Corp 2: Army Robot

Operational Readiness Review
1 May 2013

Auburn University
MECH 4250 – Spring 2013
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AMRDEC

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Executive Summary:

Corp 2 was formed in August 2012 to develop a tension control device for an AMRDEC thermoplastic applicator robot. In its current state, the device has no method for knowing or controlling tension in the thermoplastic. The goal is to develop a design that will allow an operator to input a desired tension between 1 lb and 50 lbs, which will be maintained throughout the thermoplastic application process regardless of orientations or vibrations.

As detailed in the Critical Design Review (CDR), the group's plans for this semester included the construction of both a test apparatus and final design. As soon as the test apparatus was assembled, testing began to develop an optimal controller design for the system. The process began with MATLAB simulations using specifications for the purchased motor. After these model based simulations were proven, physical control was attempted on the test apparatus. Although the tension control system was rough at first, tools such as MATLAB System Identification Toolbox and Zeigler Nichols method of PID controller selection were used to tune the controller. Details about this controller design method are presented later in the report.

Once the group felt comfortable with the control design, manufacturing of the final system as it is to be implemented on the robot became the main priority. Changes to the final design since the CDR included a roller near the application point to prevent the tape from snapping, a fully customizable motor driver, a printed circuit board to handle the electronics, and an additional electrical box designed to handle voltage regulation for the system. The group is currently testing and tuning a final controller that will be interfaced with the robot on Friday, May 3, 2013.

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Introduction:

The purpose of the project outlined in this report is to develop a tension control device for a robot owned by AMRDEC, located on the Redstone Arsenal in Huntsville, AL. The robot is capable of developing various parts by wrapping a thermoplastic material around different molds. Currently, the robot has no method of sensing or controlling tension in the thermoplastic applicator. Corp 2 was approached to develop a system to provide this function.

Although there are several tension control systems commercially available, none of the researched systems adequately satisfied the design requirements. There were three main design constraints that ruled out the commercially available objects. The first was the size limitation. All of the commercial designs were too large and would be unable to fit on the end effector of the thermoplastic robot. The commercial designs also relied upon a known feed rate into the system whereas the thermoplastic robot has a variable feed rate. The last constraint that ruled out the commercially available systems was the requirement to be able to operate at different orientations relative to the ground. Most commercial systems used either a dancer tension control systems that needed to maintain the dancer orientation perpendicular to the ground or a radial sensor which can only operate in one orientation. These systems were ruled out since the control system would be mounted onboard a constantly moving and rotating robot head.

The proposed design for final implementation was outlined previously in the Critical Design Review (CDR). There was concern at the CDR that a sufficient motor and sensor could not be found that would be implemented within the design constraints. These concerns were addressed by conducting further research to find a suitable motor that utilized a gearbox to deliver the additional torque necessary to control the system and by moving from a three-spool tension sensor to a custom tension sensor developed from a load cell. The justification for the aforementioned design choices are outlined further into the report.

Two detailed designs were proposed at the critical design review for the implementation of the tension control device that took place after the holidays. The first was a test apparatus, shown in Figure 1: , which was used to develop a controller design. The apparatus includes two motors: one to simulate the control motor and another to simulate the thermoplastic applicator. The test apparatus contains many of the actual components that were used in the final product.

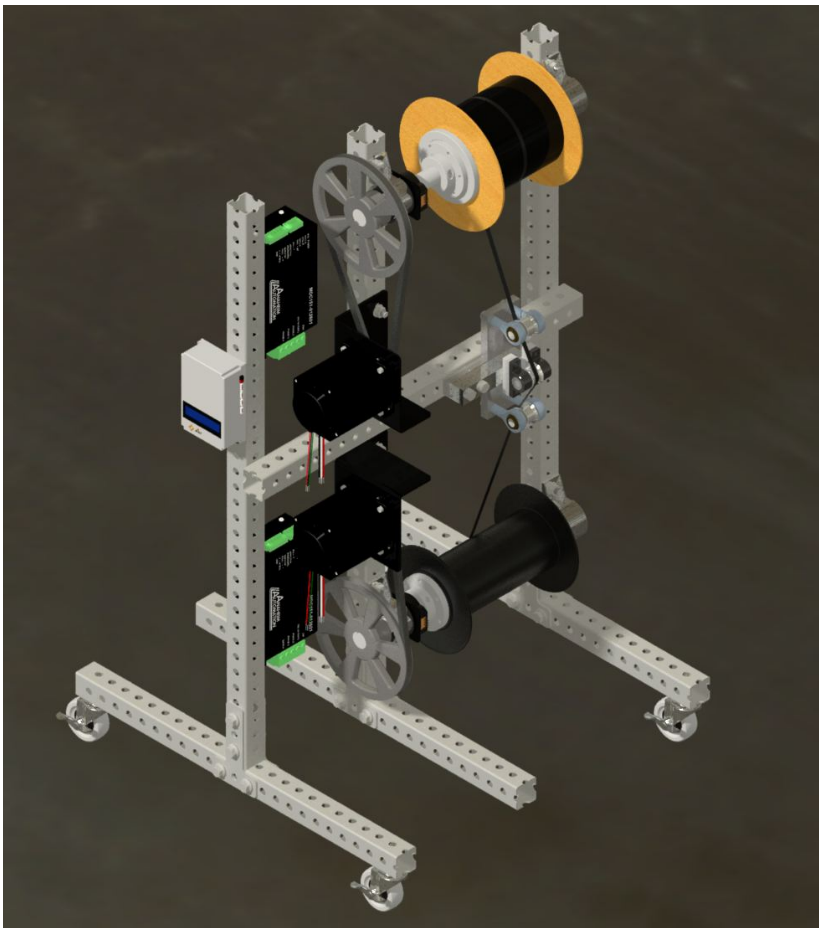


Figure 1: Test Apparatus

The second detailed design proposed during the critical design review was the final product that will be implemented on the actual thermoplastic robot. This design is shown in Figure 2, and is outlined in this report. It was proposed that the final product will only use one motor as opposed to the two motors used in the test apparatus. The second motor in the test apparatus will be packaged along with the system as a spare part for future maintenance if necessary.

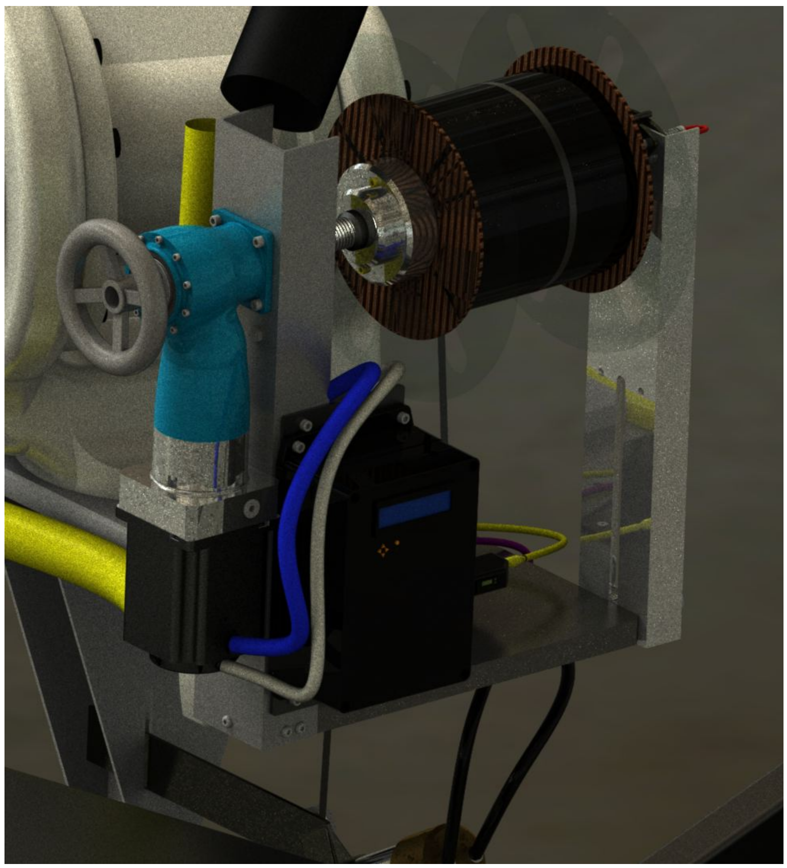


Figure 2: Final Proposed Design

The proposed design for final implementation was outlined previously in the Critical Design Review (CDR). The design was approved with the stipulation that a roller should be added below the mounting plate to keep the tape from snapping at a possible pinch point. It was also agreed that a printed circuit board would be added to handle the electronics of the system. Other updates to the proposed design included a new motor driver, keypad and a simplified tension transducer mount. The final mechanical design, as shown before it is implemented on the robot, is shown in Figure 3.

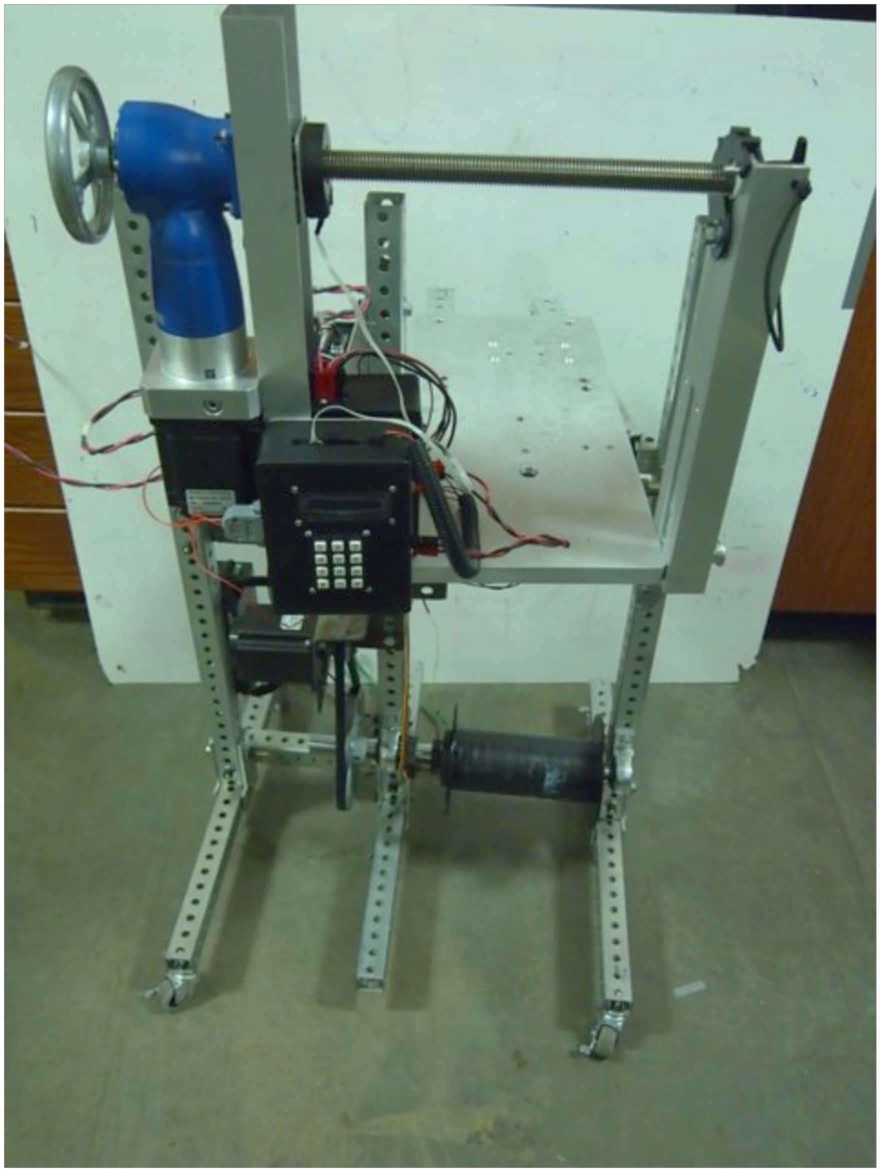


Figure 3: Final Design

Mission Objective:

The overall objective of this project is to design a system to implement with the existing robotic thermoplastic applicator which actuates the feed spool in order to maintain the desired tension of the thermoplastic tape, as determined by the operator, regardless of any vibrations or orientations of the end effector. The proposed deliverables are outlined in the MPCOD below.

1. Manufacture test apparatus
    a. Fabricate remaining parts for test apparatus
        i. Motor mounts
        ii. Tension transducer
    b. Purchase remaining parts for test apparatus
        i. Wiring
        ii. Emergency stop
        iii. Signal conditioner
    c. Interface all components of test apparatus
2. Test System at Auburn University on test apparatus
    a. Testing
        i. Use SYS ID to obtain transfer function and compare to analytical model
        ii. Design system to operate through given failure modes (i.e. tape breaking, power loss)
        iii. Phone conference and review
3. Implement final design
    a. Fabricate remaining parts for final design
        i. Controller support arm
        ii. Mechanical vibration support arm
        iii. Shaft
        iv. Support plate (dependent upon discussion)
    b. Implementation and final demonstration (unless c is required)
        i. Plan day-long implementation and operation
        ii. Interface system with robot and test
    c. If needed, follow up trip for modifications and improvements

Measures of Performance: Aside from completion of the above tasks, performance can be measured by how well the complete subsystems, and therefore the system, meet the requirements, mission objective, and concepts of operations set in the critical design phase.

Interfacing Plan: The tension control system will interface with the robot as detailed in the Critical Design Report.

Delivery Date: All tasks must be completed by the end of the spring semester (April 26, 2013)

Architectural Design:

Although several solutions to the mission objective immediately jumped out, the team followed the engineering design process to decide upon a design. The first thing the group accomplished after defining the problem statement was the development of a functional decomposition, shown below in **Error! Not a valid bookmark self-reference.**. The functional decomposition is composed of the base level functions that the design had to accomplish in order

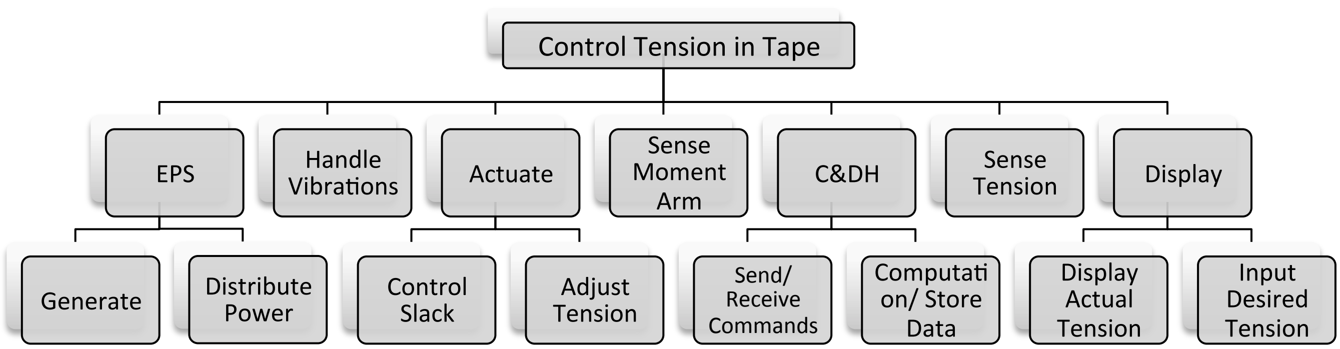


Figure 4: Functional Decomposition

to satisfy the objective.

The group then came up with different methods that would satisfy each of the base level functions. The goal was to develop as many feasible alternatives to each function as possible before deciding upon the best method. This would allow the group to combine the different solutions to each alternatives into distinct designs as well as preventing the group from getting locked into a design early which could lead to missing out on unique designs that otherwise would not have been conceived.

The different feasible design alternatives were then graded on a ten point scale based on how well they satisfied each of the design requirements in the Requirement section featured later in the report. Based on the weighted average from the decision matrix, it was determined that three of the designs were significantly superior. These three designs were analyzed further in depth to choose which would be most suitable for the project.

The group chose to proceed with the design shown in Figure 5. This design includes an electric motor with a gear box, a microcontroller for sending and receiving signals, a three-spool tension sensor, and an optical encoder to measure feed rate.

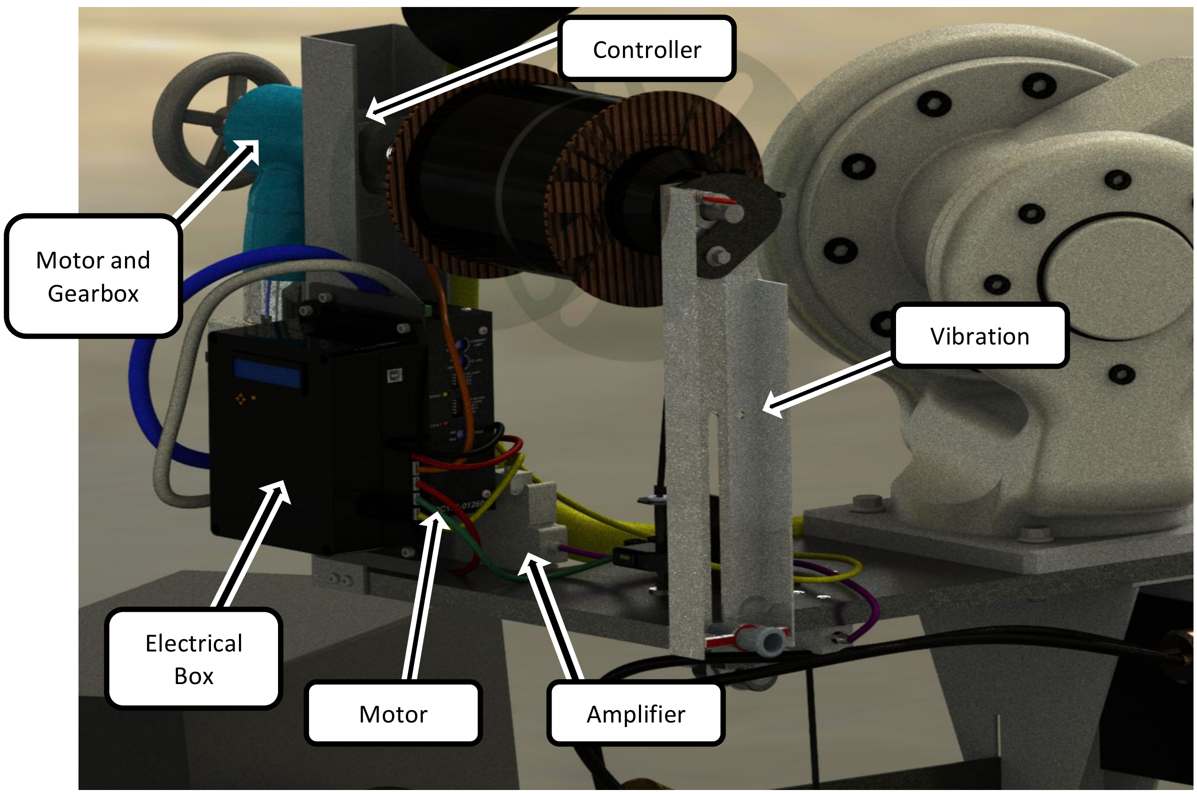


Figure 5: Final Design

The optical encoder will be eliminated when a direct transfer function between voltage and tension is determined using the test apparatus.

The above design was presented in the Preliminary Design Review and has since been modified slightly to improve the design. A breakdown of the components is shown in the product hierarchy in Figure 6 below. Beyond that, each specific component is broken down into its detailed components. A bill of materials has been included in the Project Management section of the report.

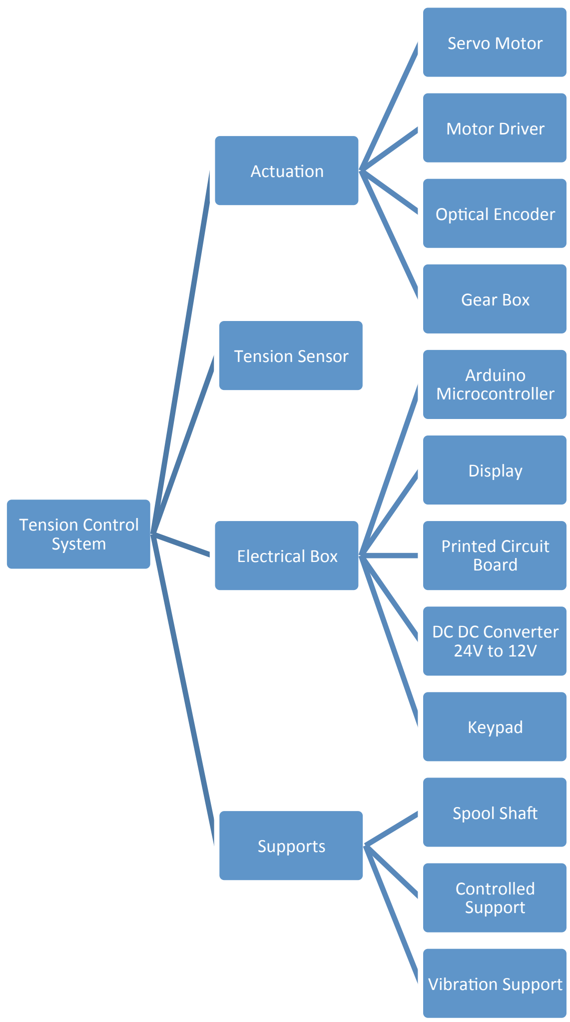


Figure 6: Product Hierarchy

Spool Actuation

It was determined that a servo motor that ran off of 48 VDC of power to supply 30 N-m of torque at a rate of 30 rpm was going to be adequate for the control design. The main difficulty was finding a motor that could deliver the required torque with such a limited power supply. It was decided that a 25:1 gear box would allow the motor to supply the correct amount of torque given the 24-48 VDC power limit.

The chosen motor was purchased from Anaheim Automation and is pictured in Figure 7. The brushless DC servo design of the motor will allow for the control angular velocity. A stepper motor would have been inadequate because the time response was too long to allow for proper motion control. There is very little required maintenance due to the brushless design. There is also no electric arc that can be created as there can be when using brushed motors so it is a safer design.

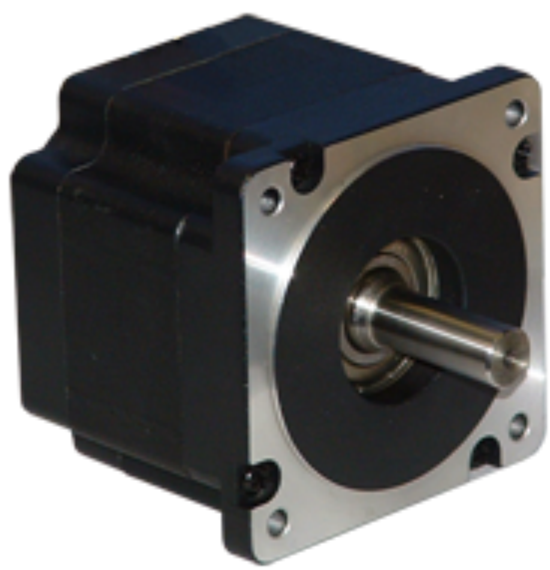


Figure 7: DC Motor

The motor will run off of 48 V DC but will not be able to supply the correct amount of torque without the 25:1 gearbox shown in Figure 8. The gearbox will feature a manual turning wheel so that the user will be able to turn the shaft manually. This 90° gearbox purchased from Wittenstein will connect to the motor and shaft to provide for the needed torque. The 90° gearbox was chosen so that it would fit the system's spatial constraints. The group was concerned about damaging the teeth of the gearbox when driving the motor in the opposite direction of the motion but after consulting a Sales Engineer at Wittenstein, he confirmed that this would not be an issue and that the gearbox would be suitable for this specific application.

Figure 8: Gearbox

The motor will also be connected to a motor driver as shown in Figure 9 and the optical encoder shown in Figure 10, which will be used for motion control. The motor driver was originally purchased from Anaheim Automation to ensure compatibility with the motor which was also purchased there. However, after testing it was shown that the motor driver did not allow for enough customizability, and the switch was made to the Roboteq LBL1350C. The encoder was purchased from US Digital. As shown in the Concept of Operations section of this report, the motor driver will receive a signal from the microcontroller specifying the angular velocity the motor needs to run at and then drive the motor to that particular angular velocity. The motor driver dynamics should be negligible. The optical encoder will measure actual angular velocity of the motor and then send this signal back to the microcontroller to be used in the closed loop cascaded control.

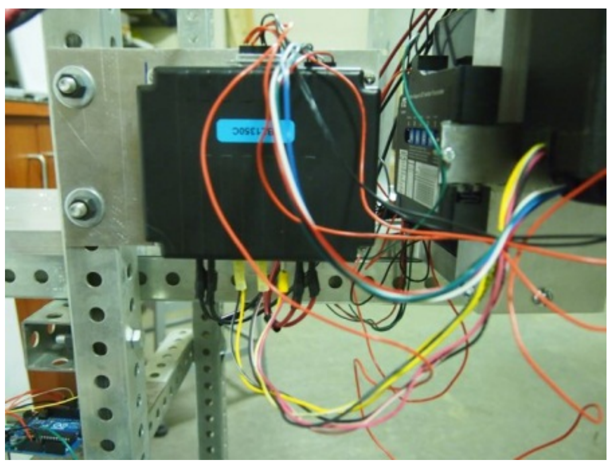


Figure 9: Motor Driver

Figure 10: Optical Encoder

The optical encoder is used to measure the angular velocity of the shaft. It was chosen because at similar price ranges, it offers superior performance to Hall-effect sensors. It operates at 1024 counts per revolution, so it has a high degree of accuracy. It will be connected directly to the spool shaft, as shown in Figure 11.

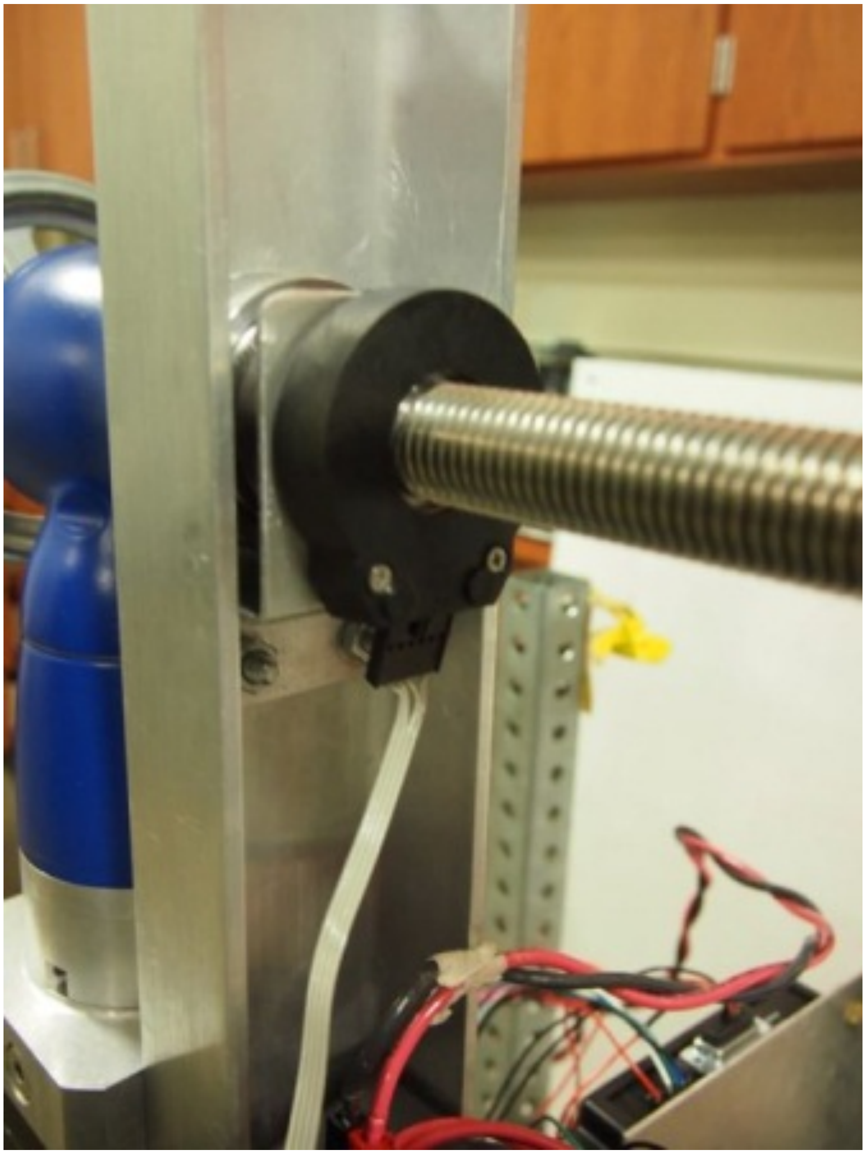


Figure 11: Optical Encoder Mounted on Spool Shaft

In order to ensure that the motor would operate correctly, it was simulated in MATLAB using the Anaheim Automation motor's technical specifications. The goal was to ensure that the motor would have a fast enough response time to control tension within the system. As shown in Figure 12, the motor is capable of tracking a desired tension. The system was given a step input for desired tension. This desired tension is reached in roughly 0.2 seconds. The MATLAB code used to generate the program can be seen in Appendix A.

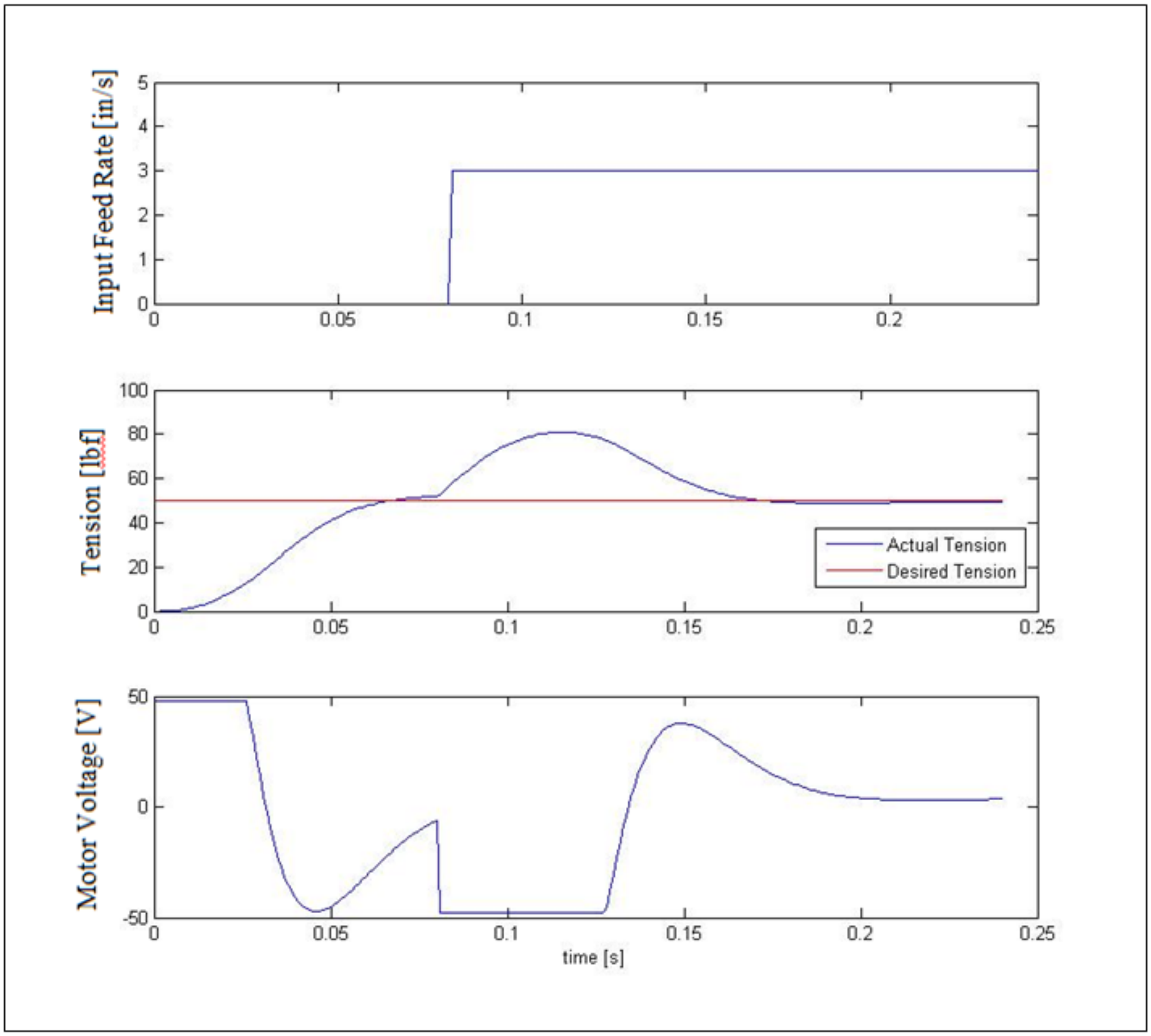


Figure 12: MATLAB Simulation of Motor Step Response

Tension Sensor

The greatest constraint in choosing a sensor for measuring tension in the thermoplastic tape was spatial limitations. A majority of the tension transducers on the market within the desired tension range do not fit these spatial constraints. These pre-assembled sensors are also significantly more expensive. It was decided that a tension transducer should be manufactured specific to the system to specifically address the spatial requirements and tension range. The designed tension transducer uses a load cell with a mounted bearing/roller assembly and can be seen in Figure 13. With the tension applied at a constant angle in a symmetrical fashion, the reaction force acting on the spool can be related directly to the tension in the tape. This force induces a voltage which is then amplified, filtered, and measured by the microcontroller.

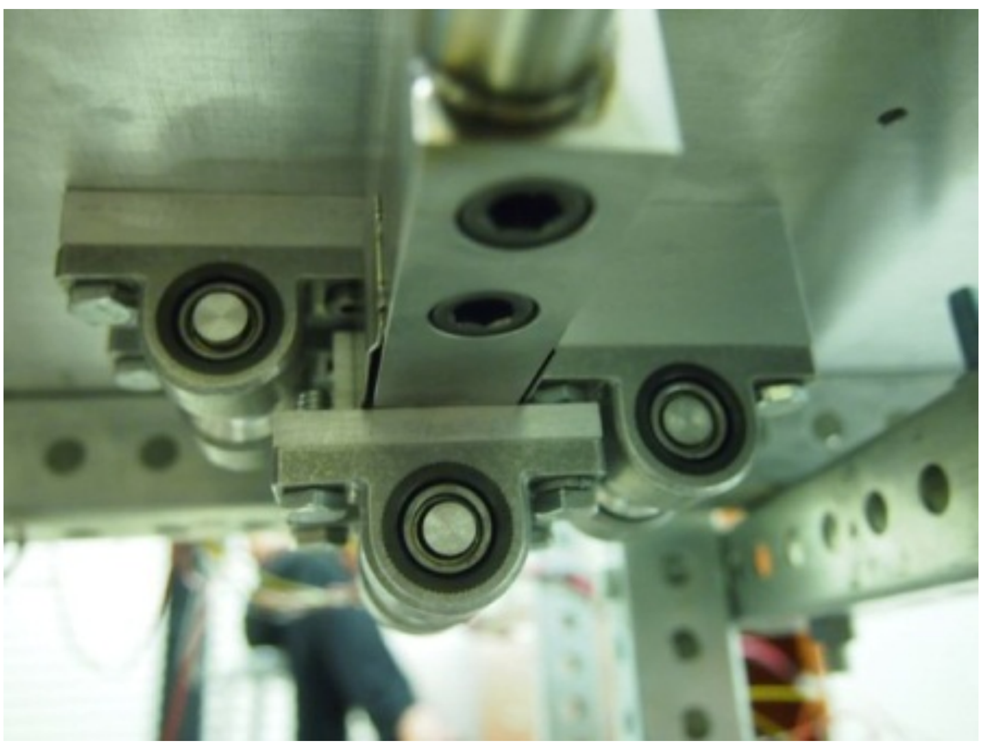


Figure 13: Tension Sensor Design

The cantilever style load cell was chosen because of its low profile, sensitivity, and ease of mounting. An outrigger bearing/roller configuration was designed because the incident angle on the roller must be held constant. This spool, which can be seen in Figure 13, also helps keep the tape in contact with the transducer roller and eliminates any catenary effects of the tape. The angle of the feed side tape is held at a symmetric angle by contact with the pre-existing feed plate. The angle of the tape to the feed plate is kept low to reduce wear on the plate itself.

The tension sensor requires a signal conditioner to amplify the signal to be readable by the microcontroller. The signal conditioner, shown in Figure 14, sends tension measurements directly to the microcontroller through Molex wire housings.

Figure 14: Signal Conditioner

Microcontroller

The chosen microcontroller was the Arduino Mega2560 which is shown in Figure 15. The microcontroller has a high count of analog and digital pins to accommodate for a variety of signals, its own internal voltage regulator for power, and it is simple to program. It was chosen based on having previous experience using this particular microcontroller as well as meeting all the technical specifications to handle a variety of inputs and outputs. More in depth detail how the different signals interact with the microcontroller are shown in both the Concept of Operations and Subsystems Engineering section of the report.

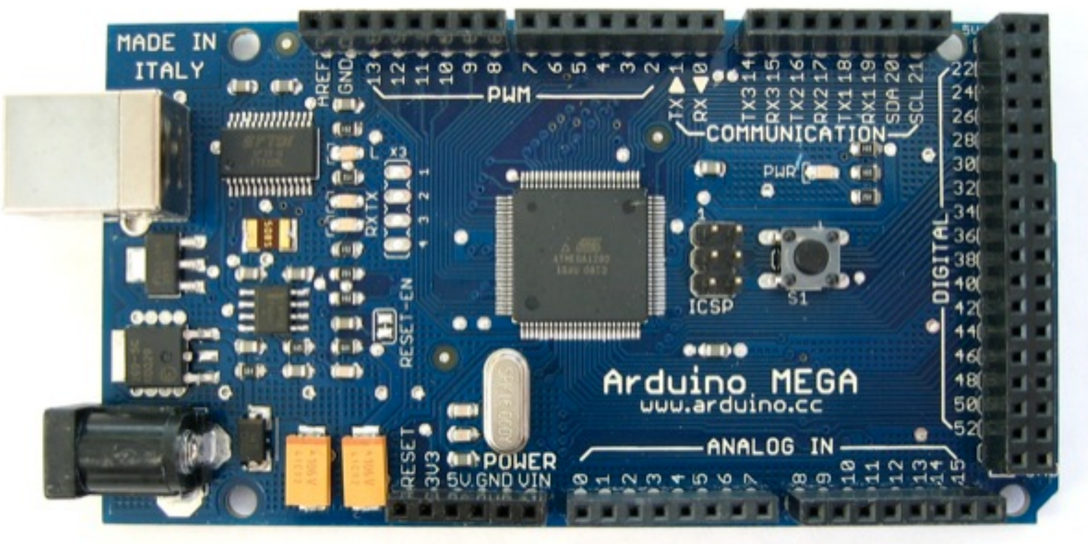


Figure 15: Arduino Mega2560 Microcontroller

Printed Circuit Board

A printed circuit board (PCB) was developed using PCB Artist, a software created by Advanced Circuits. The PCB was designed to house all of the electronics of the system that were done on a bread board for the test apparatus. The microcontroller is mounted beneath the PCB. The signal conditioner and optical encoder connect to the PCB through Molex connectors.

Traces from these connectors are routed to pins on the PCB that are connected to the microcontroller. The microcontroller also delivers signals to the motor driver using serial communication. A switch has also been implemented to shut off the microcontroller so commands can stop being sent to drive the motor in case of emergency.

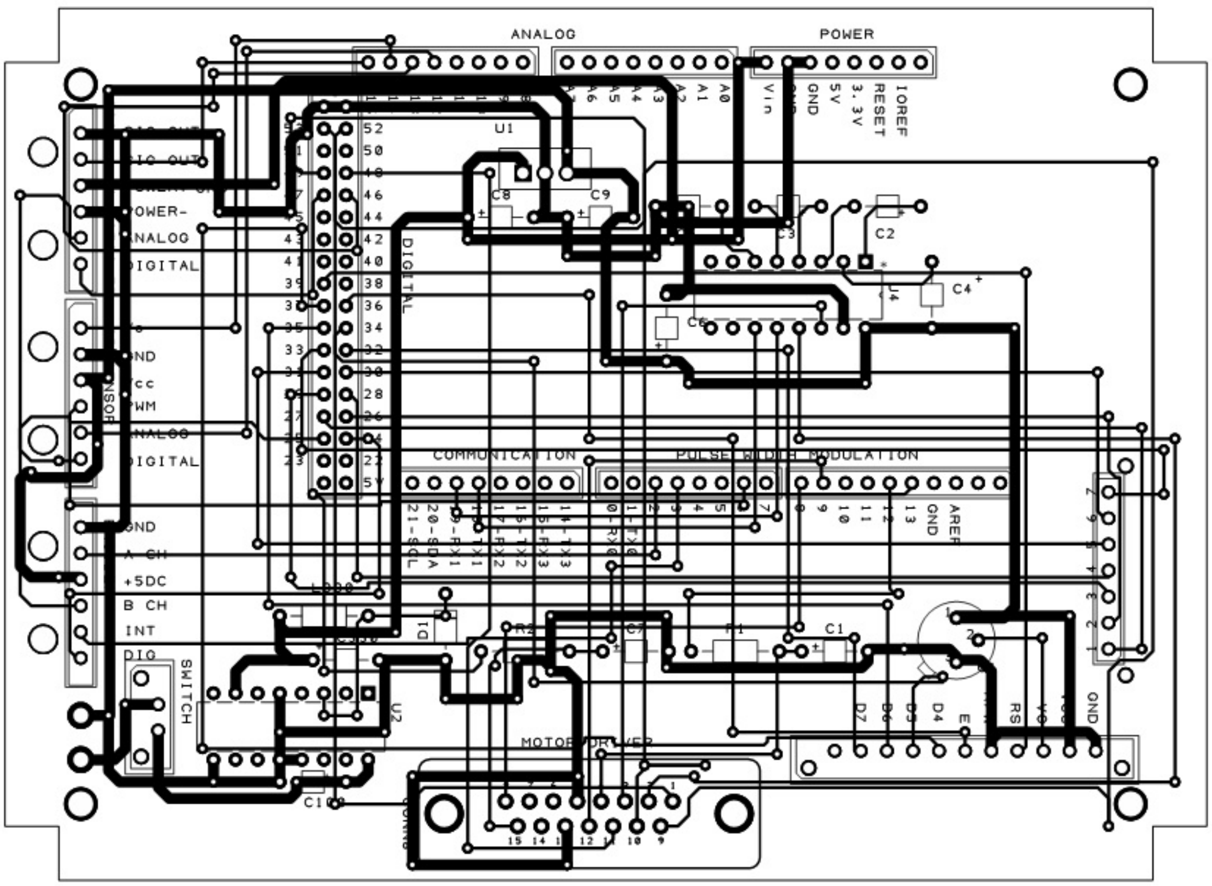


Figure 16: Printed Circuit Board

Controller Support Design

The controlled support design, shown in Figure 17, will be custom manufactured and will be made out of aluminum. Its purpose is to house the electrical box, motor, and gearbox. Fabrication for this support arm will begin at the beginning of next semester.

Figure 17: Controller Support

Mechanical Vibration Support Design

The mechanical vibration support, shown in Figure 18, will also be custom manufactured, and is made mostly out of aluminum. The gate hooks were made from steel and were cut using a plasma cutter. The additional support was included to ensure that the control system will be able to better handle orientations and vibrations introduced during the thermoplastic application process.

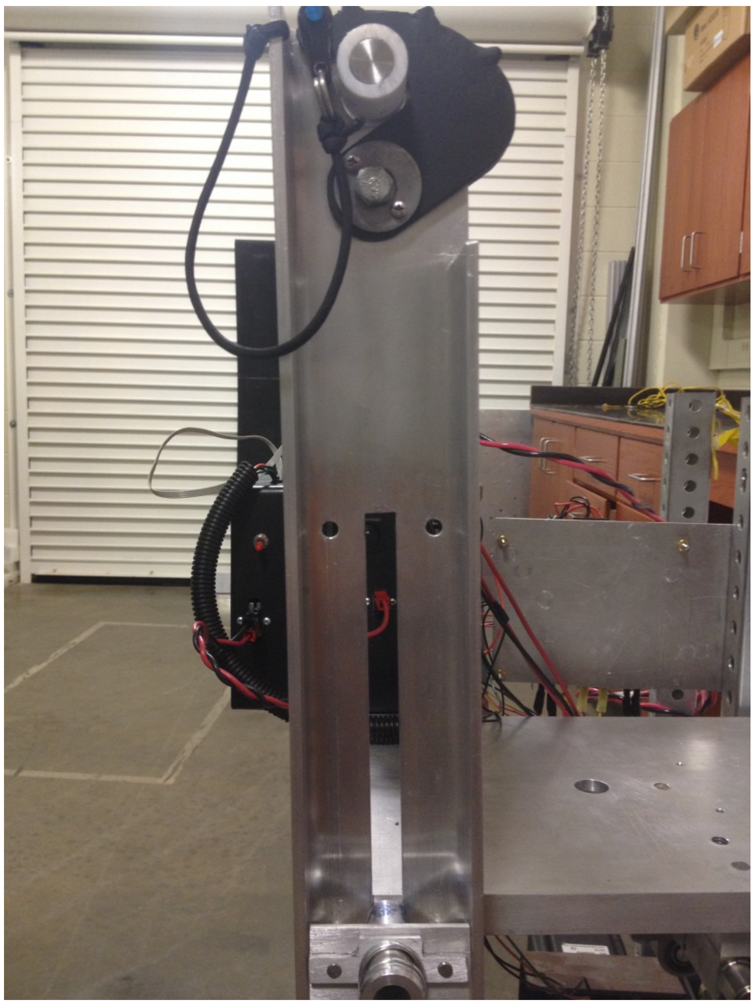


Figure 18: Mechanical Support Arm

The biggest design challenge that came during the design of the support arm was ensuring that it would still allow for easy spool replacement. Currently, the design only has one support so the spool is easy to replace. The mechanical support design operates using spring loaded pins located on the upper and lower part of the support. They can be removed to move the support up and down to allow for spool loading and unloading. After the spool is added, then the arm can be moved back up and locked into place for the application process.

Shaft Design

The shaft design, in Figure, will be redesigned from its current state. The design will be manufactured by the group and will contain the same thread as the current shaft design so spool loading will remain the same. The radius of the shaft will be turned down on both ends so it can be interfaced with the gearbox on one end and the mechanical vibration support on the other.

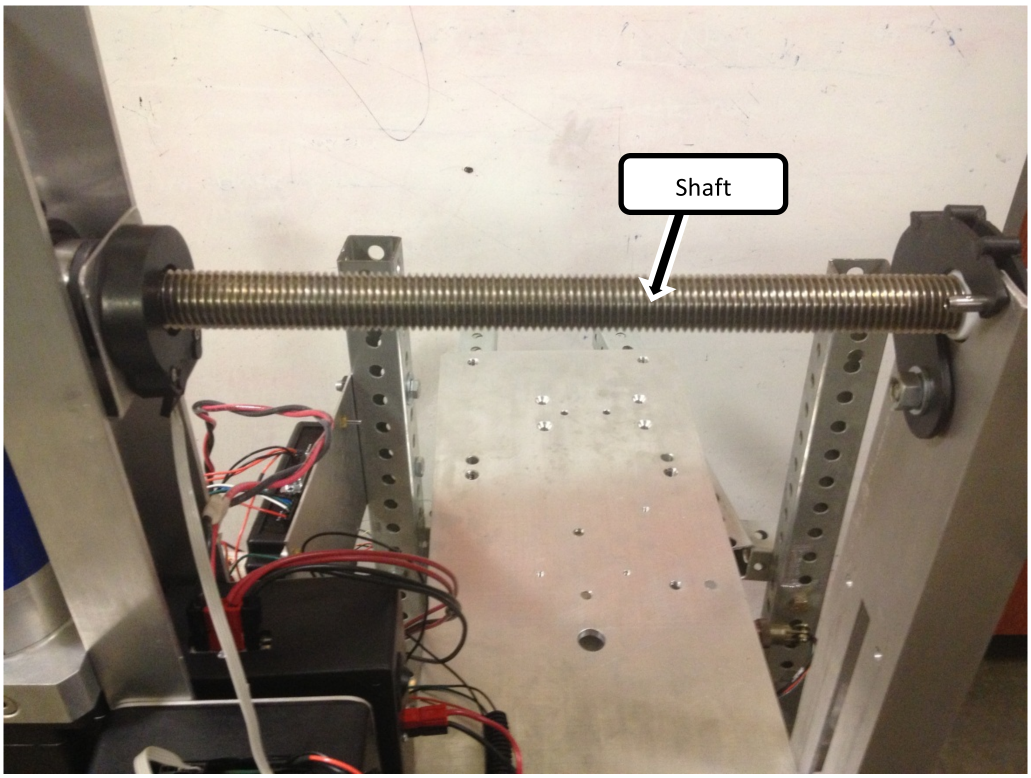


Figure 20: Shaft Design

Electrical Box Design

Some of the largest design changes that have been made since the CDR occurred in the electrical box. The system now consists of two electrical boxes, as shown in Figure 21 one for user interface, and one for voltage regulation. The voltage regulation was originally going to be handled by the printed circuit board, but because of the current flowing through the regulator chips there was a tendency for the chips to overheat. As a safety precaution, regulation for the 48 VDC to 12 VDC step down was moved from the PCB to a separate electrical box. The regulation process is handled by a chip that can handle significantly more current.

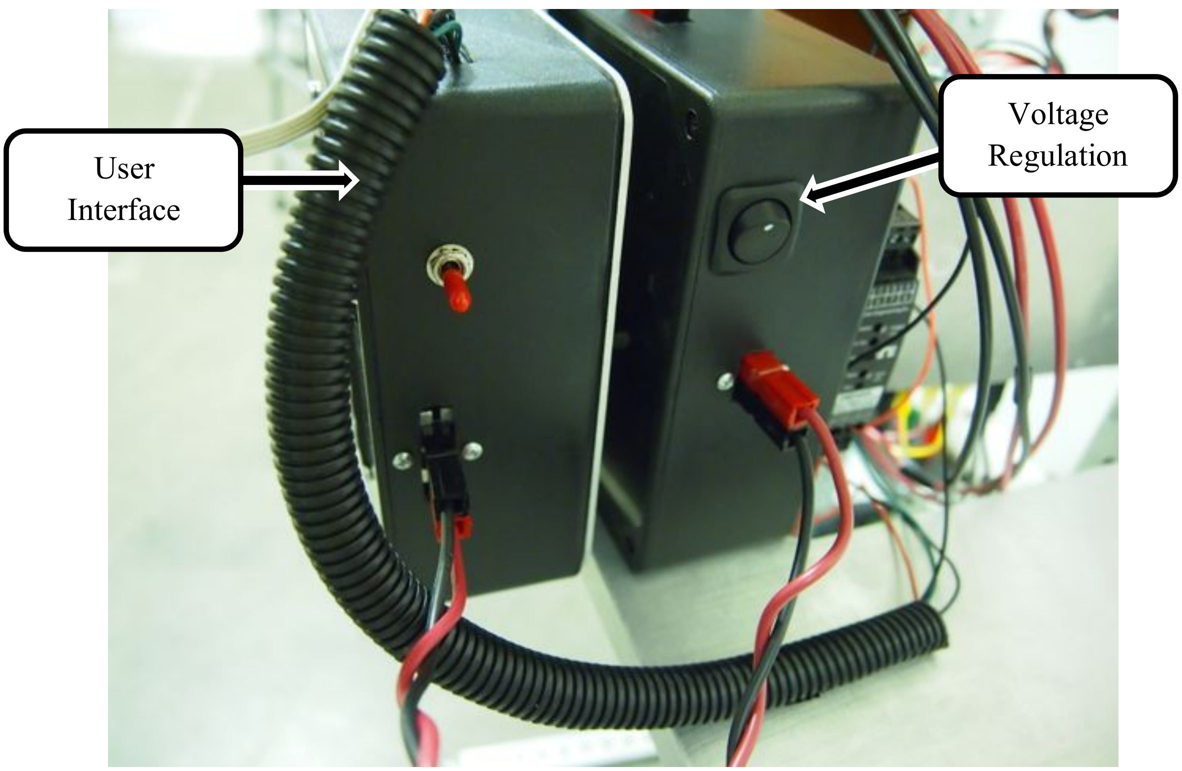


Figure 21: Electrical Box

The user interface electrical box, shown in Figure 22 has changed as well. As shown above, a PCB has been designed to handle the electronics of the system. The user will be able to input a desired tension on a keypad, and see this displayed tension on the LCD Display.

Demonstration of how to use the keypad to set a desired tension will be demonstrated during the final implementation.

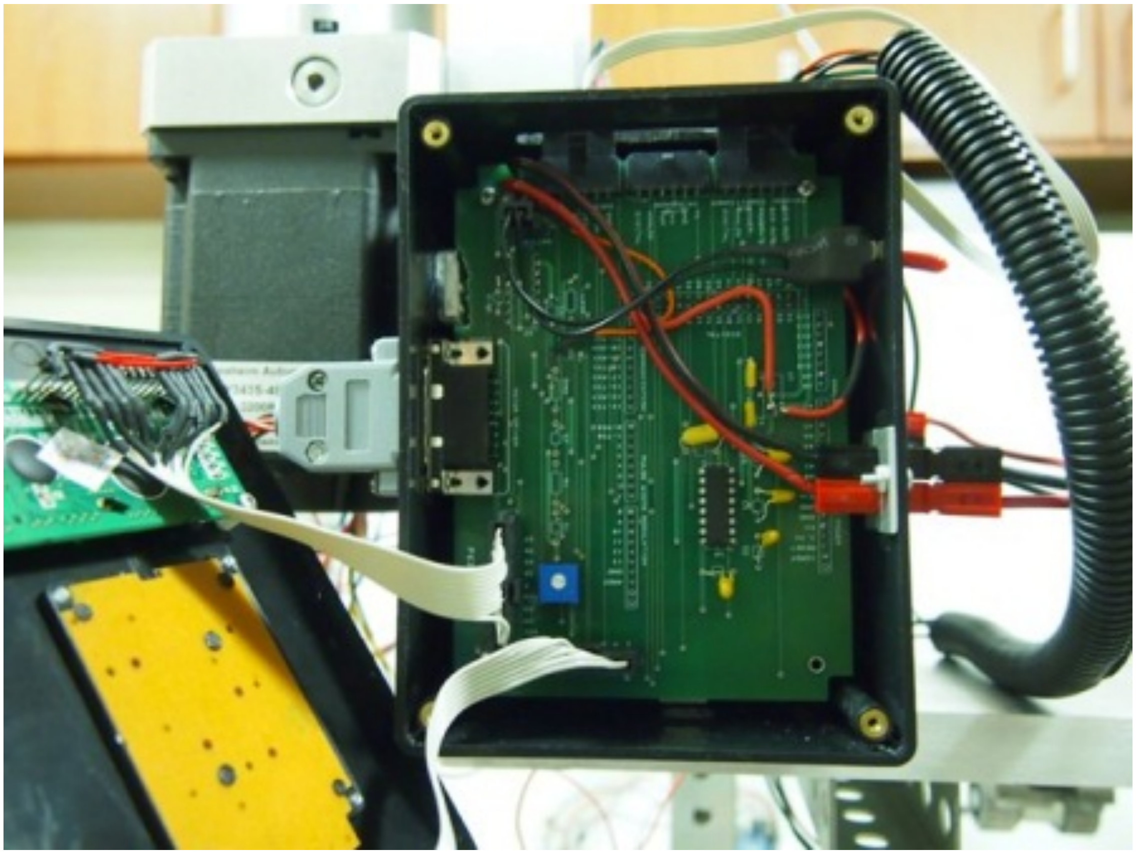


Figure 22: User Interface Box

The user interface box is also used to receive the digital signal that tells the system to control tension. This signal comes from the robot, and was originally sent to a solenoid. The same type of connector on the solenoid has been mounted in the electrical box to send this “sense tension/don’t sense tension” signal to the microcontroller. This 24 VDC signal is sent through a comparator circuit mounted on a prototype board, which sends a 5 VDC signal that the microcontroller can handle.

Power Supply

After talking with Automated Dynamics, it was determined that the tension control system should not tap into the robot's power. Instead, the system runs off of a power supply that runs off of power from a wall outlet. A 48 VDC power supply, shown in Figure 23, was implemented because of the high level tension the system is designed to control. 10 AWG wire will be run down the arm of the robot to the power supply.

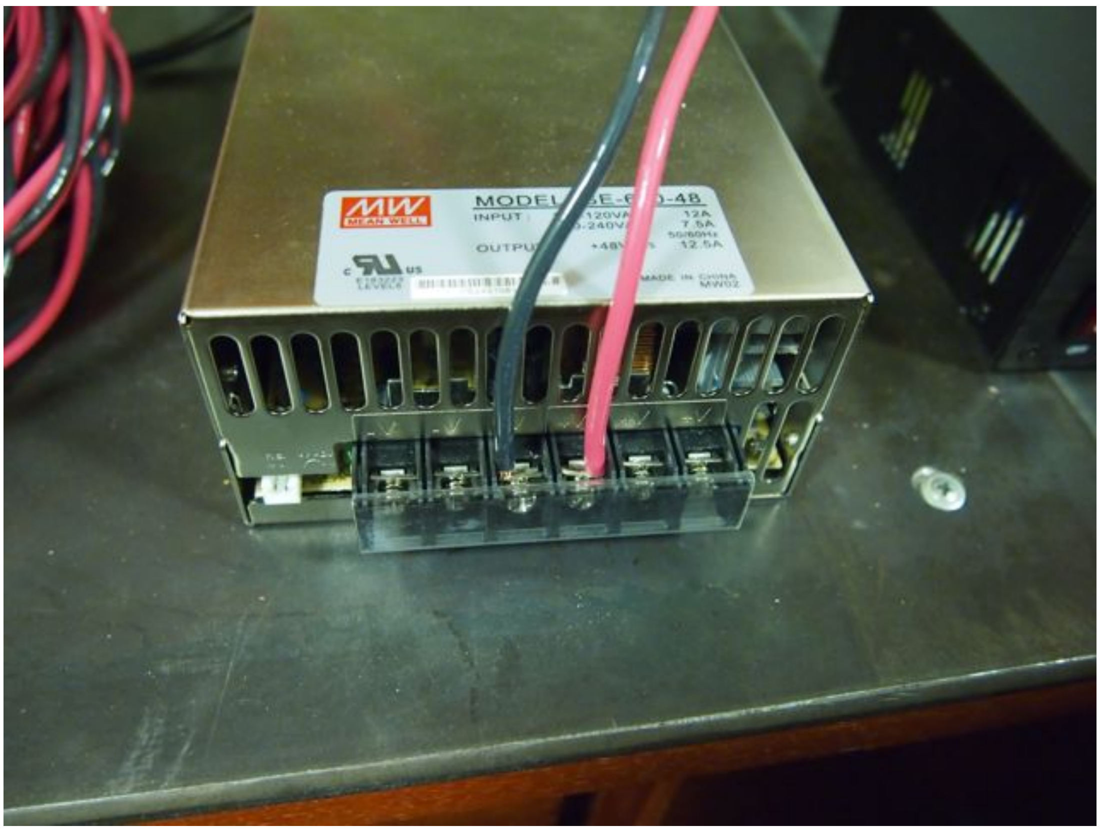


Figure 23: Power Supply

Modeling and Controller Design

The model of the system is outlined in full detail in Appendix C. The governing equation for the tension control design is,

$$T = k * (x_1 - x_2)$$

where T is tension, k is the stiffness of the thermoplastic material, x_1 is the position of the thermoplastic at the applicator, and x_2 is the position of the thermoplastic coming off of the spool. The controller design is based off of this model.

A block diagram for the system, shown below in Figure 24, was developed based on this system model. The control design operates using a cascaded control, however, only the outer loop is actually controlled by the microcontroller. The inner loop dynamics is controlled internally in the motor driver. The method of obtaining the gains is shown in the Validate and Verify section. The controller operates with gain scheduling, which varies the gain based on the desired tension in the system.

A desired tension is input and compared to a measured tension. The controller then takes this error, and converts it into a angular velocity error, which is added to a measured angular velocity, to achieve a desired angular velocity. The controller then drives the motor to the particular angular velocity, which directly relates to a particular tension output. In the system H_1 represents the tension sensor dynamics, and H_2 represents the optical encoder dynamics.

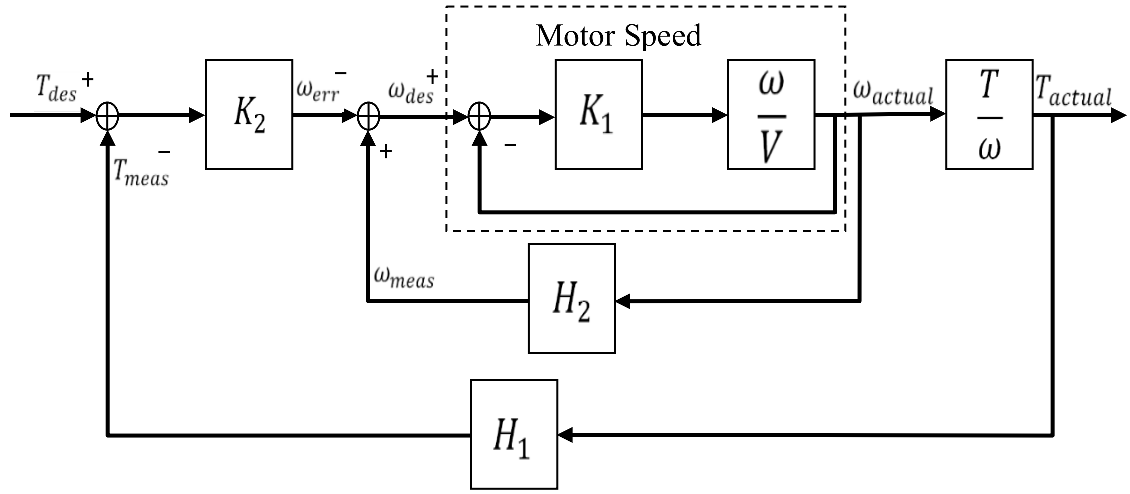


Figure 24: Block Diagram

The controller was simulated using MATLAB software. The motor driver dynamics were assumed to be perfect. Plots for the results, shown in Figure 25, show that the motor tracks tension very well. When position is graphed, there is a difference between the spool position and input position. This explains how tension is generated in the system. The difference in position when multiplied by the stiffness constant will be equal to the tension in the thermoplastic. The next two graphs show that angular velocity and tension are controlled.

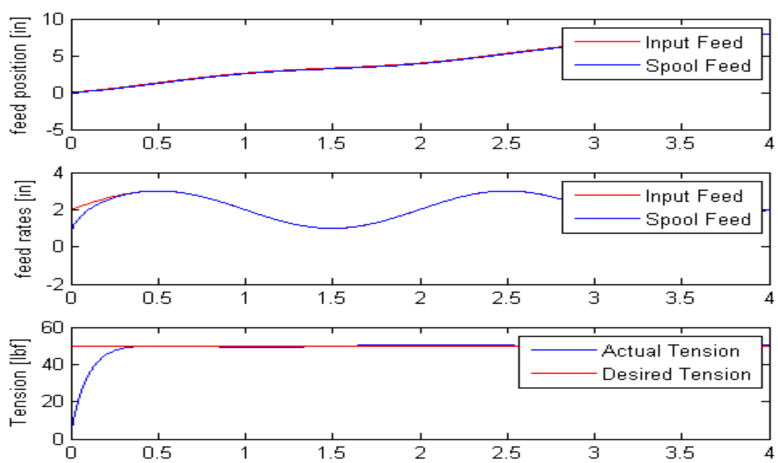


Figure 25: Controller Simulation

Requirements:

- **System Level:**
  - Maintain desired tension between 1 and 50 lbs.
  - Maintain safety throughout operation of the control system
  - Easy to maintain system
  - Cost less than $5,000 (This was a team generated goal)
  - Be reliable (This will be worked out in the test apparatus)
- **Tension Sensor**
  - Sense tension between 1 and 50+ lbs.
  - Allow for back and forth movement of spool feed
- **Actuator :**
  - Supply 30 N-m of torque to maintain tension of 50 lbs.
  - Run off of 24-48 V of power
  - Have fast dynamics so controller does not lag behind
- **Control Design**
  - Be able to maintain slack introduced during application process
  - Have a cutoff switch for when applicator is not feeding thermoplastic
- **Mechanical Supports**
  - Support actuator, electrical box, and shaft with spool in dealing with vibrations
  - Allow for quick and easy spool replacement
- **Electrical Box**
  - House microcontroller, voltage regulators, and LCD display
  - Display the measured tension while allowing for the setting of desired tension

Concept of Operations:

The tension control design operates largely on signals between all of the sensors and controllers. 48 VDC power is drawn and divided into 12 VDC and 24 VDC. The IR sensor, optical encoder, and microcontroller will operate off of 12 VDC, while the load cell operates off of 24 VDC. The motor draws from the original 48 VDC. The Arduino Mega2560 microcontroller receives signals from the IR sensor, optical encoder, and amplified signals from the load cell. Based on these signals, and the input tension, it supplies a signal to the motor controller, directing it to a desired angular velocity for the motor. The motor controller then drives the motor at that desired angular velocity to achieve the desired tension. The process iterates constantly as tension is measured, along with radius and angular velocity, and these signals are sent back to the microcontroller. The concept of operation is shown below in Figure 26.

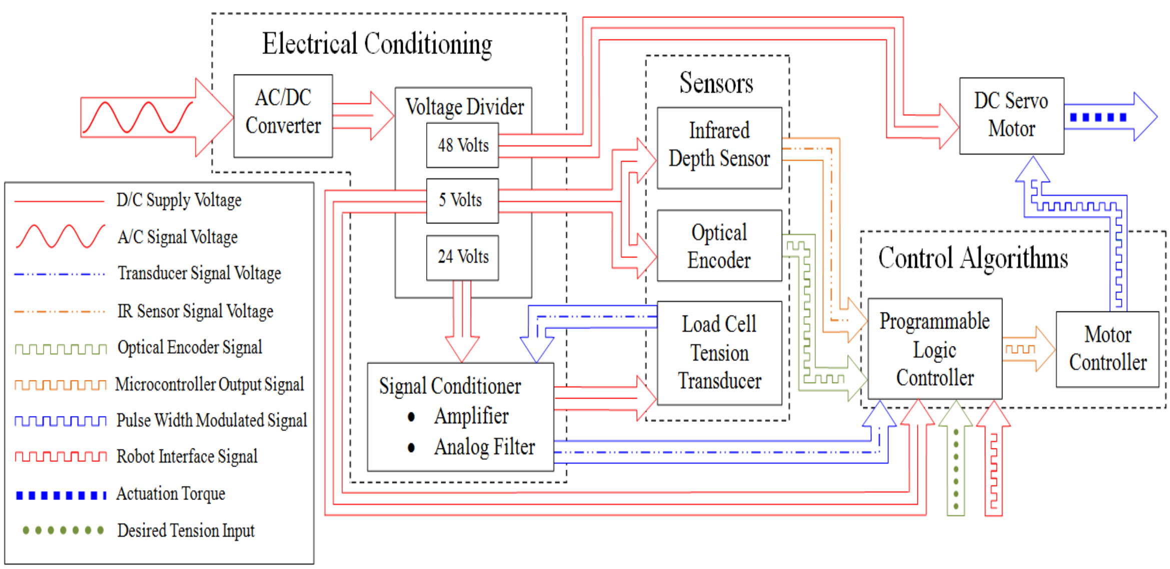


Figure 26: Concepts of Operation

To operate the tension control system safely, the thermoplastic robot must be turned on first, followed by the tension control system. The tension control system will wait for the signal from the robot to indicate that the robot is running before engaging. Built-in safety measures are programmed into the controller such that if a command is sent to control tension and one revolution of the shaft turns without an increase, the motor will disengage until the system is power reset. Power resetting occurs by unplugging the tension control system; waiting ten seconds and then plugging it back in. A power reset may also be used in emergency situations to stop the system.

Validate and Verify:

The system controller was developed by first obtaining an experimental transfer function with MATLAB. The motor, motor driver, tension transducer and microcontroller were integrated and communicating to a test computer via RS232 serial port. Constant value test commands were sent to the motor driver, which controlled the motor. Tension values from the transducer were then sent to MATLAB. The test commands were gradually incremented in values of 10 (arbitrary percentages of the maximum torque that the motor driver could push the motor) and tension values were continued to be collected. Once the full range of motor commands were sent to the driver and tension data collected, the data was run through the SYSID function in MATLAB, which returned the experimental transfer function. This transfer function was then used to plot a root locus shown in Figure 27. Gains from the root locus were then used to develop a controller for the experimental transfer function but Corp 2 was unable to successfully control the actual system with any combination of gains from the root locus.

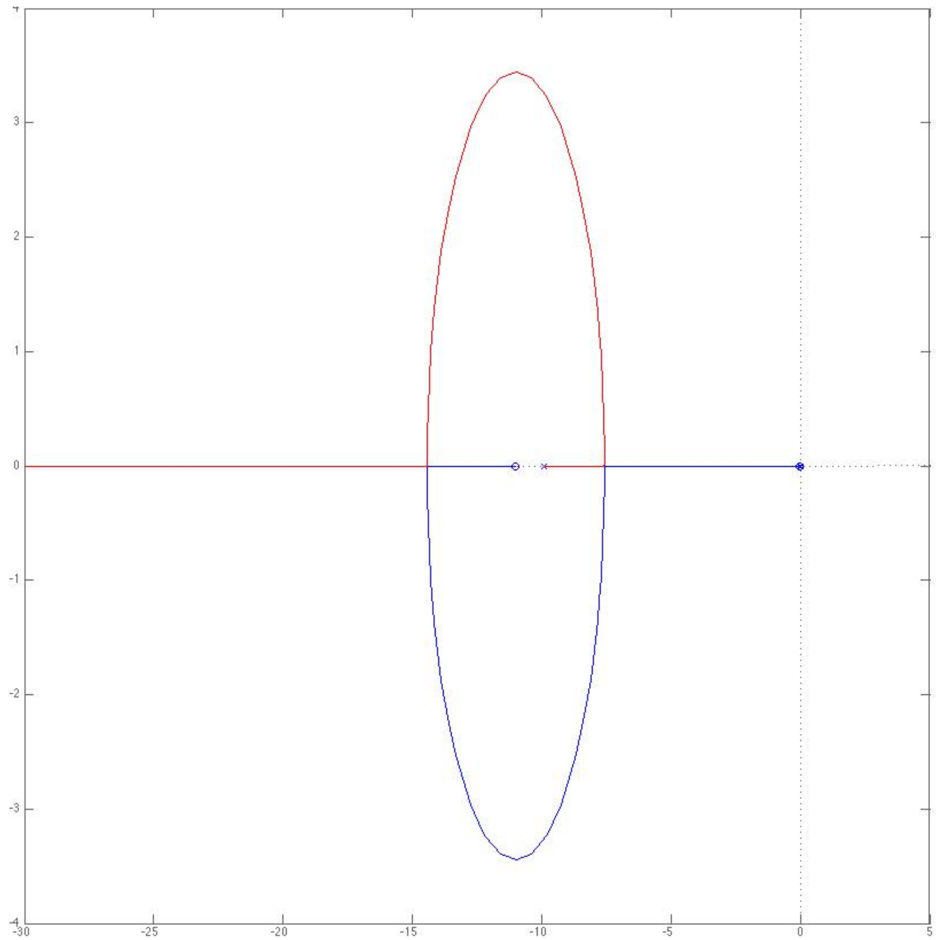


Figure 27: SYSID Root Locus

After developing a controller through root locus and SYSID, CORP 2 turned to the Ziegler-Nichols method of tuning a controller to try to improve the accuracy of the controller. The method involves systematically changing the gains with different types of controllers (P, PI, PID) until the system oscillates with constant amplitude and then repeating the method until a suitable range of gains is obtained. Figure 28 shows a sample closed loop step response in the process of selecting an appropriate controller gain.

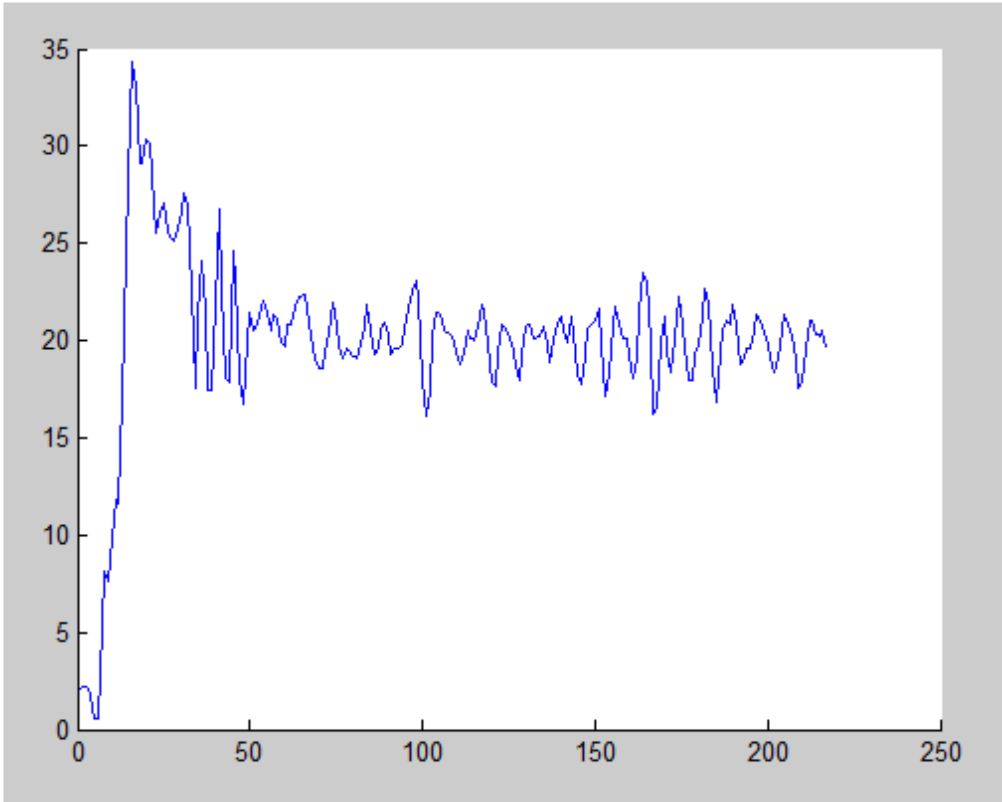


Figure 28: Step Response with Bottom Spool Running

From testing the group has proven that the system can satisfy all of the system level requirements. The desired 50 pounds of tension can be reached without overheating the motor. This goal of 50 pounds can be reached easily with the 25:1 gear reduction of the gearbox as opposed to the 7:1 gear reduction in the pulley system of the test apparatus. Safety precautions have also proven successful during testing, as the tape has snapped on several occasions, causing the motor to free spin, rather than continue to try to control tension.

The most important subsystem level design requirement involved accuracy of the tension control system. The group set the goal of having a system that is accurate to 1 pound of tolerance. Testing has shown that the system is easily capable of these accuracy requirements when the bottom motor is not running, but is less accurate when the bottom motor is running. When the bottom motor is running, the system has been shown to be accurate to around 3 pounds. Several steps are being taken to address this lack of accuracy in the system. The group is currently testing the addition of filters to the control design. Although filtering the signal would cause a slower response time, it has been shown to make the system more accurate. It is also possible that when the bottom motor is running, the top motor is actually fighting the velocity of the bottom motor. This event will not be possible when the system is implemented on the final design.

Interfaces and ICD:

Overall, the tension control design is one big subsystem to the thermoplastic application robot. The controls for the tension control cannot interface directly with the robot. 48 VDC of power will be drawn from the robot, and that will be the systems only electrical interface. The tension control subsystem does, however, interface mechanically with the robot extensively. All of the supports for the current spool will be redesigned to incorporate the electrical components and motor of the tension control design. The load sell will also interface with the thermoplastic under the plate in order to measure tension.

The user will interface with the tension control system through the LCD display. Using the display, the user can input a desired tension in lbs. As the robot operates, actual tension can also be read through the LCD display.

Mission Environment:

The major environmental concern that considered during the design of the control system was the different orientations of the end effector of the robot. This affected the selection of many different components within the system. Many tension sensors are sensitive to gravity such as dancer rolls and were thus eliminated from consideration. A second mechanical support for the spool was also added to ensure the control design could deal with sudden movements, orientations, and vibrations.

The temperature of the applicator also had to be taken into consideration. Originally, the design had an optical encoder near the applicator to measure the feed rate. However, because temperatures are around 800°C where thermoplastic is applied, an optical encoder cannot be placed there to determine a feed rate. Using the previously described test apparatus plan to find a direct transfer function should eliminate this problem.

It was also brought to our attention that carbon fiber pieces in the air had potential to short circuit a motor. This was taken into consideration during the search for an adequate motor, and the brushless design chosen should not encounter this problem.

Technical Resource Budget Tracking:

Originally it was planned to not use anything higher than 24 VDC. The problem that occurred was a motor that operated off of 24 VDC could not supply a high enough torque to drive the correct amount of tension. After talking to Lance Hall, it was determined that the motor could be supplied with 48 VDC, and a suitable motor was found.

Mass was the main requirement that was tracked and the breakdown of each component is shown below in

Table 1: System Mass Breakdown. The values in red were estimated weights, and the total mass barely exceeded the maximum limit of 20 pounds. The infrared depth sensor was not used in the final design, so taking out that estimated weight would bring the total to 19.818 lbs.

Table 1: System Mass Breakdown

Item	Weight (lbs.)
Motor	5.73
Gearbox	6
Motor Driver	1
Optical Encoder	0.25
Tension Sensor	2
Tension Sensor Supports	0.5
Infrared Depth Sensor	0.25
Electrical Box	1
Display	0.25
Arduino	0.25
DC to DC Converter	0.419
DC to DC Converter	0.419
Vibration Support	2
Total	20.068

After ordering the parts and assembling, the final product was weighed at 30 lbs. Although this weight comes in overweight, the original goal did not account for the base plate, controller support, and shaft that already exist on the current design without the control system. Overall, the added weight of the tension control system is around the planned goal of 20 lbs.

Risk Management:

The main risk identified at the Preliminary Design Review was the potential to not meet weight or special requirements. As demonstrated by 3D modeling, special requirements were met in the original design and were confirmed by taking a trip to Huntsville to compare final measurements. The weight limit of 20 lbs. was also reached. The budget for the project was set by the team as $5,000, and due to unexpected costs, that requirement was not met. The gearbox alone was $4055.80 and there were also several other items that were purchased and were not accounted for in the original design. The total cost of our product was $10,688.463. However, since there was no finite budget that needed to be kept, the costs were taken into consideration and approved by the group's sponsor but were not used as an element of risk.

Other risks being dealt with in the project involve the actual control design. At the moment, the control design has been simulated using MATLAB and has been physically tested. This was a major reason for the construction of the test apparatus. The apparatus was used to back out a transfer function for the block diagram, and also to test the final control design. A trip to Huntsville has already been made recently to look into any issues that might arise with the control design. Once the group is confident the system will work by the end of this week, the design can be implemented to the robot in Huntsville.

Configuration Management and Documentation:

Our team has developed a system of Configuration Management and Documentation which includes the use of a shared Dropbox account amongst the team members in addition to a physical composition notebook which contains a daily log of our activity. The Dropbox folder has many advantages over using a university computer network or equivalent file management architecture. One such advantage is the readily available and stable cross-platform smartphone applications that can be downloaded to each member's phone (five iPhones and two Android devices). The files uploaded to Dropbox are updated in real time and pushed to each person's individual account. The team has found this advantageous because we can simply take pictures of the designs or brainstorming activity that we collectively think of and upload them to the shared folder straight from our phones. Another advantage is that the notes, design sketches, data tables, CAD models and MATLAB test code are available to access from any web enabled device.

The composition engineering notebook that is kept up-to-date by the team's assigned scribe (Kellie Coker) is a log of the team's collective achievements. It consists of dated entries cataloging the members in attendance as well as design drawings, a summary of group activity, notes, unanswered questions, and any other relevant design or project related material. The notebook provides the team with a means for recording progress and a central reference point for what has already been attempted or what remains to be accomplished. This differs from the Dropbox account because the Dropbox account only maintains the latest version of whichever document is uploaded to it. The project notebook contains different, dated versions of the design process which is useful because the design process is inherently cyclical.

Subsystems Design Engineering:

There are too many prints to present in the body of the report so all the prints are contained in a separate binder.

Project Management:

The project management structure, shown in Figure 29, shows how tasks were assigned based on given specialties of each of the group members. Although each member had an area they were assigned to, collaboration was always necessary to ensure that the final design system would work as a whole. Regular group meetings allowed for individual work to be accomplished while providing accessibility between group members. Biweekly meetings with the group Technical Advisor, Dr. Beale, also helped the group stay on task and get some of the more complicated questions answered.

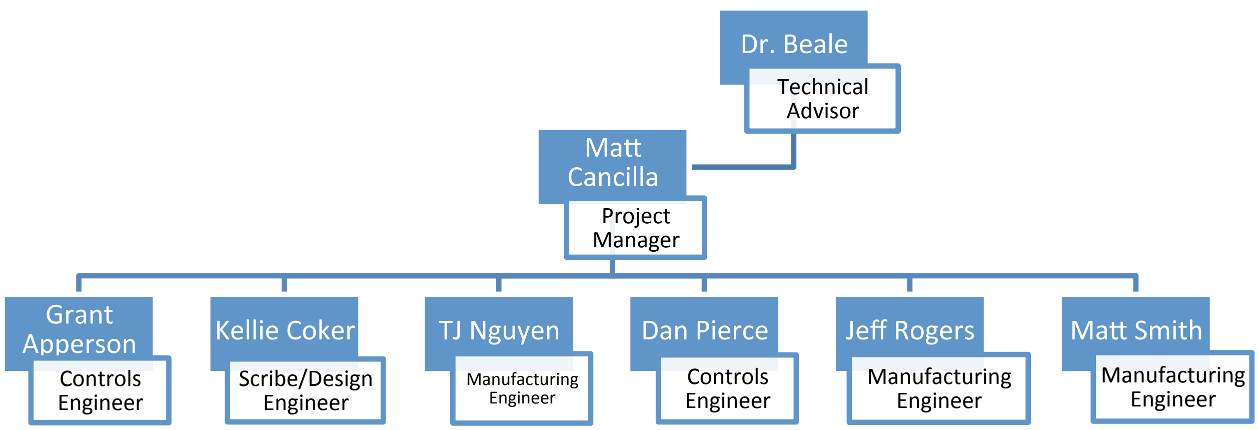


Figure 29: Project Management Structure

The bill of materials, shown in Appendix F, has been broken up into items purchased specifically for the test apparatus, items used specifically for the final design, and items used for both. Most of the items used for the final design will come directly from the test apparatus. The extra motor in the test apparatus will serve as a backup motor for the final system.

Conclusion:

Although more changes have been made to our final design this semester than was desired, our group has satisfied the requirements we set out to accomplish that the beginning of last semester. The only requirement the group failed to meet was with the budget, which was a goal set by the students and not the sponsor. A number of unforeseen costs came into play such as a replacement motor driver, power supplies, the addition of a new base plate, and a gearbox that was more expensive than the group originally planned for. However, we feel that all of these extra costs were necessary to deliver a tension control system that met the performance requirements set by the sponsor.

There are still a few days until the final design is to be interfaced with the robot. However, all of our testing to this point has shown that we are capable of implementing a control design that will satisfy the requirements of the sponsor. Based on the latest trip to Huntsville, slight modifications to the final design have been made as well to ensure that the system will be physically capable of fitting onto the robot. As we finalize these last modifications to the system, we anticipate a smooth implementation process.

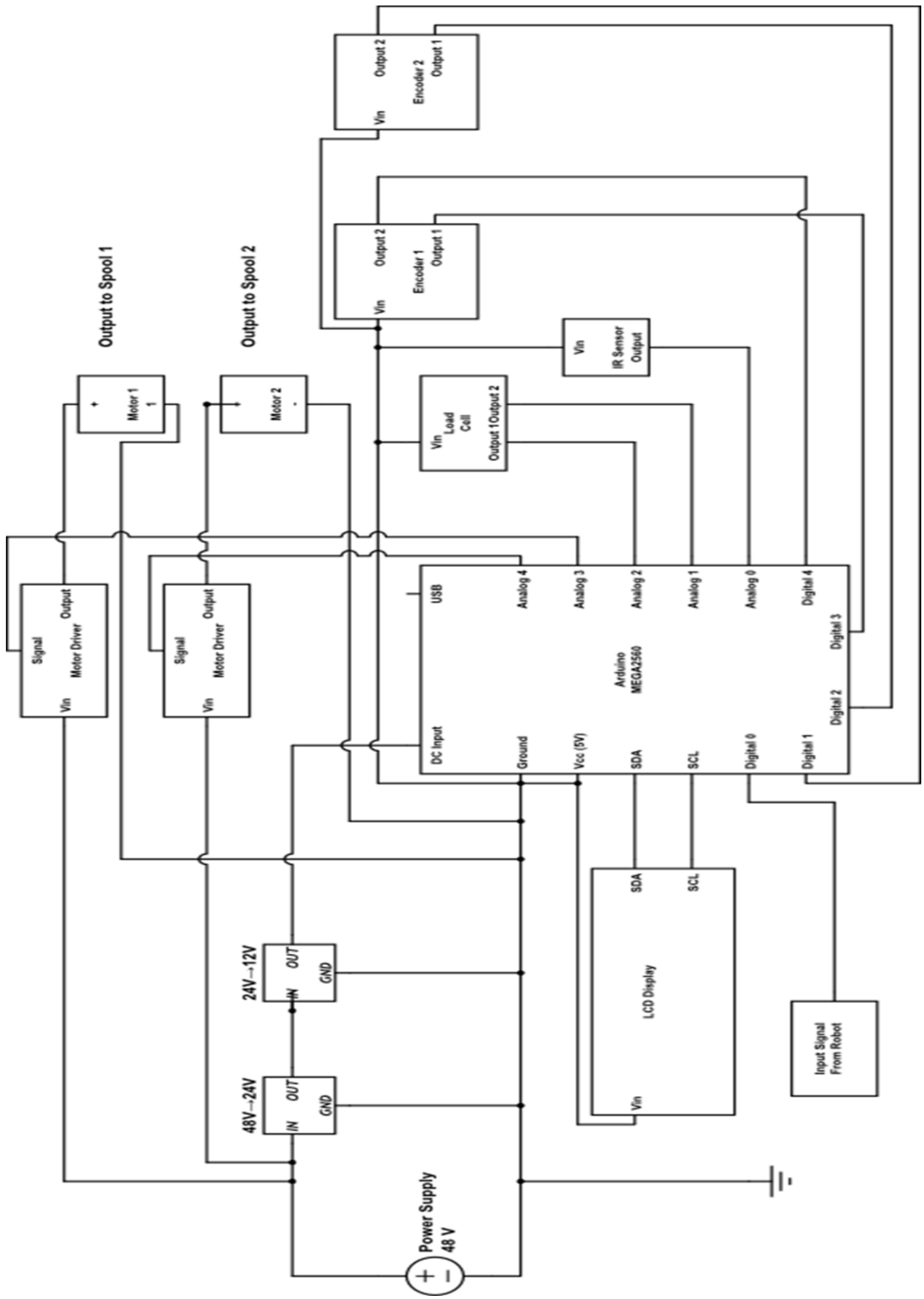
Appendix A: Motor Simulation

```
% Model with Speed Motor Controller
% Assuming perfect motor controller and neglecting system dynamics

clear
clear plots
clc
dt=.001;
tfinal=.24;
time=0:dt:tfinal;
k_stiff=500; % lbf/in

%Motor Constants
L=.00048; % Motor Inductance [H]
R=.2; % Motor Resistance [ohms]
nG=25; % Gearing Ratio [25:1]
KT=1.125*nG; % Motor Torque Constant w/ gearing ratio factor in (18 [oz-in/A]
= 1.125 [in-lb/A] )
KB=.129*nG; % Back EMF Constant w/ gearing ratio factor  (13.5[V/kRPM] = .129
[V-s/rad] )

V_max=48; % Max Voltage [V]

J_motor=0.5468; % Motor Rotor Intertia [lbm-in^2]
J_gearbox=50; % Estimated
J_spool=250;
J_tot=J_spool+J_gearbox+J_motor;

b=20; % Bearing Damping Coefficient [lbf-s/rad]
r=4; % Radius Of Spool [in]

k_p=4; % Proportional Gain
k_d=.1; % Derivative Gain
k_i=4; % Integral Gain

% k_p=4; % Proportional Gain
% k_d=.1; % Derivative Gain
% k_i=4; % Integral Gain

%x_feed_rate=4+sin(2*pi*time); % [in/s]
x_feed_rate(1:81)=0;
x_feed_rate(82:length(time))=3;

Tension_des(1:length(time))=50;% Desired Tension [lbf]
%Tension_des=15+7*sin((pi/2)*time);  % Harmonic Desired Tension

theta(1)=0; % Initial Position of Spool [rad]
x_feed(1)=0; % Initial Feed Position [in]
I(1)=0; % Initial Motor Current [A]
w(1)=0; % Initial Spool Velocity [rad/s]
dT_err(1)=0;
int_err(1)=0;
```

```
for i=1:(length(time)-1)
    x_spool(i)=theta(i)*r;

    Tension(i)=k_stiff*(x_feed(i)-x_spool(i));
    T_err(i)=Tension_des(i)-Tension(i);

    if i>1
        dT_err(i)=(T_err(i)-T_err(i-1))/dt;
    end

    V(i)=k_p*T_err(i)+k_d*dT_err(i)+k_i*int_err(i); % the amount angular
velocity needs to change
    if V(i)>V_max;
        V(i)=V_max;
    else if V(i)<-V_max
            V(i)=-V_max;
        end
    end
    %%%%%%%%%%%%%%%%%%%%%%% Motor Driver %%%%%%%%%%%%%%%%%%%%%%%%%
    % From TF
%     ddw(i)=(V(i)*KT-(b*L+J_tot*R)*dw(i)-(b*R+KT*KB)*w(i))/(J_tot*L);
%     dw(i+1)=dw(i)+ddw(i)*dt;
%     w(i+1)=w(i)+dw(i)*dt;
    % From equations
    dI(i)=(V(i)-KB*w(i)-R*I(i))/L;
    I(i+1)=I(i)+dI(i)*dt;
    dw(i)=(-KT*I(i)+Tension(i)*r-b*w(i))/J_tot;
    w(i+1)=w(i)+dw(i)*dt;
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    int_err(i+1)=int_err(i)+T_err(i)*dt;

    theta(i+1)=theta(i)+(w(i+1)+w(i))*(dt/2);
    x_feed(i+1)=x_feed(i)+(x_feed_rate(i+1)+x_feed_rate(i))*(dt/2);
end

x_spool(i+1)=theta(i+1)*r;
Tension(i+1)=k_stiff*(x_feed(i+1)-x_spool(i+1));
V(i+1)=V(i);

SSerr=Tension_des(i)-Tension(i);

hold on
subplot(3,1,1)

plot(time,x_feed_rate)
axis([0 time(length(time)) 0 5])
%plot(time,x_feed_rate,'r',time,w.*r,'b')
ylabel('Input Feed Rate [in/s]')
%legend('Input Feed','Spool Feed')

subplot(3,1,2)
plot(time,Tension,'b',time,Tension_des,'r-')
ylabel('Tension [lbf]')
legend('Actual Tension','Desired Tension')
hold off
```

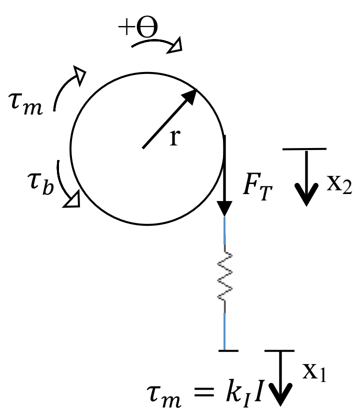
```
subplot(3,1,3)
plot(time,V)
ylabel('Motor Voltage [V]')
xlabel('time [s]')
hold off
```

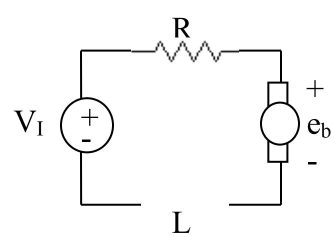
Appendix B: Electrical Circuit



Appendix C: Modeling

	Description
J	Motor Moment of Intertia
θ	Motor Angular Position
k_T	Stiffness of Thermoplastic
x_1	Applicator Feed
x_2	Actuator Feed
r	Spool Radius
τ_m	Motor Torque
τ_b	Damping Torque
F_T	Tension Force
V_{In}	Input Voltage
V_L	Voltage over Inductor
R	Resistor
I	Current
L	Inductor
e_b	Back EMF Constant
k_I	Motor Torque Constant





$$\tau_m = k_I I$$

$$\tau_b = b\dot{\theta}$$

$$x_2 = r\theta$$

$$F_T = k_T(x_1 - x_2)$$

$$\Sigma M = J\ddot{\theta} = F_T r - \tau_m - \tau_b$$

$$J\ddot{\theta} = k_T x_1 r + k_T r^2\theta - k_I I$$

$$e_b = k_b\dot{\theta}$$

$$V_L = L\dot{I}$$

$$V_{In} = IR + e_b + V_L$$

$$L\dot{I} + IR = V_{In} - k_b\dot{\theta}$$

$$I(s)[Ls + R] = V_{In} - k_b s\theta(s)$$

$$\theta(s)[Js^2 + \left(b - \frac{k_I k_b}{LS + R}\right)s + k_T r^2 = k_T r x_1(s) - \frac{k_I}{LS + R} V_{In}(s)$$

With X_1=0,

$$\theta(s)[Js^2 + bs + k_T r^2] = \frac{-k_I(V_{In}(s) - k_b s\theta(s))}{LS + R}$$

$$\frac{\theta(s)}{V_{In}(s)} = \frac{-k_I}{JLs^3 + (JR + bL)s^2 + (bR + k_T r^2 L - k_I k_b)s + k_T r^2 R}$$

Appendix D: Controller Simulation

```
clc;clear all;close all;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%              constants
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
time_step=.01; %sec
test_duration=4; %sec
material_thickness=.005; %in
time=0:time_step:test_duration;
material_stiffness=1000; %lbf/in
material_width=1/4; %in

%Motor Constants
L=.48; % Motor Inductance [H]
R=.2; % Motor Resistance [ohms]
nG=25; % Gearing Ratio
KT=1.125*nG; % motor torque constant w/ gearing ratio factored in (18 [oz-
in/A] = 1.125 [in-lb/A] )
KB=.129*nG; % back emf constant w/ gearing ratio factored in  (13.5[V/kRPM] =
.129 [V-s/rad] )

Vi_max=48; % max voltage intake [V]

J_motor=0.5468; %lbm*in^2 Motor Rotor Intertia OLD WAS 51.59 [lbm-in^2]????
J_gearbox=50; % fudge

%Motor Encoder Constants
enc_BW=10000; %Hz

%Spool Constants
spool_rad_init=4; %in
spool_length=6; %in
material_density=.0643 ;%lbm/in^3


%Rod Constants
rod_rad=.375; %in
rod_length=18; %in
rod_mass=5; %lbm
J_rod=rod_mass*(3*rod_rad^2+rod_length^2)/12; %lbm*in^2

%Ball Bearing Constant
b=10; %lbf-s/rad -> ball bearing damping

%desired Tension
Tension_des(1:length(time))=50;%lbf
%Tension_des=15+7*sin((pi/2)*time);  % harmonic reference tension

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%        Initial Conditions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

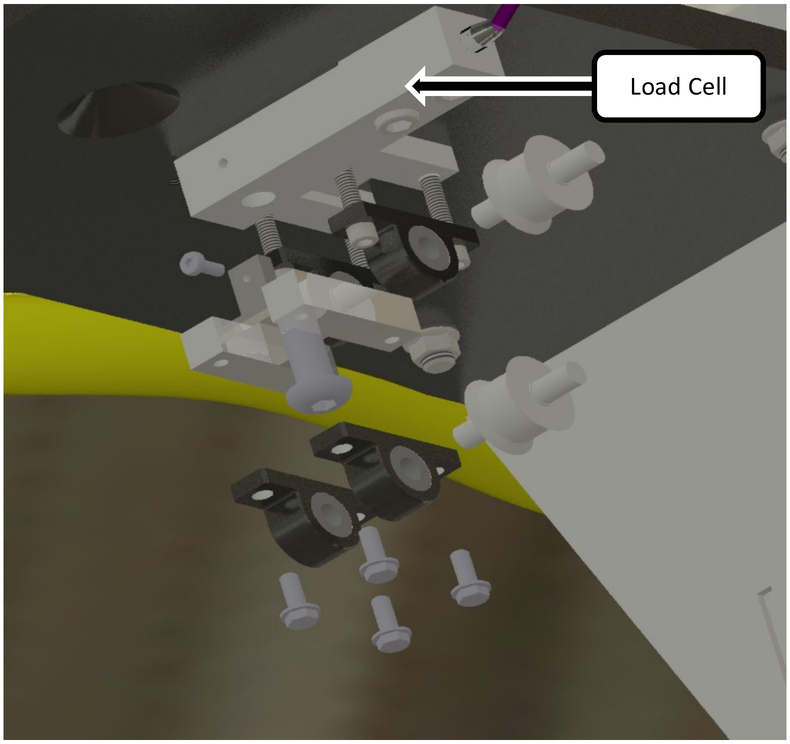
```
spool_rad=spool_rad_init;
spool_mass=material_density*spool_length*pi*spool_rad^2; %lbm
J_spool=spool_mass*(3*spool_rad^2+spool_length^2)/12; %lbm*in^2
J_total=J_spool+J_rod+J_motor+J_gearbox; %lbm*in^2

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%     Simulating Material Feed
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%X_feed_rate=2*square(time,75)+2; %in/s
X_feed_rate=0.5*ones(length(time));
%X_feed_rate=1-cos((pi/2)*time); % harmonic feed rate

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%           preallocating
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
X_feed=zeros(1,length(time));
theta=zeros(1,length(time));

%dtheta=zeros(1,length(time));
%dtheta(1)=X_feed_rate(1)/spool_rad; % if spool starts with same velocity as
feed
dtheta(1)=0;
ddtheta=zeros(1,length(time));
dddtheta=zeros(1,length(time));
theta_error=zeros(1,length(time));
dtheta_error=zeros(1,length(time));
theta_des=zeros(1,length(time));
Tension_error=zeros(1,length(time));
Tension_Meas=zeros(1,length(time));
dTension_Meas=zeros(1,length(time));
Vi=zeros(1,length (time));
int_theta_error=zeros(1,length(time));




%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%          Controller Design
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%plant TF:  theta(s)/V(s)
% num=-KT;
%
den=[L*J_total,J_total*R+L*b,R*b+L*material_stiffness*spool_rad+KB*KT,R*mater
ial_stiffness*spool_rad^2];
% H_plant=tf(num,den);
%
% %Sensor Dynamics
% Num_sensor=1;
% Den_sensor=1;
% %Den_sensor=[1,enc_BW*2*pi];
% H_sensor=tf(Num_sensor,Den_sensor);
%
```

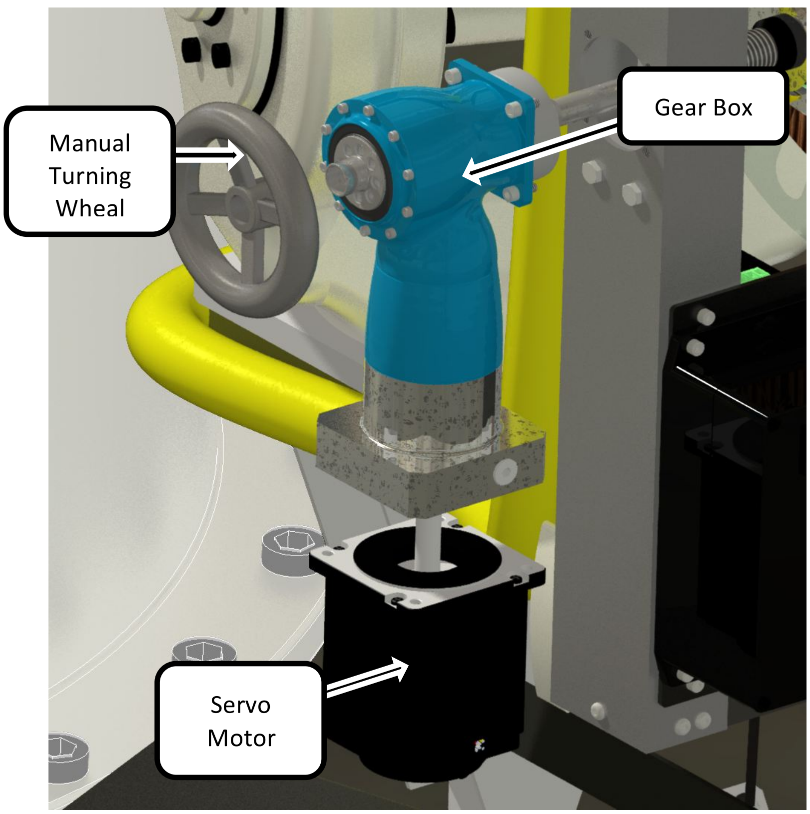
```
% %PD Controller TF:
controller_a=.001;
controller_b=.01;
% H_controller=tf([1,controller_a,controller_b],[1,0]);
% A=(1/material_stiffness*spool_rad);
% H=A;
%H_LT=-*H_plant*H_sensor*H_controller;


%rootlocus
%rlocus(H_LT)
K=-1;
% %Simulating step Response
% H_FP=K*H_controller*H_plant;
% H_FB=H_sensor;
% H_CL=feedback(H_FP,H_FB);
% figure
% %step(H_CL);
% eig_CL=eig(H_CL);
% figure
% hold on
% grid on
% title('Closed Loop eigenvalues')
% plot(real(eig_CL),imag(eig_CL),'*b')
% hold off

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%        Running Control Loop
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for k=1:length(time)-1
X_feed(k+1)=X_feed(k)+((X_feed_rate(k)+X_feed_rate(k+1))/2)*time_step;
spool_rad(k+1)=spool_rad_init-
(X_feed(k+1)*pi*2*spool_rad(k))/(2*pi*(spool_length/material_width))*material
_thickness; %in
%spool_rad(k+1)=4;
spool_mass=material_density*spool_length*pi*spool_rad(k+1)^2; %lbm
J_spool=spool_mass*(3*spool_rad(k+1)^2+spool_length^2)/12; %lbm*in^2
J_total=J_spool+J_rod+J_motor; %lbm*in^2

% if Tension_error <=0
%     theta_des(k+1)=X_feed(k+1)/spool_rad(k+1);
% elseif Tension_error >0
    theta_des(k+1)=(X_feed(k+1)-
(Tension_error(k)/material_stiffness))/spool_rad(k+1);
% end

%theta_des(k+1)=X_feed(k+1)/spool_rad(k+1)+sin(2*time(k));


dddtheta(k+1)=(-(J_total*R+b*L)*ddtheta(k)-
(R*b+L*material_stiffness*spool_rad(k+1)^2+KB*KT)*dtheta(k)-
(R*material_stiffness*spool_rad(k+1)^2)*theta(k)+X_feed_rate(k+1)*spool_rad(k
+1)*material_stiffness*L+X_feed(k+1)*spool_rad(k+1)*material_stiffness*R-
KT*Vi(k))/(J_total*L);
ddtheta(k+1)=ddtheta(k)+((dddtheta(k+1)+dddtheta(k))/2)*time_step;
```

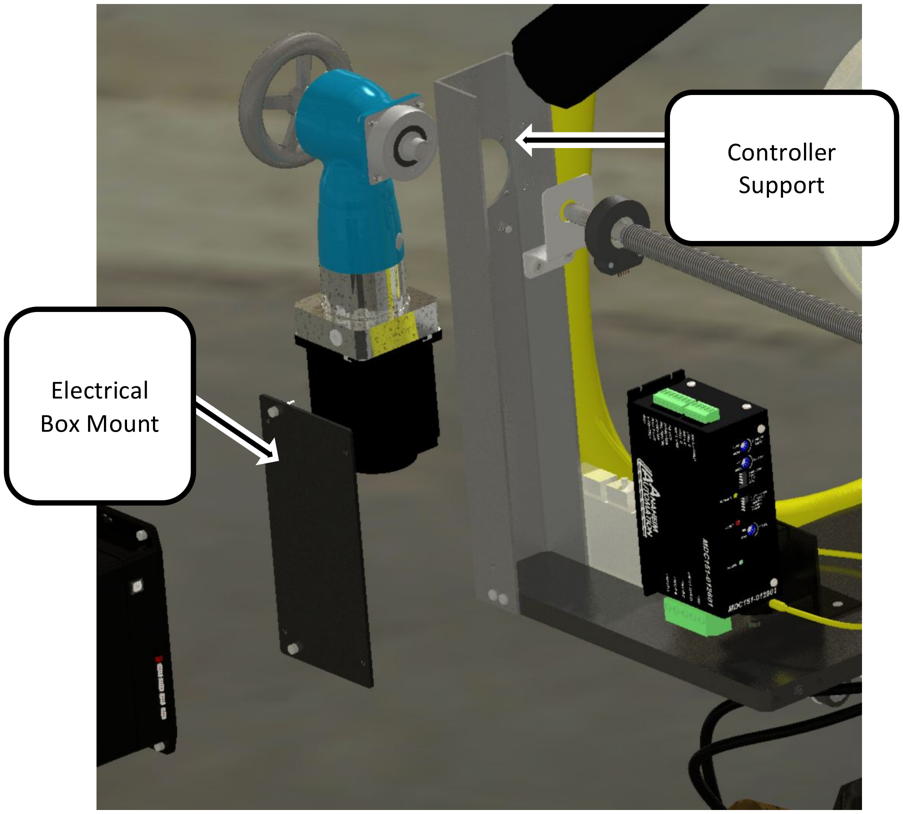
```
dtheta(k+1)=dtheta(k)+((ddtheta(k+1)+ddtheta(k))/2)*time_step;
theta(k+1)=theta(k)+((dtheta(k+1)+dtheta(k))/2)*time_step;


Tension_Meas(k+1)=material_stiffness*((X_feed(k+1)/spool_rad(k+1))-
theta(k+1));


theta_error(k+1)=theta_des(k+1)-theta(k+1);
dtheta_error(k+1)=(theta_error(k+1)-theta_error(k))/time_step;
int_theta_error(k+1)=int_theta_error(k)+((theta_error(k+1)+theta_error(k))/2)
*time_step;

Vi(k+1)=K*(dtheta_error(k+1)+controller_a*theta_error(k+1)+controller_b*int_t
heta_error(k+1));
if Vi(k+1) > Vi_max
    Vi(k+1)=Vi_max;
else if Vi(k+1)< (-Vi_max)
        Vi(k+1)=-Vi_max;
    end
end
Tension_error(k+1)=Tension_des(k+1)-Tension_Meas(k+1);

%     if Vi(k+1)>=0
%         Vi(k+1)=0;
%     elseif Vi(k+1)<-Vi_max
%         Vi(k+1)=-Vi_max;
%
%     end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%          Plotting Results
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% figure
% subplot(2,1,1)
% plot(time,X_feed_rate)
% ylabel('Feed Rate(in/s)');
% xlabel('time(sec)');
% subplot(2,1,2)
% plot(time,X_feed)
% ylabel('Feed distance(in)');
% xlabel('time(sec)');
%
% figure
% plot(time,theta_des)

figure
% subplot(4,1,1)
% plot(time,dddtheta)
% ylabel('dddtheta(rad/s^3)');
% xlabel('time(sec)');
% subplot(4,1,2)
% plot(time,ddtheta)
% ylabel('ddtheta(rad/s^2)');
```

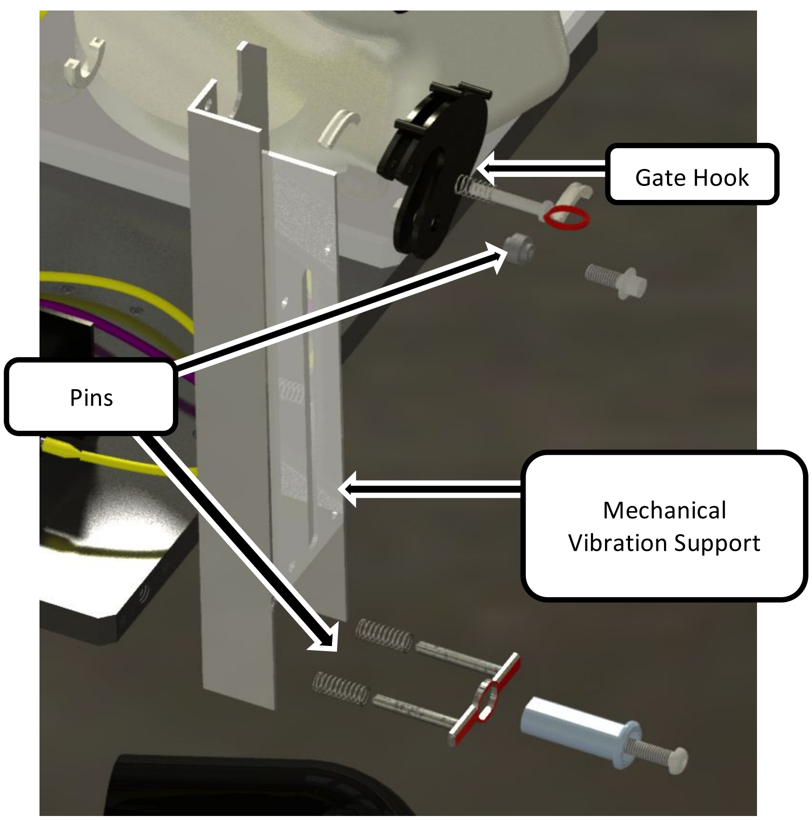
```
% xlabel('time(sec)');
% subplot(4,1,3)
% plot(time,dtheta)
% ylabel('dtheta(rad/s)');
% xlabel('time(sec)');
% subplot(4,1,4)
hold on
title('Position Tracking')
plot(time,theta)
plot(time,theta_des,'r')
ylabel('Theta(rad)');
xlabel('Time(sec)');
legend('Measured Theta','Desired Theta')
hold off

figure
hold on
plot(time,Tension_des,'r');
plot(time,(X_feed-(theta.*spool_rad))*material_stiffness+Tension_Meas);
xlabel('Time (sec)')
ylabel('Tension (lbf)')
legend('Measured Tension','Desired Tension')
hold off

%
figure
hold on
title('Motor input Voltage')
plot(time,Vi)
xlabel('time(sec)');
ylabel('Voltage (V)');
hold off

% figure
% subplot(2,1,1)
% hold on
% title('Measured Tension')
% plot(time,dTension_Meas)
% ylabel('dTension/dt (lbf/s)');
% xlabel('Time (sec)');
% subplot(2,1,2)
% plot(time,Tension_Meas);
% ylabel('Tension (lbf/s)');
% xlabel('Time (sec)');
% hold off
%
%

% %Bode Plots
%
% Loop Transmission
% figure
% bode(H_LT)
```

Appendix E: Exploded Views






Controller Support
Electrical Box Mount


Gate Hook
Pins
Mechanical Vibration Support

Appendix F: Bill of Materials

Bill of Materials			
1st Semester			
Decription	**Qty**	**Unit Price**	**Total Price**
Male Rod End Bearings, 1/2-20, RH	4	14.48	57.92
Perforated Steel Tubing, 1-1/2"W. 1-1/2"H, .083" Wall Thickness, 6' L	5	26.64	133.20
Stamped-Steel Mounted Ball Bearing--ABEC-1, 2-Bolt Base Mount, for 1" Shaft Diameter	4	12.69	50.76
Fully Keyed 1045 Steel Drive Shaft, 1" OD, 1/4" Keyway Width, 18" Length	2	35.48	70.96
Square U-Bolt, Zinc-Plated Steel, for 4" W, 6-5/8" L Inside, 1090# Work Load Limit	2	3.86	7.72
Multipurpose Aluminum (Alloy 6061) Rectangle Tube, 1/8" Wall Thickness, 2" X 3", 3' Length	1	38.92	38.92
Grade 8 Alloy Steel Hex Head Cap Screw, Zinc Yellow-Plated, 3/8"-16 Thread, 3-1/2" Length, packs of 10	3	8.42	25.23
Grade 5 Zinc-Plated Steel Hex Head Cap Screw, 3/8"-16 Thread, 2-1/4" Length, packs of 25	1	8.06	8.06
Plain Grade 8 Steel Hex Nut, 3/8"-16 Thread Size, 9/16" Width, 21/64" Height, packs of 100	1	6.51	6.51
Clamping U-Bolt, Steel, 3/8"-16 Thread, for 3-1/4" Outside Diameter	2	2.53	5.06
Zinc-Plated Steel Type A USS Flat Washer, 3/8" Screw Size, 1" OD, .06"-.11" Thick, packs of 100	11	6.65	6.65
1.5" OD, 0.5" ID Pulley	2	3.79	7.58
7" OD, 1" ID Pulley	2	13.90	27.80
4L Belt 0.5" x 5/16" x 32 3/4"	2	5.54	11.08
1" Bore Steel Flanged Shaft Collar	2	37.38	74.76
Adapter Ring 4 1/4" OD	1	33.45	33.45
3/8" shaft diameter self lubricating Al-mounted Bearing PTFE - filled bronze	2	12.47	24.94
10-24 cap screw	1	8.74	8.74
10-24 flanged nut	1	6.74	6.74
5.5"x3'x.625" Gen purpose low carbon steel	1	46.86	46.86
Al 2024 bar	1	84.53	84.53
Al 6061 rod	1	12.78	12.78
Rod End Bearing	1	45.00	45.00
Reciprocating Saw	1	59.99	59.99

Saw Blades	5	3.99	19.95
48VDC 12.5A 600W Regulated Power Supply	1	129.00	129.00
Cables	1	8.00	8.00
		TEST TOTAL	1012.19
Decription	**Qty**	**Unit Price**	**Total Price**
BLY34 - Brushless Motor	2	368.00	736.00
Brushless Speed Controllers - Under 1 HP	2	307.00	614.00
DC/DC converter 48-24	1	22.20	22.20
DC/DC converter 24-12	1	46.42	46.42
ARDUINO MEGA2560 REV 3	1	38.95	38.95
Cantilever Load Cell	1	350.00	350.00
Twist Lock Connector	1	26.50	26.50
DIN Rail Version Transducer Signal Conditioner	1	295.00	295.00
Encoders	2	105.80	211.60
		TEST &Final TOTAL	2340.67

2nd Semester			
Decription	**Qty**	**Unit Price**	**Total Price**
25:1 90° Gear Box	1	4055.80	4055.80
Base Plate	1	1090.00	1090.00
Cap Screws (10 pack)	1	1.77	1.77
U-Channels	2	25.14	50.28
1/8" drill bit	2	3.83	7.66
1/4" drill bit	3	7.18	21.54
7/16" drill bit	2	14.99	29.98
72/32" drill bit	2	16.51	33.02
X drill bit	2	16.11	32.22
7 Drill bit	2	6.18	12.36
1/2-20 socket head cap screw	1	6.95	6.95
Band Saw Blade	1	51.91	51.91
1/2" end mill	2	47.29	94.58
DC Low Voltage Signal Conditioner	1	359.06	359.06
1/2-20 Thread Flate Head Socket Cap Screw	1	1.84	1.84
3/8 Soft Self Lubricator	4	12.47	49.88
Countersink Sets	1	39.29	39.29
Combination Drill Countersinks	1	19.35	19.35
Lathe Tool Set	1	29.99	29.99
Power Supply	1	338.30	338.30
1/4-20 tap	1	13.08	13.08

Threaded Shaft	1	87.00	87.00
Motor Driver 48V 30 A	1	235.00	235.00
3/8" Inscribed circle, 3-point carbide lathe bit	2	5.74	11.48
Power Pole Connectors	1	11.99	11.99
15 Pin Connector	2	5.43	10.86
9/32" Drill Bit	1	2.77	2.77
1/2" Drill Bit	1	8.85	8.85
1/2" Boring Bar	1	16.36	16.36
Carbide Lathe Tool Set 3/8"	1	61.25	61.25
1/8" Aluminum Plate	1	10.98	10.98
11 Gauge Drill Bit	1	2.18	2.18
1" Spring Pack	1	9.13	9.13
Bulgin Contact Pins	2	7.50	15.00
100 Ft. 10 Gauge Wire- Red	1	41.45	41.45
100 Ft. 10 Gauge Wire- Black	1	37.80	37.80
D-Sub Standard Connectors 15C Plug W Contacts	2	5.24	10.48
Headers & Wire Housings MICRO-FIT 3.0 Header	1	1.08	1.08
Headers & Wire Housings Receptacle 2 POS Single Row	1	0.59	0.59
Aluminum Electrolytic Capacitors- Leaded 50 volts 10000uF 0.2 L/s	2	5.31	10.62
Film Capacitors 630V .1uF 5%	1	1.08	1.08
Film Capacitors 250V .33uF 5%	1	1.16	1.16
Linear Regulators- Standard 1A Pos Vol Reg	1	0.69	0.69
Linear Regulators- Standard 5.0V 100mA	1	0.33	0.33
Headers & Wire Housings 2.54MM CGRID111 HDR 10P VERT SR TIN	2	1.20	2.40
Headers & Wire Housings 8P Header Tin Single Row	7	0.97	6.79
Headers & Wire Housings 2.54MM HDR VT 2X18P 240/110 SNPB	1	2.07	2.07
D-Sub Standard Connectors 15P RA Solder Female Europe Standard	1	2.73	2.73
Trimmer Resistors- Through Hole 3/8" 10Kohms 10% 0.5 Watts Square	3	1.30	3.90
Headers & Wire Housings 3MM Micro-Fit Vert. 11 CKT Gold	1	2.89	2.89
Headers & Wire Housings 3MM Micro-Fit Recept. 11 CKT	1	1.08	1.08
Headers & Wire Housings 3MM Micro-Fit Recept. 7 CKT	1	0.78	0.78
Headers & Wire Housings 3MM Micro-Fit Vert. 7 CKT Gold	1	1.80	1.80
Enclosures Boxes & Cases 5.59x4.34x1.75	1	7.70	7.70
RS-232 Interface IC 5V MultiCh RS-232 Driver/Receiver	1	3.65	3.65
LCD Character Display Modules & Accessories LCD 2X16 LCD Board	1	9.53	9.53
Schottky Diodes & Rectifiers Vr/40V Io/1A Bulk	1	0.12	0.12
Fixed Inductors 330uH 10%	1	2.42	2.42
Aluminum Electrolytic Capacitors- Leaded 16 volts 330uF 8x16 20%	1	0.80	0.80
Aluminum Electrolytic Capacitors- Leaded 50v 100Uf 10% 10x21mm	1	1.45	1.45
DC/DC Switching Regulators 1-A Step-Down Vltge	2	2.87	5.74
Film Capacitors 250V 1uF 5%	4	1.13	4.52

Headers & Wire Housings R/A Header 6P Gold	4	1.96	7.84
Headers & Wire Housings 6P 1R Recpt. HSNG	4	0.72	2.88
Headers & Wire Housings 08 MODII HDR SRST B/A .100CL	5	1.17	5.85
D-Sub Standard Connectors DB-15 IDC RECEPTACLE	1	10.45	10.45
Powerpole Mounting Clamp Pair for 4 or 8 PP15/30/45 Powerpoles	1	3.39	3.39
45 Amp Unassembled Red/Black Anderson Powerpole Sets (Sets: 25)	1	29.99	29.99
Straight-thru Cable DB15MM All Pins Wired; Metalized Backshells	1	27.50	27.50
Aluminum Organic Polymer Capacitors 330uF 20V 20%	1	3.19	3.19
Aluminum Electrolytic Capacitors - Leaded 50volts 100uF 20%	1	0.34	0.34
Tantalum Capacitors - Solid Leaded 10uF 20volts 10% W case Axial	1	1.88	1.88
Tantalum Capacitors - Solid Leaded 1uF 35volts 10% A case Axial	4	5.22	20.88
	1	1.09	1.09
	1	1.09	1.09
PCBs & Breadboards .1" Plated Holes Lead Free 4"x5"	1	12.75	12.75
Wirewound Resistors - Through Hole 10watts 100Kohms 1%	1	5.91	5.91
Wirewound Resistors - Through Hole 10watt 22K 1% Axial	1	2.58	2.58
Optical Encoder Disk	1	43.60	43.60
Solenoid Valve	1	43.84	43.84
Mouser Products for Comparator	1	120.00	120.00
Connector Assy	2	1.68	3.36
		Gearbox& Plate	5145.80
		SEMESTER 2 TOTAL	7335.77
		OVERALL TOTAL	10688.63