Welding Robot Application [Online]. Available: http://www.robots4welding.com/applications.php?app=arc+welding

[5] Automation.com. (2004). NI Introduces Four PCI Motion Controllers for Manufacturing and Test Applications [Online]. Available: https://www.automation.com/content/ni-introduces-four-pci-motion-controllers-for-manufacturing-and-test-applications

[6] Trust Automation, Inc. (April 2000). TA115 Datasheet. [Online PDF] Available: http://trustautomation.com/Library/pdf/Datasheets/TA115.pdf

[7] P. Nagy, "The PUMA 560 Industrial Robot: Inside-Out," *Industrial Robot Journal*, pp 4.67-4.79, 1988.

[8] National Instruments (2008). 735x Datasheet. [Online PDF] Available: http://www.ni.com/pdf/products/us/735x.pdf

[9] Parasar Kodati. (2004, Aug.). Implementation of an open-architecture for PC-based control of PUMA 560. NUS, Singapore. [Available]: http://udel.edu/~parasar/documents/puma_report.pdf

[10] National Instruments (2005, November). NI-Motion VI Help [Microsoft Windows Help format – Online]. Available: http://digital.ni.com/manuals.nsf/websearch/BF588B77C64200BE8625711B0050D137

[11] M. Knights, Six axis robot: where they fit in injection molding, *Plastics Technology* [Online Article]. October 1, 2004. Available: http://goliath.ecnext.com/coms2/summary_0199-1325378_ITM

[12] Unimation (1985, March). PUMA Mark II Robot 500 Series Equipment Manual for VAL II and VAL PLUS Operating System.

[13] A. Lauletta (2006, April), The Basics of Harmonic Drive Gearing, *Power Transmission Engineering*, [Magazine]. pp.32.

[14] KUKA Roboter GmbH, "KR 5 sixx R850," [Company Website], Available: http://www.kuka-robotics.com/usa/en/products/industrial_robots/small_robots/kr5_sixx_r850/start.htm

[15] RobotWorx, "Motoman NX100 Teach Pendant," [Company Website], Available: http://www.robots.com/motoman.php?controller=nx100

[16] M. Faroog, "Implementation of a new PC-based Controller for a PUMA robot," Journal of Zhejiang University-Science A," vol. 8, no.12, pp. 1962-1970, Nov. 2007.

[17] W. Bihr and F. Degrange. (1999). "Interfacing of a Force/Torque sensor on a PUMA 500 robot," *Georgia Institute of Technology*, [Online]. Available: http://helix.gatech.edu/Students/SiouxWill/project.html

APPENDIX A – MATLAB CODE

Shown below is the Matlab code used to determine the voltage constant

```matlab
% v1 and v2 represents the input voltage, where r1 and r2 represent
% the rpm corresponding to the input voltage.
% This data are collected from actual testing.
v1 = 1:35;
v2 = 1:22;
r1 = [0 40 80 120 155 195 220 275 305 340 380 420 460 500 545 585 630
660 690 720 725 760 795 828 867 903 940 976 1011 1053 1087 1124 1161
1197 1239];
r2 = [12 111 225 335 446 560 664 782 887 1001 1117 1238 1345 1462 1573
1687 1809 1926 2044 2155 2272 2382];

% Determine and plot the 1st-order best-fitting polynomial.
P1 = polyfit(v1, r1, 1);
new_r1 = polyval(P1, v1);
P2 = polyfit(v2, r2, 1);
new_r2 = polyval(P2, v2);

% The voltage constant is the inverse of the 1st-order coefficient
% of the polyfit constant.
vc1 = 1000/P1(1)
vc2 = 1000/P2(1)

hold on
plot(v1, r1, 'r+', v2, r2, 'b+', v1, new_r1, 'k', v2, new_r2, 'k')
legend('Motor 1', 'Motor 6')
xlabel('Input Voltage (V)')
ylabel('Speed (rpm)')
title('Input Voltage vs. Speed')
```

APPENDIX B – THE UNIMATION PUMA 560 ROBOT

The arm robot has six revolute joints, and each joint is driven by a DC servomotor. The orientation of each axis and the angle of rotation of each joint are shown in Figure B1. This six-axis configuration allows the robot to reach any point in its working envelope in any direction.

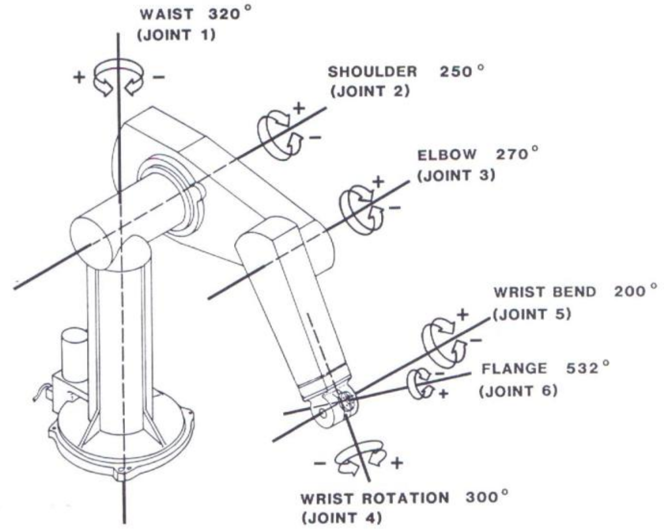


Figure B1. Schematic of Unimation PUMA 560 robot with joint angles, axis of rotation, and maximum rotation range [16].

Figure B2 provides detailed physical dimensions of the arm robot. The information is necessary for the implementation of forward and inverse kinematics.

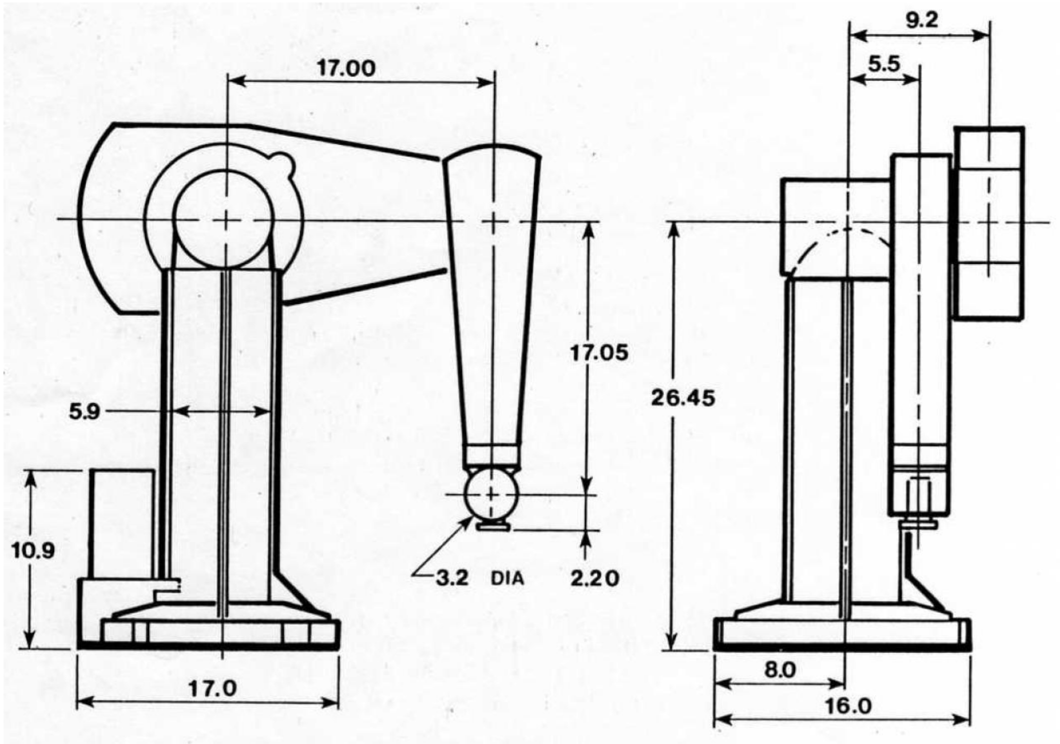


Figure B2. Schematic of Unimation PUMA 560 robot with dimensions of the robot in inches [17].

Detailed technical specifications of the arm robot can be viewed in Table B1. Since the project only modifies the control system, the actual performance of the robot should be close to these specifications.

Table B1. Detailed Technical Specifications of the Unimation PUMA 560 Robot

Axes	6 revolute axes
Drive	Electric Brushed DC Servomotors
Repeatability	± 0.1 mm
Maximum Static Load	25 N
Maximum Straight Line Velocity	51 cm/sec
Reach	86.6 cm to the wrist 92.2 cm to the flange
Weight	54.4 kg

APPENDIX C – PINOUT DIAGRAM

Motor Pinout

Two types of motors are used. Motors 1 to 3 are shown in Figure C1 in the center, and Motors 4 to 6 are shown in Figure C1 to the right.

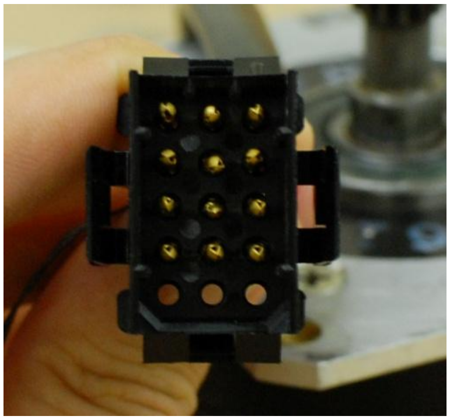
Figure C1. Two types of motor.

The sample pictures of the connector along with the pin numbering are provided in Table C1 and Table C2.

Table C1. Motors 1-3 Pinout Diagram

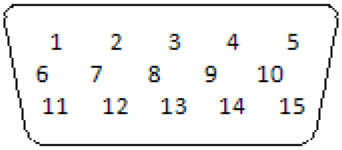
3	2	1
6	5	4
9	8	7
12	11	10
-	-	-

(a) Pin Numbers

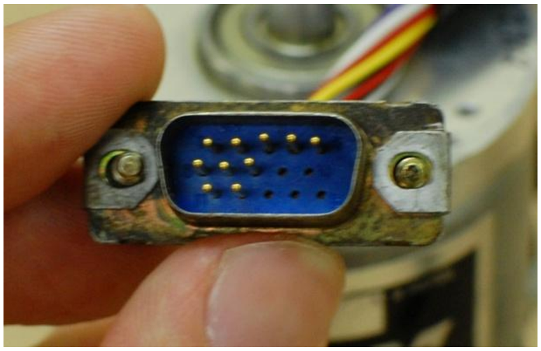


(b) Sample Picture

Table C2. Motors 4-6 Pinout Diagram



(a) Pin Numbers



(b) Sample Picture

Table C3 gives the description of every pin. Note that the pin number applies to all motors and the small motors have no brake.

Table C3. Pin Details for Motors in PUMA 560 robot

Pin #	Description	Motors 4-6 Cable Colors
1	Motor PWR +	Red
2	Motor PWR -	Black
3	Encoder A	Green
4	Encoder PWR (+5V)	Yellow
5	Encoder B	White
6	Encoder GND	Brown
7	Encoder I	Purple
8	Pot PWR (+5V)	Orange
9	Brake PWR	-
10	Brake RET	-
11	Pot RET	Gray
12	Pot o/p	Blue

Since all motors were disassembled from the robot, matching female connectors were needed to test the motors on the bench. Two 15-pin VGA connectors were obtained and made for the small motors, as shown in Figure C2. Note that the color of the wires corresponds to Table C3.

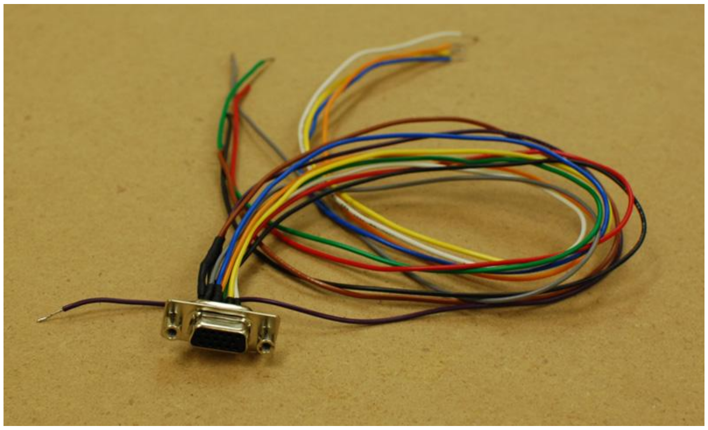


Figure C2. Connectors for Motor 4-6.

Unfortunately, since the matching female connector for the big motors could not be found, the team implemented pin-to-pin connection to setup the big motor for bench testing.

Motor Driver Pinout and Control

There are two connectors and one DIP switch on the motor driver. Table C4 describes the setting on the DIP switch. Note that the values on the right-most column were used for the project.

Table C4. TA115 Switch Setting

Switch S1	Description (Up)	Description (Down)	Value Used
1	User-Supplied +5 V V_{AUX} (Opto-isolation)	TA115 supplied +5 V V_{AUX}	Up
2	Power GND and AUX GND isolated (Opto-isolation)	Power GND and AUX GND Shared	Up
3	Fault Signal Active High	Fault Signal Active Low	Up
4	Voltage Mode	Current Mode	Down
5	Gain/Limit Select bit 0		Down
6	Gain/Limit Select bit 1		Down

The opto-isolation is enabled to protect the PCI controller card in the case of an over-current flow or a short circuit. The motor driver was run in current mode, because in voltage mode the amplification gain is fixed at 14, which translates a ± 10 V command signal to ± 140 V. Furthermore, the lowest current mode gain which is 0.2 was chosen to protect the motor from over-current condition during bench testing. Table C5 shows the setting for the Gain/Limit Select bits.

Table C5. TA115 Gain and Current Limit Setting

S1-5 (bit 0)	S1-6 (bit 1)	Current Mode Gain (A_o/V_i)	Voltage Mode Current Limit ($\lvert A_{o,max}\rvert$)
Down	Down	0.2	2 A
Up	Down	0.4	4 A
Down	Up	0.6	6 A
Up	Up	0.8	8 A

In current mode the gain/limit select bits control the gain, and in voltage mode the bits only control the maximum output current. Even with the lowest setting, the maximum output current is over the rated current for the small motors.

The pinout for the connectors is also necessary to complete the wiring. Table C6 shows the information about each pin on the connectors.

Table C6. TA115 Motor Driver Pinout

Connector J1		**Connector J2**	
Pin	**Description**	**Pin**	**Description**
1	Command Signal Input +	1	Motor Power +
2	Command Signal Input -	2	Motor Power -
3	Aux GND	3	GND
4	Aux GND	4	GND
5	Not Use	5	V_{SUPPLY} (24V Used)
6	Not Use	-	-
7	/ENABLE	-	-
8	FAULT	-	-
9	Aux GND	-	-
10	V_{AUX} +5V	-	-

With opto-isolation enabled, it is necessary to provide Ground and 5 V to J1-9 and J1-10, in addition to the 24 V powering the motor driver. The enable pin J1-7 has to be pulled to the AUX Ground for the motor driver to start. The Enable pin was hard-wired into the Aux GND J1-9 and the Fault pin J1-8 was not connected. However, it is possible to control these two pins through the digital ports on the controller.

Controller Pinout

The motors and motor drivers cannot be connected to the controller directly, as breakout boxes are required to secure the connection. There are four 68-pin VHDCI (Very High Density Cable Interconnect) connectors in the back of the NI PCI-7356. Four 68-pin breakout boxes were purchased as well as four male-to-male connectors. Figure C3 gives a sample picture of the breakout box used.

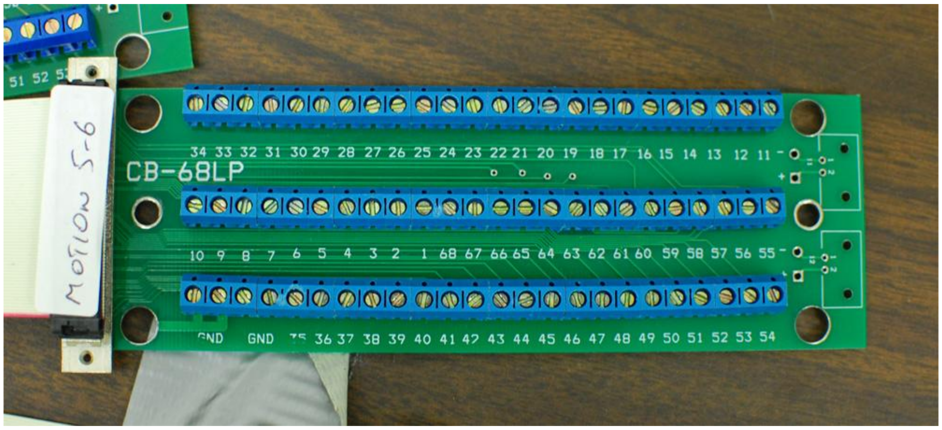


Figure C3. Breakout box for the NI PCI-7356.

Since there are a total of 272 pins coming out from the controller, it is suggested to look at the datasheet for NI PCI-7356 [5]. Note that the pins for Axis 7 and Axis 8 are not available for this 6-axis controller.

APPENDIX D – FINAL DEMO VI

The FinalDemo.vi is the main VI that needs to be opened using LabVIEW to run the software. The purpose of the VI is to be able to read the encoder signals and the potentiometer signal from the motor, control the rotation of the motor, and provide a user interface to the user. The block diagram of the VI is shown in Figure D1. In addition to LabVIEW and NI Motion VIs, the FinalDemo.vi also utilizes the developed RampFinal.vi.

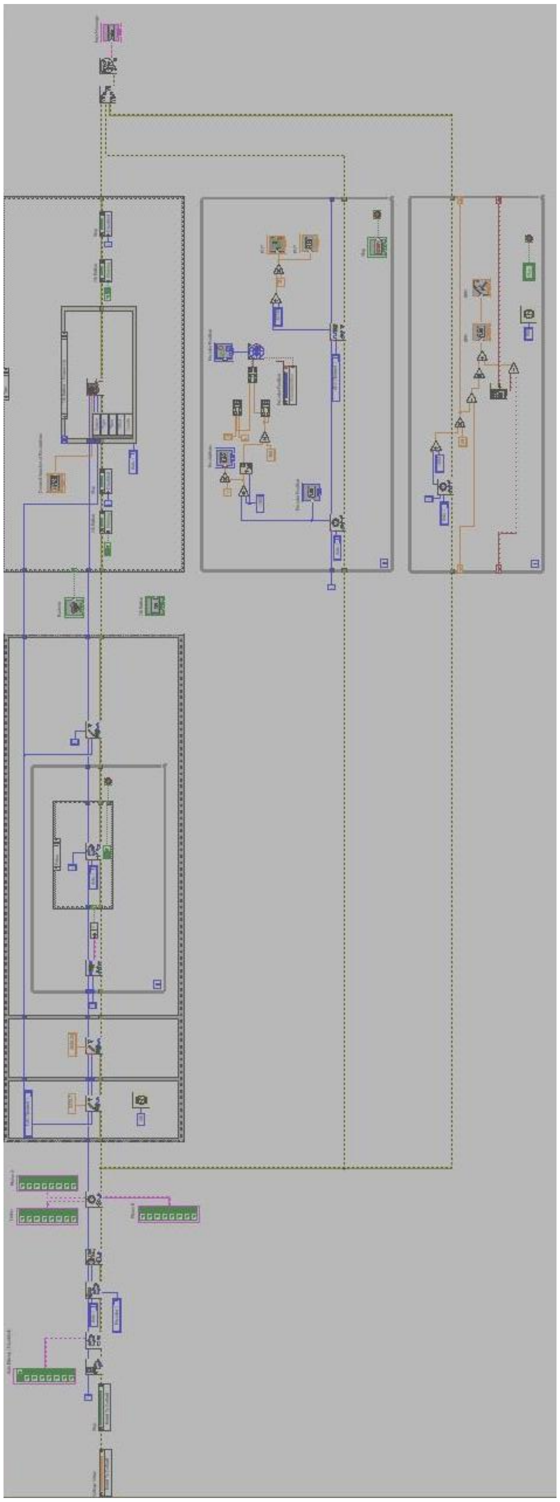


Figure D1. Block diagram of the FinalDemo VI.

For analytical purposes, the FinalDemo.vi can be broken down into 5 components:

- Initialization
- Home calibration
- Run mode loop
- Encoder and pot reading loop
- Speed calculation loop

Initialization

The parameters needed to properly control the motor is defined in the initialization section. A block diagram of the initialization section is shown in Figure D2. The initialization section performs the following tasks:

- Initialize the voltage control value to zero
- Initialize the motion control
- Enable the operating axes
- Configure the encoder polarity. All encoders that are used are active low. The assigned value that indicates active low is the Boolean false.

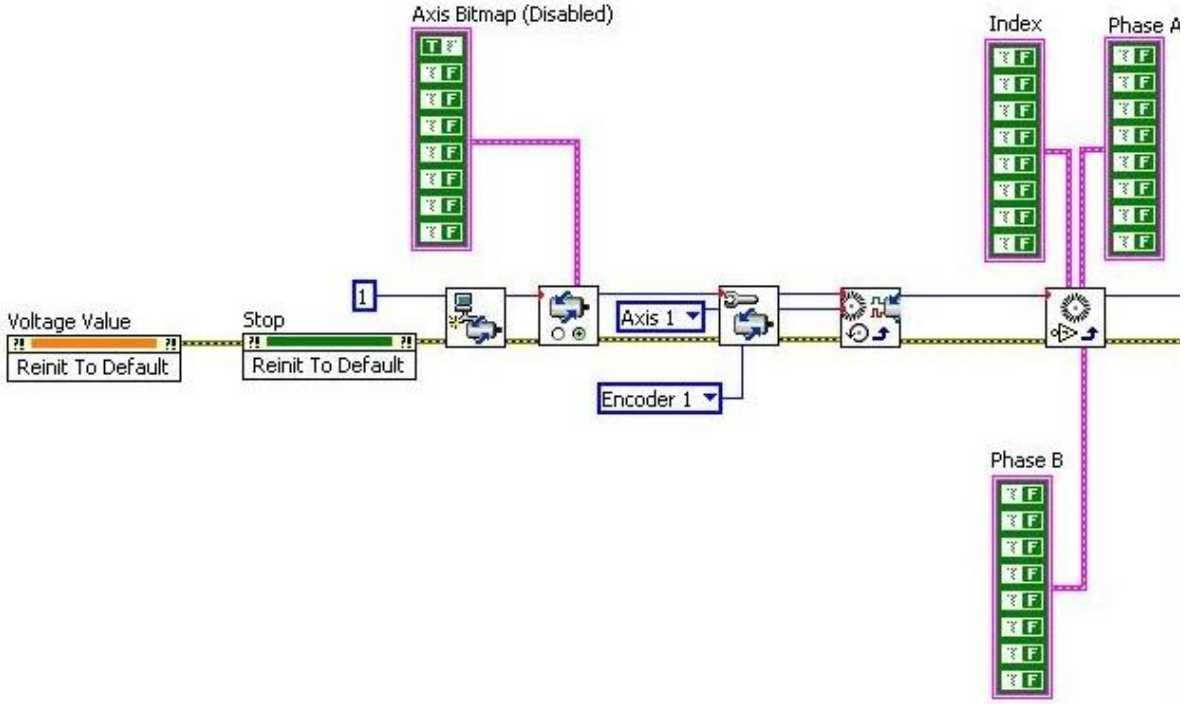


Figure D2. Block diagram of the initialization section.

Home Calibration

The purpose of the home calibration section is to find the encoder index position and set the index position as the home encoder zero position. A block diagram of the home calibration section is shown in Figure D3. The flat sequence structure is used to construct the home calibration section because there is a need to make sure that a certain task is completed before moving to the next task. The home calibration section performs the following tasks:

- Send a 1 V signal to start the motor. This is performed by sending a constant value of 3276.7. The analog output voltage ranges from -10 V to +10 V. However the corresponding digital value range to send the signal is -32768 to +32767. Thus the value +1 V is equivalent to +3276.7. This condition is then held for 10 ms before moving to the next task.
- Next, a 0.79 V signal is sent to the motor. It is the minimum required voltage to move the motor without load. Note that a higher voltage is needed to start the motor due to static friction. Generally the static friction constant is higher than the dynamic friction constant.

- Then, the digital input port is constantly checked for positive encoder index reading. Note that the encoder index is active low. The parameters sent to the Read I/O Port VI shows that the encoder index data is sent through the digital input port 1 digit 0.

- If the encoder index position is found, the input port 1 digit 0 will go low, the encoder position is reset to zero, break out from the loop, and set the output voltage to zero to stop the motor.

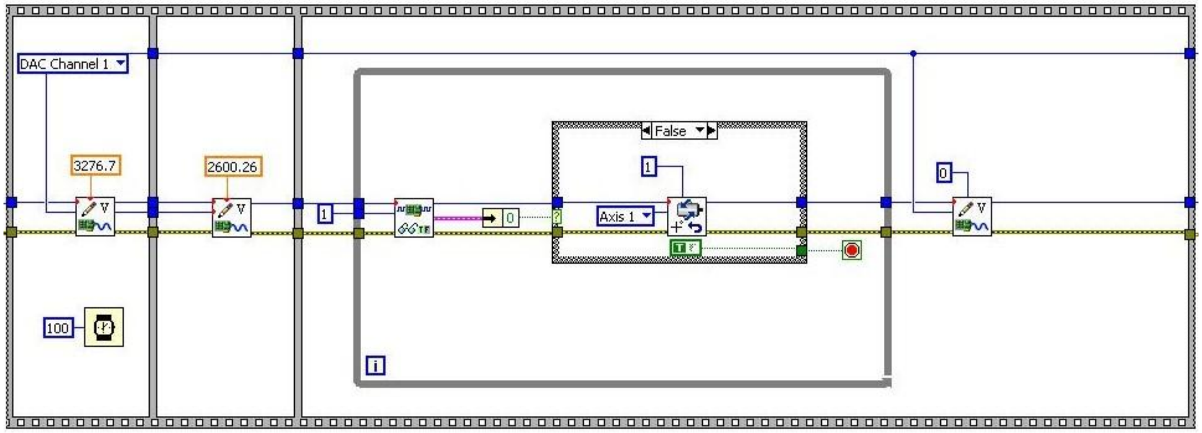


Figure D3. Block diagram of the home calibration section.

Run Mode Loop

The case structure is used to construct the run mode loop because there are two possible run modes available: the manual mode and the auto mode. The case decision is based on the value sent by the Boolean control switch. The block diagram of the manual mode is shown in Figure D4 and the block diagram of the auto mode is shown in Figure D5.

The manual mode does the following tasks:

- The integer constant 48 and the double constant 11 is used to make sure that the case condition inside the while loop is true during the first loop run. The integer constant is compared with the axis value, which is supposed to be one, and the double constant is compared with the control knob voltage.

- The current loop run axis value and the voltage value is then stored in the shift register for the next loop run. After the first loop run, the axis value will not change anymore. Therefore, as long as the control knob voltage value does not change, the condition for the second case structure will remain false, and the Load DAC VI is not called.

- Inside the condition true of the second case structure is the third case structure. The third case structure is used to make sure that the appropriate factor is used in both negative and positive output voltage case. The -1 V is equivalent to -3276.8 in Load ADC VI, while +1 V is equivalent to 3276.7. This factor is than multiplied with the value from the voltage control knob to convert it to the corresponding Load ADC VI value.

- Pressing the stop button will break the while loop and stop the motor.

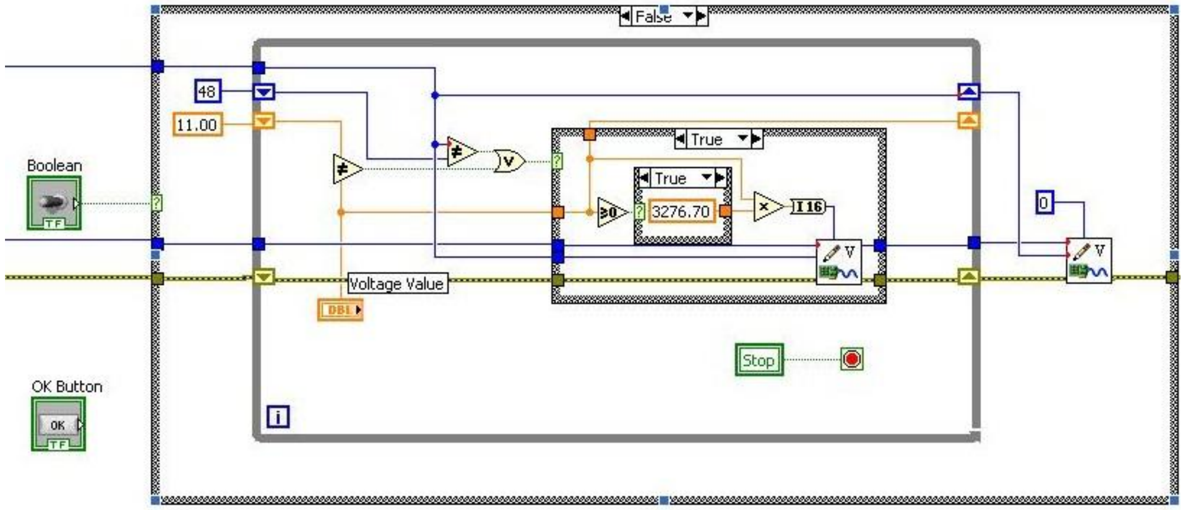


Figure D4. Block diagram of manual run mode.

The auto run mode does the following tasks:

- The go button (labeled as OK button in the block diagram) blinks and disables the stop button.

- Calls the RampFinal VI once the go button is pressed. For this purpose, the event structure is used.

- Enables the stop button once the motion is completed.

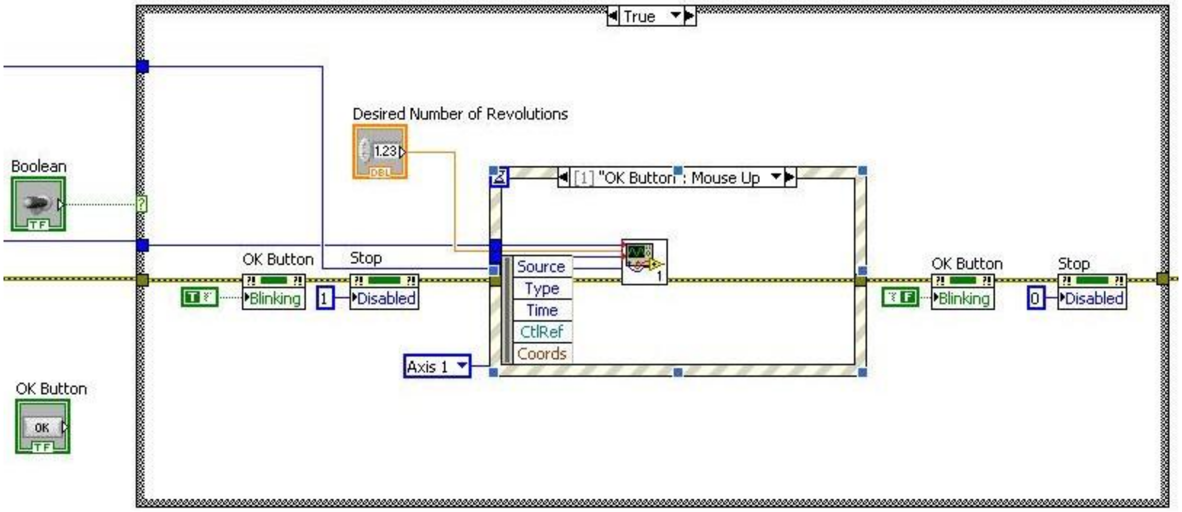


Figure D5. Block diagram of the auto run mode.

Encoder and Pot Reading Loop

The purpose of the encoder and pot reading loop section is to read and display the encoder position and the analog input signal from the potentiometer. The block diagram of this section is shown in Figure D6. In order to graphically display the encoder position in terms of degrees, the following calculation is performed:

CurrentPositionInDegrees = Mod(EncPos/1000, 1000)*360°

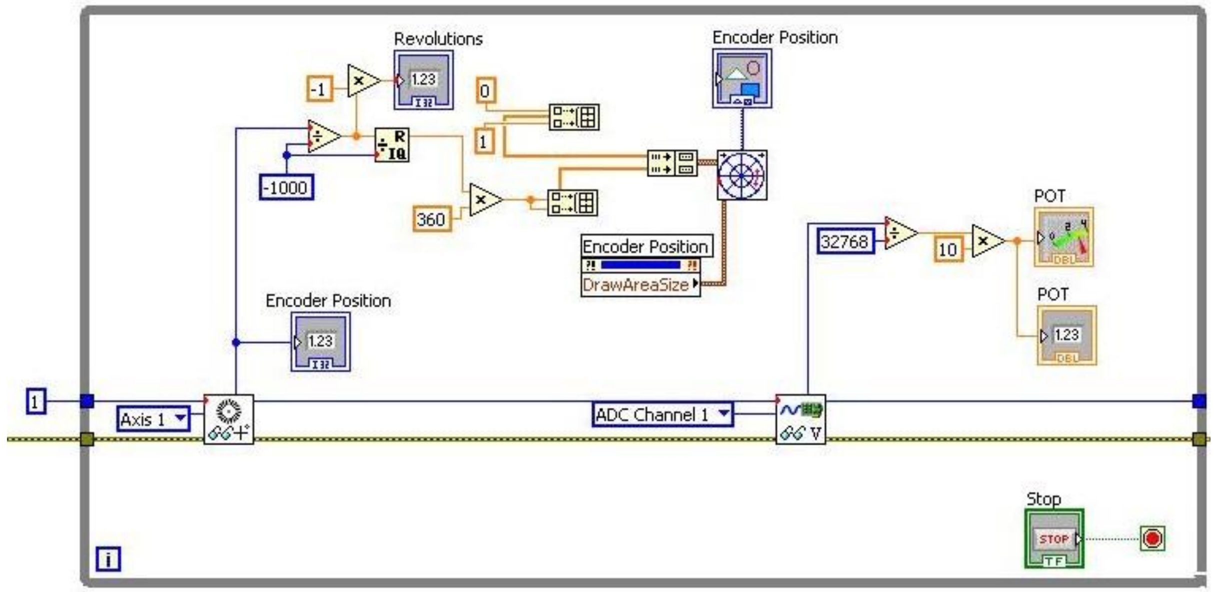


Figure D6. Block diagram of the encoder and pot reading section.

Speed Calculation Loop

The purpose of the speed calculation loop is to calculate the speed of the rotation in RPM. The block diagram of the speed calculation loop is shown in Figure D7. The speed calculation loop has a delay of 0.5 second between each loop run. The time delay is to allow more encoder ticks over a longer period of time, thus creating an averaging effect, and makes the result more stable and more accurate than the result performed by faster loop run. The formula used to calculate the speed is:

$RPM = Abs(\Delta EncPos/1000*60)/\Delta t$

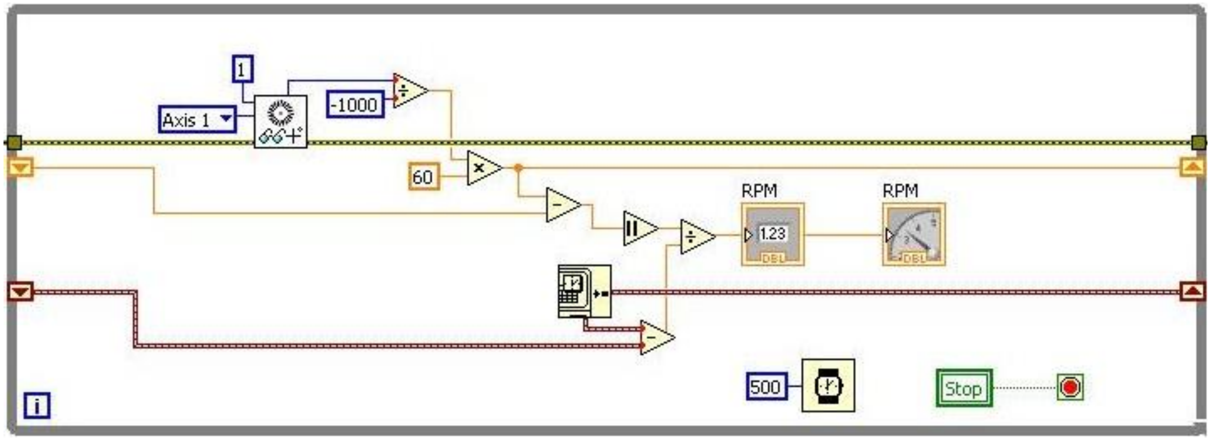


Figure D7. Block diagram of the motor speed calculation.

APPENDIX E – USER MANUAL

The user manual is made available to guide the user in running the software application with ease.

In order to use the software, the following items will be needed:

- Windows based PC capable of running NI LabVIEW
- NI PCI-7356 Motion Controller
- NI LabVIEW 8.5 software
- NI Motion 7.6 software driver
- FinalDemo VI
- RampFinal VI

The current developed software is not a standalone application. Therefore the correct version of NI LabVIEW, NI Motion, and the VIs listed above will be needed to run the software application.

Follow the steps below to run the software:

- Open the FinalDemo.vi using NI LabVIEW.
- Switch between the manual (manual voltage control using the knob) and auto (voltage is controlled automatically based on the input number of revolutions) mode.
- If the switch is set to auto, put in the desired number of revolutions in the numeric control. The numeric control accepts decimal input.
- Click the start button.
- The home calibration algorithm will run automatically, wait until the home calibration is completed. The motor will stop spinning and the encoder position will be reset. This will be the indication that the home calibration is complete.

- If the switch is set to manual, use the voltage control knob to control the motor.
- If the switch is set to auto press the blinking go button to start position command.
- Press the stop button to close the software. In auto mode, user has to wait until the motion is completed before pressing the stop button. The stop button is disabled during the auto mode motion.

The flowchart of the user interaction is shown in Figure E1.

Troubleshooting

Q: Why does not the motor move during the home calibration mode?

A: It means that the motor doesn’t have enough voltage supply. To solve this problem, change the voltage value in the second sequence in the home calibration section to a value that is higher than 2600.26 (0.79 V) or wait until the mot warms up.

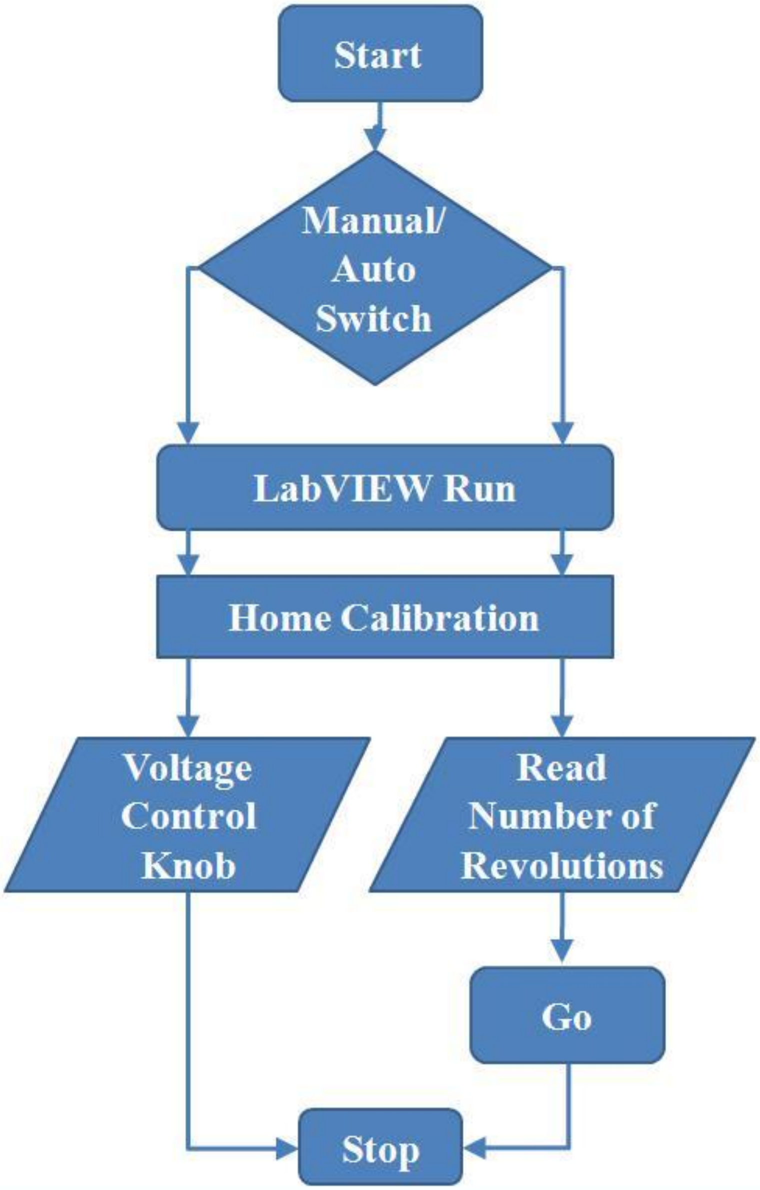


Figure E1. User interaction flowchart.

APPENDIX F – RAMP FINAL VI

The RampFinal.vi is called by the main VI in the run auto mode section. The purpose of the RampFinal VI is to automatically create the motion profile as seen in Figure 7, which consists voltage incline (40% of the distance), constant voltage (20% of the distance), and voltage decline (40% of the distance). The block diagram of the RampFinal VI is shown in Figure F1. The diagram of the RampFinal input and output ports are shown in Figure F2. The input and output ports of the VI are listed in Table F1.

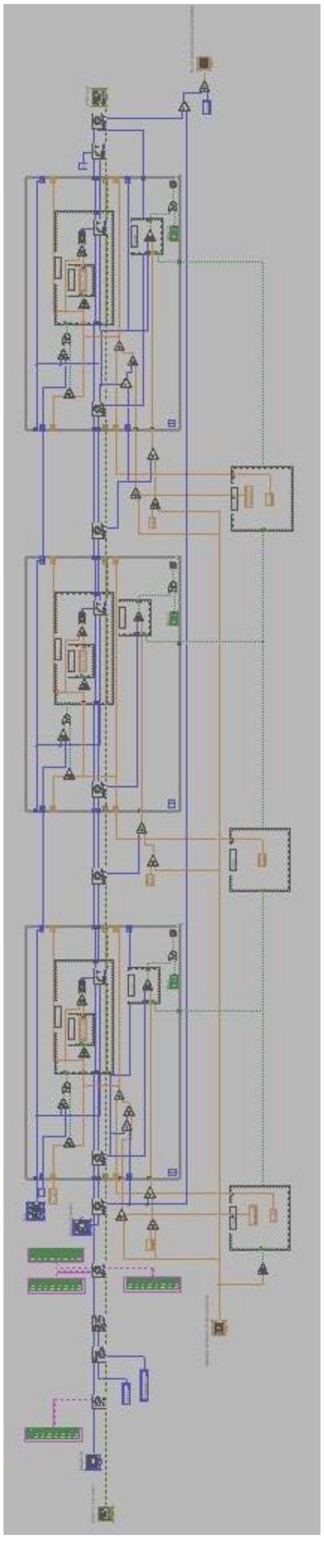


Figure F1. Block diagram of the RampFinal VI.

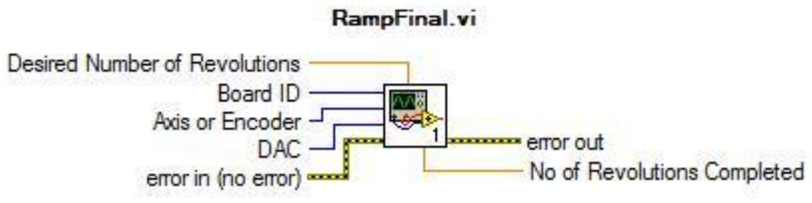


Figure F2. Diagram of the RampFinal VI

Table F1. I/O Ports of RampFinal VI

Name	**Direction**	**Description**
Desired Numer of Revolutions	Input	The desired number of revolutions to perform.
Board ID	Input	Number assigned and used by NI MAX to identify the PCI-7356.
Axis or Encoder	Input	The encoder axis to read.
DAC	Input	The analog output port to control. DAC Channel 1 means control the analog output channel 1.
No of Revolutions Completed	Output	The elapsed number of revolution performed.

For analytical purpose, the RampFinal VI can be broken down into 4 components:

- Initialization (identical to the initialization section in the FinalDemo VI)
- Voltage incline
- Constant voltage
- Voltage decline

Voltage incline

The block diagram of the voltage incline section is shown in Figure F3. The following calculation is performed in this section:

- The initial voltage is 1 V, the target end voltage is 2 V, and therefore the change in voltage over the first 40% of the distance is 1 V.

- Rate of change of the Output Voltage = 1/(0.4*1000) = 0.0025 Volts/tick
- NewVoltage = PrevVoltage + 0.0025*(NewEncoder – PrevEncoder)

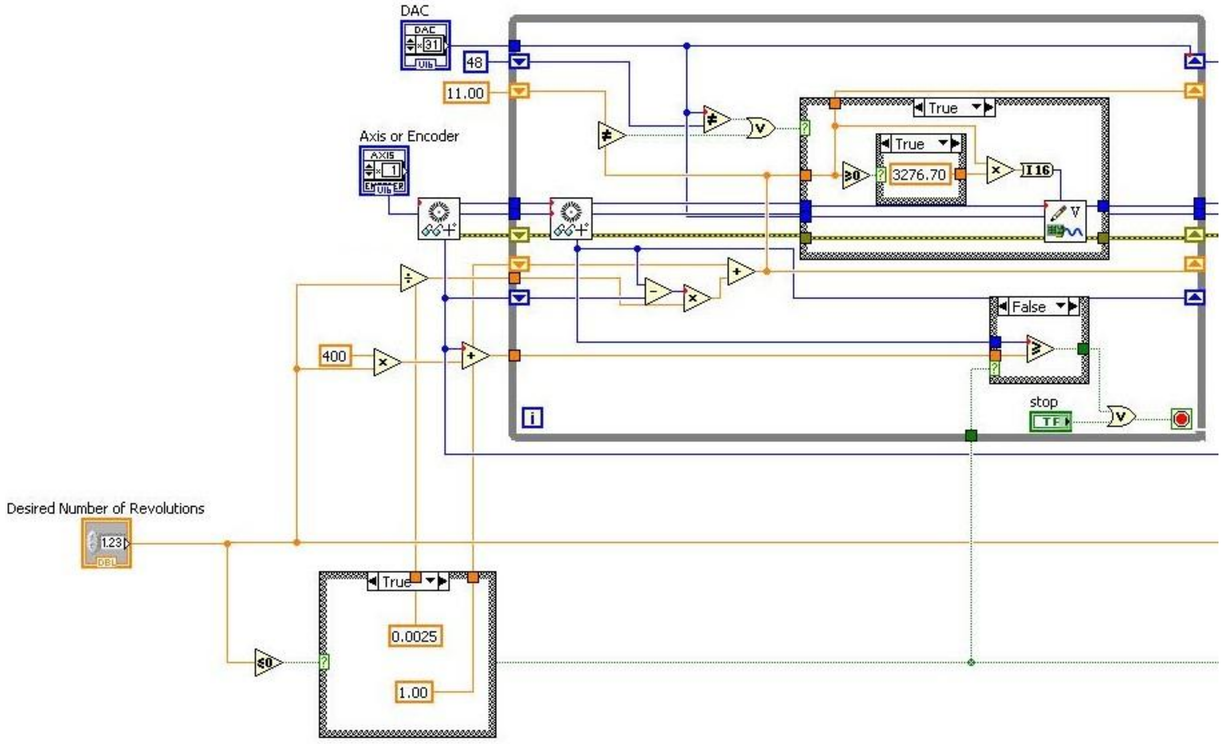


Figure F3. Block diagram of the voltage incline section.

Constant Voltage

The constant voltage section runs the motor at a constant 2 V over the next 20% of the total distance. A block diagram of the constant voltage section is shown in Figure F4.

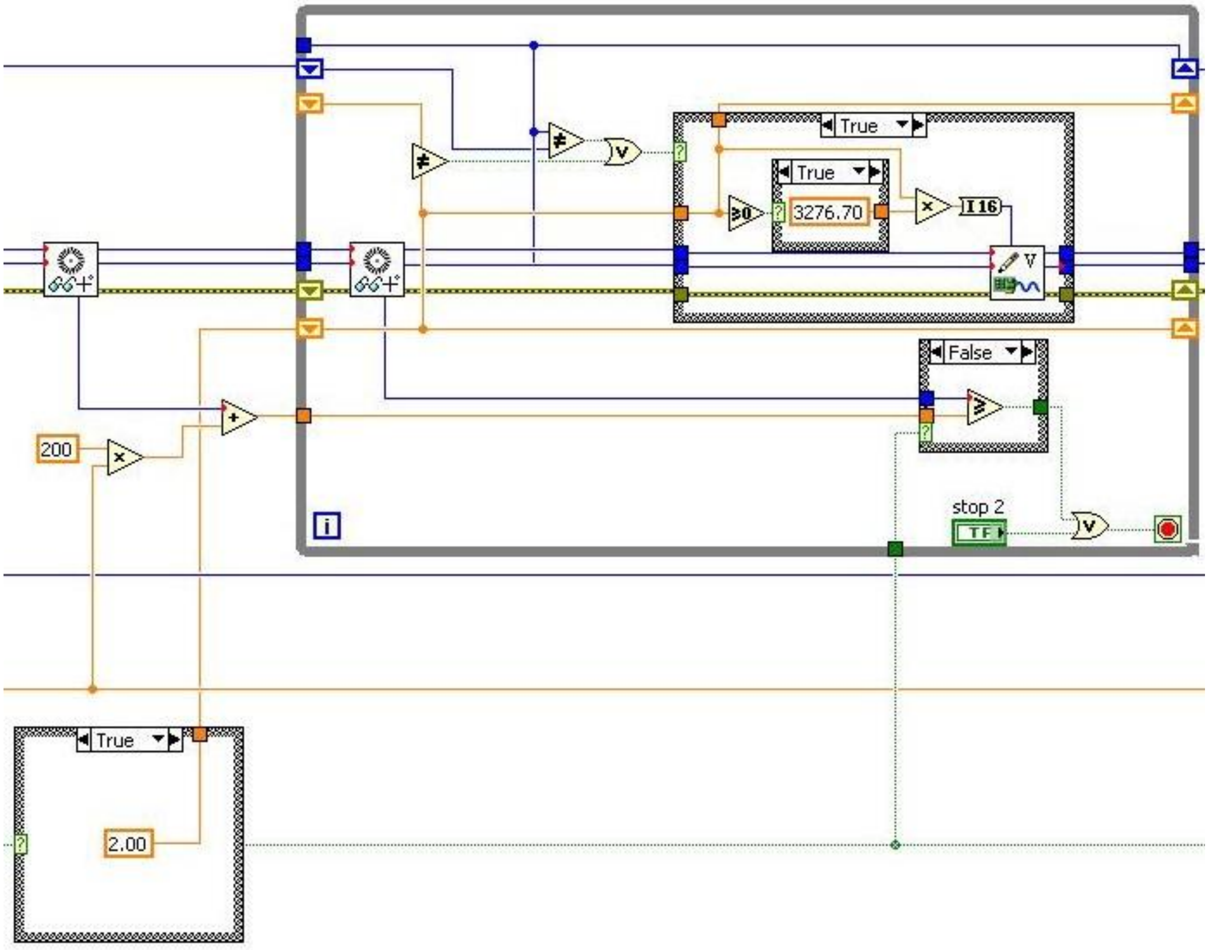


Figure F4. Block diagram of the constant voltage section.

Voltage Decline

The block diagram of the voltage incline section is shown in Figure F5. The following calculation is performed in this section:

- The initial voltage is 2 V, the target end voltage is 1 V, and therefore the change in voltage over the last 40% of the distance is -1 V.
- Rate of change of the Output Voltage = 1/(0.4*1000) = 0.0025 Volts/tick
- NewVoltage = PrevVoltage – 0.0025*(NewEncoder – PrevEncoder)

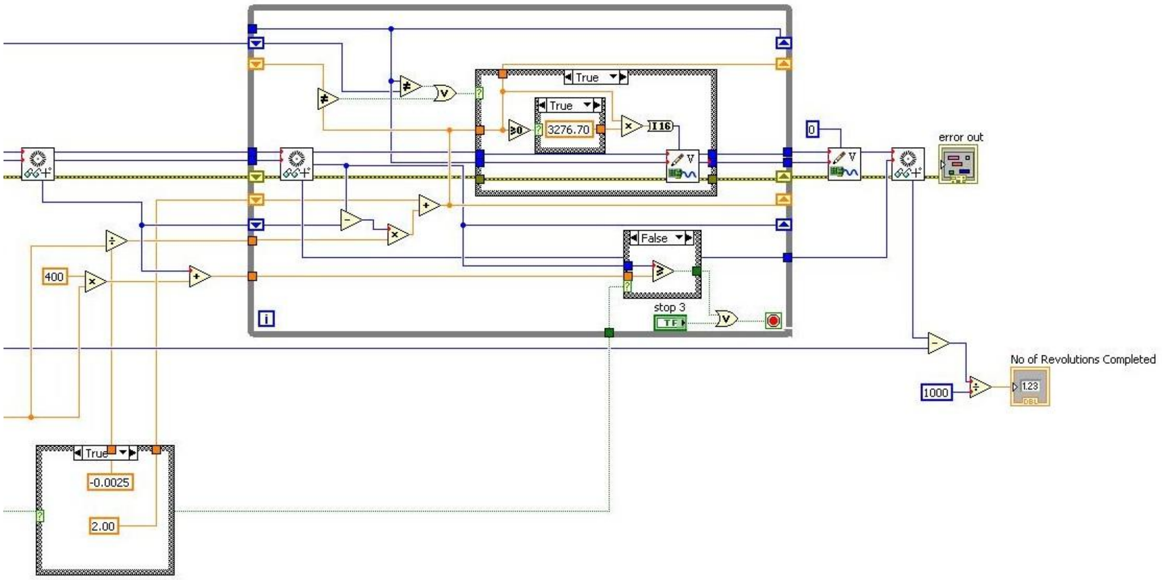
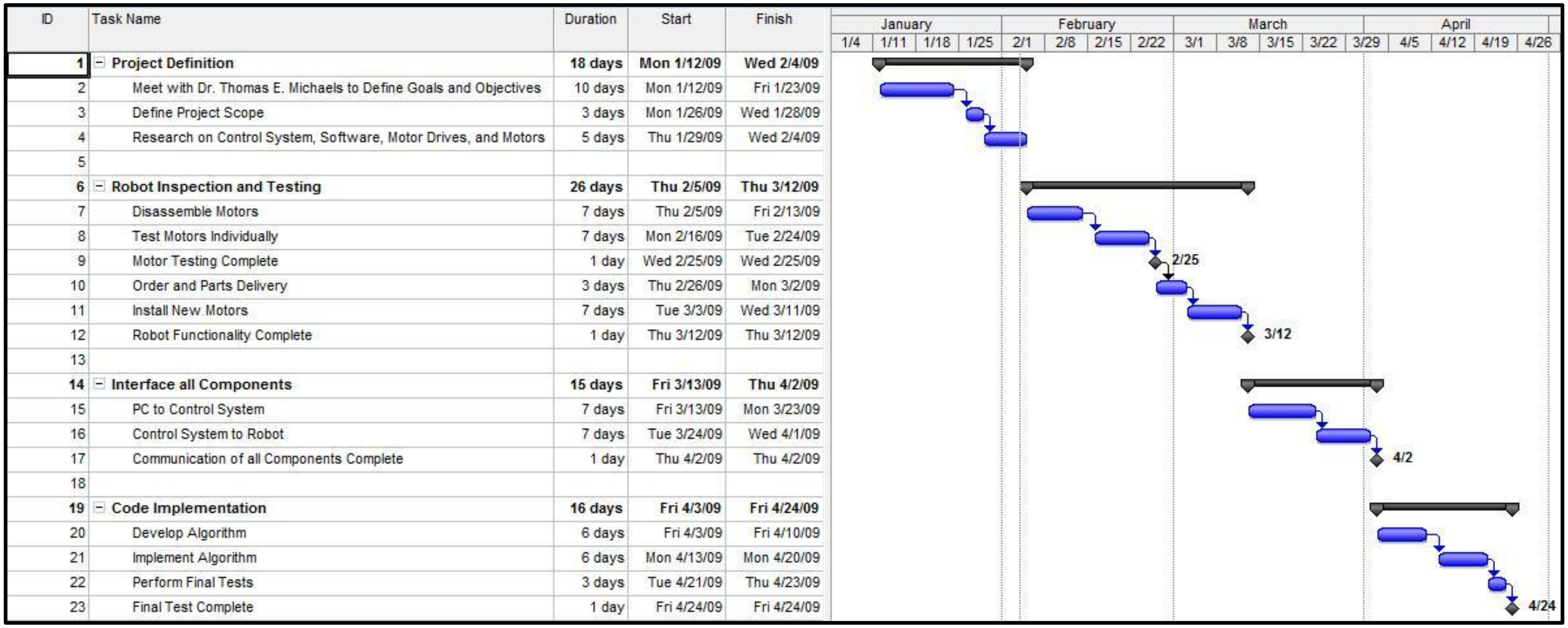


Figure F5. Block diagram of the voltage decline section.

APPENDIX G – PROPOSED PROJECT GANTT CHART

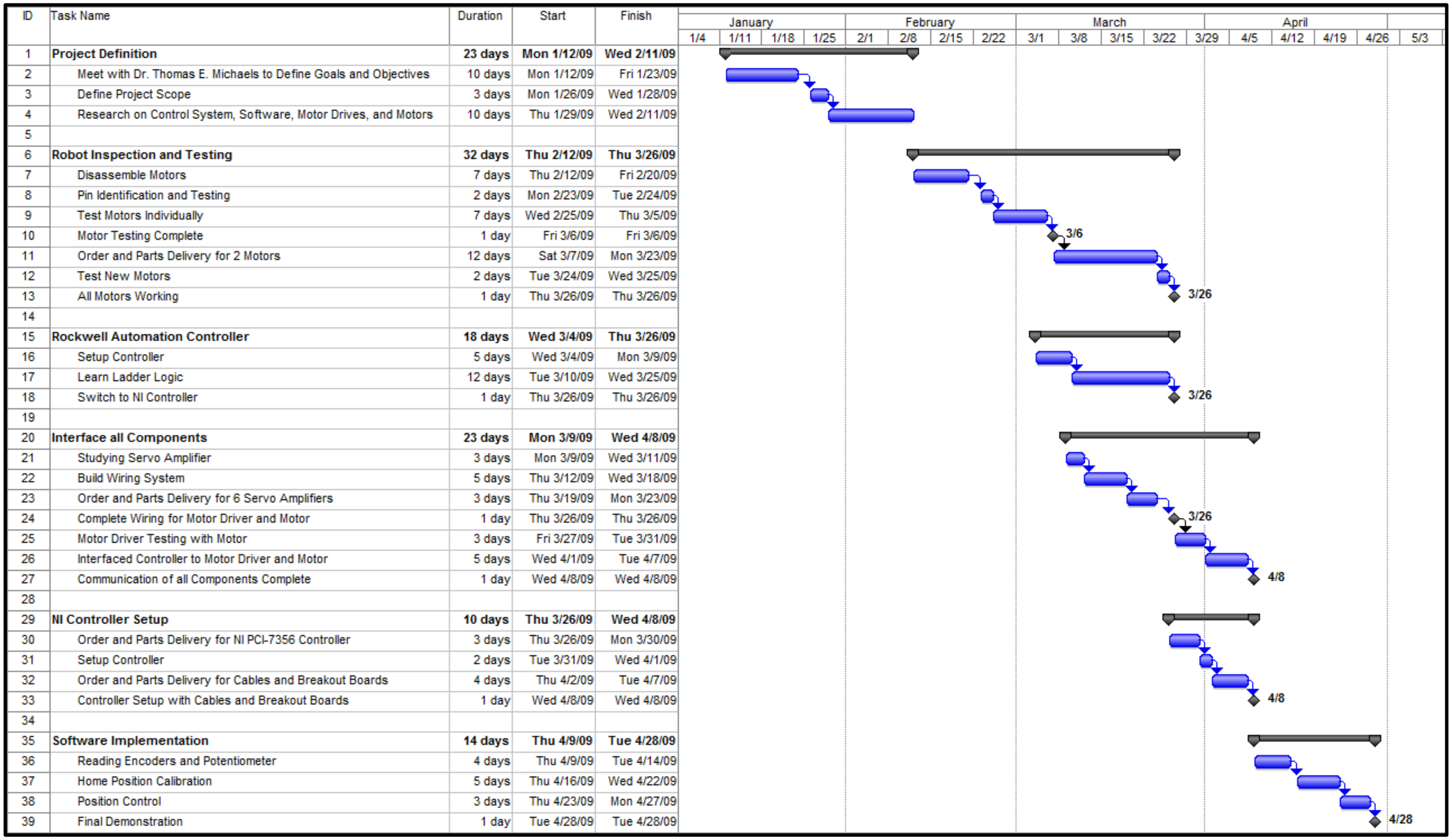
See next page for project Gantt chart.



ID	Task Name	Duration	Start	Finish
1	**⊟ Project Definition**	**18 days**	**Mon 1/12/09**	**Wed 2/4/09**
2	Meet with Dr. Thomas E. Michaels to Define Goals and Objectives	10 days	Mon 1/12/09	Fri 1/23/09
3	Define Project Scope	3 days	Mon 1/26/09	Wed 1/28/09
4	Research on Control System, Software, Motor Drives, and Motors	5 days	Thu 1/29/09	Wed 2/4/09
5				
6	**⊟ Robot Inspection and Testing**	**26 days**	**Thu 2/5/09**	**Thu 3/12/09**
7	Disassemble Motors	7 days	Thu 2/5/09	Fri 2/13/09
8	Test Motors Individually	7 days	Mon 2/16/09	Tue 2/24/09
9	Motor Testing Complete	1 day	Wed 2/25/09	Wed 2/25/09
10	Order and Parts Delivery	3 days	Thu 2/26/09	Mon 3/2/09
11	Install New Motors	7 days	Tue 3/3/09	Wed 3/11/09
12	Robot Functionality Complete	1 day	Thu 3/12/09	Thu 3/12/09
13				
14	**⊟ Interface all Components**	**15 days**	**Fri 3/13/09**	**Thu 4/2/09**
15	PC to Control System	7 days	Fri 3/13/09	Mon 3/23/09
16	Control System to Robot	7 days	Tue 3/24/09	Wed 4/1/09
17	Communication of all Components Complete	1 day	Thu 4/2/09	Thu 4/2/09
18				
19	**⊟ Code Implementation**	**16 days**	**Fri 4/3/09**	**Fri 4/24/09**
20	Develop Algorithm	6 days	Fri 4/3/09	Fri 4/10/09
21	Implement Algorithm	6 days	Mon 4/13/09	Mon 4/20/09
22	Perform Final Tests	3 days	Tue 4/21/09	Thu 4/23/09
23	Final Test Complete	1 day	Fri 4/24/09	Fri 4/24/09

APPENDIX H – FINAL PROJECT GANTT CHART

See next page for project Gantt chart.



ID	Task Name	Duration	Start	Finish
1	**Project Definition**	**23 days**	**Mon 1/12/09**	**Wed 2/11/09**
2	Meet with Dr. Thomas E. Michaels to Define Goals and Objectives	10 days	Mon 1/12/09	Fri 1/23/09
3	Define Project Scope	3 days	Mon 1/26/09	Wed 1/28/09
4	Research on Control System, Software, Motor Drives, and Motors	10 days	Thu 1/29/09	Wed 2/11/09
5				
6	**Robot Inspection and Testing**	**32 days**	**Thu 2/12/09**	**Thu 3/26/09**
7	Disassemble Motors	7 days	Thu 2/12/09	Fri 2/20/09
8	Pin Identification and Testing	2 days	Mon 2/23/09	Tue 2/24/09
9	Test Motors Individually	7 days	Wed 2/25/09	Thu 3/5/09
10	Motor Testing Complete	1 day	Fri 3/6/09	Fri 3/6/09
11	Order and Parts Delivery for 2 Motors	12 days	Sat 3/7/09	Mon 3/23/09
12	Test New Motors	2 days	Tue 3/24/09	Wed 3/25/09
13	All Motors Working	1 day	Thu 3/26/09	Thu 3/26/09
14				
15	**Rockwell Automation Controller**	**18 days**	**Wed 3/4/09**	**Thu 3/26/09**
16	Setup Controller	5 days	Wed 3/4/09	Mon 3/9/09
17	Learn Ladder Logic	12 days	Tue 3/10/09	Wed 3/25/09
18	Switch to NI Controller	1 day	Thu 3/26/09	Thu 3/26/09
19				
20	**Interface all Components**	**23 days**	**Mon 3/9/09**	**Wed 4/8/09**
21	Studying Servo Amplifier	3 days	Mon 3/9/09	Wed 3/11/09
22	Build Wiring System	5 days	Thu 3/12/09	Wed 3/18/09
23	Order and Parts Delivery for 6 Servo Amplifiers	3 days	Thu 3/19/09	Mon 3/23/09
24	Complete Wiring for Motor Driver and Motor	1 day	Thu 3/26/09	Thu 3/26/09
25	Motor Driver Testing with Motor	3 days	Fri 3/27/09	Tue 3/31/09
26	Interfaced Controller to Motor Driver and Motor	5 days	Wed 4/1/09	Tue 4/7/09
27	Communication of all Components Complete	1 day	Wed 4/8/09	Wed 4/8/09
28				
29	**NI Controller Setup**	**10 days**	**Thu 3/26/09**	**Wed 4/8/09**
30	Order and Parts Delivery for NI PCI-7356 Controller	3 days	Thu 3/26/09	Mon 3/30/09
31	Setup Controller	2 days	Tue 3/31/09	Wed 4/1/09
32	Order and Parts Delivery for Cables and Breakout Boards	4 days	Thu 4/2/09	Tue 4/7/09
33	Controller Setup with Cables and Breakout Boards	1 day	Wed 4/8/09	Wed 4/8/09
34				
35	**Software Implementation**	**14 days**	**Thu 4/9/09**	**Tue 4/28/09**
36	Reading Encoders and Potentiometer	4 days	Thu 4/9/09	Tue 4/14/09
37	Home Position Calibration	5 days	Thu 4/16/09	Wed 4/22/09
38	Position Control	3 days	Thu 4/23/09	Mon 4/27/09
39	Final Demonstration	1 day	Tue 4/28/09	Tue 4/28/09

APPENDIX I – TASK LIST

Below is the list of tasks that were completed by the team during the semester.

- Define and discuss design goals with Dr. Michaels
- Research and gather technical specifications about the PUMA 560 and motors
- Determine pin layout for the main wire harness connector ELCO 8016
- Check existence of limit switches
- Remove all motors from the robot
- Test brake release for the three big motors
- Test Encoders A, B, and Index for all six motors
- Test potentiometer output for all six motors
- Replace and test the two broken motors
- Learn to use the purchased motor driver
- Build wiring system to connect the motor driver and motor
- Replace Rockwell CompactLogix L43 controller with NI PCI-7356 controller
- Interface the NI controller with the motor and motor driver
- Develop a GUI to control the motor

- Control the motor using command analog voltage
- Read encoder and potentiometer feedback signals
- Calculate RPM of the motor in motion
- Control the position and speed of the motor

Below is the list of tasks that need to be achieved by future senior design teams.

- Implement the control PID loop for position and speed control
- Add limit switches algorithm within the software program
- Wire and interface all 6 motors
- Program to control all 6 axes
- Install the 6 motors into the robot
- Determine the actual limit switch values
- Program forward and inverse kinematic equations
- Test overall system and make necessary adjustments