Army Robot

MECH 4240 Preliminary Design Report

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Abstract:

The purpose of the Army Robot design group is to design a tension control device for an AMRDEC robot. The design is required to allow for the setting and holding of tension in a thermoplastic material fed by the robot. The design process began with a list of engineering and functional requirements for the overall system. Solutions to the functional requirements were developed, and matched together in a logical way to produce six feasible designs. Evaluations were made based on how well each of the designs met the overall engineering requirements, and tests that revolved around proof of concept for specific solutions. A final architectural design was decided upon after these evaluations took place, and this design is laid out later in the report.

Aside from the physical system components, the group has been at work coming up with a model and block diagram that can be used to accurately control the system. The block diagrams have been shown to professors who specialize in the subject and approved of the design. Also, MATLAB simulations of the program have been developed to allow for proof that the control design will work.

As the design process continues, the group plans on developing a more concrete test apparatus that will allow for the simulation of the overall design system. The test apparatus will be used to back out a transfer function between tension and voltage for the design of the controller. Final actuators, sensors, and microcontrollers are also currently being researched before final purchases are made for the design. As of right now nothing in this report is final, and recommendations are welcomed as always.

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Introduction:

The design solution detailed in this report deals with a robot for AMRDEC on the Redstone Federal Arsenal in Huntsville, AL. The robot, in its current state, has no method for calculating or controlling the tension in the thermoplastic material. The intention of the design process is to produce a control system that would satisfy this overall goal. The current system without tension control is shown below.

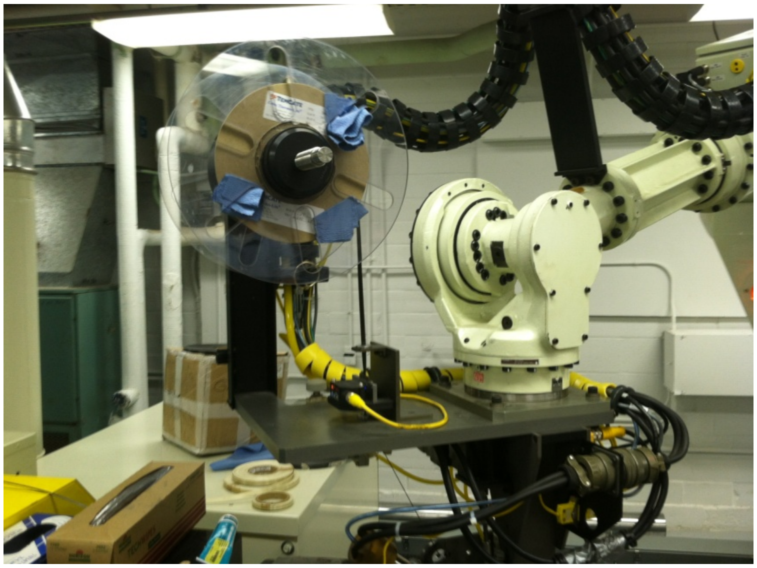


Figure 1- Design Environment

The design to be developed has to satisfy a number of characteristics. It has a rough weight limit of about 20 pounds and has to run on a 24 volt supply. Most importantly, it must be able to set tension anywhere from 1 to 50 pounds, with an accuracy of ±0.5 pounds. Several requirements also needed to be taken into consideration. In addition to being able to set tension and control slack in the thermoplastic material, the design also had to be safe, easy to maintain, easy to use, and reliable.

The following document will outline the entire design process to this date. It will also look at where the project is headed, and what future steps need to be taken to ensure a successful design. To this point the report will outline in detail the mission objective, set of requirements, feasible alternatives generated, and a final recommended design. The Critical Design Review conducted at the end of the semester will outline the final design in detail.

Mission Objectives:

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 orientation of the end effector

Architectural Design and Development:

One of the first steps taken was to create a functional decomposition of what the system needs to accomplish. In doing this, each sub-system and sub-sub system could be analyzed and designed for individually. The lowest sub-systems will later be used to pick options for the design. The functional decomposition can be seen below.

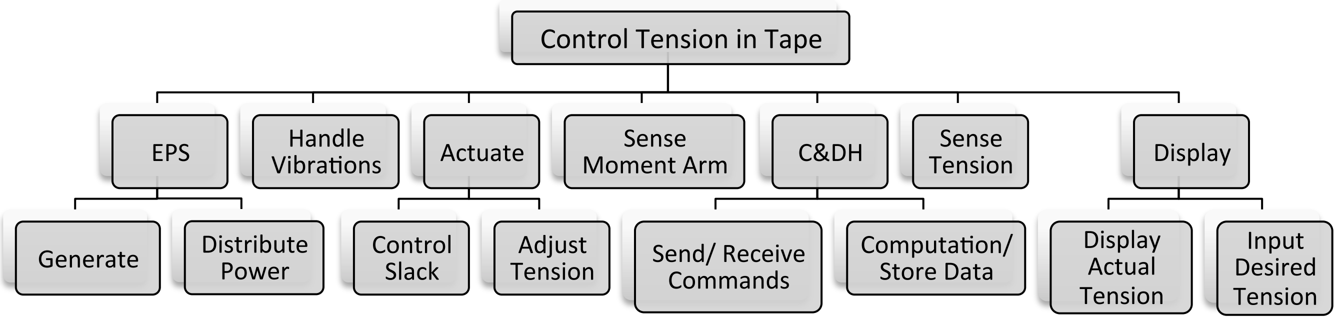


Figure 2 - Functional Decomposition

Using the lowest level functions from the functional decomposition, multiple concepts that solved each were created. Below is a morphological matrix showing the concepts and ideas derived from the functions.

Table 1: Morphological Matrix

Functions	Option 1	Option 2	Option 3	Option 4
Generate Power	Battery	Wall Supply	Mechanical system	
Distribute Power	Wires	Multiple Power Supplies		
Control Slack	Electric Motor with Controller	Arm and Roller	Torsional Spring with Clutch	Pneumatic motor
Adjust Tension	Clutch	Motor	Hydrodynamic Bearing	
Computation/ Store Data	Microcontroller	Fully mechanical	Motor with Controller	OP Amp Circuit
Send/ Receive Commands	Wireless Data	Wire	Mechanical System	
Handle Vibrations	Isolate (Spring/ Damper System)	Mechanical Supports	Rigid Attachment	
Sense Moment Arm	Constant Radius	IR Sensor	Ultrasonic	
Tension Sensor	3-Spool Sensor	Radial Force Sensor	Dancer Roll	From Motor
Display Tension	Analog	Digital		
Input Tension	Analog	Digital		

Concept 1

Advantages:

The overall concept is fairly simple and straightforward which is always a great design characteristic. Accuracy and reliability of this design are high because with the motor attached to the main spool controlling the tension and slack, there are fewer components to have to rely on.

Disadvantages:

The rigid attachment means that the system remains as a cantilever beam. This would not help the vibrations as much as some of the other concepts.

Overview:

The IR sensor will provide a value for the constantly changing spool radius which will factor into the tension calculation using the microcontroller. The motor torque will change continuously based on these values increasing or decreasing the tension when necessary. The 3 spool sensor will provide an accurate reading of the current tension in the tape and will use the microcontroller to output a digital value on the display.

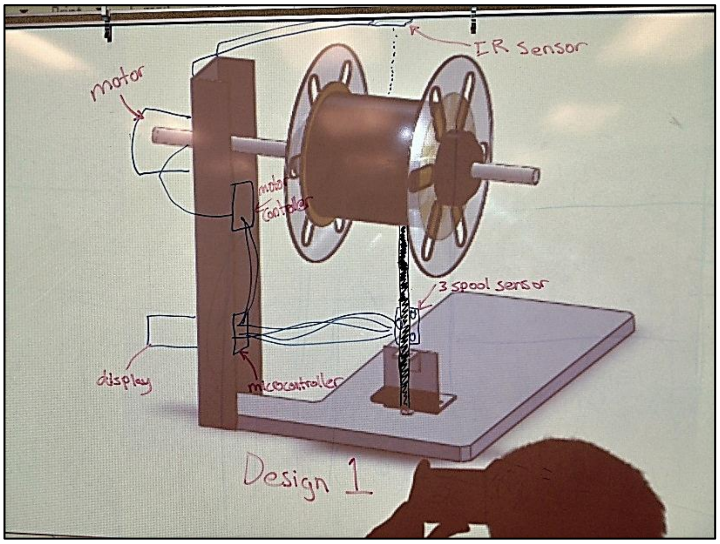


Figure 3- Design 1 Sketch

This design was tweaked by adding a mechanical support at the end of the shaft and is currently being used as the final design. It was chosen because of its simplicity, accuracy, and dependability.

PRODUCT HIERARCHY:

- SUBSYSTEM 1: Electrical Power Supply
  - Wall Supply
  - Wires
- SUBSYSTEM 2: Handle Vibrations
  - Rigid Attachment
- SUBSYSTEM 3: Control Tension and Slack
  - Electric Motor with Controller
- SUBSYSTEM 4: Sense Moment Arm
  - Infrared Sensor
- SUBSYSTEM 5: Control and Data Handling
  - Microcontroller
  - Wires
- SUBSYSTEM 6: Sense Tension
  - 3-Spool Sensor
- SUBSYSTEM 7: Display
  - Digital

Concept 2

Advantages:

This idea is also straightforward but with a new concept of measuring the radius. With only a few simple components, this design rated fairly high on the accuracy and reliability as well.

Disadvantages:

The constant radius theory might not be effective depending on if the tape slips instead of moving with the spool at a desired tension. This idea was tested using a small test apparatus and the tape slipped, so this idea will not move forward in the decision process.

Overview:

This design is similar to design 1, but instead of an infrared sensor, the tape is fed onto another spool which houses another motor. This idea was generated so that the radius of the smaller spool would always be known and one less thing would need to be calculated. This value will factor into the tension calculation using the microcontroller. The motor torque will change continuously based on these values for increasing or decreasing the tension when necessary. The radial force sensor will provide an accurate reading of the current tension in the tape and will use the microcontroller to output a digital value on the display.

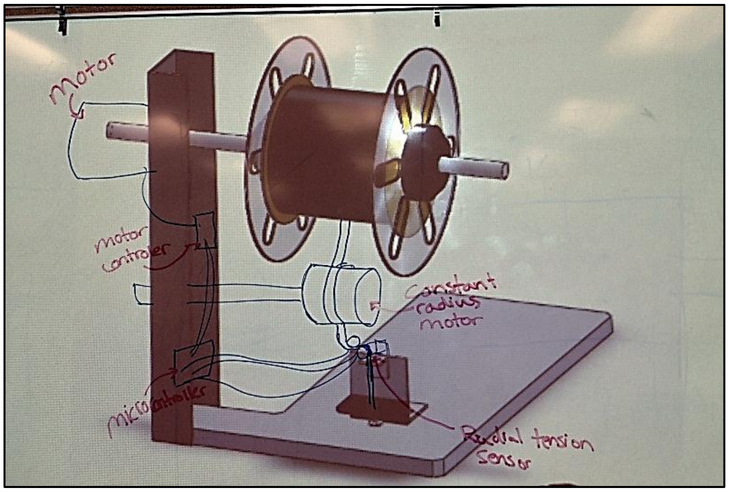


Figure 4 - Design 2 Sketch

This design was tested and the constant radius motor ended up not being effective. The material slipped on the spool and would ultimately affect the measure of tension in the tape.

PRODUCT HIERARCHY:

- SUBSYSTEM 1: Electrical Power Supply
  - Wall Supply
  - Wires
- SUBSYSTEM 2: Handle Vibrations
  - Mechanical Supports
- SUBSYSTEM 3: Control Tension and Slack
  - Pneumatic Motor
- SUBSYSTEM 4: Sense Moment Arm
  - Constant Radius Concept
- SUBSYSTEM 5: Control and Data Handling
  - Microcontroller
  - Wires
- SUBSYSTEM 6: Sense Tension
  - Radial Force Sensor
- SUBSYSTEM 7: Display
  - Digital

Concept 3

Advantages:

This design has a gyroscope to measure the orientation of the spool which is beneficial since the system operates upside down as well.

Disadvantages:

The setup for this design would be more complicated and take longer than any other concept idea. There would also be more maintenance involved.

Overview:

This design has an IR sensor to measure the radius of the spool that factors into the tension value which is calculated indirectly using the programmed microcontroller. The air-driven gyro is connected to a vacuum pump which also activates the hydrodynamic bearing that controls the angular velocity of the spool. The dancer rolls at either side of the spool measure the tension and are connected to the microcontroller and are dependent on the gyroscope.

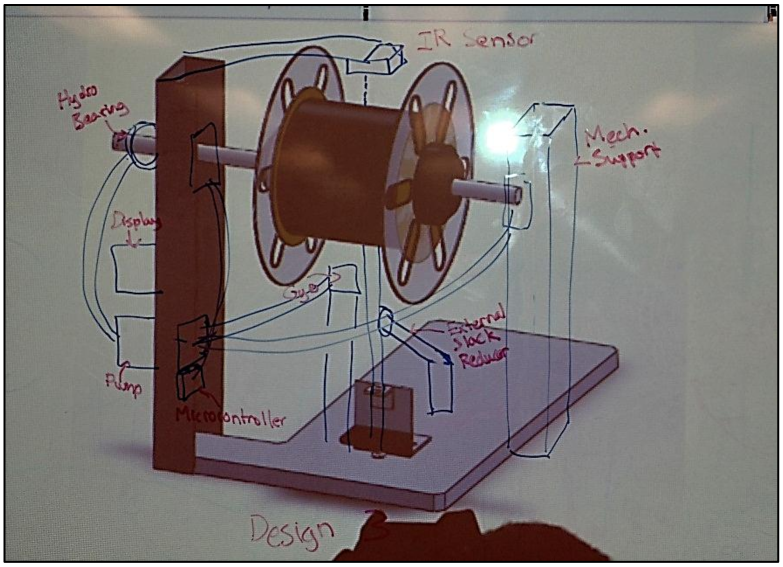


Figure 5 - Design 3 Sketch

This design was not chosen to continue in the design process because of its complicity and difficulty in setup. One of the main requirements is ease of use and this design is rated poorly in that area.

PRODUCT HIERARCHY:

- SUBSYSTEM 1: Electrical Power Supply
  - Wall Supply
  - Wires
- SUBSYSTEM 2: Handle Vibrations
  - Mechanical Supports
- SUBSYSTEM 3: Control Tension and Slack
  - Hydrodynamic Bearing
  - Arm and Roller Concept
- SUBSYSTEM 4: Sense Moment Arm
  - Infrared Sensor
- SUBSYSTEM 5: Control and Data Handling
  - Microcontroller
  - Wires
- SUBSYSTEM 6: Sense Tension
  - Dancer Roll
- SUBSYSTEM 7: Display
  - Digital

Concept 4

Advantages:

One positive thing about this design is that the motor is capable of controlling and sensing the tension. With even fewer parts, the price is very good, and with it being a simple concept as well, many of the requirements scored high.

Disadvantages:

The accuracy for this concept will need to be tested if taken any further into the design stage though. The use of just one motor for so many functions would need to be proven effective with the maximum possible precision.

Overview:

The IR sensor will provide a value for the constantly changing spool radius which will factor into the tension calculation using the OP Amp. The motor torque will change continuously based on these values increasing or decreasing the tension when necessary. If there is too much slack in the tape, the motor is capable of rotating the spool in reverse until the tension is correct. This servo motor with a controller inside will also provide a reading of the current tension in the tape and will use the Op Amp to output a digital value on the display.

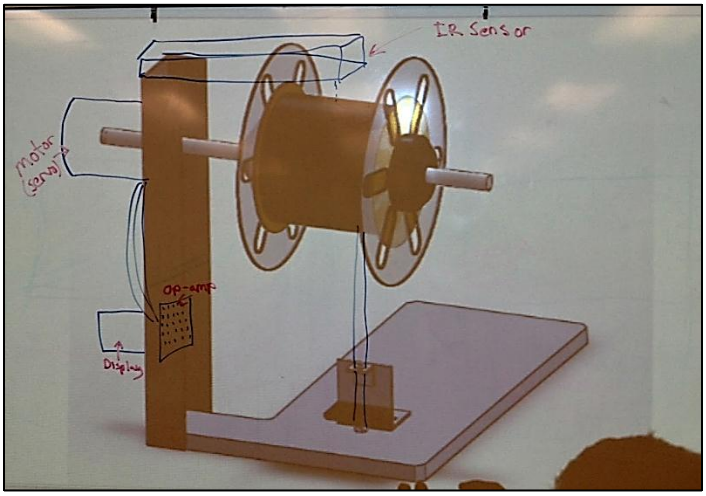


Figure 6- Design 4 Sketch

This design was chosen to continue in the decision process, but it did not rate as well because this concept would be optimal for a constant feed. Our system will have acceleration due to changing radius and slack adjustment. A microcontroller would also be favored more than an op amp.

PRODUCT HIERARCHY:

- SUBSYSTEM 1: Electrical Power Supply
    - Wall Supply
    - Wires
- SUBSYSTEM 2: Handle Vibrations
    - Rigid Attachment
- SUBSYSTEM 3: Control Tension and Slack
    - Electric Motor with Controller
- SUBSYSTEM 4: Sense Moment Arm
    - IR Sensor
- SUBSYSTEM 5: Control and Data Handling
    - Op Amp Circuit
    - Wires
- SUBSYSTEM 6: Sense Tension
    - Motor
- SUBSYSTEM 7: Display
    - Digital

Concept 5

Advantages:

The ultrasonic sensor is probably more accurate than an infrared sensor would be. The external slack reducer is a simple but efficient means of tightening the limp tape when the head of the robot arm is raised.

Disadvantages:

The clutch is probably not going to be as accurate or precise as a motor would be.

Overview:

The ultrasonic sensor will provide a value for the constantly changing spool radius which will factor into the tension calculation using the microcontroller. The clutch will change the force of the brake continuously for increasing or decreasing the tension when necessary. If there is too much slack in the tape, the spring loaded arm and roller mechanism will apply a force to tighten the tape. The 3-spool sensor will provide a reading of the current tension in the tape and will use the microcontroller to output a digital value on the display.

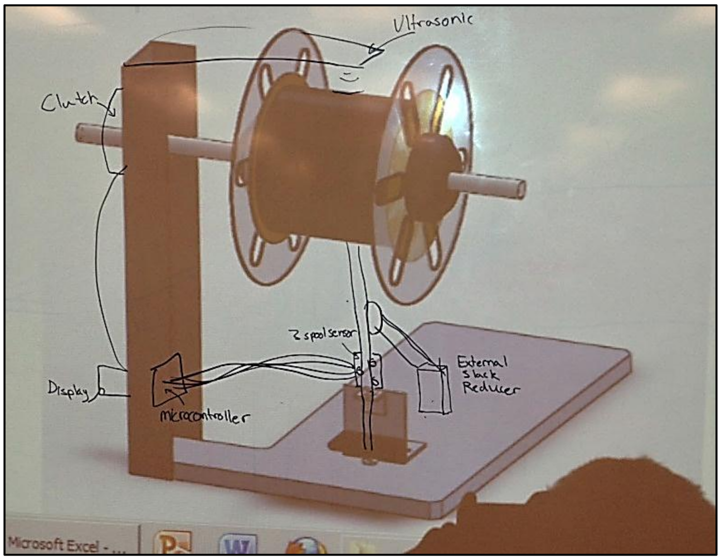


Figure 7- Design 4 Sketch

This design was not chosen to proceed in the decision process because it was decided that a clutch would not be as effective as a motor for this situation. The arm and roller mechanism also did not rate as well against a motor controlling the slack in the tape.

PRODUCT HIERARCHY:

- SUBSYSTEM 1: Electrical Power Supply
  - Wall Supply
  - Wires
- SUBSYSTEM 2: Handle Vibrations
  - Mechanical Supports
- SUBSYSTEM 3: Control Tension and Slack
  - Arm and Roller Mechanism
  - Clutch
- SUBSYSTEM 4: Sense Moment Arm
  - Ultrasonic Sensor
- SUBSYSTEM 5: Control and Data Handling
  - Microcontroller
  - Wires
- SUBSYSTEM 6: Sense Tension
  - 3-Spool Sensor
- SUBSYSTEM 7: Display
  - Digital

Con

Concept 6

Advantages:

With this design being fully mechanical, there is no need for a power supply. The external slack reducer is a simple but efficient means of tightening the limp tape when the head of the robot arm is raised. The mechanical support will help the vibration issue of the system.

Disadvantages:

The clutch is probably not going to be as accurate or precise as a motor would be. With the system being fully mechanical, there is no programming in this control system.

Overview:

The knob and spring attached to the clutch are used to set the tension by controlling the speed of the constant radius spool. The spring loaded arm and roller mechanism reduce the slack by applying a horizontal force to the tape.

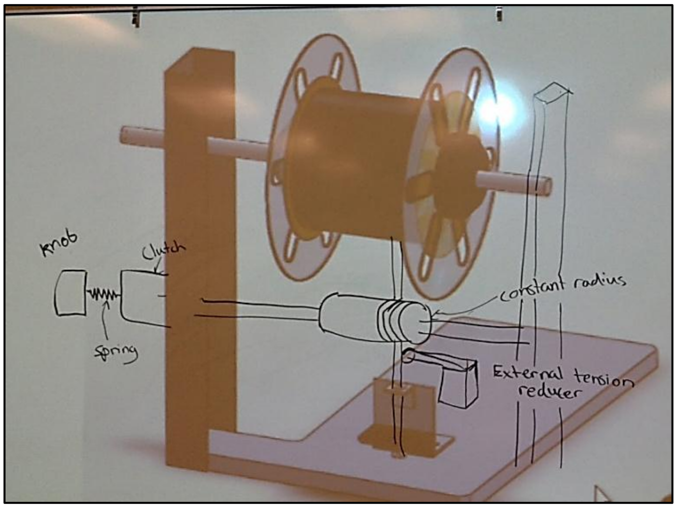


Figure 8-Design 6 Sketch

This design was created to have a fully mechanical concept, but it isn't the most ideal model for our functional requirements. The lack of programming and a digital display would be less effective than a digital microcontroller.

PRODUCT HIERARCHY:

- SUBSYSTEM 1: Electrical Power Supply
  - Fully Mechanical (No Power)
- SUBSYSTEM 2: Handle Vibrations
  - Mechanical Supports
- SUBSYSTEM 3: Control Tension and Slack
  - Arm and Roller Mechanism
  - Clutch
- SUBSYSTEM 4: Sense Moment Arm
  - Constant Radius Concept
- SUBSYSTEM 5: Control and Data Handling
  - Fully Mechanical
- SUBSYSTEM 6: Display
  - Analog

Table 2-Decision Matrix

	Weight	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**	**Design 6**
Safety	0.5	8	8	9	8	9	10
Display Tension	0.8	10	10	10	10	10	5
Set Tension	0.7	10	10	10	10	10	5
Control Slack	0.7	9	7	8	9	7	7
Setup	0.8	8	6	3	9	6	5
Ease of Maintenance	0.7	7	6	4	9	7	5
Cost	0.2	6	5	4	7	6	10
Accuracy/ Precision	1	10	9	6	8	4	6
Reliability	0.9	9	8	6	9	7	7
Total	**63**	**55.9**	**50.1**	**42.5**	**56.3**	**45.6**	**39.2**

From the evaluation, two designs seemed to meet all requirements well. Designs one and four were selected for further development and analysis. Both designs ideally function well for the required system, so tests were designed to properly evaluate the two concepts.

Testing was set up to help determine if an IR sensor or a constant radius model would be more appropriate for the given system. A test apparatus (shown below) was used to test the constant radius theory. Thermoplastic was wrapped around the spool several times, and with both ends held in tension we attempted to turn the spool. If the thermoplastic slipped on the spool then friction between the spool and thermoplastic would not be high enough to support a constant radius wrap and tension measurements would be thrown off. Testing showed that the thermoplastic would slip, and the constant radius theory was proved to not be a viable option.

The final design proposal consists of the existing power supply, wires to distribute power, a servo motor with controller to control slack, another servo to adjust tension, a microcontroller for data handling, rigid attachment for all components, a possible mechanical support for the cantilever shaft the spool rests on, an IR sensor to sense the radius, a three-spool tension sensor, and an all-digital display of tension with the capability of tension adjustment.


Figure 9-Test Apparatus

More analysis and adaptation of the final design will be discussed in the critical design report.

Requirements:

- Control Tension
    - Maintain Safety
    - Display Tension
    - Set Tension
    - Control Slack
    - Allow for spool replacement
    - Ease of maintenance
    - Cost
    - Accuracy/ Precision
    - Reliability

Concept of Operations:

In order to meet the requirements of the design and ultimately satisfy the stakeholders, the system must take an input of desired tension and control this tension within the tolerance bounds. To meet this goal, multiple subsystems will work contributively to accomplish a certain task. The operator will start by loading a spool of thermoplastic carbon fiber and linking the gears with an electric motor. He will then unwind the thermoplastic tape and feed it through a three spool tension sensor. The tape will then be loaded as necessary to start the thermoplastic application process. Before running the program for the robotic arm, the operator will first power up the tension control system. Direct current will be used to power the electrical components of the system through a set of wires which branch from pre-existing electrical components on the end-effector.

The system will require the user to input the desired tension through digital interface linked to a microcontroller. Desired tension may range from 1 to 50 pounds force. The microcontroller will receive input from multiple sensors: The tension sensor will feed information to compare to the reference, and an infrared depth sensor will determine the radius of the spool to calculate the moment arm on the system model and to approximate a mass of the spool. A tachometer linked to the electric motor will feed information about the angular velocity of the feeding spool. All of this information will be sent to the microcontroller which will calculate a voltage to actuate the motor. This process will iterate in fractions of a second in order to actively control tension within the desired bounds. Information from the tension sensor will also be communicated to the operator through a digital interface. In the occasion where the thermoplastic applicator retracts from the mold, the microcontroller will actuate the motor as necessary to remove slack in the tape.

Encoded safety precautions will be developed to ensure the safety of the operator and the machine. This would include a maximum tension limit at which the system would disengage the actuating motor. Also linked to the kill switch would be a physical E-stop button. The three spool tension sensor will be an easy load/unload with an output of D/C voltage. Mechanical supports, if implemented, would be hinged for an easy load/unload of the spool.

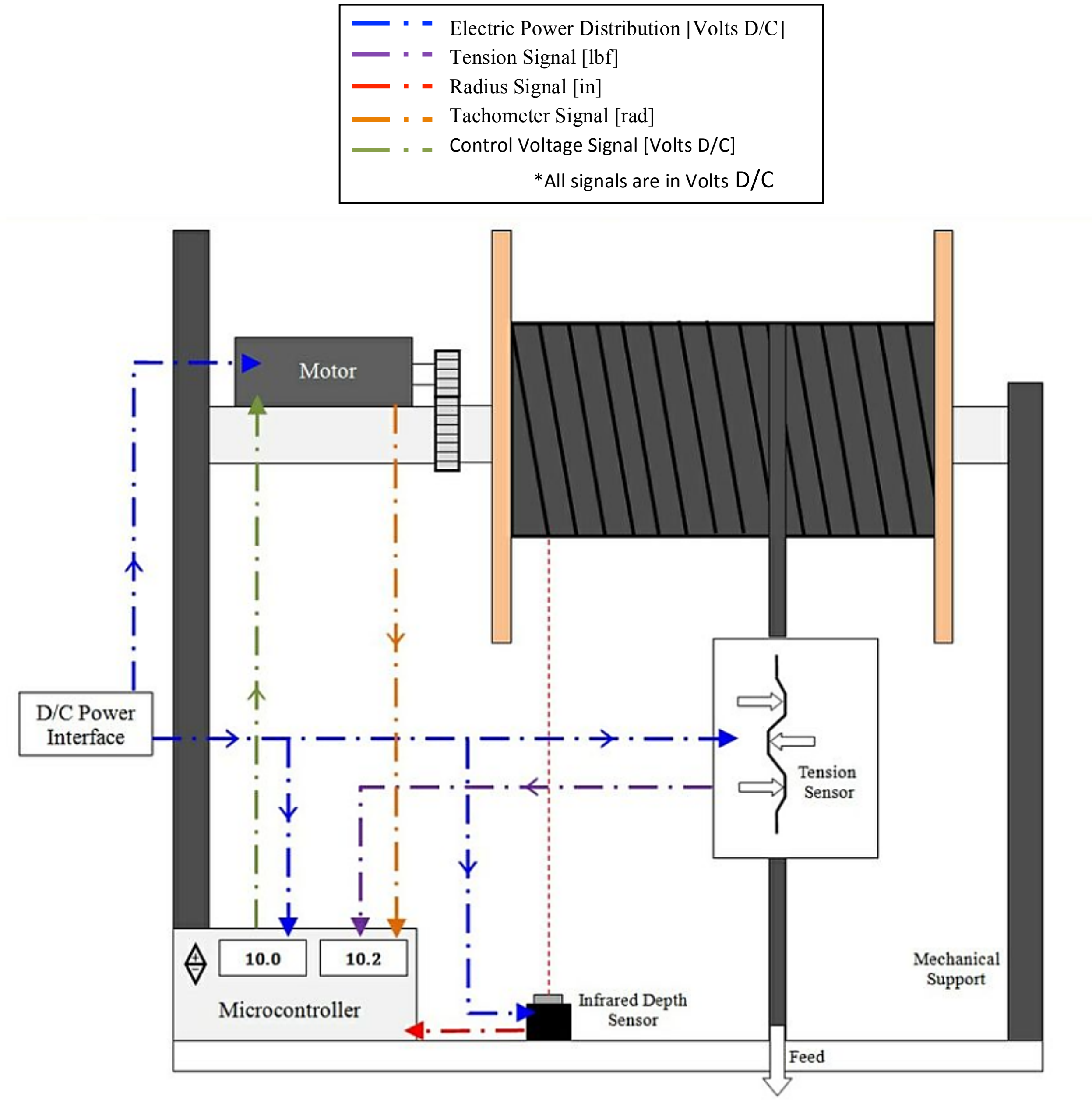


Figure 10- Concepts of Operation

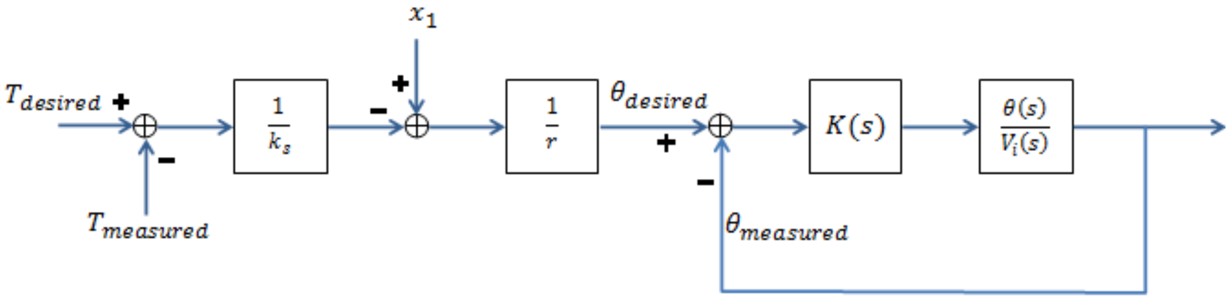


Figure 11-Block Diagram

Validate and Verify:

The control loop described in Fig. # was validated through extensive MATLAB simulation. PID controller gains were selected to limit the overshoot and give the system a fast response time. The simulation takes in a set tension and then controls the position of the spool relative to the feed of the thermoplastic onto the work piece. The simulation looks at the time response of the system when a step input is applied. Fig. #1 shows the controller tracking a steady feed rate. The theta reaches its desired value within 1 second. Similarly Fig. #2 shows the tension reaching its desired value, thus tension can be controlled directly by controlling the relative position of the spool. MATLAB code can be seen in appendix A.

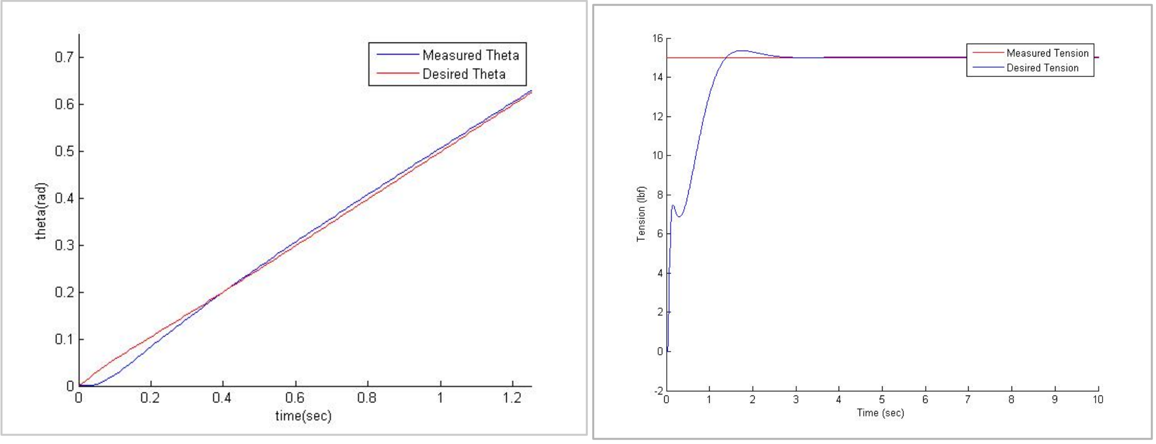


Figure 12-Position and Tension Tracking

Interfaces and ICD:

The main interface for a tension control system is the microcontroller. The controller uses all of the other components to achieve the desired tension. The tension sensor outputs a measured tension to the controller. The controller compares this data to the desired tension value, and adjusts accordingly. The algorithm within the controller is a feedback control loop includes the change in radius of the spool, the torque of the motor, and an output of the current tension value to a display. In this stage of the design, it is assumed that all components of the tension control system will be rigidly mounted to and the system will receive power from the existing end effector. Further interface details will be discussed in the critical design report.

Mission Environment:

The design of the tension control system is constrained by the mission environment. The motion of the end-effecter can be considered an environmental factor. The end-effecter goes through a series of different orientations. This consideration removes the option to use a dancer roll or any gravity dependent tension sensor. The end-effecter may induce vibrations as it works around the curvature of a mold. This might require the use of mechanical supports to reduce the error in tension measurements from this vibration. At the applicator of the thermoplastic, the temperature gets up to 800°C. Because of this, the system must be designed so that this high temperature area does not affect the electronics or the measurand itself. The robot arm of which the tension sensor will be applied to is used for indoor operation. This eliminates the option to use gas power or any other adulterating power generation. Another consideration, as for any aerospace manufacturing, is the material which is being applied. It is important not to damage the material by fraying or slicing. It is also important to reduce the amount of debris that may find its way into the lay-up of the part. Either of these would jeopardize the integrity of the final part. This also reduces the option of physically clamping the material or using friction in some way to actuate tension.

Technical Resource Budget Tracking:

Tracking resource budgets is necessary for this project to ensure the following specifications are met.

- Design weight must be less than twenty pounds
- Design size is limited to 2500 in^3
- Voltage must not exceed 24 Volts
- Minimum Tension 1 lbs.
- Maximum Tension 50 lbs.
- Tension accuracy must be within ± 0.5 lbs.

Risk Management:

The main risk of this project is failure to meet dimensional and performance related requirements. The maximum weight limit is 20 pounds, and with the current design, the only components that will come close to weighing this value are the motor and side mechanical support. These risks will be evaluated when material and a specific motor are chosen. The performance risks will be weighed during final testing of our design. Since there was no finite budget that needed to be kept, the costs will be taken into consideration but not used as an element of risk.

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.

Project Management:

In order to play to the strengths of each individual within the group, tasks have been divided up as shown in the project management structure below. Although everyone has had a specialty, there is still a lot of overlap in what each individual member will work on.

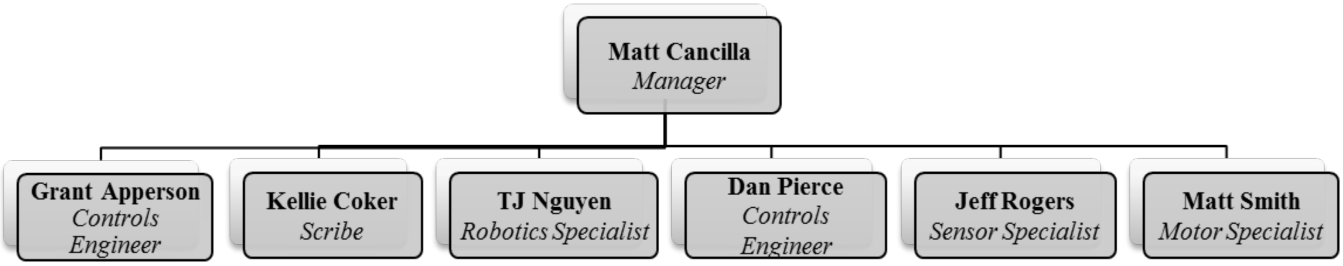


Figure 13-Project Hierarchy

Another important design element that must be kept into consideration in project management is the design cost. Although restrictions on cost are loose, our group decided to cap spending at $5,000. A bill of materials is shown below to show that our current design stays well within the $5,000 limit.

Conclusions:

Keeping the system requirements in mind, our team has determined that the best concept is one with a 3-spool tension sensor, servo motor, and IR sensor, all controlled by a microcontroller. The design will be easy to maintain while providing an accurate reading for tension.

Our group has several tasks to complete in order to get to the Critical Design Review in December. We have designed a test apparatus that will allow us to test our tension control design. As shown in the figure to the right, the apparatus will consist of 2 spools; one to represent the spool that is to be controlled by a motor, and the other to represent feed rate of the applicator. Both spools will be controlled by a motor. We plan on hitting the motor with voltages of multiple known frequencies and measuring the output. Based on this output we can develop a Bode plot, from which we can back out a transfer function between voltage and tension that can be used to control the motor. This test apparatus will be crucial to the development of the controller design.

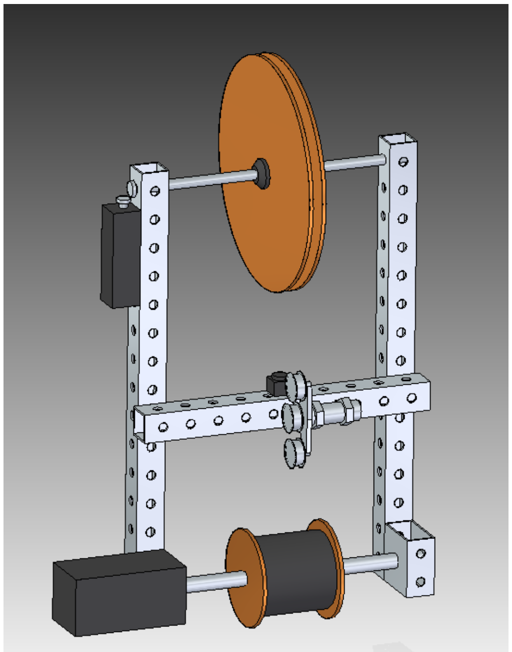


Figure 14- Future Test Apparatus

In further preparation for the Critical Design Review we plan on finalizing specific motors and sensors. We also need to take another trip to Huntsville in order to finalize the dimensions of our design. All of this will get us to the Critical Design Review. The implementation of our design should begin immediately next semester. A week-by-week chart of future work can be seen below, and a Gant chart has been included in the appendix to provide more detail.

Table 3- Future Work

Week	**Tasks to Complete**
22-Oct	Presentation Finalize Test Apparatus Design Order Test Parts at End of Week
29-Oct	Modify Design if Necessary Pick Specific Parts to Use for Design
5-Nov	Trip to Huntsville
12-Nov	Finalize Dimensions Order Parts for Build Have Test Apparatus Built
19-Nov	Thanksgiving Break
26-Nov	Test on Apparatus
3-Dec	Finals/Final Presentation

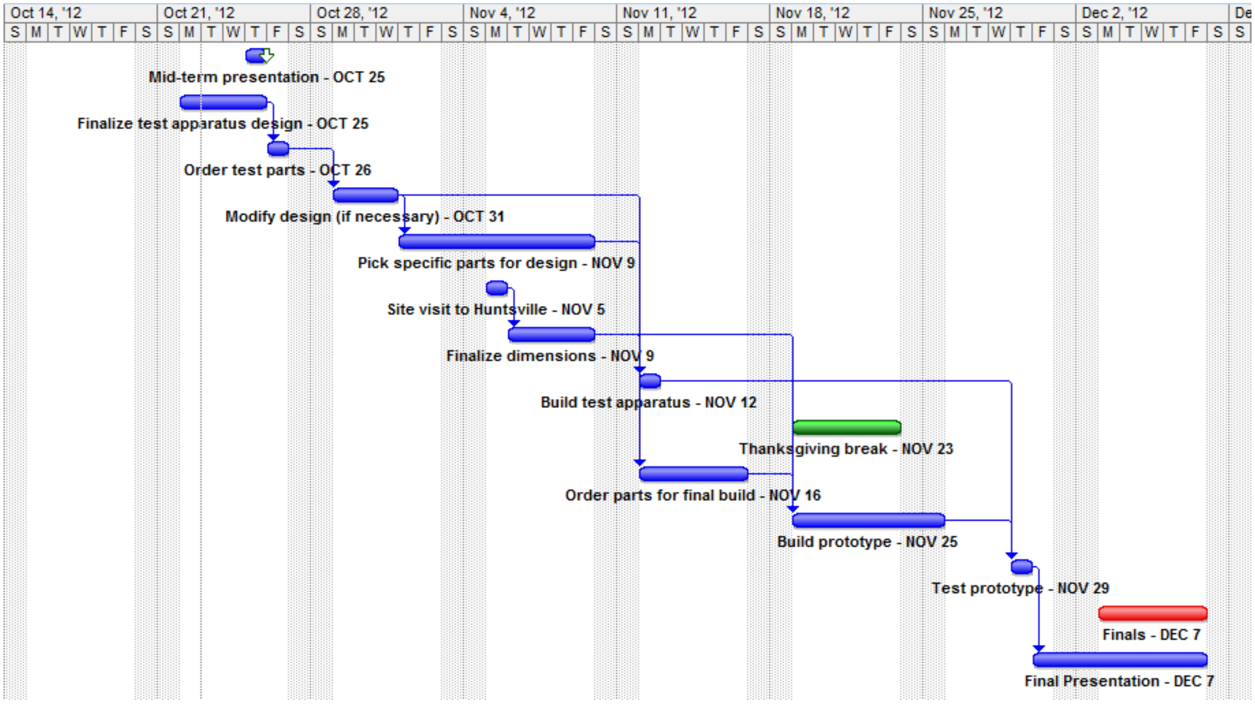
Appendix A: MATLAB Simulation

```
%AMRDEC Tension Control # 3

clc;clear all;close all;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%              constants
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
dt=.001; %sec
tf=20; %sec
time=0:dt:tf;
kT=100; %lbf/in

%Motor Constants
L=.0023; %mH   -> motor inductance
R=.13; %ohms  -> motor resistance
KT=4.314; %in-lbs/A  -> motor Torqe Constant
KB=4.314; %V-s/rad  -> motor back EMF Constant
J_motor=51.59; %lbm*in^2
Vi_max=24;%V


%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

%Spool Constants
r=4; % in
spool_length=6; %in
material_density=.0643 ;%lbm/in^3
spool_mass=material_density*spool_length*pi*r^2; %lbm
J_spool=spool_mass*(3*r^2+spool_length^2)/12; %lbm*in^2
J_total=J_spool+J_rod+J_motor; %lbm*in^2

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

%desired Tension
T_des=15; %lbf

feed_rate=2;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%        Initial Conditions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
x1(1)=0;
x1=x1(1)+feed_rate*time;
theta(1)=0;
dtheta(1)=feed_rate/r; % initially at feed rate
ddtheta(1)=0;
theta_error(1)=0;
int_theta_error(1)=0;
Vi(1)=0;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%          Controller Design
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%plant TF:  theta(s)/V(s)
num=-KT;
den=[L*J_total,J_total*R+L*b,R*b+L*kT*r+KB*KT,R*kT*r^2];
%!!!G_s=tf(num,den);

%PID Controller TF:
k_p=10; % 10, 10 and 1 w/ int_count at 100 - stable
k_i=10;
k_d=1;
K=k_d;
a=k_p/K;
b=k_i/K;

%!!K_s=tf([1,a,b],[1,0]);
% %H_LT=-H_plant*H_sensor*H_controller;
%
%!!A=(1/(kT*r));
%!!H=-kT*r;

%!!H_LT=-A*K_s*G_s*H;
%rootlocus
%!!rlocus(H_LT)

% Simulating step Response
% H_FP=H_controller*H_plant;
% H_FB=H_sensor;
%!!!!CLTF=A*K_s*G_s*H/(1+A*K_s*G_s*H);
% % 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
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
int_count=0;
for q=1:length(time)

    T_meas(q)=kT*(x1(q)-theta(q)*r);


    T_error(q)=T_meas(q)-T_des;
    theta_error(q)=T_error(q)/(kT*r);
    dtheta_error(q)=-dtheta(q);

    Vi(q)=k_d*dtheta_error(q)+k_p*theta_error(q)+k_i*int_theta_error(q);
    if Vi(q)>Vi_max
        Vi(q)=Vi_max;
```

```
    else if Vi(q)<(-Vi_max)
            Vi(q)=-Vi_max;
        end
    end
    dddtheta(q)=(-(J_total*R+b*L)*ddtheta(q)-(R*b+L*kT*r^2+KB*KT)*dtheta(q)-
(R*kT*r^2)*theta(q)+feed_rate*r*kT*L+x1(q)*r*kT*R-KT*Vi(q))/(J_total*L);
    ddtheta(q+1)=ddtheta(q)+dddtheta(q)*dt;
    dtheta(q+1)=dtheta(q)+ddtheta(q)*dt;
    theta(q+1)=theta(q)+dtheta(q)*dt;

    int_theta_error(q+1)=int_theta_error(q)+theta_error(q)*dt;

    theta_des(q)=(x1(q)-T_des/kT)/r;
    %clear integral control
    int_count=int_count+1;
    if int_count == 100;
        int_theta_error(q+1)=0;
        int_count=0;
    end
%     if abs(T_error(q))< 1;
%         int_theta_error(q+1)=0;
%     end
end


% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %          Plotting Results
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
hold on
plot(time,T_des)
plot(time,T_meas)
xlabel('Time (sec)')
ylabel('Tension (lbf)')
legend('Measured Tension','Desired Tension')
hold off

figure(2)
hold on
title('Position Tracking')
plot(time,theta_des)
plot(time,theta(1:(length(theta)-1)),'r')
ylabel('Theta(rad)');
xlabel('Time(sec)');
legend('Measured Theta','Desired Theta')
hold off

figure(3)
hold on
title('Motor input Voltage')
plot(time,Vi)
xlabel('time(sec)');
ylabel('Voltage (V)');
hold off
```

Appendix B: Gant Chart



Appendix C: Bill of Materials

Part	Quantity	Cost
Arduino Mega 2560 Microcontroller	1	$38.95
Motor and Gear Box*	1	$1,500
Sharp IR Sensor	1	$14.50
Sabertooth 2x25 Motor Controller	1	$124.99
Lumex LCD	1	$24.58
TERX Tape & Band Tension Sensor + Amplifier	1	$1,500
Automation Direct Incremental Encoder	1	$90.00
Test Apparatus Supplies	1	$500.00
	Total	$3,793.02