EZ-Labels Inc.	On-Demand Labeling

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We Make the Cut

Sponsor: Gerald E. Finken, *Clinical Supplies Management Inc.*	Engineers: Nathan Cheadle Natecheadle@gmail.com Lorne Stoops LorneStoops@gmail.com Tony Wang Tonywang91@gmail.com Robert Zimmerman RZimmerm@calpoly.edu	Purpose: To create a die-cutting machine capable of producing pharmaceutical labels of varying size.

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Introduction

Team EZ-Label has been formed to provide an innovative solution that satisfies the need of Mr. Gerald E. Finken of Clinical Supplies Management (CSM) Inc. to print clinical trial prescription drug labels on demand. Printing labels on demand drastically differs from the current method of producing pharmaceutical trial labels and requires a machine that will assist in streamlining this new process. The final product will have, but is not limited to, the following basic characteristics:

- Print and cut labels of varying size
- Integrate the printing and cutting operation into a single device
- Be Portable

The original project proposal was to design and build a thermal transfer printer, label cutter, and auto-inspector for making labels that are used on prescription drugs in clinical trials. After a meeting with the sponsor and project advisor, it was decided that Team EZ Labels will focus on designing a label cutter that can quickly cut labels of varying size.

Through testing and analysis it was determined that the most effective design will use a cutting wheel that is able to move along an x and y axis. This decision was made by testing different cutting methods, and finding that the wheel cutter had the largest tolerance of acceptable applied force for cutting through the label and not the backing. It also holds other advantages over a laser and drag blade. With the wheel there is no need for ventilation of the cutting space, or the possibility to catch and tear the label stock. The x-y axis motion was chosen because this method offers the capability of cutting complex shapes with a reliable mechanism design. Ultimately, this product will reduce the time and resources required to produce clinical trial labels, resulting in significant savings for CSM Inc.

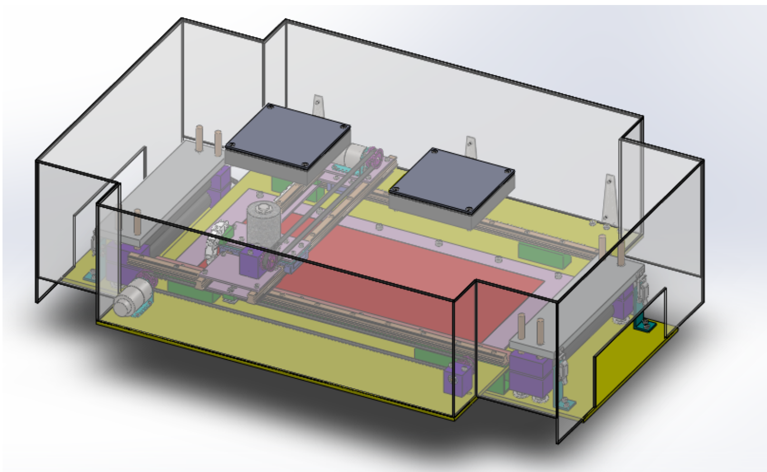

Figure 1. Solidworks model of Final Design

Background

Currently labels for clinical trials are printed on pre-cut label rolls weeks before patients have signed up for a trial. For each different sized label a different roll of pre-cut label stock needs to be purchased. Each clinical trial will require different sized labels, and each trial package requires different sized labels for the different items in a package. The traditional approach to satisfying clinical trial orders has been to produce all the prescription packages before the trial begins and then distribute the medications as individuals sign up for the trial. This requires warehousing the prescription drugs and printing more labels than will actually be used. This warehousing and wasted product is costly. The process of printing the labels is also very time intensive when each different size of label needs to be loaded into the printer separately.

Many of the regulations for prescription labeling come directly from the Federal and Drug Administration (FDA). These regulations require that the label clearly convey prescription information even after exposure to water, blood, alcohol, or rubbing. The labels must also be printed in color to provide clear instructions. The FDA also requires 200% inspection of the labels to make sure that all labels are printed correctly and accurately. Another important requirement for labels used in clinical trials is to make sure that there is no visible difference between drug kits. This is to make sure that the trial stays blind, meaning that the patient cannot determine whether the medication is a placebo or not.

Specific FDA regulations relevant to drug labeling include:

21 CFR 201 (FDA, 2012)

- Includes all FDA regulations that are directly related to labeling
- Almost all regulations in regards to content of label, not label itself

21 CFR 201.56 (FDA, 2012)

- Summary for the safe and effective use of the drug
- Informative and accurate
- Not promotional, false, or misleading
- No implied claims or suggestions for use if evidence of safety or effective is lacking
- Based whenever possible on data derived from human experience

21 CFR 210 (FDA, 2012)

- Overviews good manufacturing practice regulation and investigational new drugs
- Stage 1 clinical trial generally includes no more than 80 subjects
- Stage 2 & 3 trials can include substantially more subjects
- Stage 2 & 3 allow drugs to be used for treatment

21 CFR 210.1 (FDA, 2012)

- Status of current good manufacturing practice regulations

21 CFR 211.63 – 211.68 (FDA, 2012)

- Overviews the needs and the manufacturing requirements for equipment used to make labels in clinical trials

21 CFR 211.122 – 211.130 (FDA, 2012)

- Reviews the practices that should be followed for the packaging and shipping of prescription of drugs.

21 CFR 211.184 (FDA, 2012)

- Overviews the requirements for recording and reporting shipments and packages in the prescription drug market.

21CFR Part 11 (FDA, 2012)

- Overviews the need for change tracking in any computer programs that are used in conjunction with the manufacture of prescription drugs

There exist three major methods that are suitable for cutting prescription labels. The first and most common method currently in use is a stamping die. The die can be flat and stamp the label by moving vertically (Platen Press); or the die profile can be contoured over a cylinder and the labels are cut as they feed under this roller (Rotary Die Cutter). Both of these types of die cutting use a machined die to cut out hundreds of thousands of labels to the exact same size. This is economical for mass production, but can take hours to reset the machine with a different die, and cut a different size label. The equipment and dies are also extremely large and expensive. Once a die is machined it is only capable of cutting a single design, and thus is not versatile enough to meet the needs of CSM's on demand process.

The second method uses a computer guided blade to cut out a shape. This blade is able to cut at a specific depth so the label backing can be peeled off and removed. This method allows many unique shapes to be cut, but does not allow for as large a scale of production as stamping dies. These machines are complex, and in order to provide the greatest degree of versatility, they are very large in order to provide more cutting area. Individual sheets must be placed into the cutting area for each run. This method is an applicable cutting method to satisfy the needs of CSM, but a more unique device that is specifically tailored to smaller, roll fed material is needed.

The third major method currently on the market that could cut out prescription labels is a laser cutter. The laser cutter runs at about the same speed and accuracy as the blade cutter, but

has the advantage of not requiring the cutter to be replaced. Depth of cut is easily changed by adjusting the power setting of the laser. However, the laser system is more expensive than the drag knife blade system, and also requires ventilation of the cutting area; therefore a laser solution cannot be portable if it is to require a ventilation system designed for a specific room or building.

Table 1. Pertinent data of commercial products

	ROLAND SV-15	Universal VLS 3.50	KAMA ProCut74
Type	Desktop Vinyl Cutter	Laser Cutter	Platen Press
Max Cutting Area	13.25" x 39.25"	24" x 12"	23.6" x 29.1"
Cutting Speed	0.44 - 3.88 in/min	Not Listed	5000 sheets/hr
Max Material Thickness	0.004 in	50 W laser max	1.8 mm
Weight (lb)	7.3	95	6000 estimated
Cost (USD)	1095	6000	20000+

Objectives

Our team is working to design a device that will be able to accurately cut prescription drug labels of various sizes. The labels will first be thermal transfer printed on a continuous roll feed of label stock, and then be fed into the label cutter. The EZ Labels team worked with Mr. Finken to define the scope of this project and understand what capabilities the final design should have.

It is understood that this prescription label die cutter will meet the following requirements:

Functional Performance

- Quickly satisfy orders
- Accurately cut labels
- Be able to perforate label and backing
- Cut from a continuous roll feed of label stock
- Cut different label materials
- Cut label stock of varying thickness
- Cut variably sized rectangular labels
- Be reliable

Human Interaction

- No open access to cutting device
- No toxic exposure to user
- Include handholds for easy lifting and relocation
- Minimal user involvement
- Can be operated by one person

Physical Requirements

- Be portable
- Fit on service cart
- Able to roll through a door
- Operate in an office space

Life Cycle Concerns

- Device should be highly serviceable, have easy access to critical components
- Device should be recyclable at end of operating life

Resource Concerns

- Interface with printer and computer by a common file type
- Function with label stock at least six inches wide.

Manufacturing Concerns

- All parts can be manufactured without CNC control
- Not require components to be welded
- Have Readily available parts

Safety is of course the most critical requirement. Team EZ Labels will work diligently to ensure the safety of the operator. Mr. Finken has also identified the requirement of accurately cutting labels to be one of critical importance. From this list of customer requirements, the quality function deployment (QFD) method was used to establish a set of engineering specifications that the final design should meet.

As a result of working through the quality function deployment model, Team EZ Labels was able to rank the relative importance of the engineering specifications. From this process a better understanding of the influence each requirement has on the engineering specifications was developed. This allowed the importance of each specification to be quantified, resulting in concrete values that can be designed towards. Analyzing the relationship between the customer requirements and engineering specifications led the team to think about how each customer requirement may influence the design. If there is a strong relationship between a specification and requirement, then that specification is numerically ranked with a larger number. Ranking the influence each specification has on the fulfillment of each requirement allowed the team to more objectively determine which specifications are most influential in satisfying the customer requirements. See appendix A for complete QFD table.

From the QFD process the engineering specifications were ranked as follows:

Table 2. Relative ranking of engineering specifications

Engineering Specification	Relative Importance %
Cutting speed	100
Cutting tolerance	97
Setup time	93
Overall Machine Size	87
Cutting range	85
Feed Speed	76
Depth of cut Variability	76
Total Weight	55
Teardown time to major components	47
Life of cutting tool	29

The final design for this project should meet a set of both Quantitative and Qualitative requirements. Qualitative requirements pertain to certain characteristics the final design must have. The quantitative requirements are specific values that the final design must meet with regard to performance, operation, and physical constraints.

Qualitative Requirements

- Perforates Label
- No open access to cutting device
- No Toxic exposure to user
- Includes hand holds for easy lifting and relocation
- Recyclable
- Interface with printer using a common file type
- All parts can be manufactured without CNC control
- Not require components to be welded

Quantitative Specifications

- Total Weight: 50lbs maximum
- Feed Speed: 2.25 in/min minimum
- Cutting Speed: 17 in/min minimum
- Cut rounded corners of 0.125 inch radius minimum
- Cutting Tolerance:
    - Size of Rectangle ±0.031 in
    - Location of Text Relative to Label Edge ±0.031 in
    - Perpendicularity of Label Edges 0.040 in
    - Depth of Cut $^{+0.001}_{-0.000}$ in
- Label Thickness Range: 0.002-0.005 inches
- Overall Machine Size: 43 inches long, 25 inches wide, 24 inches tall maximum
- Cutting Range: 9 inches wide, 20 inches long
- Setup Time: 10 minutes
- Teardown Time to Major Components: 15 minutes
- Life of Cutting Tool: 80000 inches

Design Development

Over the course of several meetings with Mr. Finken, a set of requirements were established that the sponsor would like the product to satisfy. Once the requirements were established, further research was performed to narrow down possible technologies currently on the market that would be influential to the project design. A number of conceptual designs were conceived and analyzed to determine which best satisfies the need of CSM. At this point in the design process the EZ label team has narrowed the proposed ideas down to a single concept model that should effectively satisfy CSM's need for a variable label cutter.

Going into the design phase of the project, many ideas had already been considered during the design requirements stage. But to make sure no ideas would be overlooked, a brainstorming session took place where any and all ideas were put on a whiteboard under the categories: How Does it Cut Variable Path, How Does it Feed Stock, What Does it Cut With, Cutting Depth Control, and Power. Some notable ideas are listed in the table below.

Table 3. A sample of interesting ideas that were considered but ultimately ruled out

Cutting Path	Feed Mechanism	Cutting Depth	Power
Single Axis Motion	Lift and Place Geneva Mechanism	Cam and Follower	Electric
Lone Robot	Gravity	Linear motion and Hardstop	Hydraulic
Beam Steering Mirror	Robotic Suction Cups	Gear Rack and Pinion	Pneumatic

The ideas in the categories of "How does it cut", "What does it cut with", and "Cutting depth control" were then brought together in every possible combination, yielding 378 potential solutions in what is known as a morphological matrix. Upon initial review of these potential solutions, many were eliminated based on "feasibility". This criterion is simply the engineering intuition of our team to make an educated decision of which ideas are most likely to succeed. The complete morphological matrices can be found in Appendix A.

Certain ideas were eliminated for the following reasons:

- The use of lasers as a cutting tool was ruled out due to the requirement for ventilation. The device could not satisfy the requirement for portability if the room in which it would operate requires air ducting to the outdoors.

- Stamping blades were ruled out as a cutting tool due to the inability of pre-formed blades to cut custom complex shapes.

- The use of a stationary cutter head was ruled out because this method would require the label to move in two axes. A continuous label feed is only suited to move along the feed axis.

- Cutters that exclusively move in one axis cannot be used to cut rounded corners.

- A small blade that repeatedly stabs to cut small sections as it moves along the cut path would provide a more ragged cut and also be less reliable due to the high number of stabbing cycles.

- A robotic arm to control the cutting path would require the system to operate in more complicated polar coordinates. Deflection at the end of the arm is also an important factor when a very precise depth of cut is required.
- Controlling the depth of cut by moving the label up and down would be more complicated than moving the cutter head.

- Controlling the depth of cut by inserting different sized blades into the device would not offer the capability of lifting the cutter up to create perforations.

After eliminating some of the ideas in each category, the matrix results were significantly narrowed down to 14 feasible concepts that were then more closely investigated.

Table 4. Decision matrix ranking of feasible concepts

Ideas	Reliability 30% (10 Reliable)	Versatility 25% (10 simple)	Safety 32% (10 safe)	Repairable 13% (10 easy)	Total
Cam; Cartesian CS; Single Blade	6	7	5	4	5.67
Cam; Cartesian CS; Wheel Cutter	7	6	6	4	6.04
Cam; Move Label Feed Axis; Single Blade	4	7	5	4	5.07
Cam; Move Label Feed Axis; wheel Cutter	5	6	5	4	5.12
Hardstop; Solenoid; Cartesian CS; Single Blade	7	5	5	6	5.73
Hardstop; Solenoid; Cartesian CS; Wheel Cutter	8	4	5	6	5.78
Hardstop; Solenoid; Move Label Feed Axis; Single Blade	5	5	5	6	5.13
Hardstop; Solenoid; Move Label Feed Axis; Wheel Cutter	6	4	5	6	5.18
Actuator; Cartesian CS; Single Blade	5	7	5	5	5.5
Actuator; Cartesian CS; Wheel Cutter	6	6	6	5	5.87
Actuator; Move Label Feed Axis; Single Blade	3	7	5	5	4.9
Actuator; Move Label Feed Axis; Wheel Cutter	5	6	5	5	5.25
Applied Force; Cartesian CS; Wheel Cutter	9	8	5	5	6.95
Applied Force; Move Label Feed Axis; Wheel Cutter	7	6	5	5	5.85

For each concept design a score between 1 to 10 was given in categories of Reliability, Versatility, Safety, and Reparability. The score for each design was determined by setting the score to 5 as default and adding or subtracting points based on each defining characteristic.

For reliability- hardstops, wheel cutter, and cartesian coordinates were given +1 while actuator and label feed were given -1. Hardstops were seen as more reliable because the height would be extremely consistent assuming it is made out of hard enough material. A Wheel cutter is less likely to tear the label and deemed safer than a drag knife. Actuators were less reliable because it is harder to control its motion compared to a cam or hardstop. Label feed was also deemed less reliable because it would involve more and bigger moving parts to function properly.

For the versatility category- the cam, single blade, and actuator were given +1 and hard stop was given a -1. Both Cam and actuator received a +1 because unlike hard stops, a continuous range of depths can be cut. Hard stop received a -1 since it can only cut at one specific depth per hard stop. A single blade design was considered more versatile because of its ability to cut sharper corners than cutting wheel.

For safety- label feed, single blade, and solenoid were all given -1. By feeding the label it creates more moving parts outside of the cutting area that a worker can get articles caught in. The blade was deemed less safe than the cutting wheel so it received a -1, while cutting wheel got a +1. Solenoid was also given a -1 because it produces an abrupt force creating a potential pinch hazard.

The final category was reparability. Hard stops were given a +1 because it is an extremely simple design and would be easily replaced. Cam was given a -1 because it involves more unique moving parts which would make repairing/replacement more complex.

Each category was then weighted, with safety being the highest at 0.32. Reliability was given a 0.30 because in the interest of productivity the final device should not need to be constantly adjusted and repaired. Versatility was given a 0.25 because a major point that the sponsor made was that the product should anticipate future needs of CSM and be capable of satisfying future demands. This means creating a device that is able to cut labels of different thicknesses, stock of different widths, and cut complex shapes. Reparability was rated 0.13 because if the product is reliable then it would not require much repair. Also the product will be designed with easily acquired parts which should make finding replacement parts simpler.

Table 5. Top 3 concepts gleaned from matrix ranking

Top 3 Results	Score
Applied Force; Cartesian CS; Wheel Cutter	6.95
Cam; Cartesian CS; Wheel Cutter	6.04
Actuator; Cartesian CS; Wheel Cutter	5.87

From these results it is easy to see that Cartesian coordinates and cutting wheel were the best method. To determine whether applied force, cam, actuator, or even hard stops would be the best method some testing was performed. We took force measurements with two different cutting wheels to see what range of force would provide an acceptable cut. From our tests it was found that the actuator or cam must be able to position the cutter with a dimensional tolerance of $^{+0.001}_{-0.000}$ in, while the applied force method allows for a tolerance of ±0.5 lbs. The tolerance with respect to force is a much easier design target to achieve.

All three ideas use the Cartesian coordinate system and cutting wheel. This method would allow the cutting wheel to move along two perpendicular axes simultaneously providing the ability to cut labels of any shape.

Description of Final Concept

The final concept contains four distinct mechanisms that work together to provide the kind of on demand label cutting capability that CSM has requested. These mechanisms are the inlet feed, outlet feed/tensioner, cutter unit, and cross arm. These subsystems work together to provide one complete cutting operation.

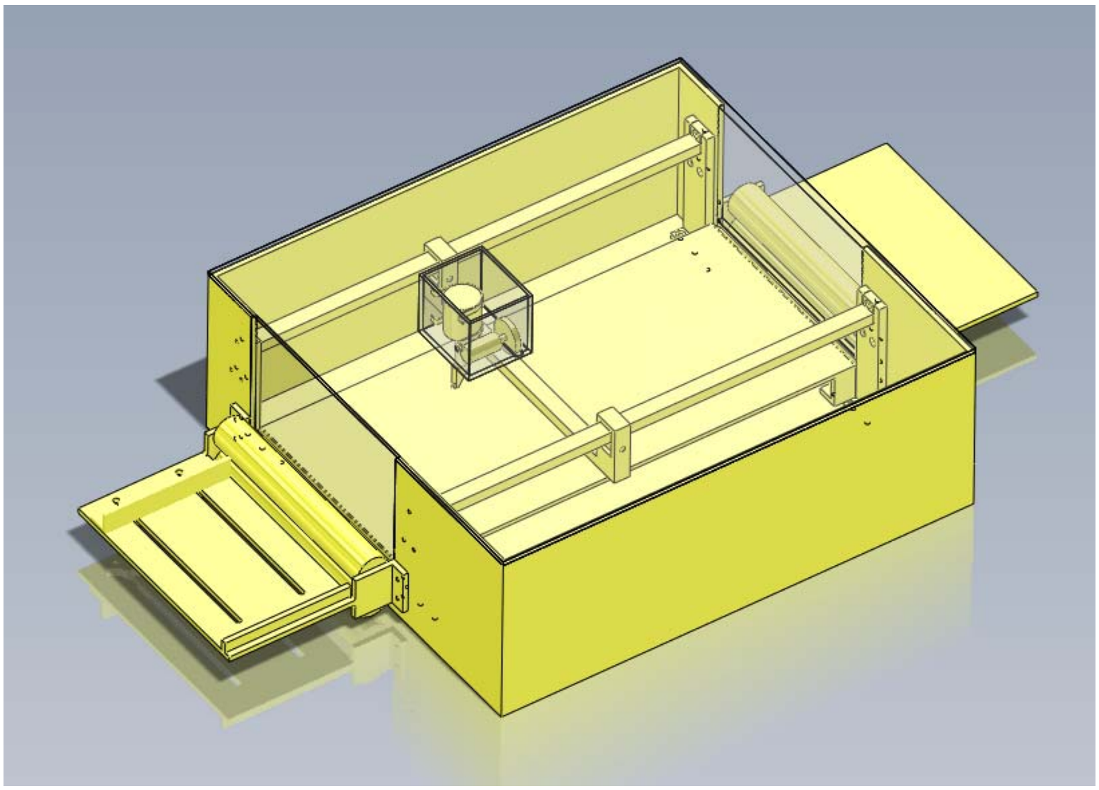

Figure 2. Overall depiction of label cutter

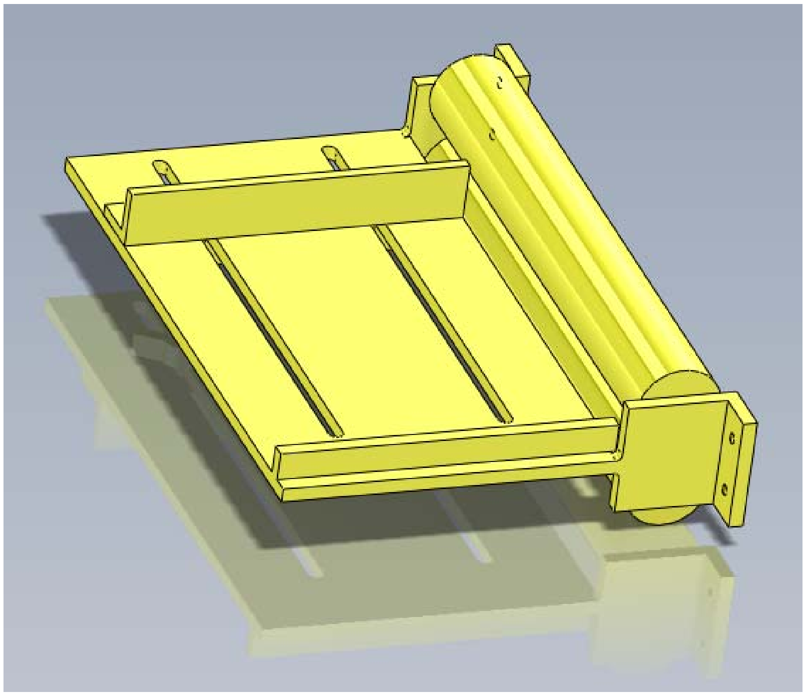

Figure 3. Inlet feed mechanism

The inlet feed mechanism receives the printed label and pushes the label until it reaches the outlet feed rollers. Two powered rollers pinch the label between them and provide the force necessary to move the label. A simple, adjustable guide is used to ensure the label enters the rollers straight. Because there is no slip between the label and rollers, if the label enters the rollers straight, it will feed into the cutting area straight. The free end of the label moves across the cutting area until it is picked up by a second set of driven rollers at the outlet feed/tensioner mechanism.

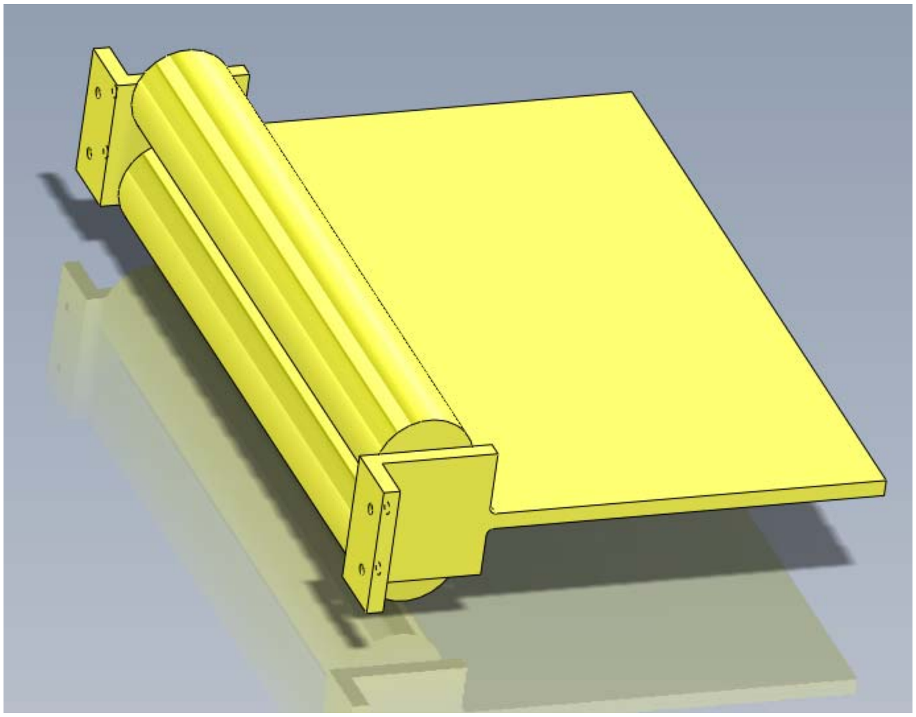

Figure 4. Outlet feel/tensioner mechanism

The second set of rollers at the outlet is also driven so as to automatically pick up the free end of the label after it crosses the cutting area. Upon reaching the second set of rollers, both sets will stop feeding and no longer be able to rotate. At this point the second roller set will move vertically downwards to tension the label over the cutting surface. It is important to secure the label flat over the cutting surface to provide an accurate cut. The next step is to locate the label text around which label shapes must be cut.

Locating the label text relative to the coordinate system of the label cutter is critical in order to accurately cut shapes around the text. To accomplish this, a specific grouping of black dots will be printed near the edge of the label stock. These dots will not appear on the final prescription label product, they are merely printed in unused space on the label stock. An optical sensor on the cutter unit will "find" these black dots to establish the location of the label text based on the information provided by the computer file containing the label text information and formatting.

In summary up to this point this point the label has been fed into the die cutter, tensioned over the cutting surface, and the location of the label text has been identified by the sensor. Now the labels can be cut by moving the cutter unit over the cutting surface and pushing the cutting wheel down using a solenoid.

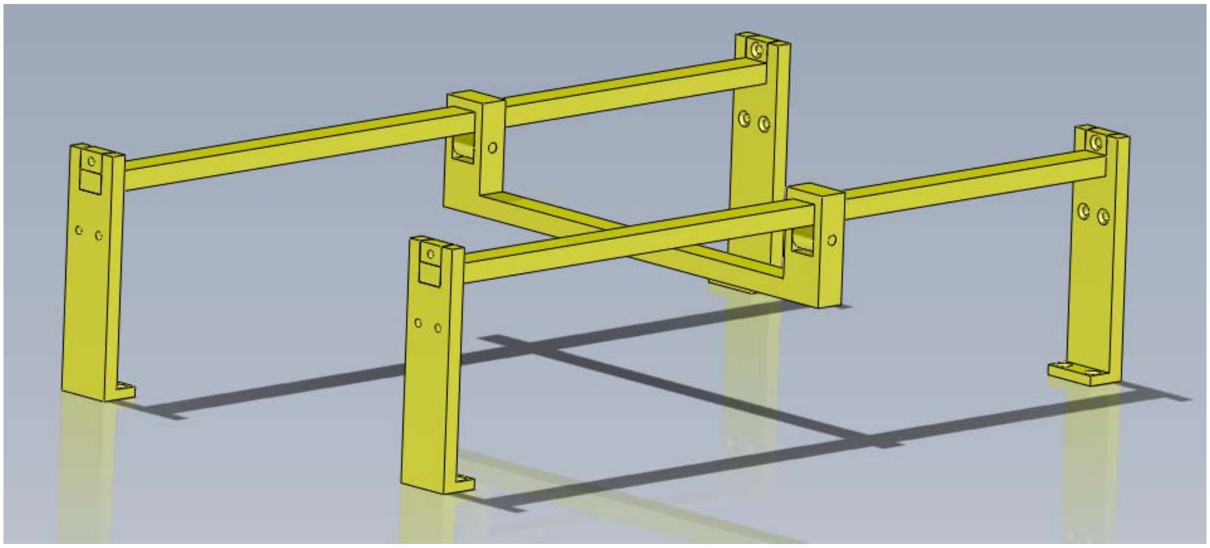

Figure 5. Cross arm

The cross arm is a simple mechanism. It too uses a rack and pinion gear system driven by a motor with an optical encoder. The arm itself serves as a track over which the cutter unit can move. The cross arm itself moves on a track parallel to the label feed direction. The optical encoder again serves to accurately locate the position of the cutter along this second axis of motion. The cross arm and cutter unit move together to provide full motion control capable of tracing any shape. When the labels are finished being cut, the outlet rollers will move vertically upward to release the tension on the label, and both roller sets will feed the label out of the device. This entire operation is expected to take no more than five minutes.

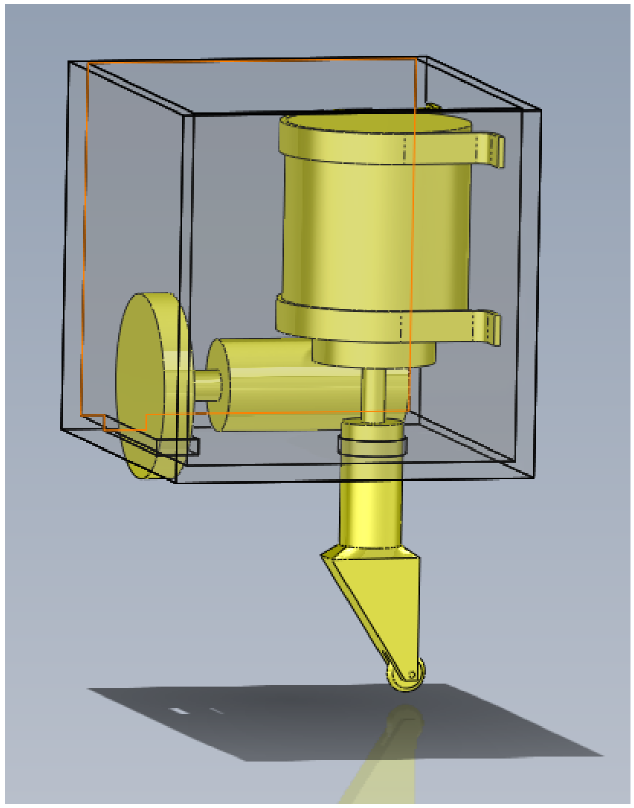

Figure 6. Cutter unit

The cutter unit contains 3 major components. First is the cutter itself which has been previously described. The cutter is a sharpened wheel that is free to swivel, and is pushed onto the label with a specific force by use of a solenoid. The second component is the optical sensor that is used to locate the label text. Third is a motor which uses a rack and pinion gear system to move the cutter unit back and forth along the cross arm. The position of the cutter unit along the cross arm can be precisely established through the use of an optical encoder on the motor. The optical encoder will provide a signal that can be used to compute the number of degrees of revolution the motor has turned. This information will be used to calculate the position of the cutting wheel along one axis. The cross arm itself also moves to provide motion along a second axis.

The cutting wheel is a wheel where the outer edge is sharpened into a blade. The blade is then secured onto an axle, and by pushing and rolling the blade along the label, is able to cut through it. The blade angle on the wheel is important in determining how much force must be applied to completely cut through a label. Out of the two cutting blades that were tested, the glass cutter blade was found to be superior to the paper cutter. The glass cutter uses a durable tungsten carbide cutting wheel. The wheel is of a small diameter making it better suited for cutting rounded corners. The blunter blade angle also allows for a greater range of applied force to provide a suitable cut.

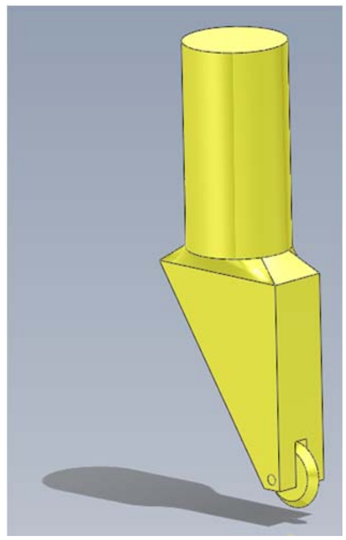

Figure 7. Offset cutting wheel design (Appendix A-1)

The “Cam” concept would use a cam to adjust the vertical height of the cutter. The shape of this cam determines how far the cutter will move per degree of revolution. Manipulating this cam profile would allow great flexibility in controlling the vertical position, velocity, and acceleration of the cutter. The hard stop-solenoid method uses a solenoid to push the cutting mechanism into a hard stop which would control the depth of the cut. Both these ideas however were ruled out due of the extremely tight dimensional tolerances required to completely cut the label but not the backing. The cam design is also a more complicated mechanical system.

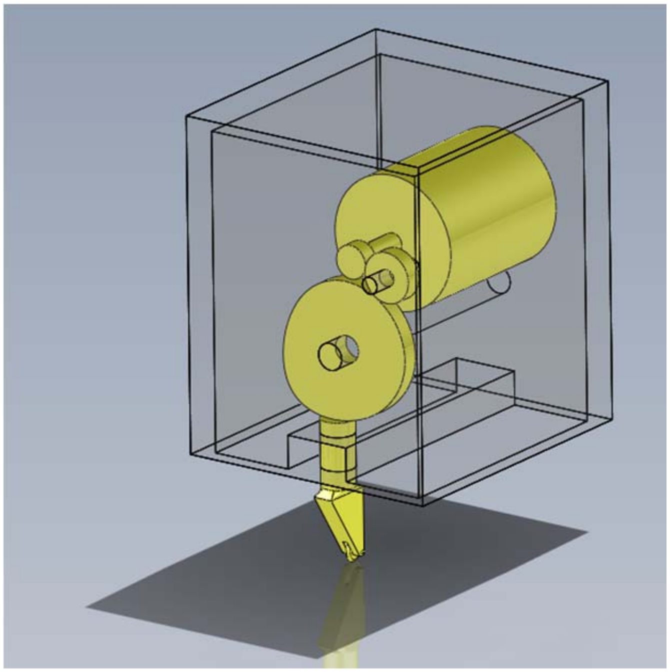

Figure 8. Cam concept for adjusting z-axis height

Using a solenoid to apply a specific force was decided to be the best method in controlling the depth of cut. The depth of cut can be controlled by the amount of force applied. This force can be varied by changing the voltage sent to the solenoid. With this method the resolution in what force is appropriate to cut through the label and not the backing depends on the cutting blade. An X-Acto style blade with a very fine point will penetrate both the label and backing with even a very small amount of force and is thus not suitable for the design. The more acute blade angle of a paper cutter wheel had a distinct force range for cutting which ranged from .9lbs to 1.5lbs, but because of the large wheel diameter and flimsy blade it too was ruled out. The glass cutting wheel had the largest resolution for providing an acceptable cut with a range of 3.5lbs to 4lbs for an ideal cut and 3.5lbs to 5lbs for an acceptable cut. It also has a smaller, stronger blade which would be more durable and versatile in the final product. The use of a solenoid is also a very simple and reliable mechanism.

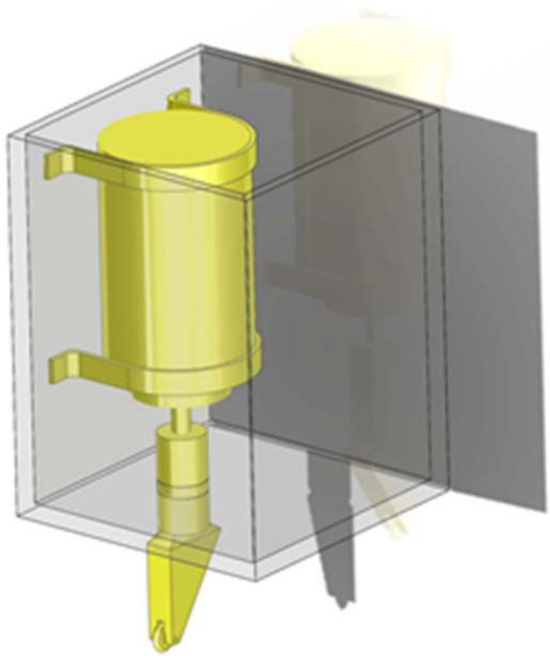

Figure 9. A simple picture of the solenoid concept inside of a transparent housing

Fabricating the cutter would involve mounting a small diameter (0.2in) cutting wheel of moderate blade angle to a fixture that would allow it to swivel about the axis of the solenoid shaft. The wheel is positioned slightly off axis, which allows the cutting wheel to passively swivel and follow the motion of the housing unit much like a shopping cart wheel.

Preliminary Testing:

Testing was done to determine the best method of cutting through the label stock. Three different styles of cutting blades were tested:

- "Olfa" 18 mm Rotary Cutter
- "Red Devil" Glass Cutter
- "X-Acto" knife.

These three blades were tested by applying a range of forces and analyzing the quality of the cut. The force required to move the cutter over the label was also measured for an applied force that provided a suitable cut.

A few main points were gleaned from this testing. The first is that using a force to determine the depth of cut works well for the two rotary blades, but is ineffective for use with the "E-Xacto" Blade. The second is that the glass cutter provided the largest range of force that cut the label without cutting the backing. Finally, the dimensional tolerance for using an x-acto style blade to provide a clean cut is a slim $\begin{smallmatrix}+0.001\\-0.000\end{smallmatrix}$ in, meaning that the label must be cut entirely through (-0.000) and the backing can be cut into up to +0.001 inches.

The solenoid that will be used in the final design was also tested. Though the manufacturer provides force curves, EZ Label wanted to test the solenoid that was received to verify with the manufacturers data. The results from testing matched closely with the manufacturer's data. By testing the solenoid, the team was also able to determine the optimal operating point of the solenoid. This is extremely important due to the fact that many other dimensions of the cutter will be based on the operating stroke length of the solenoid. With an appropriate stroke length chosen, dimensions can be finalized and so production can begin.

Another important factor that will need to be tested is the ability of the various cutting wheels to take corners. This will allow us to determine the minimum cut radius that can be done with the machine. It still needs to be determined how accurately an off axis following cutting wheel follows the path of the solenoid axis.

Also, a system that optically registers the location of the label text on the cutting plane must still be designed and tested. First the location of the label text must be precisely defined, only then the rest of the system accurately cut the label shape relative to the text location.

Final Design

The final design was developed by beginning with the concept model, and developing all of the individual components that would either need to be purchased or manufactured. The full and complete solid model of the device can be seen below in Figure 10.

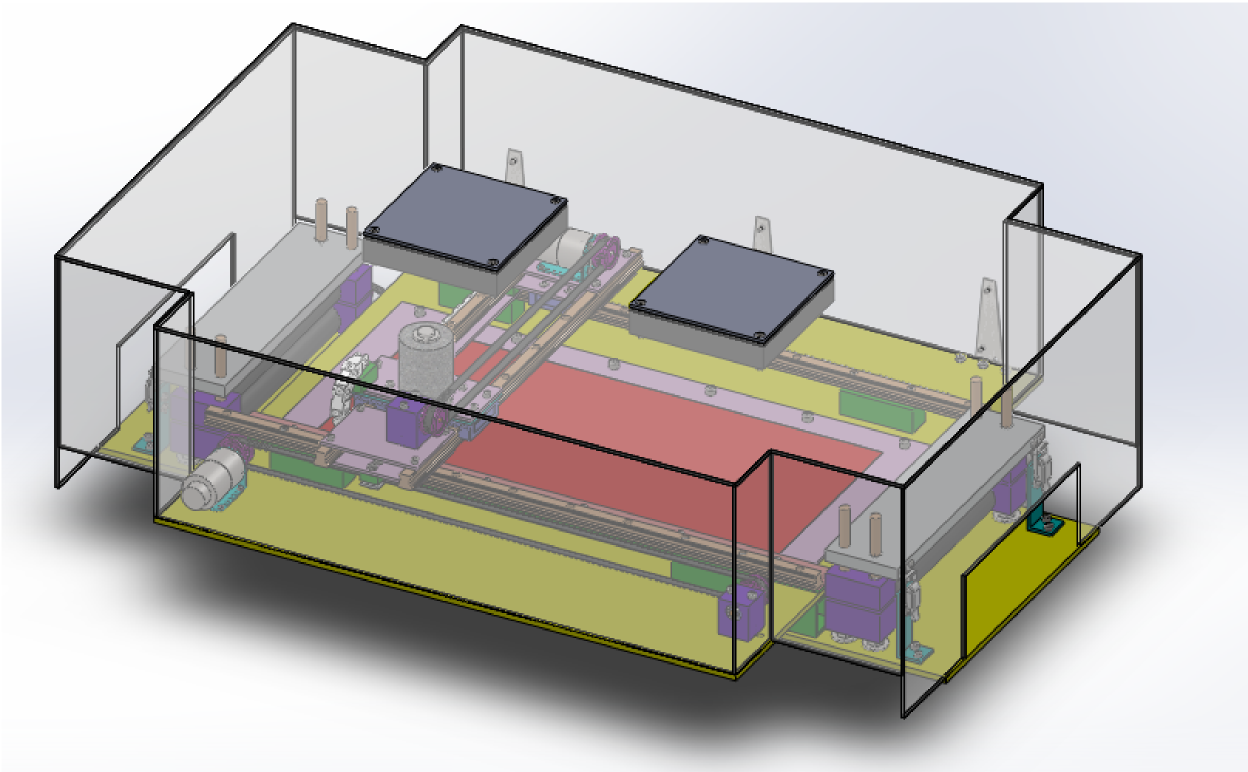

Figure 10. Solidworks model of final design

Cutting Area:

Figure 11. Cutting surface as mounted

As shown in Figure 11, a replaceable cutting surface will be attached to the main plate structure. This surface must be hard to provide a clean cut by the cutting wheel and so 0.125 inch aluminum plate is used. The aluminum plate will become scratched by the tungsten carbide cutting wheel when the label backing is cut clean through, but since a majority of cuts will not cut through the backing, the cutting surface should last a while before needing to be replaced. The exact amount of time is yet unknown, but will depend on the frequency of through cuts and the operation time of the label cutter. Even when the cutting surface is scratched by through cuts, these scratches are not generally deep enough to significantly affect the quality of future cuts.

Regardless, this cutting surface is designed to be easily replaceable. When the label cutter is initially constructed the guide fence will be precisely located and should not be moved or removed. For this reason, one edge of the cutting surface will be secured by being slid into a 0.125 inch gap under the fixed fence. The other edge will be bolted to the main plate. The fence will be used to align the label when a new label roll is being loaded through the device. This method defines the location of the label in one axis as well as ensures the label is perpendicular to the rollers for proper feeding.

Roller Assembly:

As discussed in the review of the final concept, two sets of rollers are to be used to feed and tension the printed label with the exact operation of these rollers being revised slightly in the final design. The label will no longer be fed in blind for the first cutting run of new label stock coming from the printer. The label is to be initially secured between both sets of rollers by the operator so subsequent runs can be automatically carried out by feeding the continuous label stock through the device.

With this in mind, the final design of the roller sets needed to provide clamping force on the label between rollers, but also easily release this clamping force so the label cutter can be loaded when a new roll of label stock is required. By estimating the friction between the rollers and label, and considering the tensioning force desired, it was determined that the label should be clamped between two rollers with a force of at least ten pounds. In order to accurately capture the location of the label text during the cutting operation, it is imperative that the label does not slip between the rollers during tensioning. To achieve this while still providing easy loading, the top roller in each roller set will have a set force applied to it by two springs that are held in compression by a bar that is guided by the vertical shaft and held in place with draw latches. The draw latches, similar to those on tool boxes, will allow this compression force to be quickly released, and the top roller will then be able to move vertically creating space for a new label feed to be inserted.

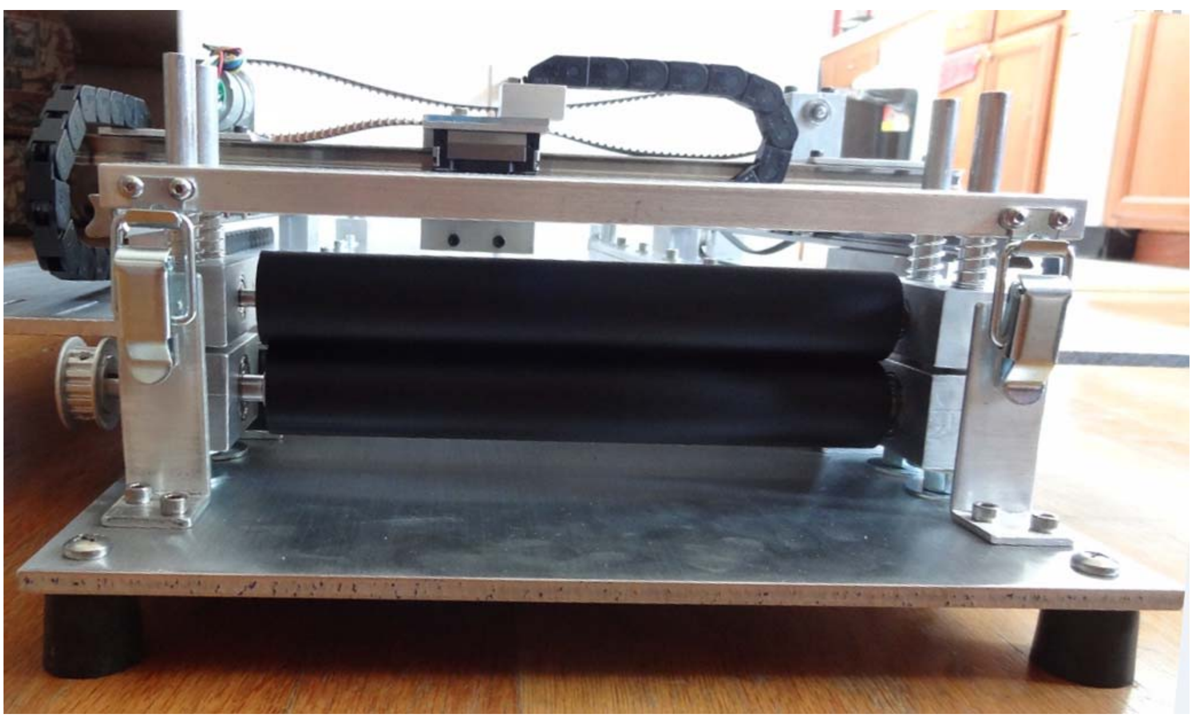

Figure 12. Roller mechanism

The outer diameter of the roller material is 1.25 inches to provide adequate spacing between the aluminum blocks at each end that support the roller shaft bearings. In the selection of the rubber material, polyurethane of 60A durometer hardness was selected. This polyurethane will provide sufficient friction between the rubber and label. 60A is a medium hardness so that deformation of the roller material will provide sufficient contact area to prevent marking and marring of the label surface. Neoprene 90A was tested but proved to be too hard and also marked the labels. Silicone was also tested and showed to have an appropriate hardness and did not mark the label, but the material did not provide enough friction between the roller and label to prevent slipping.

These rollers are secured by bearings supported in aluminum blocks that are guided by the four vertical shafts. The bottom roller in each assembly is either driven by a pulley/motor system or braked. These actions are applied to the bottom roller so that this more complicated component does not need to be moved when loading a new label roll. Due to space constraints the application of the driving or braking force needed to be applied away from the label and rubber roller. This is done outside of the space between the vertical guide shafts. It is for this reason that there exist two vertical guide shafts at each end so that the bottom roller shaft can protrude through the bearing block, between the vertical guide shafts, into the more open area to the outside of the guide shafts. Having two vertical guide shafts on each side also stiffens this cantilever structure to prevent any bending due to tensioning or the compression of the rollers. When not considering the pulley or brake, the two roller set assemblies at each end are mirror images of one another, thus reducing the number of unique parts needed.

Figure 13. Shaft Brake as assembled on roller mechanism

The shaft brake is mounted directly on the protruding drive shaft and secured to the bearing support block. This in-line brake proved to be the simplest and most reliable method of fixating the roller. When a voltage is applied to the brake, an electromagnet releases the spring force used to brake the shaft and allows the roller to spin freely. This design keeps the roller braked when no voltage is applied. Because a majority of the operation of this device will be the tensioning and cutting operation, the label can be tensioned without needing to provide any power to the brake.

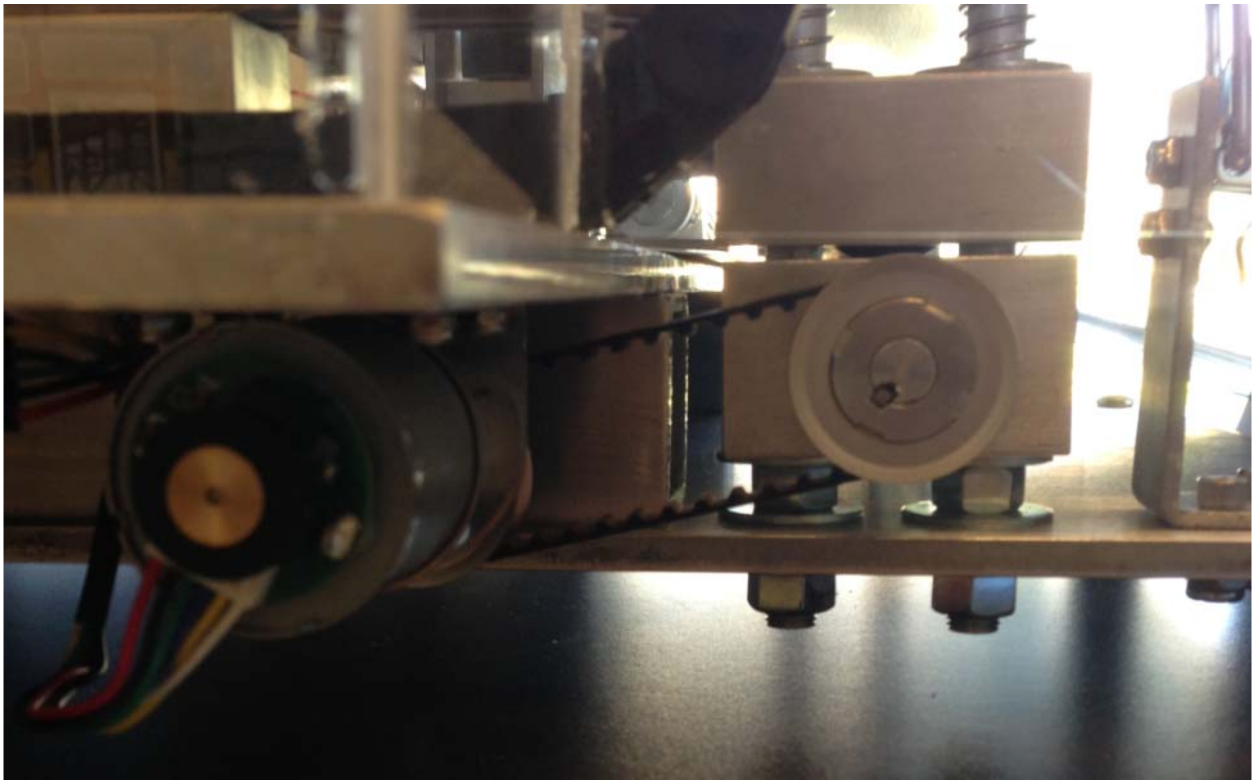

Figure 14. Driven roller set system

The roller set with the driven roller will feed the label through the device as well as provide the tensioning force during the cutting operation. The motor will be mounted to the underside of the main plate, keeping the drive components away from the cutting operation and label feed. The brushed DC gear motor that is used to drive the cutter in two axes is the same motor used to drive the label feed. During tensioning a low voltage can be applied to this motor to provide a constant force. This is why a brushed DC motor was selected instead of a stepper motor. The encoder on this motor will allow a program designer to control the speed of the label feed as well as the length of label that is fed through. Speed control will be important when a scanner head is implemented to provide verification of label quality. The label will need to pass under the scanner head at a specific speed to provide a good scan. Room exists on the main plate just before the label set where a scanner head could be mounted.

Of all the designs considered, this modular roller set design proved to be the simplest and most reliable design. The draw latches will allow the roller set to be quickly and easily unlocked. The vertical guide shafts may either be steel or aluminum depending on wear considerations, but the linear travel of the top roller is so infrequent and limited in range that either material should be sufficient. Care should be taken to keep these guide rails clean and lightly oiled. Smoothness of operation will be mostly dependent on the manufacturing tolerances of the hole diameter and location in the guide blocks to prevent binding.

Cutter Assembly:

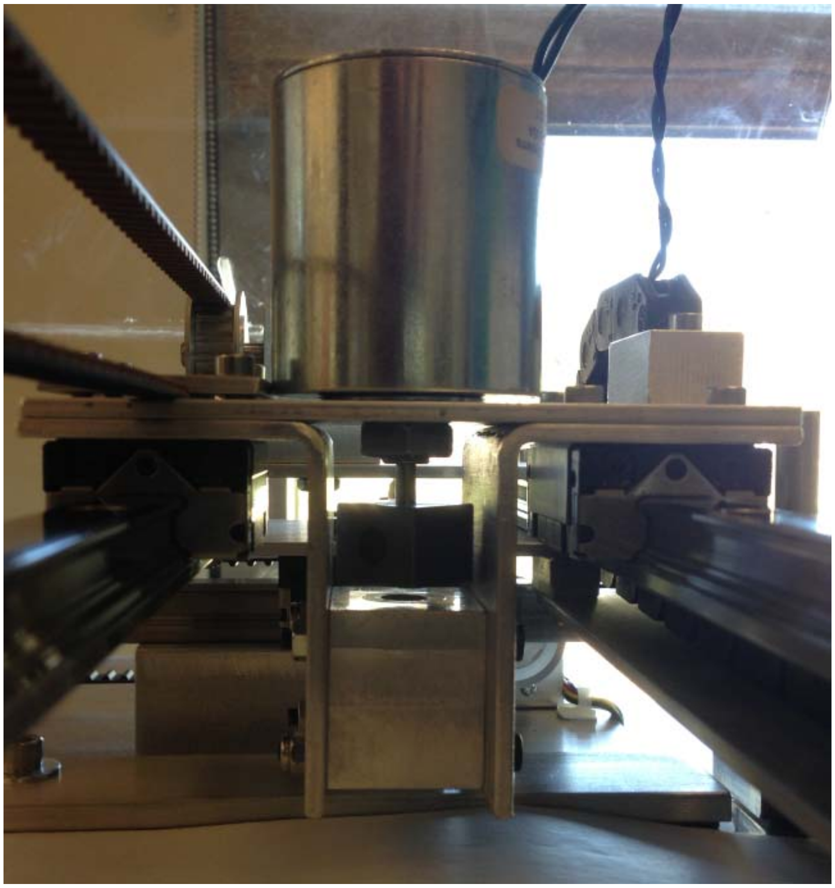

Figure 15. Overall solid model of cutter assembly

The function of this assembly is a combination of being able to apply a controlled downward force onto the cutting surface, have a free rotating cutting wheel, optical sensor to precisely determine location, and be driven on a single axis rail. Multiple iterations went into designing this part as the design was simplified and parts combined into what it is now.

The ability to precisely control the downward force being applied to the cut surface is crucial to the function of this device. Different designs for force and distance control were considered and evaluated. It was determined that the most efficient way to apply the appropriate force was through a push solenoid. From there the required cutting force was determined for proper cut of the label stock, with that information a solenoid model was specified that fit the design. Specifying the proper solenoid is one of the critical steps to the design. There were many considerations to take into account. The first was whether the solenoid could produce the force needed to cut through the label and, in the case of perforations, the label backing. Because a range of force is needed to cut different types of labels and to perforate, we decided that varying the voltage would serve as the control parameter. Another parameter was the stroke length of the solenoid and the corresponding force at a specific stroke. The combination of these two determined the optimal operating condition for the solenoid. Through testing, it was determined the optimal voltage and stroke. A copy of the results plot from this testing is located in Appendix D.

The free rotating cutting wheel was one of the more challenging components to design in this assembly and is what required the most iteration. In the final design a Teflon linear bearing is used to allow for free rotation of the cutting head while still allowing unrestricted movement in the vertical direction. This allows the cutting head to come off the cutting surface while not active so that it’s out of the way when the label stock feeds. The cutting head is held to the solenoid plunger by a magnetic adapter. The adapter is essentially a 0.75in steel cube that attaches to the solenoid plunger shaft through a setscrew. It is magnetized by a magnet which is then able to attract the steel cutting head. The cutting head will have a machine rounded end at the contact point between the cutting head and the adapter. This will minimize friction between the two surfaces therefore maintaining free rotation of the cutting head.

An optical diode sensor is attached near the bottom of the bearing bracket so that it’s close to the cutting surface. The role of this optical sensor is to detect the location of the label that needs to be cut relative to a locating block. The locating block will be a black square printed on the left margin of the label stock. The diode sensor will search within this margin area until it finds the locating block. Due to the diode conducting voltage when in the presence of light, when the sensor detects the black locating block, there will be a drop in voltage which will notify the program that the sensor is above the locating block. Once found, the sensor will measure the vertical and horizontal distance of the locating block. Once measured, it will be able to locate the precise center of the locating block. The location of the label relative to the center of the locating block will be preprogrammed into the coding. That way the cutter will reference the cut path relative to its distance from the center of the locating block. The optical sensor has a detection area of 0.25mm^2. A 3mm by 3mm detecting block will be printed onto the label stock. This way the sensor area is smaller than the locating block thus will be able to locate the edges.

Short Rail Assembly

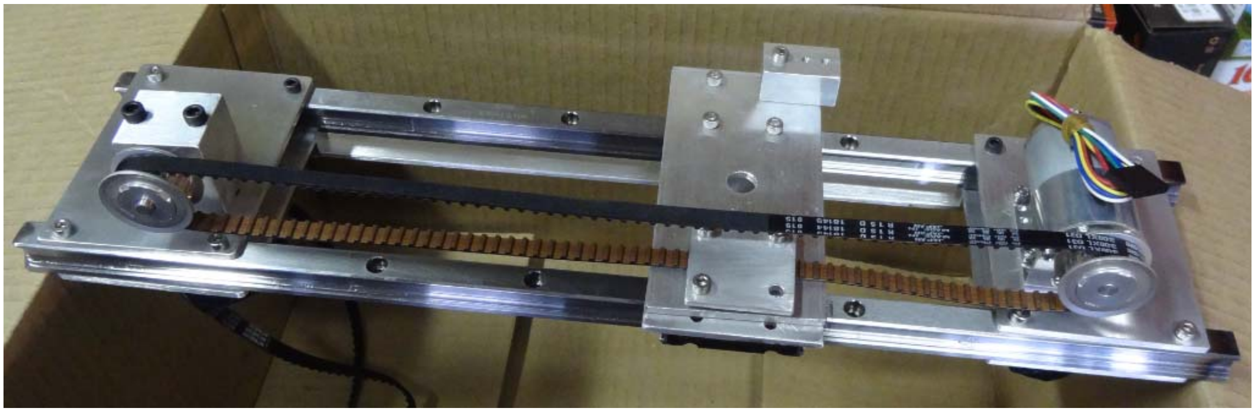

Figure 16. Short Rail Assembly

The short rail assembly involved a system comprising of two rails, two carriages, and mounting plates. The decision to use two rails was made due to the concern that mounting everything on one rail would cause the assembly to torque about the rail. With the two rail system the cutter assembly is properly supported so that there is no play in the motion of the assembly. The mounting brackets are used to mount motors, pulley blocks, and belt clamps to the assembly to move the assemblies along the rails through use of linear bearings.

Final Assembly Components:

Many components come together in the final assembly. The large assemblies described above are mounted, but smaller components are also involved to tie the interaction of these larger assemblies together. The same size motor is used to drive the cutter along the two axes as well as feed the label. The cutter assembly and short rail assembly are clamped to the timing belts that are driven by the motors. Cable carriers are used to manage the wiring while the cutter moves so the device does not become entangled and wires do not get caught on other components.

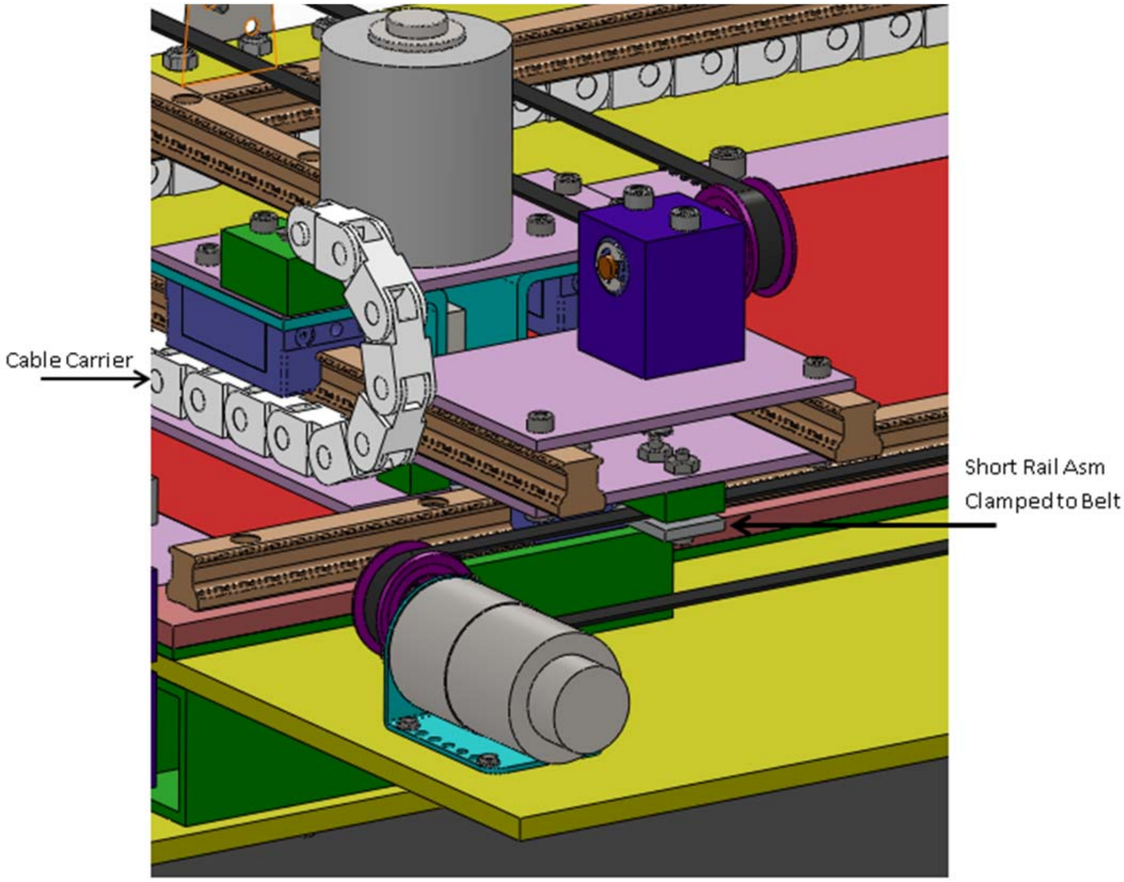

Figure 17. Solid model showing how the short rail assembly is connected to the timing belt as well as the cable management system

The clear acrylic cover serves as a shield to all moving parts while still allowing the operator to see what is going on. Computer fans have been mounted to the cover to keep the motors and solenoids cool. These filtered fans pull air out of the case. A computer power supply will be used to convert the 120V AC power from a wall outlet to the various voltages that the cutter will operate off of.

A microcontroller and motor drivers will be used to control the motors and solenoid. The microcontroller will be capable of providing proportional, integral, and derivative control and supply a pulse width modulated signal to the motor driver. These electronics will allow the microcontroller to govern both the speed and direction of the motors. Depending on the microcontroller, separate encoder counter chips may need to be purchased to count the signal from the optical encoder used in each motor. These electronics will be mounted on the front of the main base plate to allow easy access during the prototyping phase. If desired the cover can easily be lifted up to provide full access to all components of the label cutter.

Description of Cutting Program:

What follows is a rough outline of how the cutting operation will be carried out. Upon startup, the cutter unit will move towards a corner of the cutting area on the outlet feed side. A rough registration of the cutter location will be established using limit switches. The cutter will then move a roughly an inch towards the inlet feed side. The label will then be fed through until a registration mark is picked up by the optical sensor on the cutter unit. If no registration mark is identified after 24 inches of label has been fed through, the feed will stop and an error will be displayed. When the registration mark is identified, the inlet feed roller set will lock and the label will be tensioned over the cutting area. At this point more care will be taken to precisely locate the registration mark. Once the location of the text is identified, the cutter unit will begin to carry out the prescribed cutting path. After this is complete the cutter will drive itself back to the corner until the limit switches are tripped, and the entire feeding/locating operation will be carried out again.

Maintenance Schedule

Daily After Use:

1. Wipe down rails using a rag/paper towel oiled with WD-40 (QTY 4)
2. Wipe down the cutting surface with denatured alcohol (QTY 1)
3. Wipe down the rollers with denatured alcohol (QTY 4)

Weekly:

1. Clean and oil vertical shafts for roller sets. (QTY 8)
   a. Remove the roller compression bar, springs, and top roller.
   b. Wipe down the vertical shafts using a rag/paper towel oiled with WD-40.
   c. Reassemble top roller, springs, and compression bar.
   Note: Be sure to reassemble the top roller so the markings on the bearing blocks match up. Bearing blocks, and the side of the compression bar marked P/B should be reassembled so that these markings are on the same side as the Pulley/Brake.
2. Lubricate linear bearings (QTY 4)
   a. Remove the set screw on the end of the linear bearing using a 1.5mm hex wrench.
   Note: There is a set screw on both ends of the linear bearing. Either will suffice.
   b. Using a can of WD-40 with straw attached, spray oil into the set screw hole.
   c. Reinstall set screw such that the screw is flush with the outside of the linear bearing.
   d. Wipe down rail to remove excess oil.
3. Lubricate cutter tool and solenoid block (QTY 1, QTY 1)
   a. Using a can of WD-40 with straw attached, spray on the cutter tool into the Teflon bushing.
   b. Wipe down solenoid block using a rag/paper towel oiled with WD-40.

Timeframe Unknown:

1. Polish cutting plate (QTY 1)
   a. Remove the ¼-20 screws (QTY 6) securing the cutting plate to the main base plate.
   ! Note: Do not remove the ¼-20 (QTY 6) screws securing the guide fence to the main base plate.
   b. Slide the cutting plate away from the guide fence towards the linear rail supports by at least 0.25 inches.
   c. Lift the cutting plate out.
   d. Polish cutting surface with 200 grit sand paper to remove deep scratches.
   Note: Use a sanding block or other mechanical means to ensure a flat cutting surface is maintained.
   e. Polish cutting surface with 400 grit sand paper.
   f. Clean with denatured alcohol.
   g. Reinstall cutting plate by sliding the plate back under the guide fence and securing with the ¼-20 screws (QTY 6).

2. Replace cutting head (QTY 1)
    a. Move the solenoid carriage over the cutting tool drop out hole located in the corner of the cutting plate nearest the roller shaft brake.
    b. Move the solenoid carriage away from the drop out hole and remove the cutting tool.
    c. Secure the tapered end of the cutting tool in a vice using rubber pads so as not to mar the shaft surface.
    d. Unscrew the replaceable cutter head and dispose of.
    e. Unscrew the treaded brass connector rod and dispose of.
    f. Thread a new brass connector rod into the tapered cutter shaft until hand tight.
    g. Screw on a new cutter head and tighten.
    h. Drop the refurbished cutting tool into the drop out hole.
    i. Move the solenoid carriage over the drop out hole.
    j. Lift the cutting tool into the linear bushing and move the carriage away from the dropout hole.

Design Verification and Testing

In regards to the whole project the major component that was deemed to be a worry, when the device began running under a large duty cycle was the solenoid that is used to press the cutter down and cut the paper. According to the manufacturer to operate at its maximum load the solenoid needed to be attached to roughly a six inch by six inch aluminum plate to allow for a large enough heat sink. The solenoid in the final design is only attached to a four inch by two inch aluminum plate.

To make sure that the solenoid during a long production run would not overheat, it was decided that it was necessary to test it under its operating load to find its expected maximum temperature. This was done in the following way. The solenoid was attached to a force transducer and put at the design load of 7 pounds for 1 hour with the temperature being read by a thermocouple attached to the edge of the solenoid.

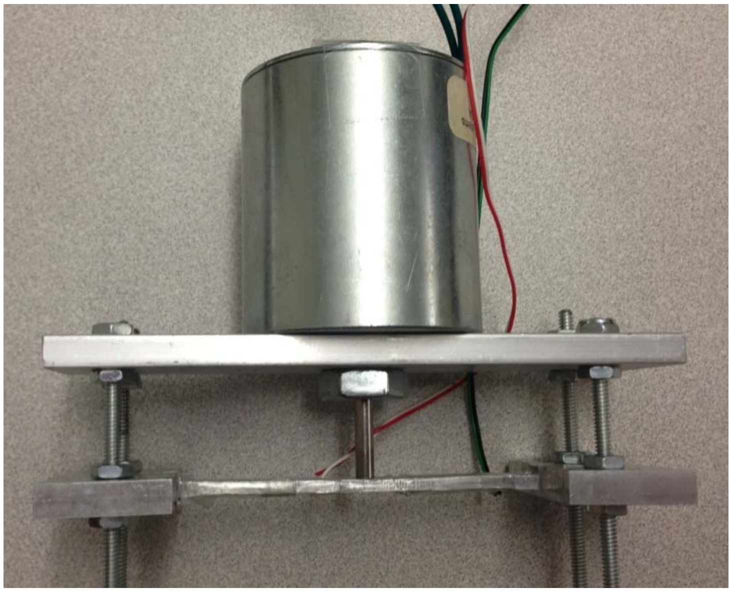

Figure 18. This is a picture showing the test fixture that was used to test the solenoid.

Figure 18 shows an image of the entire test fixture that was used to test the solenoid. The plate that it was mounted to was also similar size as the one that is used on the final device, so it should see similar level heat sinking.

For the test the device was run constantly for one hour, with the temperature being checked every four minutes. After one hour of running the solenoid the temperature was seen to rise roughly 30 degrees from a room temperature of 78 degrees Fahrenheit to 108 degrees Fahrenheit. Though the temperature rose roughly thirty degrees, based on the data that was collected it was expected to go to a steady state temperature of roughly 130 degrees.

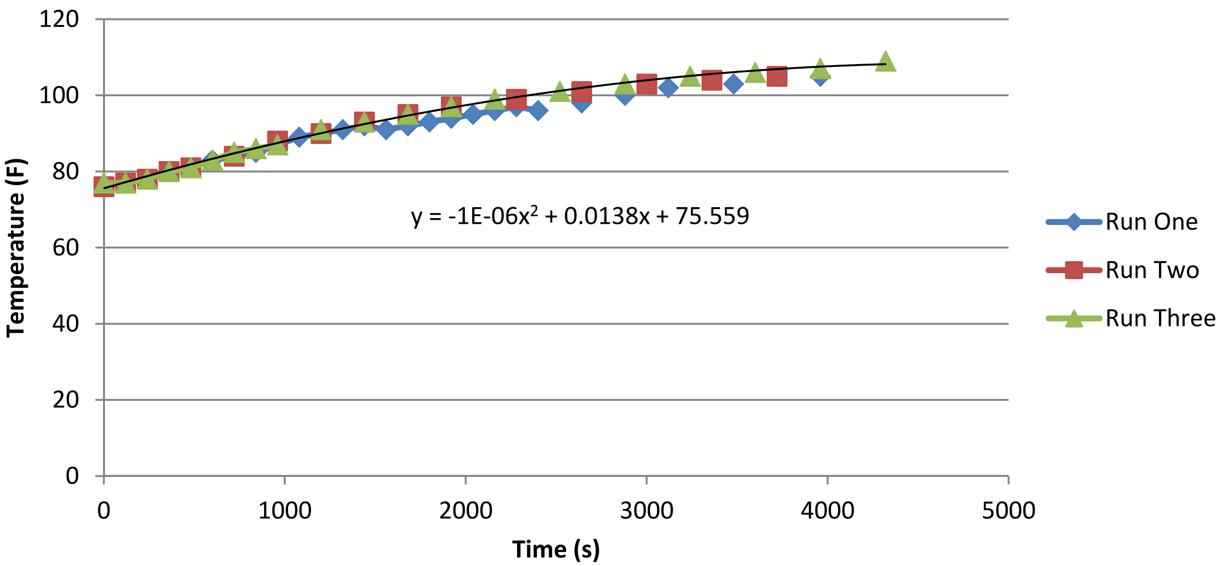

Figure 19. The results of the temperature of the solenoid with respect to time.

These results which can be seen in Figure 19 show that there is no worry for the solenoid at these particular loads, because it stays well below a dangerous temperature level under a 100% duty cycle. The manufacturer states that a temperature above 170 degrees Fahrenheit is considered dangerous to the solenoid.

Another concern with the solenoid was that the manufacturer warned that as temperature increases the force output of the solenoid can tend to decrease. As can be seen in Figure 20 under the temperatures seen in this loading condition the force output of the solenoid is reasonably constant.

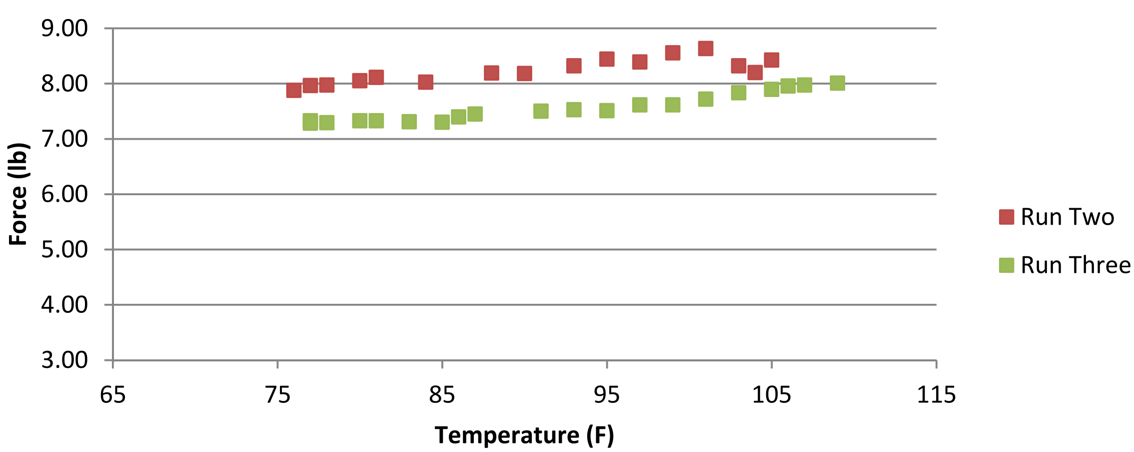

Figure 20. The results of the force output of the solenoid relative to its temperature.

These results conclude that under our loading conditions of the solenoid, that there should be no worry for the solenoid overheating or having a force output that changes too much with temperature. For a complete report on all of the findings refer to Appendix D of this document.

Product Realization

In approximately 100 hours of time in the machine shops our team was able to manufacture the parts designed during winter quarter. Parts were designed to be simple so that the label cutter could be manufactured in a single quarter. The numerous blocks and plates soon came together to be through bolted in the final assembly. Some design changes were made on the fly during manufacturing and assembly and have been updated in the final drawing packet. These changes were mostly insignificant and include such things as changing the diameter of holes, extending the motor mounting slots, and using different fasteners. Nylon locknuts were used where possible and four springs were used to compress the roller stack instead of two. All parts can be made on a mill, lathe or drill press in a fairly short amount of time.

Figure 18. Counterbore for bearing blocks.

The most significant design/redesign went into mounting the electronics and redesigning the cutter tool and linear bearing. The locations and hole patterns used to mount the electronics were not specified in the original drawing set. This is because the electronics had not yet been selected. Holes were drilled after assembly and as a result are not accurately positioned. When mounting the motor drivers, microcontroller, and power supply, we discovered that these components must be electrically insulated from the aluminum base plate. Nylon screws with

nylon spacers were used to mount the drivers and microcontrollers. The power supply was modified to use the circuit board mounting screws as the means to mount the power supply to the base plate.

The cutter tool was modified to use a threaded brass connector rod because it was found the pilot hole drilled in the stock cutter head is not concentric with the outer cylindrical surface. This connector rod is designed to deform when tightened and the stock cutter head is forced to be concentric by the perpendicular faces that push against one another. Another problem that arose was that the linear bearing originally selected did not allow for smooth rotation of the cutter. Smooth rotation is critical so an aluminum block with a Teflon bushing was used instead. Upon further testing it was found that the cutter was still having trouble rotating because the through hole of the Teflon bushing is slightly too large and the stock cutter head has non-cylindrical geometry near the cutting wheel that causes the cutter to bind in the bushing when the direction of motion changes abruptly by more than 30 degrees. A new design is suggested for the cutting tool that would encapsulate the stock cutter head and provide a smooth cylindrical surface over the entire length that makes contact with the Teflon bushing.

The coding for this project is still in development. Many electrical issues arose through the use of a switching power supply that kept us from being able to test more advanced parts of the code. The switching power supply creates a significant amount of noise in the ground line. This noise caused problems for the microcontroller to identify when the limit switches had been tripped. The high inductive loads of the motor and solenoid make the noise issue even worse. As of the time of the expo, we were able to get the label to successfully feed, and have the carriage move in a prescribed path.

We recommend that a combined computer science and mechanical engineering mechatronics team work to:

- Successfully cut circles and rectangles
- Implement the use of an optical sensor to locate the label text.
- Interface the microcontroller with a more user friendly computer program
- Develop an algorithm to compile the code for a cut path from a word processing file.
- Scan labels upon feeding out of the machine to verify quality

Another mechanical engineer on the future team could work to:

- Optimize the design of parts
- Increase manufacturability
- Decrease the overall size and weight of the machine
- Work to combine packaging with a thermal transfer printer

Another year and another phase of engineering would benefit the development of this label cutter immensely. After the work done by team EZ Labels this year we believe we have produced a robust platform that is flexible enough to adapt to future design decisions.

Management Plan

Due to the way the senior project class is set up the design process can be broken down into three main sections. Each section defines what is to be accomplished during that quarter. During Fall quarter (October-November) the main goal is to define and initiate the project. Winter quarter (January-March) involves designing the overall system that will ultimately be produced. Spring quarter (March-June) includes the actual manufacturing, assembly and testing of the designed product. These are very broad descriptions of the work to be done during each quarter. Needless to say, there will be overlap of tasks between the quarters. For the most part, the specific goals of each quarter will be as follows.

Fall quarter involved setting up the project and defining a general concept model. Our team performed background research on the company the product is for, other comparable products that are already on the market, and alternative products or processes that the sponsor may not have considered. Researching the company helped establish the requirements the product must meet. Researching comparable products not only provided information on how other devices have tried to solve the problem, but also give indications on how current technologies fall short of what the sponsor is looking to accomplish. After setting design requirements and specifications, we moved onto brainstorming and testing ideas of how to accomplish what we set out to do. Through brainstorming, testing and engineering aids such as morphological matrixes and QFD we concluded that the best method of satisfying all the requirements was to use a solenoid powered cutting wheel with x-y axis motion. A Solidworks model was then developed to give us an idea of the size and proportioning of the parts involved in building the final product.

During winter quarter further progress was made to bring the device from a conceptual model into a fully engineered device. This required extensive detailed design work to be done by all three group members to create a device that meets the initial design specifications. From this design we have created a set of fully annotated engineering drawings, and from these drawings we were able to put together a detailed purchase list for the entire part design.

Finally, during spring quarter we worked to build the actual product. This will be the toughest part of the project because in this step, the concept will move from being a series of engineering drawings into a physical and fully functioning machine. As expected, most of this quarter was spent in the shop building and troubleshooting the final prototype. There were many full days were the team would meet up, after manufacturing parts independently, to assemble the cutter. We also spent time supporting Robert with the programming and helping to trouble shoot issues as they arose

The projected responsibilities for the group members can be summarized by the following:

Winter Nathan: Rail Assembly Design, Mfg considerations, Test Equipment Design

Lorne: Roller Unit Design, Overall Assembly Design

Tony: Cutting Unit Design, Overall Assembly Design

Spring Nathan: Part Fabrication, Testing

Lorne: Part Fabrication, Mechatronics Considerations
Tony: Part Fabrication, Procured Parts Qualification
Robert: Mechatronics Design

Ultimately for the project to be a success there is a certain amount of the sponsor’s involvement required. Listed below are some key milestone dates that required sponsor feedback.

Conceptual Design Review – Submitted 12/3/12
Design Report – Submitted 03/14/13
Design Expo – 5/30/13

Conclusion and Recommendations

CSM presented a very ambitious project to the undergraduates for Fall 2012 Mechanical Engineering Senior Projects program. Through the past three quarters team E-Z Labels has worked with Mr. Gerald Finken to understand, design, and produce a prototype model that satisfies the proposed needs of CSM. Our team believes the design set forth in this report will be able to reliably meet the established requirements.

Though the machine that was built is far from a final product and requires further design and refining, it will satisfy the performance goals that were originally set. A free rotating cutting head allows the machine to easily cut any shape that can be programmed. The rail system driven by geared motors and pulley blocks is able to move the cutting head in any direction along a horizontal plane. The driven and locked rollers allow the paper to be fed and tensioned over the cutting plane. The system should have a long lifespan due to the low operating forces and industrial design.

Further refinement can be done on many areas of the machine. The first and foremost would be the programming. Robert Zimmerman the mechatronics student was not recruited for the project until April of spring quarter and the programming for the system is unfinished. In the last two months of the project we were able to specify and install the required electrical hardware and get the solenoid moving in a prescribed path

The cutting head assembly can be improved by implementing the suggested redesign of the Teflon bushing and cutting tool. Many other parts can be optimized to lessen the weight and improve manufacturability. To keep required tolerances large, parts were designed to be through bolted whenever possible. This makes the parts easier to manufacture but requires more time during assembly to ensure everything is properly aligned before tightening it down.

In moving forward with this project we suggest that the label cutter go through another phase of engineering to provide:

-More thorough testing and verification.
-Optimization of hardware
-Increased manufacturability
-Further development of cutter control system and optical recognition.

We believe a team comprised of mechanical engineering students with design and mechatronics skills, as well as a computer science student, will allow this product to be more fully realized.

During the past year, team E-Z Labels has learned a lot about what goes into designing and producing a product. There were many long nights and heated discussions, but in the end we believe the design is sound and the product is well on its way to being fully functional. We have produced a robust platform that is flexible enough to adapt to future design decisions. Finally we would like to thank Mr. Finken for giving us the opportunity to work on this project and Mr. McFarland for his invaluable advice and guidance on this project.

APPENDICES:

Appendix A: QFD, Decision Matrix, and Test Results

Quality Function Deployment Analysis

Table A1. QFD table which provides the most important attributes for the project

Variable Die Cutter — Customer Requirements	Adjusted Weights	Weighting (1 to 5)	Engineering Requirements: Total Weight	Feed Speed	Cutting Speed	Cutting Tolerance	Depth of cut Variability	Overall Machine Size	Setup Time	Teardown time to Major Components	Life of Cutting tool	Cutting Range(x,y)		Benchmarks: M60 Laser Cutter	GRC Die Cutter	Stamping Die Cutter	Roland Vinyl Cutter
Quickly Satisfy Order	3.51	3	0	9	9	6	3	0	9	2	0	4		4	5	5	4
Accurately cut labels	5.85	5	0	4	5	9	3	0	0	0	0	1		5	4	5	4
Perforates label	3.51	3	0	3	5	9	9	0	1	0	0	2		5	1	4	2
Cuts from continous roll feed	4.68	4	0	1	3	4	1	2	3	1	0	0		1	4	5	1
Accomodates different thickness of label stock	3.51	3	0	3	7	2	9	1	3	1	2	6		5	4	3	3
Cut variably sized rectangular labels	5.85	5	0	1	3	3	2	2	2	0	0	9		5	5	2	5
No open access to cutting device	5.85	5	1	0	0	0	3	1	1	3	0	0		3	1	3	2
No toxic exposure to user	5.85	5	1	0	0	0	1	0	0	3	0	0		4	5	4	5
Operates in office space	4.68	4	3	1	1	0	0	6	0	0	0	0		2	1	1	5
Include handholds for easy lifting and relocation	2.34	2	1	0	0	0	0	2	0	0	0	0		1	1	1	5
Minimal user involvment	4.68	4	0	1	3	4	3	0	7	0	0	1		3	2	2	3
Can be operated by 1 person	4.68	4	1	1	1	1	1	1	7	0	0	0		5	3	2	5
Portable	3.51	3	9	1	1	0	0	9	1	3	0	3		1	1	1	5
Highly serviceable	3.51	3	3	0	2	1	2	4	1	9	9	0		1	2	2	3
Fits on a cart	3.51	3	3	0	0	0	0	9	0	1	0	2		1	1	1	5
Able to roll through a doorway	3.51	3	3	0	0	0	0	6	0	1	0	2		3	1	1	5
Recyclable	1.17	1	1	0	0	0	0	0	0	0	2	0		2	3	3	2
Reliable	4.68	4	1	7	7	4	3	1	3	0	6	2		3	4	4	2
Die cutter adaptable to different label printers	2.34	2	0	0	1	1	1	1	5	0	0	2		1	1	3	3
Interface with printer and computer by a common file	4.68	4	0	0	0	0	0	0	6	0	0	3		4	4	2	1
Cut while receiving stock from printer	5.85	5	1	3	3	1	0	1	2	2	0	2		1	3	1	3
Function with label stock of 6 in wide	5.26	4.5	3	5	3	1	0	4	1	0	0	6		5	5	5	5
All parts can be manufactured without CNC control	3.51	3	1	0	0	3	1	1	0	0	0	0		3	2	2	3
Not require components to be welded	3.51	3	1	0	0	3	1	1	0	0	0	0		2	1	2	3
Units			lbs	in/min	in/min	in	in	in	min	min	in	in					
Targets																	
Importance Scoring			130	181	237	229	180	207	220	111	69	201	0				
Importance Rating (%)			55	76	100	97	76	87	93	47	29	85	0				

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Decision Matrices

Table A2. Morphological Matrix #1 combining proposed cut path and cutter ideas

		How Does it Cut Variable Path								
		Cartesian CS	**Polar CS**	**Move Label 2 axis**	**Beam Str Mirror**	**move label feed axis**	**lone robot**	**robotic arm**	**repeated stabbing**	**single axis motion**
Cutter	**Single Blade**	Cartesian CS Single Blade	Polar CS Single Blade	Move Label 2 axis Single Blade	Beam Str Mirror Single Blade	move label feed axis Single Blade	lone robot Single Blade	robotic arm Single Blade	repeated stabbing Single Blade	single axis motion Single Blade
	CO2 Laser	Cartesian CS CO2 Laser	Polar CS CO2 Laser	Move Label 2 axis CO2 Laser	Beam Str Mirror CO2 Laser	move label feed axis CO2 Laser	lone robot CO2 Laser	robotic arm CO2 Laser	repeated stabbing CO2 Laser	single axis motion CO2 Laser
	stamping blades	Cartesian CS stamping blades	Polar CS stamping blades	Move Label 2 axis stamping blades	Beam Str Mirror stamping blades	move label feed axis stamping blades	lone robot stamping blades	robotic arm stamping blades	repeated stabbing stamping blades	single axis motion stamping blades
	Stationary Cutter	Cartesian CS Stationary Cutter	Polar CS Stationary Cutter	Move Label 2 axis Stationary Cutter	Beam Str Mirror Stationary Cutter	move label feed axis Stationary Cutter	lone robot Stationary Cutter	robotic arm Stationary Cutter	repeated stabbing Stationary Cutter	single axis motion Stationary Cutter
	wheel	Cartesian CS wheel	Polar CS wheel	Move Label 2 axis wheel	Beam Str Mirror wheel	move label feed axis wheel	lone robot wheel	robotic arm wheel	repeated stabbing wheel	single axis motion wheel
	UV laser	Cartesian CS UV laser	Polar CS UV laser	Move Label 2 axis UV laser	Beam Str Mirror UV laser	move label feed axis UV laser	lone robot UV laser	robotic arm UV laser	repeated stabbing UV laser	single axis motion UV laser

Feasible
Undesireable
Unsuitable

Table A3. Morphological Matrix #2 combining proposed depth control and matrix 1 results

		Depth Control						
		Force guage	**cam**	**hardstop-solenoid**	**rack/pinion**	**change label height**	**change blade**	**actuator**
Matrix 1 Results	**Cartesian CS Single Blade**	Force guage Cartesian CS Single Blade	cam Cartesian CS Single Blade	hardstop-solenoid Cartesian CS Single Blade	rack/pinion Cartesian CS Single Blade	change label height Cartesian CS Single Blade	change blade Cartesian CS Single Blade	actuator Cartesian CS Single Blade
	Cartesian CS wheel	Force guage Cartesian CS wheel	cam Cartesian CS wheel	hardstop-solenoid Cartesian CS wheel	rack/pinion Cartesian CS wheel	change label height Cartesian CS wheel	change blade Cartesian CS wheel	actuator Cartesian CS wheel
	move label feed axis Single Blade	Force guage move label feed axis Single Blade	cam move label feed axis Single Blade	hardstop-solenoid move label feed axis Single Blade	rack/pinion move label feed axis Single Blade	change label height move label feed axis Single Blade	change blade move label feed axis Single Blade	actuator move label feed axis Single Blade
	move label feed axis wheel	Force guage move label feed axis wheel	cam move label feed axis wheel	hardstop-solenoid move label feed axis wheel	rack/pinion move label feed axis wheel	change label height move label feed axis wheel	change blade move label feed axis wheel	actuator move label feed axis wheel

Feasible
Undesireable
Unsuitable

Table A4. Decision matrix Ranking Feasible ideas

Ideas	Reliability 30%	Versatility 25%	Safety 32%	Repairable 13%	Total
	10 Reliable	10 simple	10 safe	10 easy	
Cam; Cartesian CS; Single Blade	6	7	5	4	5.67
Cam; Cartesian CS; Wheel Cutter	7	6	6	4	6.04
Cam; Move Label Feed Axis; Single Blade	4	7	5	4	5.07
Cam; Move Label Feed Axis; wheel Cutter	5	6	5	4	5.12
Hardstop; Solenoid; Cartesian CS; Single Blade	7	5	5	6	5.73
Hardstop; Solenoid; Cartesian CS; Wheel Cutter	8	4	5	6	5.78
Hardstop; Solenoid; Move Label Feed Axis; Single Blade	5	5	5	6	5.13
Hardstop; Solenoid; Move Label Feed Axis; Wheel Cutter	6	4	5	6	5.18
Actuator; Cartesian CS; Single Blade	5	7	5	5	5.5
Actuator; Cartesian CS; Wheel Cutter	6	6	6	5	5.87
Actuator; Move Label Feed Axis; Single Blade	3	7	5	5	4.9
Actuator; Move Label Feed Axis; Wheel Cutter	5	6	5	5	5.25
Applied Force; Cartesian CS; Wheel Cutter	9	8	5	5	6.95
Applied Force; Move Label Feed Axis; Wheel Cutter	7	6	5	5	5.85

Table A5. Decision matrix results- Top 3 ideas

Top 3 Results	Score
Applied Force; Cartesian CS; Wheel Cutter	6.95
Cam; Cartesian CS; Wheel Cutter	6.04
Actuator; Cartesian CS; Wheel Cutter	5.87

Cutter Testing Results

Table A1.1 Testing data for Red Devil glass cutter

Downward force ±0.5 lbs	Cut Label	Cut Backing	Comments
2	No	No	--
3	No	No	--
3.5	Yes	No	Good
4	Yes	No	Good
4.5	Yes	No	Creased back
5	Yes	No	Significant Crease
5.5	Yes	No	Split when peeling label
6	Yes	Yes	Not Acceptable

Downward force ±0.5 lbs	Pull Force ±0.3 lbs
4	1.5
4	1.1
4	1.3
4	1.3
4.5	1.3
4.5	1.2

Table A1.3Testing data for Olfa rotary cutter

Downward force ±0.5 lbs	Cut Label	Cut Backing	Comments
0.1	No	No	--
0.5	No	No	--
0.9	Yes	No	Good
1.5	Yes	No	Good
2	Yes	Yes	Not Acceptable

Downward force ±0.5 lbs	Pull Force ±0.3 lbs
1.3	0.4
1.3	0.3
1.3	0.4
1.3	0.5

Table A1.2 Testing data for X-Acto blade cutter

Downward force ±0.5 lbs	Cut Label	Cut Backing	Comments
0.3	Yes	Yes	Not Acceptable
0.3	Yes	Yes	Not Acceptable
0.5	Yes	Yes	Not Acceptable

Table A1.3 Testing data for X-Acto blade position depth of cut

Mill Z Display (in)	Results
1.323	No Cut
1.325	No Cut
1.326	No Cut
1.327	No Cut
1.328	Top Surface of Label
1.329	Inadequate Cut
1.33	Inadequate Cut
1.331	Inadequate Cut
1.332	Perfect Cut
1.333	Backing Still in tact, Label cut
1.334	backing cut

Appendix B: Drawing Packet- See Attached Documents

Manufactured Parts Assembly Map: See Attached Documents

Appendix C: Vendors and Pricing

Purchased Parts Cost Estimate:

Part No	Description	Vendor	QTY	Cost	Total Cost	Purchased
55835K31	Cable Carrier	McMaster	6	9.95	59.70	Yes
55835K1	Cable Carrier Mounting Bracket	McMaster	2	5.85	11.70	Yes
TBN90XL031	45 tooth belt	Misumi	1	3.28	3.28	Yes
TBN300XL031	150 tooth belt	Misumi	1	5.68	5.68	Yes
TBN460XL031	230 tooth belt	Misumi	1	6.48	6.48	Yes
ATP16XL031-A-NUE	16 tooth pulley keyed	Misumi	1	13.20	13.20	Yes
ATP16XL031-A-PUC	16 tooth pulley 1/4" bore	Misumi	2	10.56	21.12	Yes
ATP16XL031-A-P6	16 tooth pulley 6mm bore	Misumi	3	10.22	30.65	Yes
1590A13	Draw latches. 10 Count	McMaster	1	10.57	10.57	Yes
60355K45	3/8 ID bearing shielded	McMaster	4	5.81	23.24	Yes
60355K43	1/4 ID bearing shielded	McMaster	8	5.81	46.48	Yes
CPC-AR15N-0940-20-20	15mmx940mm Rail	Anaheim Automation	1	92.00	92.00	Yes
CPC-AR15N-0700-20-20	15mmx700mm Rail	Anaheim Automation	2	71.00	142.00	Yes
CPC-AR15MNSZV0N	Rail Block	Anaheim Automation	4	38.00	152.00	Yes
SPPB-M08	Cutter linear bearing 8mm diameter	Applied.com	1	92.29	92.29	Yes
1447	131:1 Gearmotor with Encodor	Pololu	3	39.95	119.85	Yes
1084	37D Gearmotor Bracket	Pololu	2	7.95	15.90	Yes
97431A300	.25" E-Clip	McMaster	1	5.55	5.55	Yes
97431A320	.375" E-Clip	McMaster	1	7.82	7.82	Yes
N82E16835242011	Prolimatech PRO-BV14 140mm Blue Vortex 14 Case Cooler	Newegg	2	10.00	20.00	Yes
N82E16817148044	APEVIA ITX-AP250W 250W Mini ITX Power Supply - OEM	Newegg	1	40.00	40.00	Yes
FF141B	SilverStone 140mm Fan Filter	Amazon	2	9.00	18.00	Yes
S-22-200-23H	SOLENOID	Magnetic Sensor Systems	1	150.00	150.00	Yes
P50.25-7T052	SENSOR	MOUSER.COM	1	12.30	12.30	Yes
1530A51	HINGE MCMASTER	McMaster	3	3.54	10.62	Yes
BRK-18H-240-024-375	ELECTROMAGNETIC BRAKE	Anaheim Automation	1	107.00	107.00	Yes
2193	Arduino Due Microcontroller	Polulo, etc	1	49.95	49.95	Yes
706	VNH2SP30 Motor Driver	Polulo, etc	3	34.95	104.85	Yes
1403	Snap Action switch with 50mm lever	Polulo, etc	2	0.95	1.90	Yes
98535A125	3/8 SHAFT ANSI KEY X 12"	Mcmaster	1	1.67	1.67	Yes
58605K33	0.25 DIAMETER MAGNET	Mcmaster	1	2.95	2.95	Yes
9657K312	Spring 1.00" L, .500" OD, .041" Wire, packs of 12	Mcmaster	1	9.8	9.80	Yes
BLU2300	BLUE SEA SYSTEMS 2300 Terminal Strip	BUSBAR-10-GANG-COMMC	5	16.95	84.75	Yes
----	Fastener Estimate	----	--	--	150.00	---
----	Shipping Estimate	----	--	--	120.00	---
----	Tax	----	--	--	117.86	---
				Total	**1743.30**	

Material Cost Estimate:

Part #	Description	Vendor	QTY	Cost	Total Cost	Purchased
100001	24" X 24" X 0.25" AL PLATE 6061-T6	onlinemetals	2	88.58	177.16	Yes
100002-1,-2; 140002-1,-2	24" LENGTH 0.125" X 3.00" AL FLAT BAR 6061-T6	onlinemetals	1	4.23	4.23	Yes
100003	24" LENGTH 1.50"X 0.125" SQUARE TUBING	onlinemetals	2	10.93	21.86	Yes
100004	24" LENGTH 0.25" X 1.25" AL FLAT BAR 6061-T6	onlinemetals	1	3.52	3.52	Yes
100005;110002	24" LENGTH 0.125" X 1.00" AL FLAT BAR 6061-T6	onlinemetals	2	1.41	2.82	Yes
100006	12"x24"x.125" 6061 Al	onlinemetals	1	28.05	28.05	Yes
100007	12"x.25"x.75" 6061 Al	onlinemetals	1	1.10	1.10	Yes
100008	.125"x.75"x12" 6061 Al	onlinemetals	1	0.55	0.55	Yes
100009	12" LENGTH 0.375" X .5" AL BAR 6061-T6	onlinemetals	1	1.10	1.10	Yes
100010	24" LENGTH 0.125" X 1.25" AL FLAT BAR 6061-T6	onlinemetals	1	1.76	1.76	Yes
100011	12" LENGTH 0.75" X .75" AL BAR 6061-T6	onlinemetals	1	3.30	3.30	Yes
110001	24" LENGTH 0.5" X 3.00" AL FLAT BAR 6061-T6	onlinemetals	1	16.93	16.93	Yes
111001	12" X 12" X 0.25" AL PLATE 6061-T6	onlinemetals	3	28.54	85.62	Yes
111101	24" length 0.375 cold finish AL round 6061-T651	onlinemetals	3	2.85	8.55	Yes
112001; 113001	24" length 0.50" cold finish AL round 6061-T651	onlinemetals	3	5.06	15.18	Yes
112002	Roller 87235K82 36" length Polyurethane 60A tube ID:0.5" OD:1.25"	McMaster	1	77.01	77.01	Yes
112003	12" length 1.25" X 1.25" AL 6061-T6 extruded square bar	onlinemetals	1	9.18	9.18	Yes
112004	12" length 1.00" X 1.25" AL 6061-T6 extruded square bar	onlinemetals	1	7.35	7.35	Yes
130002	24"x1"x1.25" Extruded Aluminum Bar Square 6061 T6511	onlinemetals	1	14.11	14.11	Yes
150001;150003	24"x.125"x2.5 Extruded Aluminum Bar Square 6061 T6511	onlinemetals	1	3.52	3.52	Yes
150002	.125"x1.5"x 12" Extruded Aluminum Bare Rectangle 6061 T6511	onlinemetals	1	1.10	1.10	Yes
150004	.5"x.5"x12" Extruded Aluminum Bare Square 6061	onlinemetals	1	1.47	1.47	Yes
151001	.75"x.75"x12" Extruded Aluminum Bare Square steel	onlinemetals	1	5.49	5.49	Yes
151002	0.375"X12" cold finish rod	onlinemetals	1	1.05	1.05	Yes
151003	Scoremaster 03-703 cutter head	Stained Glass Worksho	3	18.69	56.07	Yes
160001	1.25"x1.5"x12" EXTRUDED Aluminum Bare Rectangle 6061	Onlinemetals	1	11.02	11.02	Yes
160002	.25" Drive Shaft 1327K66	McMaster	1	6.94	6.94	Yes
180001;2,3,4	0.118 X 24 X 24 ACRYLIC	onlinemetals	2	11.40	22.80	Yes
180005	0.118 X 24 X 48 ACRYLIC	onlinemetals	1	22.80	22.80	Yes
----	Shipping Estimate	---	--	---	120	---
----	Tax	---	--	---	48.93	---
		Total Cost	--	---	**731.64**	

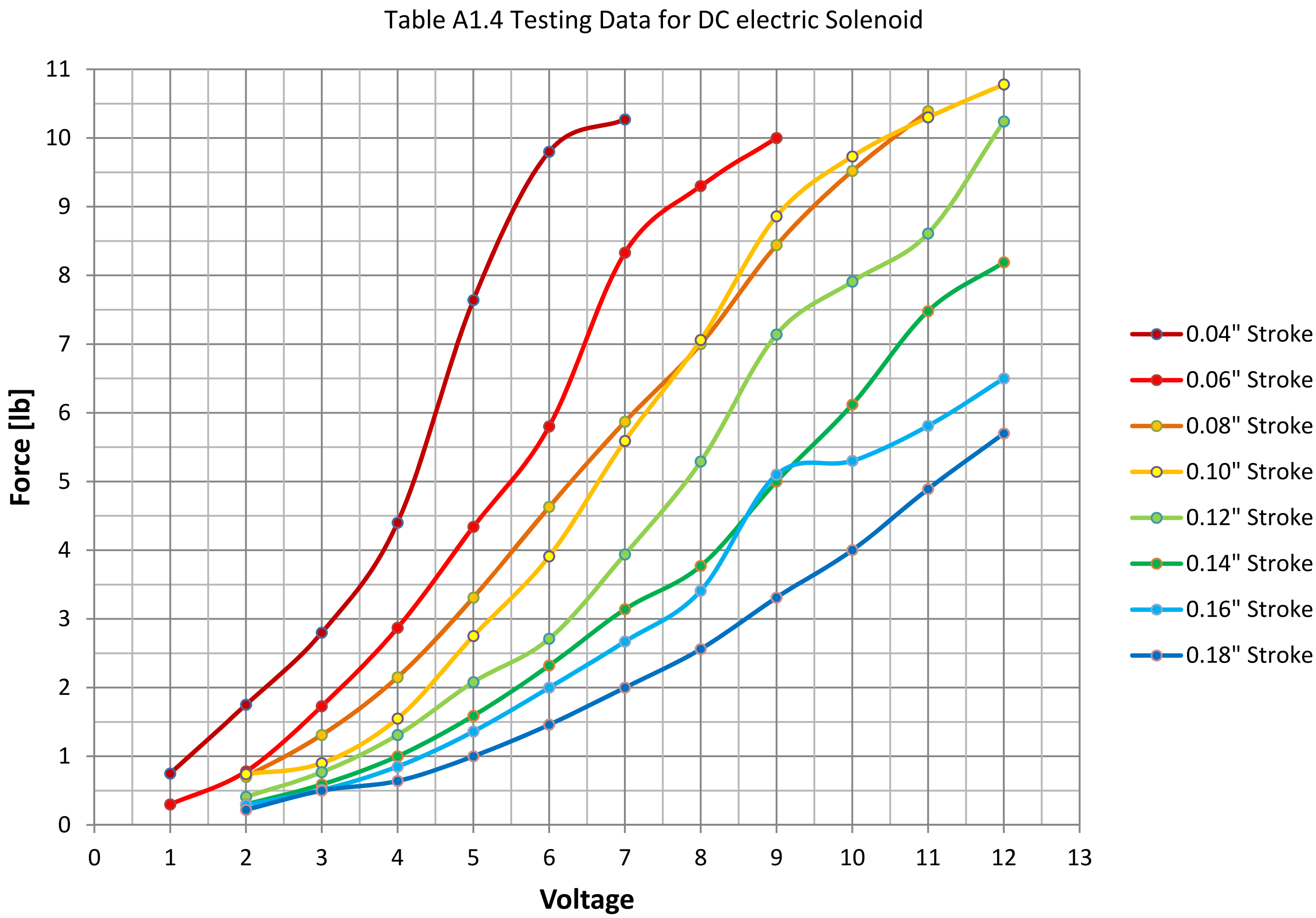
Final Order History:

Date	Vendor	Items Purchased	QTY	Total	Purchased By
1/15/2013	Feedroller.com	HP Transfer roller RF5-0596	1	17.40	Lorne Stoops
1/18/2013	Home Depot	Glass Cutter	1	4.09	Lorne Stoops
1/20/2013	Feedroller.com	HP 2100 Pressure roller RF5-2601	4	63.58	Lorne Stoops
1/30/2013	McMaster	Steel Precision Compression Spring	1	154.88	Nathan Cheadle
		3/8" Steel Flange-Mount Linear Ball Bearing	1		
		3/8" Steel Thrust Ball Bearing	1		
		3/8"-16 Stainless Steel Spade Head Thumb Screw	1		
		Combination Push/Pull Sealed Linear Solenoid	1		
		Neoprene Spring Rubber, Tube	1		
1/30/2013	Onlinemetals	0.75"X.75"X12" AL SQUARE BAR	1	68.83	Nathan Cheadle
		0.75"X.24" STEEL ROUND	1		
		1.75"X12" AL ROUND	1		
		.375"X12" STEEL ROUND	1		
		.375"X8"X8" AL PLATE	1		
2/5/2013	Magnetic Sensor System	Tubular Push Solenoid S-22-200-23H	1	175.24	Tony Wang
3/16/2013	Onlinemetals	24" X 24" X 0.25" AL PLATE 6061-T6	2	283.78	Lorne Stoops
		24" LENGTH 0.125" X 3.00" AL FLAT BAR 6061-T6	1		
		24" LENGTH 1.50"X 0.125" SQUARE TUBING	2		
		24" LENGTH 0.125" X 1.25" AL FLAT BAR 6061-T6	1		
		24" length 0.375 cold finish AL round 6061-T651	3		
		24" length 0.50" cold finish AL round 6061-T651	3		
		12" length 1.25" X 1.25" AL 6061-T6 extruded square bar	1		
		12" length 1.00" X 1.25" AL 6061-T6 extruded square bar	1		
		.5"x.5"x12" Extruded Aluminum Bare Square 6061	1		
		.75"x.75"x12" Extruded Aluminum Bare Square steel	1		
3/16/2013	eBay	Scoremaster Replacement Head	1	18.00	Lorne Stoops
3/19/2013	McMaster	Draw latches. 10 Count	1	118.57	Lorne Stoops
		3/8 ID bearing shielded	4		
		1/4 ID bearing shielded	8		
		.25" E-Clip	1		
		.375" E-Clip	1		
		0.25 DIAMETER MAGNET	1		
		.25" Drive Shaft 1327K66	1		
3/19/2013	McMaster	Roller 87235K82 36" length Polyurethane 60A tube ID:0.5" OD:1.2	1	88.61	Lorne Stoops
4/3/2013	Ace Hardware	10-32 Tap	1	4.96	Lorne Stoops
4/6/2013	Onlinemetals	24" LENGTH 0.25" X 1.25" AL FLAT BAR 6061-T6	2	241.06	Lorne Stoops
		24" LENGTH 0.125" X 1.00" AL FLAT BAR 6061-T6	1		
		12"x24"x.125" 6061 Al	1		
		12"x.25"x.75" 6061 Al	1		
		24" LENGTH 0.5" X 3.00" AL FLAT BAR 6061-T6	1		
		12" X 12" X 0.25" AL PLATE 6061-T6	3		
		24"x1"x1.25" Extruded Aluminum Bar Square 6061 T6511	1		
		.125"x1.5"x 12" Extruded Aluminum Bare Rectangle 6061 T6511	1		
		1.25"x1.5"x12" EXTRUDED Aluminum Bare Rectangle 6061	1		
		0.118 X 24 X 24 ACRYLIC	2		
		0.118 X 24 X 48 ACRYLIC	1		
4/7/2013	Amazon	140mm fan filter	2	19.42	Lorne Stoops
4/7/2013	Newegg	Prolimatech Pro-BV14 140mm fan	2	69.46	Lorne Stoops
		Apevia itx-ap250w power supply	1		

4/7/2013	Stained Glass Workshop	Scoremaster 03-703 cutter head	3	61.22	Lorne Stoops
4/8/2013	Mcmaster	8mm shaft 200mm length	1	99.86	Lorne Stoops
		Cable carrier 6 ft	1		
		cable carrier mounting bracket	2		
		Hinge	3		
4/8/2013	Misumi	45 tooth XL timing belt	1	81.85	Lorne Stoops
		150 tooth XL timing belt	1		
		230 tooth XL timing belt	1		
		Timing Pulley	6		
4/8/2013	Anaheim Automation	700mm rail	2	545.27	Lorne Stoops
		940mm rail	1		
		Rail block	4		
		Electromagnetic brake	1		
4/9/2013	Onlinemetals	0.5"x12" aluminum round	3	23.36	Lorne Stoops
4/10/2013	Pololu	Arduino Due Microcontroller	1	308.4	Lorne Stoops
		VNH2SP30 Motor Driver	3		
		Snap Action switch with 50mm lever	2		
		131:1 Gearmotor with Encodor	3		
		37D Gearmotor Bracket	2		
4/10/2013	Ralphs	Gallon ziplock bags	1	5.71	Lorne Stoops
4/16/2013	Home Depot	Epoxy	1	5.91	Lorne Stoops
4/24/2013	Ace Hardware	Threadlocker	1	21.76	Lorne Stoops
		Silicon Glue	1		
		Metal Epoxy Putty	1		
		Sandpaper	2		
4/28/2013	McMaster	Tube Made of Teflon(R) PTFE, 5/8" OD X 1/4" ID, 1' Length	1	48.81	Lorne Stoops
		Aluminum (Alloy 6061), 1/8" Thick X 2-1/2" Width X 3' Length	1		
		1/4" ID Bearing	1		
		Steel Compression Spring 1.00" L, .500" OD, .041" Wire, packs of 1	1		
5/2/2013	Mouser.com	Optical Sensor	1	21.27	Tony Wang
5/2/2013	Ace Hardware	Fasteners		68.69	Tony Wang
5/5/2013	Ace Hardware	Fasteners		50.46	Lorne Stoops
5/6/2013	Ace Hardware	Fasteners		10.51	Lorne Stoops
5/7/2013	Radio Shack	wire, switches, transistors		31.53	Lorne Stoops
5/7/2013	Mcmaster	M4x55 screws		11.34	Lorne Stoops
5/9/2013	Amazon	Bus Bar	5	94.85	Lorne Stoops
5/9/2013	Pololu	VNH2SP30 Motor Driver	2	74.85	Lorne Stoops
5/13/2013	Home Depot	Denatured Alcohol, Silicone lubricant		11.61	Lorne Stoops
5/15/2013	Ace Hardware	Fasteners		17.97	Lorne Stoops
5/16/2013	Ace Hardware	Fasteners		4.58	Lorne Stoops
5/17/2013	Ace Hardware	Fasteners		11.40	Lorne Stoops
5/17/2013	Radio Shack	Spade connectors		12.39	Lorne Stoops
5/20/2013	Ace Hardware	Fasteners, Silicon Glue		6.04	Lorne Stoops
5/20/2013	McMaster	Hinges	3	10.47	Lorne Stoops
5/26/2013	Radio Shack	Power Resistors	4	18.90	Lorne Stoops
		Barrel connector	1		
		Cable Wrap	1		
5/28/2013	El Corral Bookstore	Poster Board	2	21.93	Lorne Stoops
		3 Ring Binder	2		
6/1/2013	Newegg	Power Supply	1	52.97	Lorne Stoops
				3061.79	**Total**

Appendix D: Component Specifications

Solenoid Testing Results



CAL POLY MECHANICAL ENGINEERING DEPARTMENT

Temperature Effect on Solenoid Force Output

Nathan Cheadle, Tony Wang

5/29/2013

Introduction

During fall 2012 a team of undergraduate engineers took on a senior project involving the design of a trial prescription label cutting machine. Through a meticulous process of brainstorming, design, and redesign a final product was created which uses a solenoid to cut the label stock. Due to the nature of the design, solenoid temperature is a major concern for the following reasons:

- The solenoid is mounted to a heat sink smaller than that specified in the datasheet
- It will be functioning within a small closed off acrylic case
- The wire coil will increase in resistance as temperature increases

Due to the lack of heat dissipation, increases in temperature can cause the solenoid performance to become unpredictable. Therefore the goal of this project is to model and test the effects heating will have on the force output of the solenoid, allowing for better prediction of performance under normal use.

Background

A solenoid is a device that uses a coil of wiring with current running through it to generate a magnetic field. The magnetic field forces a moveable plunger in a certain direction depending on the orientation of the magnetic field. For the On-Demand Label Cutter Senior Project, a solenoid is used to provide the downward force required to cut through the label material. Due to the use of electrical wiring in the solenoid, temperature is a major concern in regards to the proper function of the solenoid. This is because as current runs through the wire, the resistance in the wire causes it to heat up. As the wire heats up, it loses conductivity which weakens the magnetic field. A weaker magnetic field would mean the force output is smaller. This results in a drop in force when the solenoid runs for a long period of time.

The goal of this experiment is to determine if the force output from the solenoid ever falls below the minimum force needed due to self heating. Through prior testing it was determined the cut head required a minimum force of 4lbs and a maximum of 5lbs to properly cut through the label stock. If the force output were to fall below 4lb, the cut head would fail to cut through the label stock rendering the machine useless. By performing the test we can not only determine if further heat dissipation is required in terms of additional heat sink and forced ventilation but also, in a worst case scenario, recommend a duty cycle for the solenoid.

As mentioned above, by increasing temperature of the coil there is a measureable increase in coil resistance. More specifically, for every degree above 20°C, an increase in temperature of one degree would increase the resistance by .393 percent. Rearranging the equation we can get a function for the ratio of resistance change in terms of temperature.

$$\frac{R_t}{R_{initial}} = 1 + 0.00393(T_t - T_{initial})$$

Testing

The testing to find a relationship between output force of the solenoid and its temperature was done in the following way. As can be seen in Figure 1 the solenoid is mounted to a to the force transducer which uses two strain gages to find the output force of the solenoid. For more details regarding the design of the force transducer see Appendix A.

Figure 1. This picture shows the solenoid attached to the force transducer in the exact state that it was tested in.

For measuring the temperature of the solenoid a thermocouple was taped in direct contact with the solenoid wall. It was assumed that this would be a reasonably good measurement of the entire solenoid because the wall of the solenoid was made of aluminum and the coils of the solenoid are made of copper both of which are very good thermal conductors. To verify this assumption when a testing run was finished the thermocouple was then used to check the temperature of the interior of the solenoid. The temperature that was seen inside of the solenoid was within 5 degrees Fahrenheit of the exterior temperature. This shows that although measuring the exterior temperature of the solenoid was not a perfect way to get the temperature of the entire device, it was definitely within a range to say that the data gathered was valid.

To cause the temperature of the device to change, instead of providing an external heat source, which was suggested in the project proposal, it was instead decided to just allow the solenoid to heat up naturally so that the device would only see temperatures that it by itself created. This was so the testing would simulate the working conditions the solenoid would be under when in actual use.

The strain data for this transducer was taken using a half bridge wired through a P-3 box. The P-3 box was applicable due to the low sampling rate and because it would provide the highest strain accuracy and easiest set up. It automatically converts the output voltage from a Wheatstone bridge into a strain due to a built in DAQ system so was one less thing to worry about.

Results

Calibration

The transducer was calibrated using weights ranging from 1lb to 8lb. The actual values that ended up being measured through the transducer were off from those predicted from the FEA model. This was determined to be due to the fact that the end supports of the transducer were somewhere between being a fixed-fixed and a pinned-pinned. Both models were analyzed in FEA and the strain profile could best be summarized as an average of the fixed-fixed and pinned-pinned model. The reason was due to the design of the transducer. It was due to combination of the nuts keeping the ends qausi-fixed while the low stiffness rods allowing for bending attributed to the result.

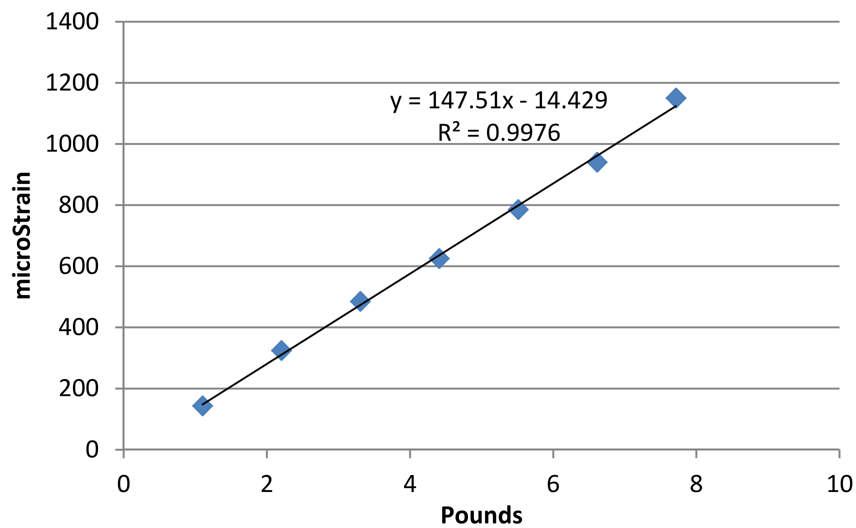


Figure 2. Calibration curve for force transducer

Temperature Change with Respect to Time

The data in Figure 3 shows that temperature does increase with respect to time, but as time goes on the temperature increases at a slower and slower rate. This is expected because as will be shown in the next section as the exterior temperature of the solenoid increases so does the rate of heat transfer from natural convection.

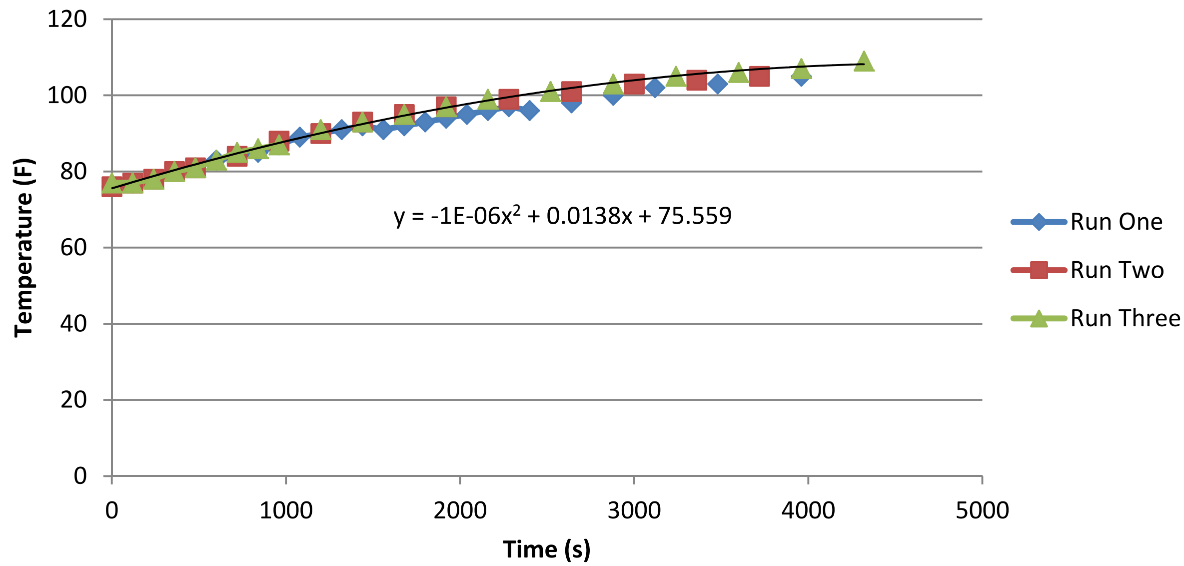


Figure 3. This is a graph that shows the three different runs of data for the testing of the solenoid, and it graphs the temperature of the solenoid in Fahrenheit with respect to time in seconds.

Change in Force with Respect to Temperature Change

The following data shows all three runs temperature with respect to force. From Figure 4 a few things can be seen first of all. The data from the first run has some obvious outliers in comparison to runs two and three and that the data because it is so inconsistent should not be considered valid. The second and third runs both show similar relations in regards to force and temperature. This is that at least as far as this data shows as temperature increases the force output of the solenoid tends to increase slightly.

The reason that is believed to have caused issues with the first run is that during the testing if the wires touch and this goes unnoticed, the perceived strain that is shown by the data acquisition system will appear to be much different than is actually there.

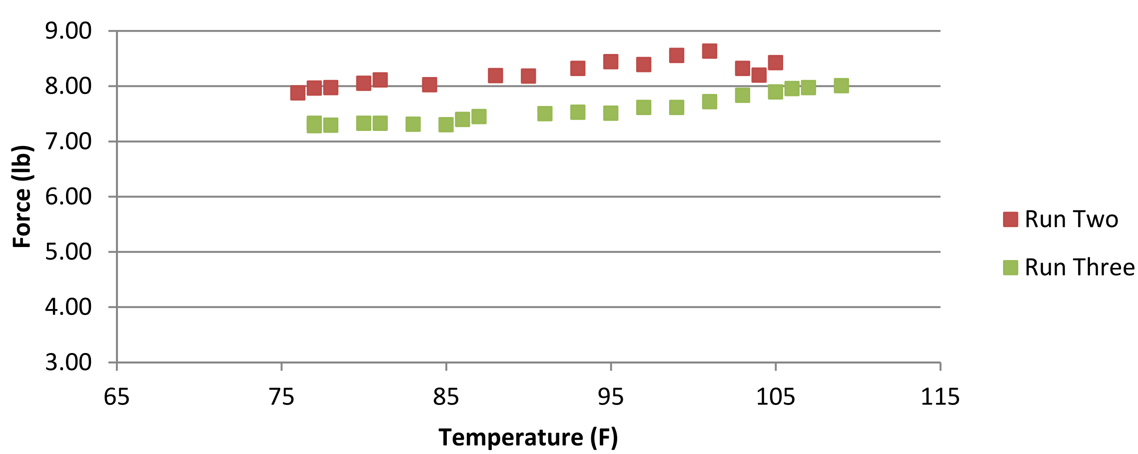


Figure 4. This graph displays the force as it relates to temperature for all three runs.

Analysis of Results

Heat Transfer from Solenoid

For this testing a good analysis that was thought to go along with the testing would be how much heat the solenoid would be able to dissipate based on the temperature of its exterior. For this calculation it was assumed that all heat transfer occurred through natural convection, and that the convection coefficient for the top of the solenoid could be modeled as the upper surface of a hot plate and the convection coefficient for the sides could be modeled as a vertical flat plate. The ambient temperature of the air was also assumed to be 298K. A graph of the resulting heat transfer based on temperature can be found in Figure 5. A sample calculation for this data can be found in Appendix C.

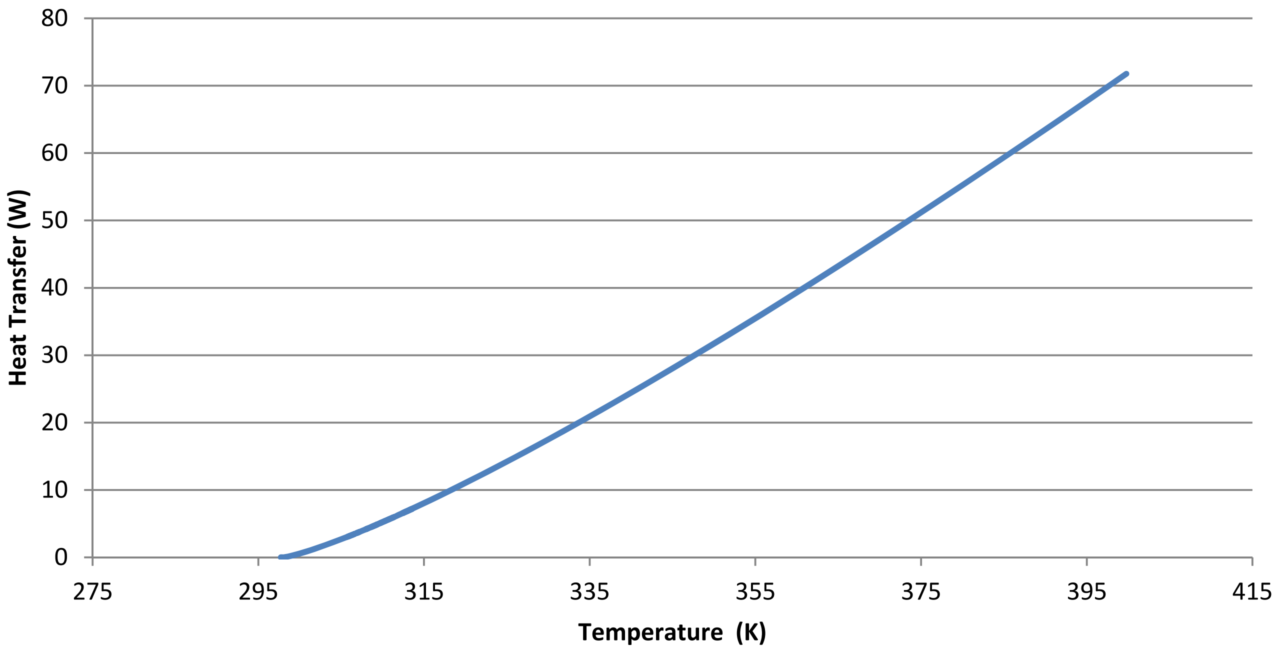


Figure 5. This figure shows the relationship between the heat transferred to the atmosphere and the temperature of the outer surface of the solenoid.

Based on these results it is not expected for the solenoid to keep significantly increasing in temperature, especially not to a dangerous level for the solenoid which is about 170 degrees Fahrenheit or 350 Kelvin. This is confirmed by the test data that is based on a polynomial curve fit the temperature is expected to level off after a time of roughly 2 hours at a temperature of 123 degrees Fahrenheit.

Solenoid Temperature Relative to Time

By knowing the Resistance Factor along with the Thermal Resistance and the power at which the solenoid operates at, we can calculate the temperature change with the following equation:

$$T_h = \frac{20 + P \cdot K \cdot (1 - e^{\left(\frac{-t}{t}\right)})}{1 + 0.00393 \cdot TR}$$

where:
T_h = Temperature (∝C) at end of ON cycle
P = Power in watts at 20∝C
TR = Temperature Rise (∝C)
K = Thermal resistance (∝C/watt)
t = time (seconds)
t = thermal time constant (seconds)

(http://www.solenoids.com/imgp/tech4_4.jpg)

Due to the fact that it would be redundant to have this equation if the temperature change (TR) was known, an equation based off the temperature vs time plot is inserted. The initial temperature was also increased from 20°C to 25°C to reflect the actual testing environment.

$$T_h = \frac{25 + P * K * (1 - e^{-1})}{1 + 0.00393 * (-8 * 10^{-7}t^2 + 0.007t - 0.81)}$$

Further simplification leads to canceling similar terms in P and K which results in a function in terms of initial temperature and time only.

$$T_h = \frac{25}{1 + 0.00393 * (-8 * 10^{-7}t^2 + 0.007t - 0.81)} + (-8 * 10^{-7}t^2 + 0.007t - 0.81)(1 - e^{-1})$$

This equation is a simplified way of viewing solenoid self-heating in terms of time. It is important to keep in mind though that due to the K being held constant this is an underestimate of the actual temperature. The limitation of this function is that it applies only to the specific solenoid tested at the power tested. But the function can be used to predict the minimum temperature the solenoid will be at a time interval after being turned on. Plotting out the function tells us the maximum temperature will occur after 4000 seconds. Due to the profile being based on a second order polynomial, the max temp will be reached before the actual max. Therefore the model gives us a "worst case scenario" of what the solenoid behavior could be.

The thermal resistivity was also plotted on the same time scale as the temperature. Due to it being based on the same temperature profile it has the same shaped curve as temperature.

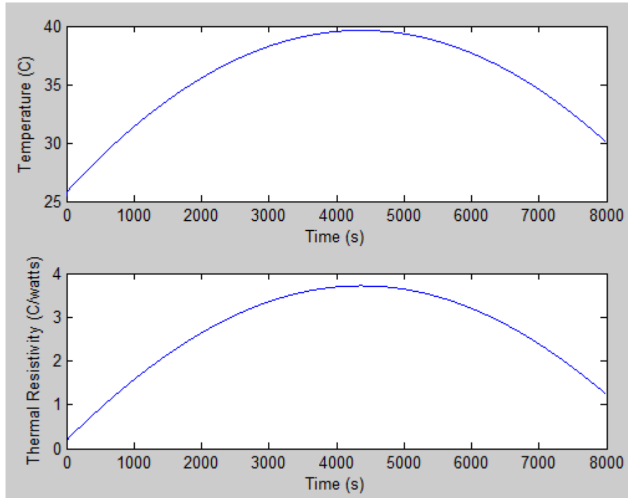


Figure 6. Solenoid temperature relative to time modeled by a polynomial and Thermal Resistivity

Conclusion

Through testing we were able to determine that the solenoid would able to be run for extended periods of time within work conditions without overheating. The original concerns of having a small heat-sink, being in an enclosure, and sensitivity to temperature were unfounded. Instead, it was determined that due to being run at lower than designed power for continuous cycle limited the self heating effects and natural convection was able to keep the solenoid cool enough to maintain a safe operating temperature for extended periods of time. So in conclusion, the solenoid would be able to be run for long periods of time under its designed conditions of at 7volts and 0.66amps in an enclosed area and still maintain the required force output.

Further analysis can be done to the model to find a better fit for extended self heating profile of the solenoid. Finding the heat distribution inside the solenoid would also be nice to have but that would require breaking open the only on-hand solenoid. Further FEA can also be done on the transducer to find better end conditions to properly model the expected strain at the strain gauges. Though not entirely relevant, the solenoid can also be tested at higher power rating to see at what power it does start overheating and decrease in force output.

Appendix A

Transducer Calibration

Overview

This transducer was designed using a mix of beam theory and a converged shell element FEA model. Two models of each type were made with one set having a pinned boundary condition and the other having a fixed boundary condition. When both of these models were compared with actual strain data neither appeared completely correct, but the data from the pinned-pinned boundary conditions most closely matched the calculated results. All of the data was tabulated using a beam cross section that was 3 inches long, .1 inches thick and .275 inches wide. This particular sizing gave us roughly 500 microstrain in the force region that we were attempting to measure, while also giving us enough of a safety factor to handle the largest force that the solenoid could output. A table overviewing the results from the calibration can be found in Table A.1 and Figure A.1.

			FEA		Beam Theory		Tested Results
Force (lb_f)	Moment (in-lb_f) (Fixed Fixed)	Moment (in-lb_f) (Pinned Pinned)	Micro Strain (Fixed Fixed)	Micro Strain (Pinned Pinned)	Micro Strain (Fixed Fixed)	Micro Strain (Pinned Pinned)	Micro Strain
1	0.28175	0.84475	63	198	54	163	145
2	0.5635	1.6895	126	396	109	327	290
3	0.84525	2.53425	189	594	163	490	435
4	1.127	3.379	251	792	218	653	580
5	1.40875	4.22375	314	990	272	816	725
6	1.6905	5.0685	377	1187	327	980	869
7	1.97225	5.91325	440	1385	381	1143	1014
8	2.254	6.758	503	1583	436	1306	1159
9	2.53575	7.60275	565	1781	490	1470	1304
10	2.8175	8.4475	628	1979	545	1633	1449

Table A.1: This table shows an overview of the expected strains and actual strains seen in the force transducer that was designed to measure the output force of the solenoid.

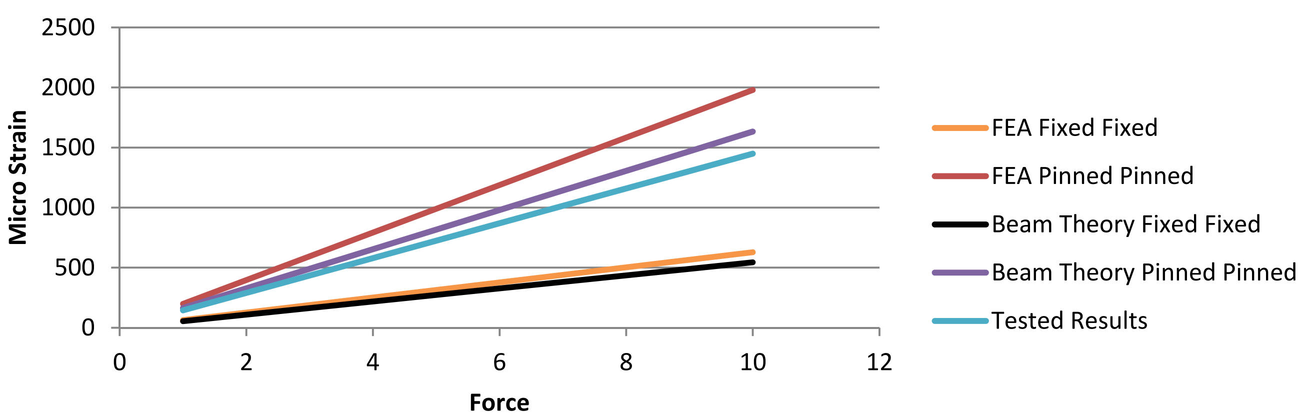


Figure A.1: This figure shows the graphed relationships between force and strain for all of the different models relative to the tested results.

FEA Model

The FEA model which is pictured in Figure A.2used shell elements that converged at roughly 1/32” in size. All of the elements were perfectly square so all the elements were of a high quality. The solenoid load was modeled as a contact between the plunger and the beam portion of the transducer. This made sure that no point loads were present near the location where strain numbers were wanted to be taken.

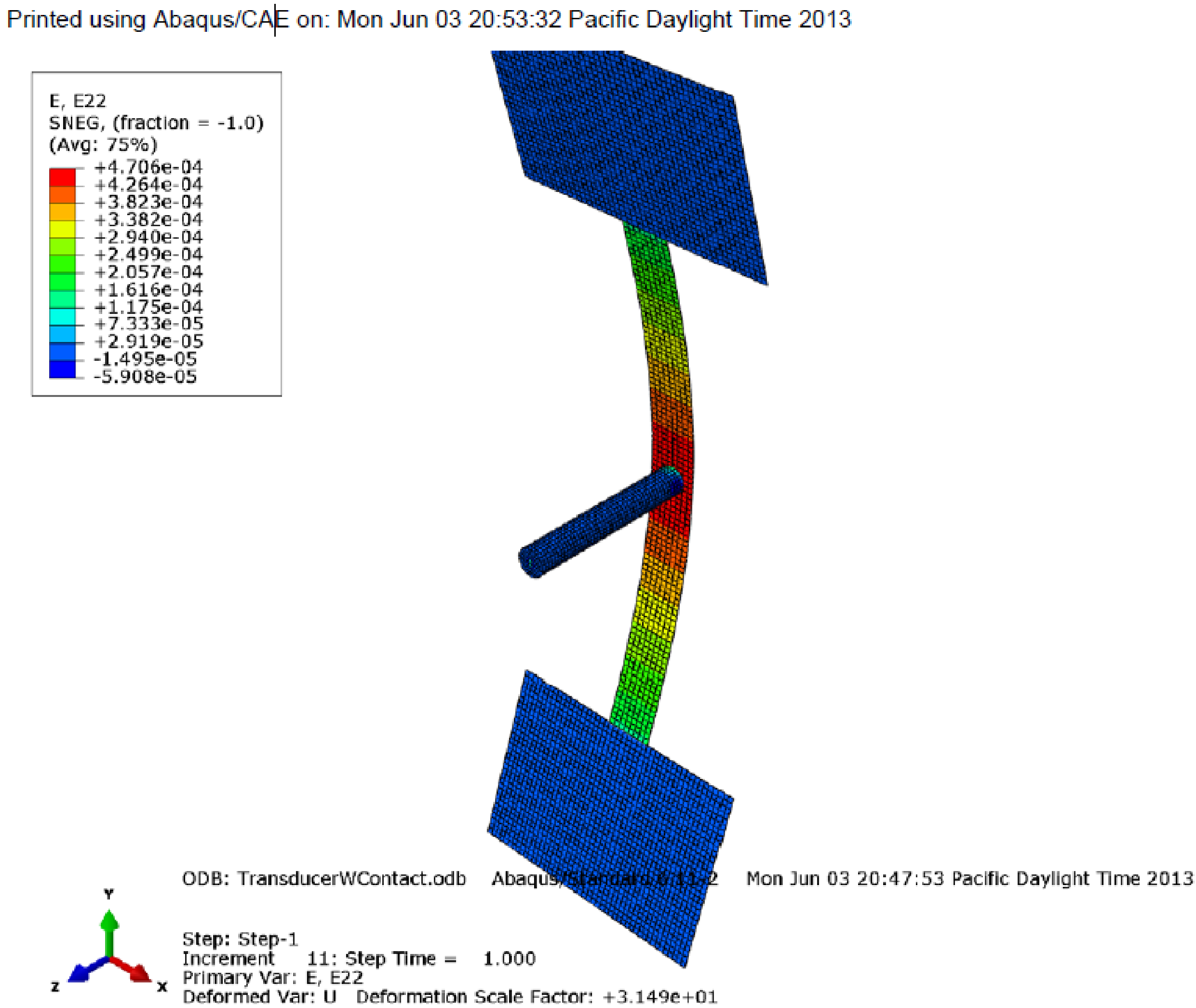


Figure A.2 This is an image of the results of the Abaqus model used to help design the final force transducer.

Plunger Length

The plunger length was set using threaded rods with nuts on each end. This allowed the distance between the un-deflected beam and the solenoid plunger to be set within a couple thousandths of an inch. This distance was determined using calipers to measure the distance at the four separate threaded rods to also make sure that the beam and the mount were parallel as well. A picture of the assembly that set the stroke length of the solenoid can be seen in Figure A.4.

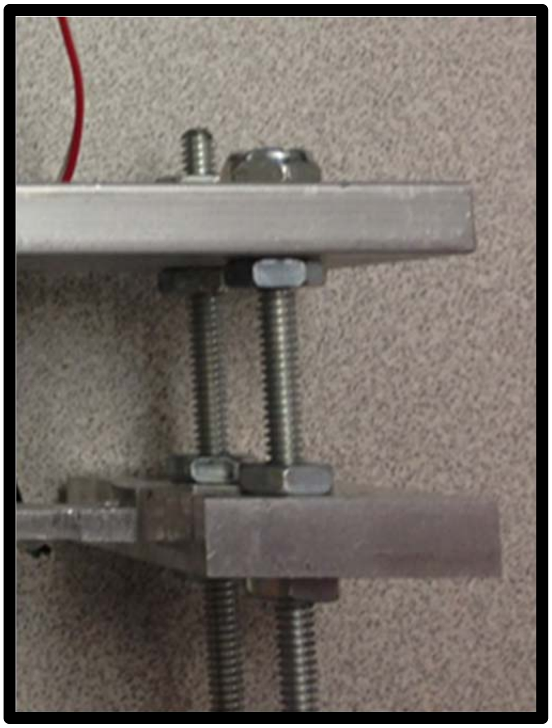


Figure A.4: This is a picture that shows the assembly that allows the transducer to be used with multiple different stroke lengths.

Appendix B

Sample Calculation for Strain in a Beam

Fixed-Fixed Beam

$$Length = 3.00\ in, Width = \ .275\ in, Thickness = \ .100\ in, \quad E = 10\ Msi,$$
$$Strain\ Gage\ Distance\ 1.313, Force = 5.00\ pounds$$

$$Moment(M) = \frac{F(4x - l)}{8}$$

$$Moment(M) = \frac{5.00(4 * 1.313 - 3.00)}{8} = 1.43\ in - lb$$

$$Moment\ of\ Inertia(I) = \frac{b * h^3}{12}$$

$$Moment\ of\ Inertia(I) = \frac{.275 *.1^3}{12} = 2.69 * 10^{-5}\ in^4$$

$$Stress(\sigma) = \frac{M * c}{I}$$

$$Stress(\sigma) = \frac{1.43 * .05}{2.69 * 10^{-5}} = 2756\ psi$$

$\sigma = E\varepsilon$

$$\varepsilon = \frac{2756}{10 * 10^6} = 272\ \mu\varepsilon$$

Pinned-Pinned Beam

$$Length = 3.00\ in, Width = \ .275\ in, Thickness = \ .100\ in, \quad E = 10\ Msi,$$
$$Strain\ Gage\ Distance\ 1.313, Force = 5.00\ pounds$$

$$Moment(M) = \left(\frac{F * x}{2}\right) - \left(F\left(x - \frac{l}{2}\right)\right)$$

$$Moment(M) = \left(\frac{5.00 * 1.313}{2}\right) - \left(5.00\left(1.313 - \frac{3.00}{2}\right)\right) = 4.22\ in - lb$$

$$Moment\ of\ Inertia(I) = \frac{b * h^3}{12}$$

$$Moment\ of\ Inertia(I) = \frac{.275 *.1^3}{12} = 2.69 * 10^{-5}\ in^4$$

$$Stress(\sigma) = \frac{M * c}{I}$$

$$Stress(\sigma) = \frac{4.22 * .05}{2.69 * 10^{-5}} = 8133\ psi$$

$\sigma = E\varepsilon$

$$\varepsilon = \frac{8133}{10 * 10^6} = 816\ \mu\varepsilon$$

Appendix C

Sample Calculations for Natural Convection

$$\beta = \frac{1}{(T_{wall} - T_{atm})/2} = \ .00336$$

$$Ra = \frac{g\beta(T_s - T_{inf})L^3}{\upsilon * \alpha}$$

$$Ra = \frac{9.81 * .00336(306 - 298).0127^3}{1.7 * 10^{-5} * 2.4 * 10^{-5}} = 1.22 * 10^3$$

$$\Pr = \frac{\alpha}{\upsilon}$$

$$\Pr = \frac{2.4 * 10^{-5}}{1.7 * 10^{-5}} = .708$$

$$Nu_{top} = .54 * Ra^{\frac{1}{4}}$$

$$Nu_{top} = .54(1.22 * 10^3)^{\frac{1}{4}} = 3.19$$

$$Nu_{side} = .825 + \frac{0.387 * Ra^{\frac{1}{6}}}{(1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}})^{\frac{8}{27}}}$$

$$Nu_{side} = .825 + \frac{0.387 * (1.22 * 10^3)^{\frac{1}{6}}}{(1 + \left(\frac{0.492}{.708}\right)^{\frac{9}{16}})^{\frac{8}{27}}} = 2.18$$

$$h_{top=\frac{k*Nu_{top}}{L}}$$

$$h_{top=\frac{3.19*3.38*10^{-2}}{.0127}=8.50\frac{W}{m^2k}}$$

$$h_{side=\frac{k*Nu_{side}}{L}}$$

$$h_{side=\frac{2.18*3.38*10^{-2}}{.0127}=5.81\frac{W}{m^2k}}$$

$$Q = h * A * \Delta T$$

$$Q_{top} = 8.50 * \pi * \frac{.0508^2}{4} * (306 - 298) = 2.54\ W$$

$$Q_{side} = 2.18 * \pi * .0508 * .0556 * (306 - 298) = .338\ W$$

$$Q_{total} = Q_{top} + Q_{side}$$

$$Q_{total} = 2.54 + .338 = 2.88\ W$$

Appendix D

Matlab Code

```
%   ME 410 Spring 2013
%   Temperature Model with Respect to Time
%   Nathan Cheadle, Tony Wang
%
%   Description:This model was made to predict the temperature of the
%               solenoid relative to time. The values of power and current
%               can be adjusted to see change in thermal resistivity and
%               the time can be changed to see change in temperature
%%
clc

% Set time parameters
tf = 8000;                           % Final Time(s)
t = 0:tf-1;                          % Time Holder (s)
tx = 1;

% Set voltage and current
v = 7;                               % Voltage (volt)
c = .659;                            % Current (amp)

% Constant values
p = c*v                              % Power (watts)



while tx-1 < tf

    % Values that change with time
    ti = (-8)*(10.^(-7))*tx.^2+.007*tx+.81;         % Temperature increase (C)

    y(1,tx) = 25/(1+.00393*(ti))+(ti)*(1-exp(-tx)); % Total Temperature
    k(1,tx) = ti/(p/(1+.00393*ti)) ;                % Thermal Resistance (C/watts)

    % Time counter
    tx = tx+1;


end

% Plot print out
subplot(2,1,1)
plot(t,y)
xlabel('Time (s)');
ylabel('Temperature (C)');

subplot(2,1,2)
plot(t,k)
xlabel('Time (s)');
ylabel('Thermal Resistivity (C/watts)');
```

Appendix E: Analysis Concerning Final Design

Gear Motor Bracket Finite-Element Model

Lorne Stoops
ME 404-72
18 March 2013

ABSTRACT

The deflection of a gear motor mounting bracket was analyzed with ABAQUS using a number of different element types. The natural frequency of the bracket-motor assembly was also analyzed for each element type. The rigid model of the motor was appropriately attached to the bracket structure at the bolt locations using tie constraints. A convergence study on a static load determined the final number of elements used. The model was also validated by hand calculations for the maximum expected load case. The model using shell elements is trusted to be most accurate and the tip of the motor shaft was found to have a deflection of 0.42 thousandths of an inch and a torsional natural frequency of the structure was calculated to be 264 Hz. The deflection of the motor shaft is acceptable to maintain timing belt alignment, and the natural frequency of the structure will not be excited by steady state operation of the motor.

BACKGROUND

For my senior project I am working with a team to design and build a CNC label cutter. The overall design incorporates the use of two high torque gear motors for XY axis control. The vendor of these motors also sell mounting brackets, which we intend to use in order to minimize the number of custom parts that need to be machined. At first glance the brackets do not appear to be very stiff, so I will be using FEA to better understand the behavior of the bracket under expected loading conditions. The gear motor drives a pulley and timing belt, so it is important that the bracket is rigid enough for the motor to maintain belt alignment.

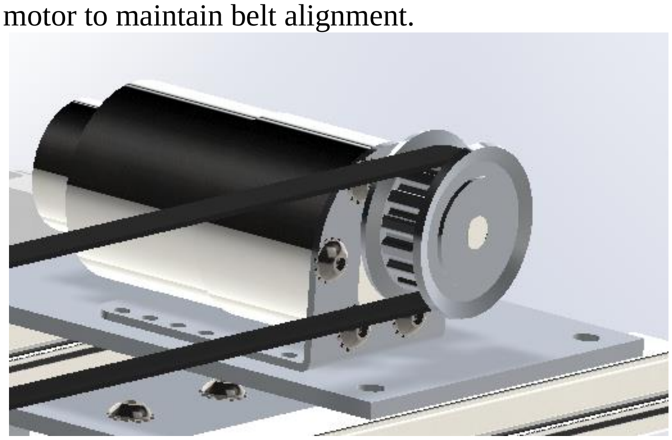


Figure 1. Gear motor assembly as mounted**.**

Static deflection of the bracket under the highest expected load condition, as well as the bracket response to vibratory input from the motor need to be analyzed to make sure that this commercial off the shelf bracket will be acceptable. Detailed drawings of the bracket and motor can be found in the appendix. The bracket will be through bolted to a 1/8th inch thick aluminum plate using four #4 socket head cap screws with washers. The four outermost mounting holes will be used, which are spaced in a square pattern 1.25 inches apart. The motor will be mounted using six M3 screws with the motor output shaft at the end of the slot furthest from the base.

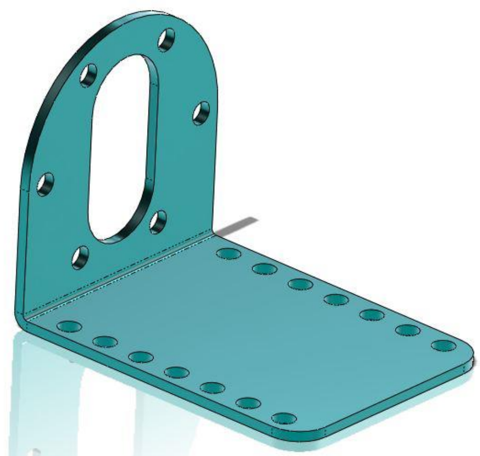


Figure 2. Fully featured bracket model.

The max torque that the motor can generate at the output shaft is 15.6 in·lbs. The 16 tooth XL type timing belt pulley has a pitch diameter of 1.02 inches. The motor will be bolted down with the timing belt having a preload tension of approximately 1 lb. This loading condition is equivalent to a 5.75 lb concentrated load applied to the tip of the motor shaft in the direction of the timing belt.

The motor itself has a no load speed of 10500 rpm while the output shaft will be turning at 80 rpm after a 131.25:1 gear reduction. The frequency of these rotations are 175 Hz and 1.33 Hz respectively. The motor itself weighs 0.51 lbs.

MODEL DEVELOPMENT

SolidWorks was used to create and simplify the geometry of the bracket. As can be seen in figure 2, the part as purchased has many mounting holes at the base to make the bracket as versatile as possible. These holes, as well as the motor mounting holes were eliminated to create a model with simplified geometry that was then imported into Abaqus. The fillet at the right angle bend of the bracket was also eliminated. In the solid model the base plate was cut short near the right angle bend to simplify the model so more elements could be used in local areas. The bracket is made from an unspecified aluminum alloy. This is not a significant concern because the deflection and stiffness of the bracket is of a greater interest and the structure will not yield under the specified loading condition.

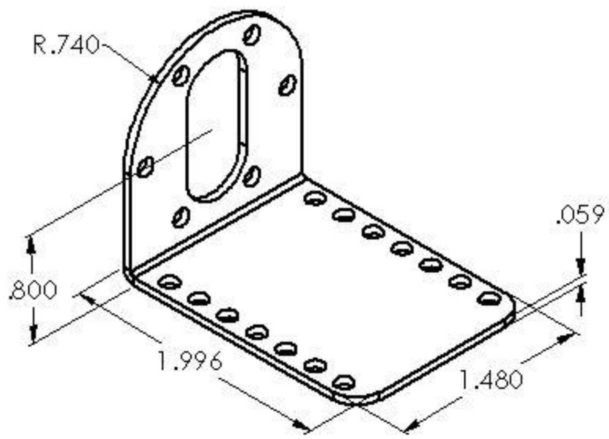


Figure 3. Motor Bracket Size

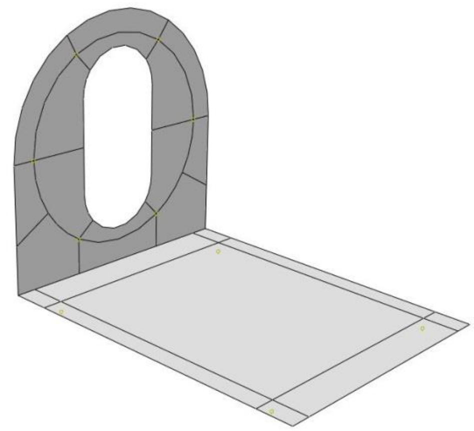


Figure 4. Simplified Bracket Shell Model

Table 1. Material Properties for Aluminum.

Property	Value	Units
Youngs Modulous	10.4×10^6	psi
Poisson's Ratio	0.333	-
Modulous of Rigidity	3.9×10^6	psi
Density	5.26	$Slugs/ft^3$
	2.54×10^{-4}	$lbf \cdot s^2/in^4$

Both a shell and solid model were created of the bracket. In the shell model the section thickness is defined outwards from the inner faces of the bracket. The part was partitioned such that the creation of element nodes are forced at the six motor mount locations on the vertical face as well as the four mounting locations on the base. The final model includes both the motor and the bracket. The motor is modeled as a rigid body with inertial properties specified at a reference point located at the center of mass of the motor. These inertial properties and the location of the reference point were determined in Solidworks. In calculating the inertial properties, the mass of the motor is assumed to be evenly distributed throughout the modeled volume. The motor will stiffen the mounting face of the bracket as well as influence the natural frequency of the system so it is important to include in the analysis. The nodes at the six mounting were tied to the master surface of the motor face.

The shell element models were simple enough that I also included the contact interaction between the motor and the bracket for the deflection analysis. This stiffened the system slightly. For boundary conditions, the bracket was pinned at the four base mounting locations, and motion of the bottom surface was constrained normal to the surface to capture the fact that this bracket will be mounted on a flat aluminum plate. In the solid element model the base of the bracket is pinned at the two mounting locations nearest the right angle bend, and a fixed constraint was placed at the surface where the rest of the bracket was cut away. The bottom surface was also constrained in the same way as the shell model.

MESH DEVELOPMENT & CONVERGENCE

The static deflection and vibration analysis were both carried out using the following element types:

- Linear quadrilateral shell elements- reduced integration
- Linear triangular shell elements- reduced integration
- Quadratic hexahedral solid elements- reduced integration

The bracket was partitioned to simplify the meshing geometry and ease up the transitions between the circular slot and bracket edge to the rectangular bend and edges. Convergence of the models was checked by observing the deflection of the motor shaft tip in the direction of the applied load. To further verify the model using linear quadrilateral shell elements, the convergence of the torsional natural frequency was also checked. For the shell model, a uniform part seed size was decreased by half with each iteration. For the solid model a biased mesh was used at the right angle bend and continued halfway up the vertical face of the motor bracket. To check convergence, the seed size of the biased region was decreased by half with each iteration while keeping the seed size of the rest of the part 5 times larger than the bias seed size.

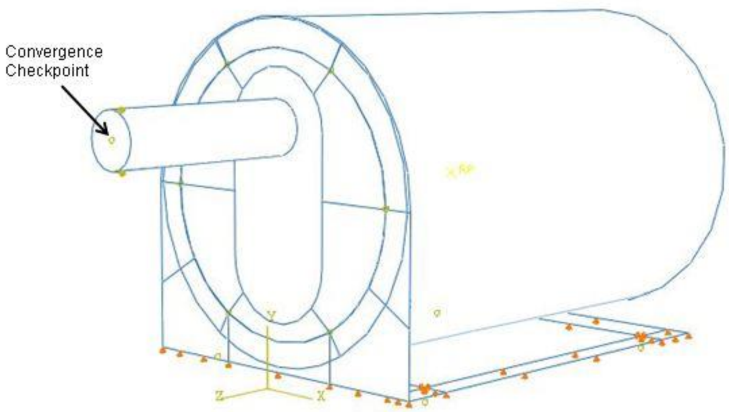


Figure 5. Convergence checked using deflection at end of motor shaft in the x-direction.

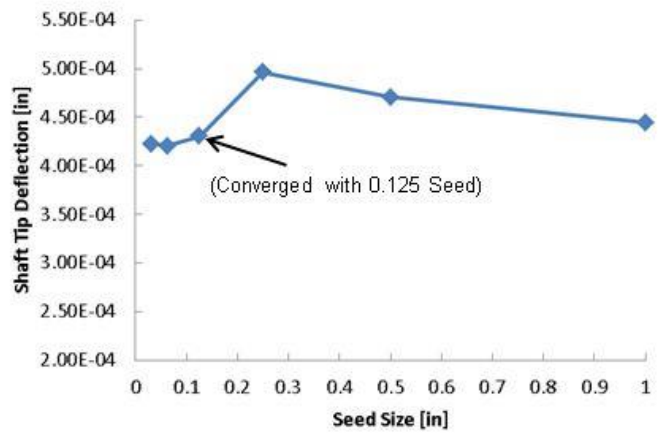


Figure 6. Convergence plot for shell model with respect to the shaft deflection.

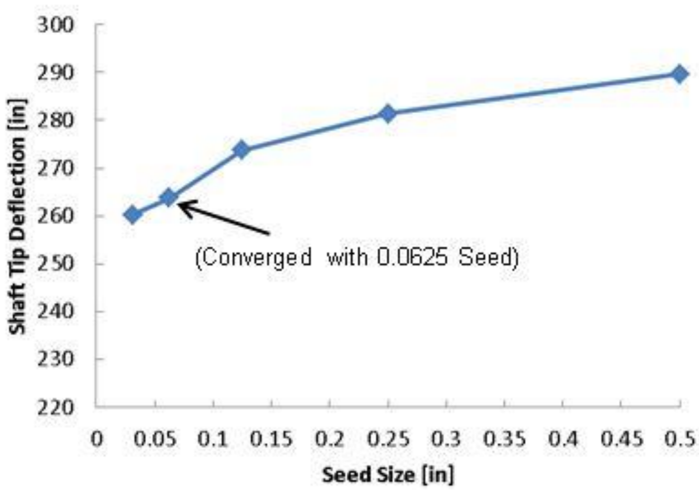


Figure 7. Convergence plot for shell model with respect to the torsional natural frequency.

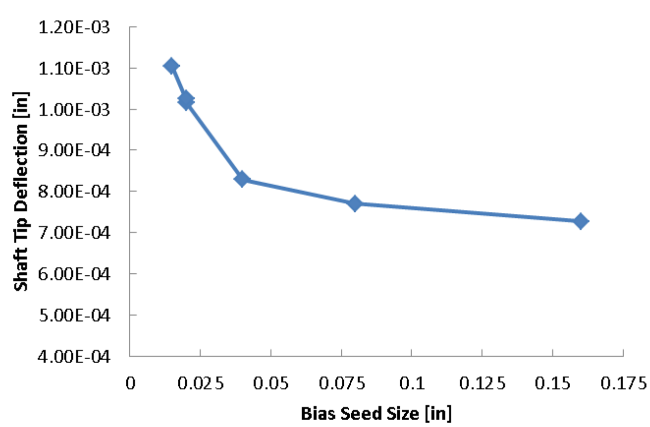


Figure 8. Convergence not achieved in solid element model.

When refining towards convergence with the quadrilateral shell model by looking at the torsional natural frequency of the model, each subsequent point was within 5% of the last, but I believe the results attained with a seed size of 0.0625 are most accurate. This more refined mesh was used because with the simpler shell elements the model was still quickly solvable by the computer. When trying to use solid elements I was not able to bias and refine the mesh enough to achieve convergence without maxing out the computer RAM. Having three elements through the thickness of such a thin part means far too many elements are required to cover the area of the bracket. Quadratic elements were used in the hope to better capture the bending of the part while using a larger element size. Solid elements are poorly suited for this analysis.

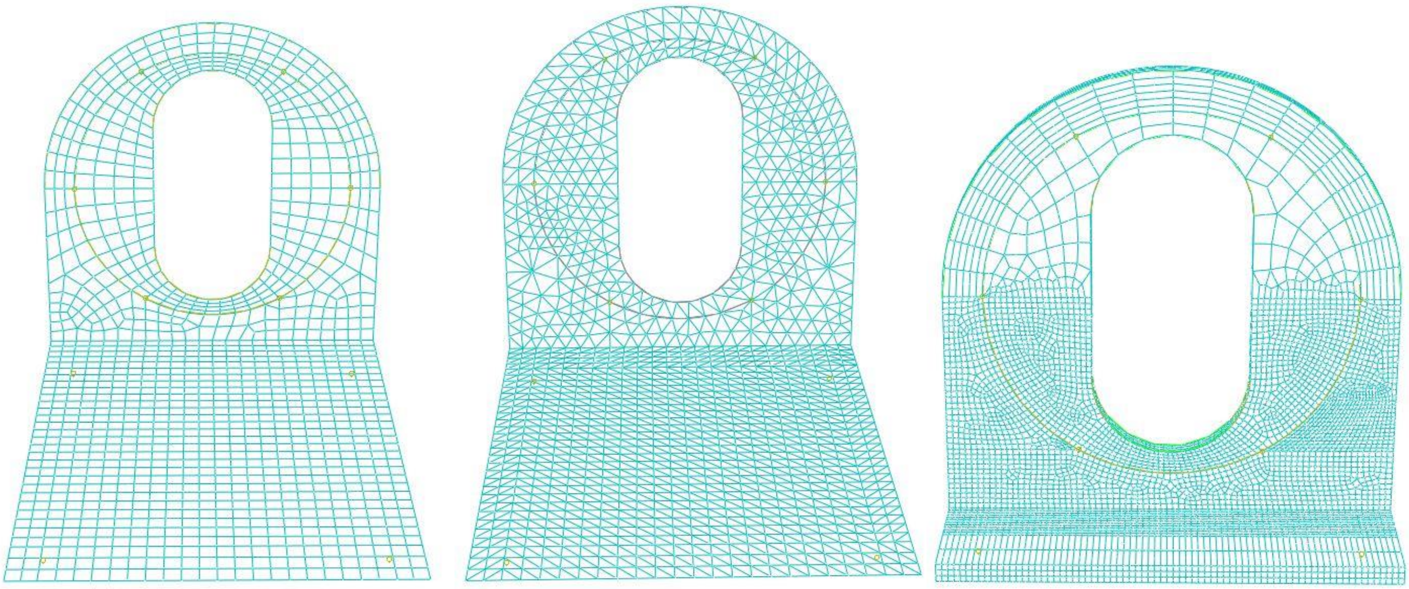


Figure 9. Comparison of element meshes for the three models ran.
Quadrilateral Shell (left), Triangular Shell (middle), Hexahedral Solid (right)

Table 2. Mesh Details

Mesh Parameter	**Quadrilateral Shell**	**Triangular Shell**	**Hexahedral Solid**
Bias Element Size	---	---	0.02
Part Element Size	0.0625	0.0625	0.10
# of Elements	1172	2279	12765
DOF	13020	14628	197391
% Meet Quality Criteria	99.83	99.74	92.4

Table 3. Mesh quality criteria for each element type

Quality Criteria	**Quadrilateral Shell**	**Triangular Shell**	**Hexahedral Solid**
Aspect Ratio	< 5	< 5	< 5
Corner Angle	45<θ<135	15<θ<105	45<θ<135

FE ANALYSIS

I performed a general static analysis to determine the deflection of the motor shaft tip in the direction of the timing belt, as well as a linear perturbation analysis to find the natural frequency of the first two bending modes. This analysis was done for each of the three element types listed. The analysis using shell elements I believe is most appropriate for the geometry of the part and should provide the most accurate results.

Over the course of this project I encountered a number of difficulties. I spent time debating how to extrude the shell element thickness in order to accurately model the bracket, only to find that small material gaps or overlaps do not affect the results considerably. I also had difficulty modeling how the bolts constrain the motor to the bracket. Tying specific nodes directly to other nodes proved troublesome, so I wound up tying the nodes located at the bolt holes on the bracket to the face of the rigid motor. The mix of the very rectangular bracket geometry with the rounded slot cut out and bracket end made nicely meshing the part problematic. Many partitions were used to ensure node locations at the tie points while also preserving mesh quality.

RESULTS

After doing the analysis the bracket structure proved to be much more rigid than I had initially presumed. The deflection of the motor shaft tip and the first two natural frequency of the structure were successfully attained.

Table 4. Analysis Results

Results	Quadrilateral Shell	Triangular Shell	Hexahedral Solid	Hand Calcs	Units
Shaft Tip Deflection	0.4202	0.3711	1.016	1.1	in x 10^{-3}
1st Bending ω_n	71.2	73.4	66.99	98	Hz
1st Torsional ω_n	263.8	279.2	220.2	208	Hz

The deflection of quadrilateral shell model was 22% different from my approximate solution. The triangular shell model was 25% different, and the solid model was 2% different. Even though the solid model was closest to my hand calculations, I believe that the shell elements most accurately predicted the behavior of the structure. This element type is best suited for modeling thin plates such as the motor bracket. Triangular elements were stiffer as was expected since these have a more simplified displacement field. The analysis with the solid elements involved a lesser quality mesh and the result is likely not converged. I only trust in my hand calculation to provide a ball park estimate of what the result should be, and by that criteria have confirmed that the FEA results are reasonable. Included on the following page are the model results for the quadrilateral shell element model. In conducting this analysis, the deflection of the motor shaft in the direction of the belt, as well as the torsional natural frequency were of greatest concern.

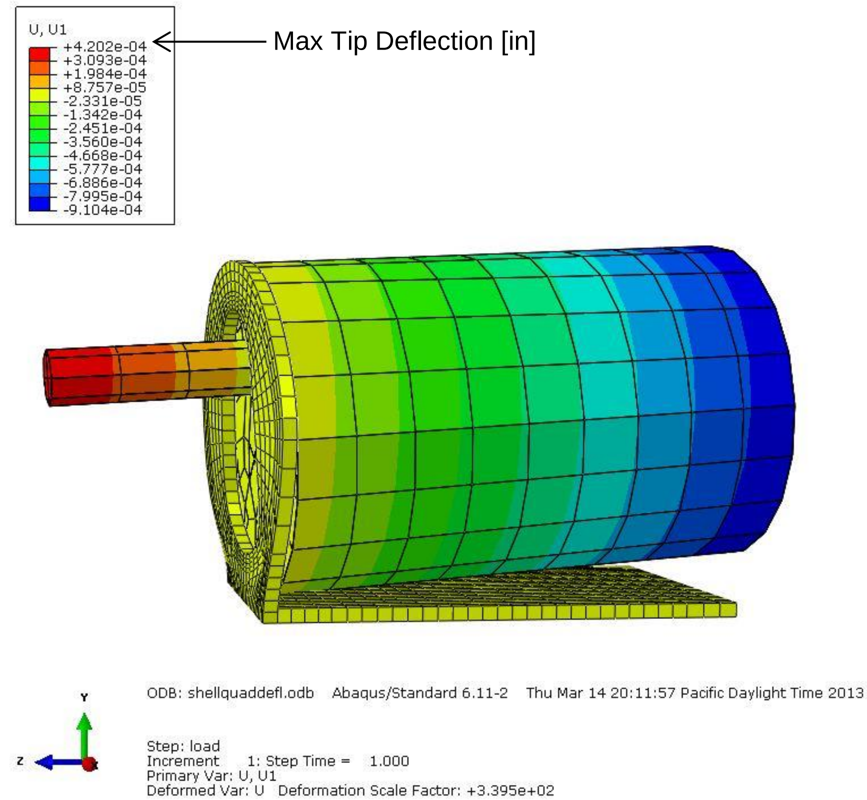


Figure 10. Quadrilateral shell element results for deflection of structure in the x-direction. Shell thickness has been rendered for visualization.

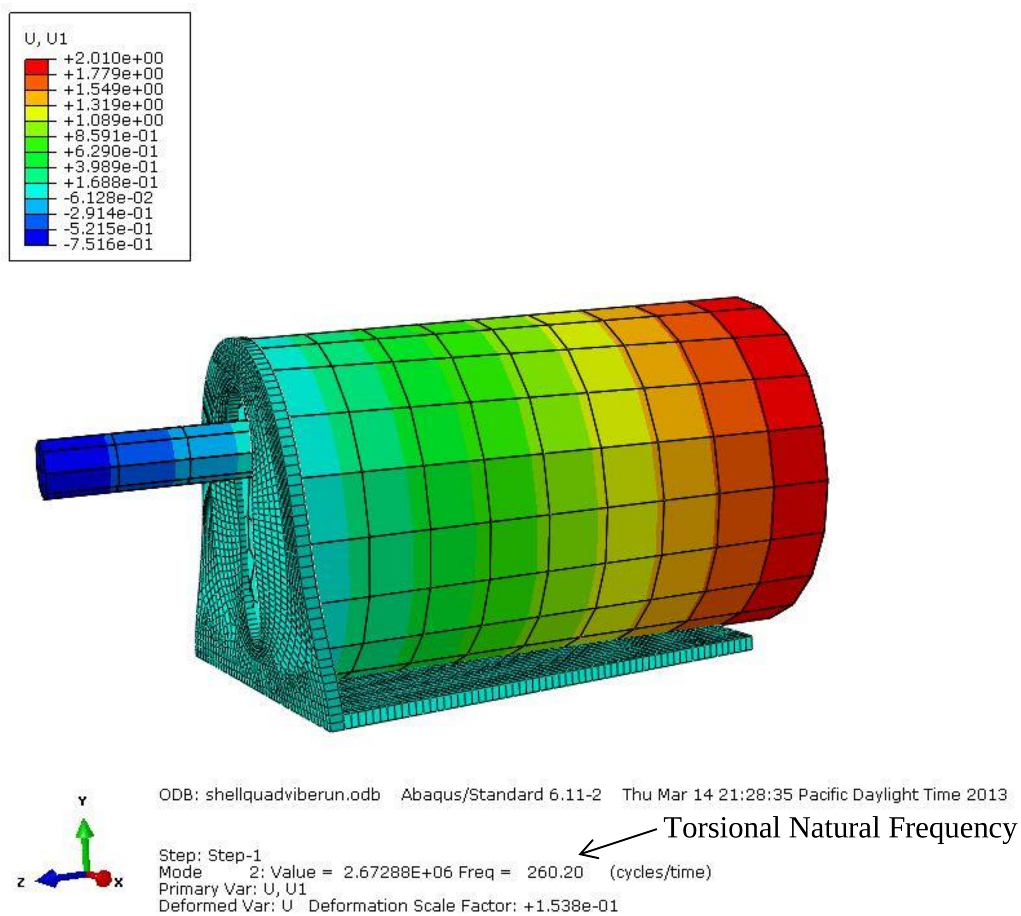


Figure 11. Quadrilateral shell element results for the torsional natural frequency of the structure. Shell thickness has been rendered for visualization.

DISCUSSION

With this analysis I have been able to confirm that the bracket will in fact be stiff enough for use with the gear motor needed to operate the label cutter. This same bracket is sold to mount all 37mm motors listed by the vendor, but the gear motor selected utilized the highest gear reduction. I am comforted to know that the design will meet the needs of my senior project even under the highest foreseeable loading condition.

When compared with my hand calculations, the structure proved to more rigid than I initially estimated. My calculations assumed that the torque caused by the load on the motor shaft was applied to the two screws nearest the bracket bend. With the torque modeled in Abaqus as being applied over all six mounting screws, strain energy was actually more evenly distributed throughout the mounting face of the bracket and as a result less deflection actually occurs. Deflection was also restricted by the bracket contacting the motor face. These two factors served to preserve the shape of the bracket under loading and resist the twisting that I had thought would be more significant. From this analysis I have a better feel for the behavior of rectangular bars in torsion and how they can be constrained to prevent warping.

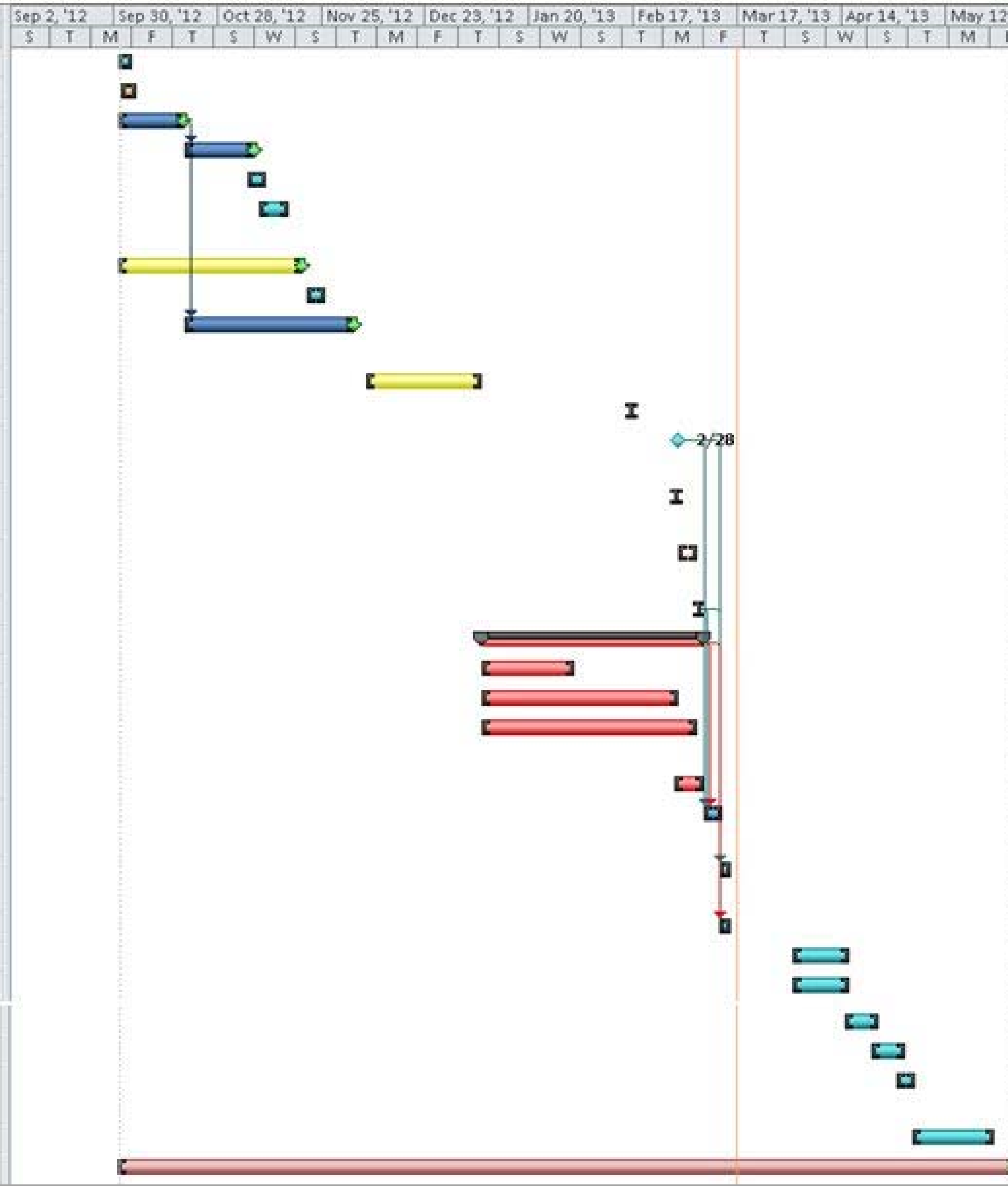
Moving forward I would be interested to see how much of the preload in the timing belt is lost under this deflection to ensure that the unloaded side of the belt does not become too loose. If I were to do anything differently, I would not bother attempting a model using solid elements on such a part again, but rather focus that effort on establishing a more detailed shell model that considers the effect of the pressure load of the screw heads. I would also like to better understand the stress concentrations associated with the right angle bend. This could be done with a biased shell element mesh at the bend.

CONCLUSION

The analysis conducted served to estimate the deflection of a motor shaft used drive a pulley with a timing belt. The natural frequency of the structure was also analyzed to ensure operation of the motor would not significantly excite the bending modes of the bracket. Under the maximum expected loading condition, equivalent to a 5.75 lb concentrated load at the tip of the motor shaft, the tip of the motor shaft will deflect approximately 0.42 thousandths of an inch in the direction of the force applied by the timing belt. The first natural frequency for bending of the bracket will occur around 71 Hz, while the torsional natural frequency of the motor mounting face will occur around 264 Hz. Neither of these modes will be dramatically excited by the 175 Hz operation of the motor. The bracket is sufficiently stiff for use with the selected motor.

Appendix F: Project Planning

ID	Task Name	Duration
2	Motto, Team Name, Group Activity	4 days
4	Brainstorming	4 days
3	Project Proposal	14 days
5	Conceptual Model	13 days
6	Force Testing	5 days
7	Finalize Concept (decision Matrix)	6 days
8	Yellow Tag	36 days
9	Thanksgiving	4 days
10	Conceptual Design Report	32 days
11	Christmas	22 days
12	Solenoid Testing	1 day
18	CDR Student Presentation	0 days
19	Individual Ethics Memo Due	1 day
20	Team Ethics Presentation	3 days
21	CDR with Sponsor	1 day
13	**Analysis Drawing & BOM Review**	**44 days**
14	Design Cutter Tester	19 days
16	Design Roller Assembly	39 days
15	Design Cutter Assembly	42 days
17	Complete Overall Assembly	6 days
25	Project Update Memo to Sponsor	3 days
22	Purchase long lead items	3 days
23	End of Winter Quarter Report	3 days
24	Begin Fabrication	11 days
26	Manufacturing & Test Review	11 days
27	Assemble SubAssemblies	7 days
28	Fabricate Overall Assembly Parts	7 days
29	Project Hardware Assembly Demo	5 days
30	Final Assembly	16 days
1	Senior Project Expo	174 days

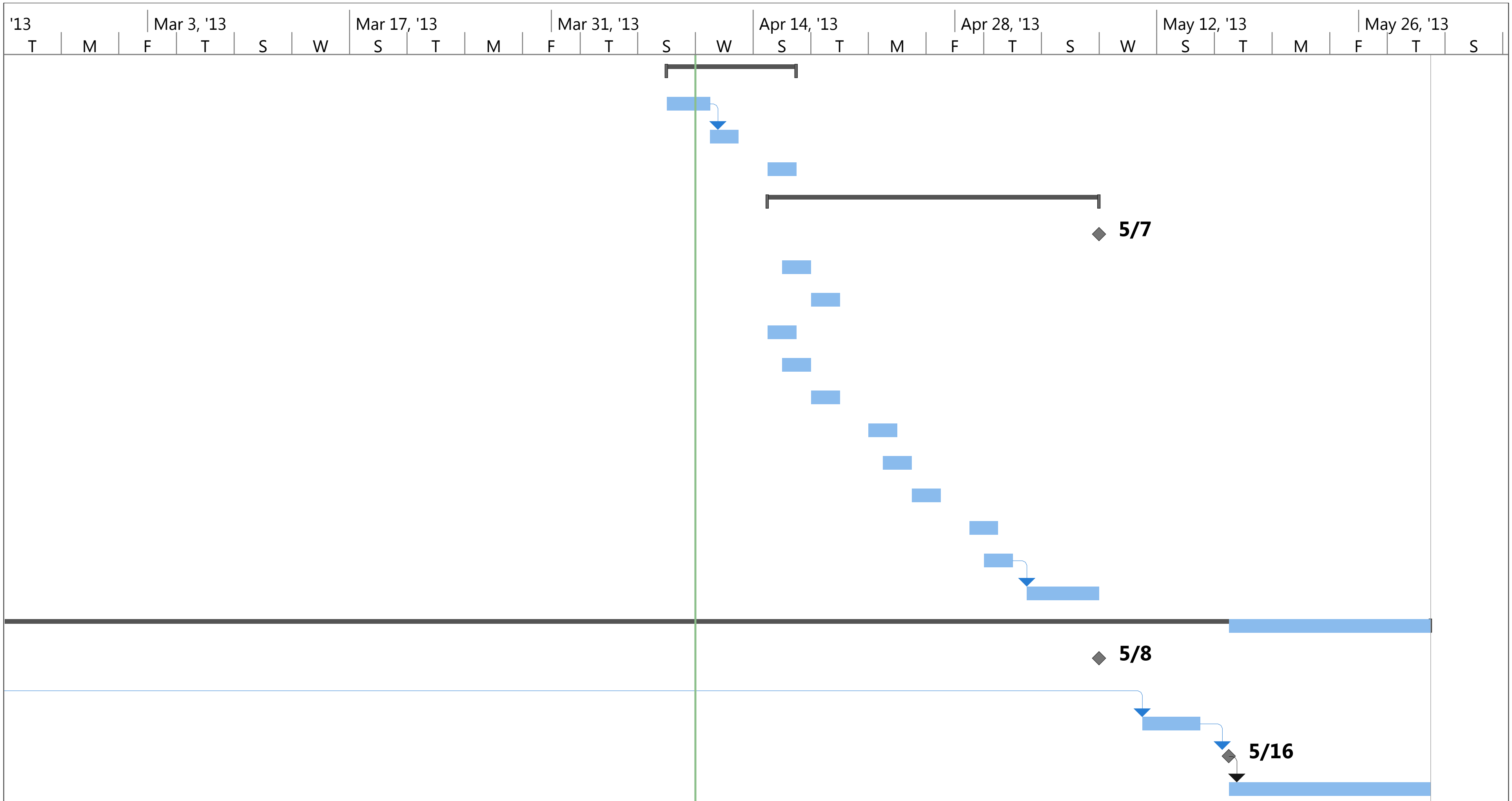


ID		Task Mode	Task Name	Duration	Start	Finish	Predecessors
1			**Rough Cuts**	**7 days**	**Mon 4/8/13**	**Tue 4/16/13**	
2			parts 100001 through 100011 (14 parts)	3 days	Mon 4/8/13	Wed 4/10/13	
3			parts 110001 through 112004 (10 parts)	2 days	Thu 4/11/13	Fri 4/12/13	2
4			Parts 130002 through 160002 (8 parts)	2 days	Mon 4/15/13	Tue 4/16/13	
5			**Fine cut parts and drill/tap holes**	**17 days?**	**Mon 4/15/13**	**Tue 5/7/13**	
6			Fine cut parts and drill/tap holes	0 days?	Tue 5/7/13	Tue 5/7/13	
7			100001, 100002-1,100002-2	2 days	Tue 4/16/13	Wed 4/17/13	
8			140002-1,14000-2,100003	2 days	Thu 4/18/13	Fri 4/19/13	
9			100004, 110002, 100005	2 days	Mon 4/15/13	Tue 4/16/13	
10			100006,100008,100007	2 days	Tue 4/16/13	Wed 4/17/13	
11			100009,100010,10011	2 days	Thu 4/18/13	Fri 4/19/13	
12			110001,111001,111101	2 days	Mon 4/22/13	Tue 4/23/13	
13			112001,113001,112002	2 days	Tue 4/23/13	Wed 4/24/13	
14			112003, 112004,130002	2 days	Thu 4/25/13	Fri 4/26/13	
15			150002,150004,151001	2 days	Mon 4/29/13	Tue 4/30/13	
16			151001,151002,151003	2 days	Tue 4/30/13	Wed 5/1/13	
17			160001,160002,18000's	3 days	Fri 5/3/13	Tue 5/7/13	16
18			**Assembly**	**268 days**	**Wed 5/23/12**	**Thu 5/30/13**	
19			Assembly	0 days?	Wed 5/8/13	Wed 5/8/13	
20			Bottom plate assembly, Rail assembly	3 days	Wed 5/23/12	Fri 5/25/12	
21			Roller assembly, Cutter assembly	3 days	Sat 5/11/13	Tue 5/14/13	20
22			Misc	0 days	Thu 5/16/13	Thu 5/16/13	21
23			**Testing and Troubleshooting**	**10 days**	**Fri 5/17/13**	**Thu 5/30/13**	22

Apr 1, '12
M F T S W

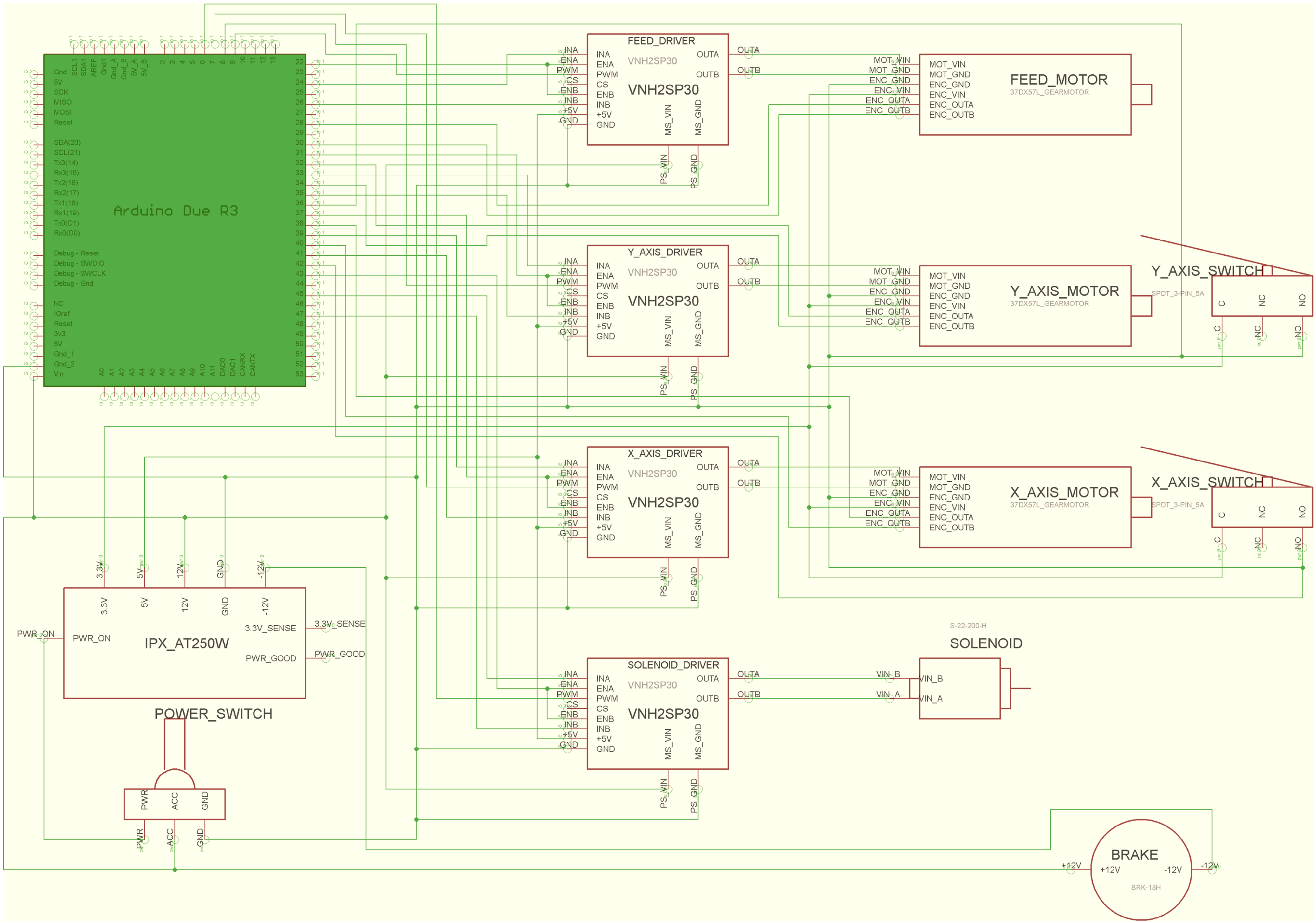
Project: FirstLaunch
Date: Wed 4/10/13

Task	Inactive Summary	External Tasks
Split	Manual Task	External Milestone
Milestone	Duration-only	Deadline
Summary	Manual Summary Rollup	Progress
Project Summary	Manual Summary	Manual Progress
Inactive Task	Start-only	
Inactive Milestone	Finish-only	



Project: FirstLaunch Date: Wed 4/10/13	Task	Inactive Summary	External Tasks		
	Split	Manual Task	External Milestone		
	Milestone	Duration-only	Deadline		
	Summary	Manual Summary Rollup	Progress		
	Project Summary	Manual Summary	Manual Progress		
	Inactive Task	Start-only			
	Inactive Milestone	Finish-only			

Appendix G: Wiring Diagram



Arduino Due R3
FEED_DRIVER
VNH2SP30
Y_AXIS_DRIVER
VNH2SP30
X_AXIS_DRIVER
VNH2SP30
SOLENOID_DRIVER
VNH2SP30
INA
ENA
PWM
CS
ENB
INB
+5V
GND
OUTA
OUTB
MS_VIN
MS_GND
PS_VIN
PS_GND
FEED_MOTOR
37DX57L_GEARMOTOR
Y_AXIS_MOTOR
37DX57L_GEARMOTOR
X_AXIS_MOTOR
37DX57L_GEARMOTOR
MOT_VIN
MOT_GND
ENC_GND
ENC_VIN
ENC_OUTA
ENC_OUTB
Y_AXIS_SWITCH
SPDT_3-PIN_5A
X_AXIS_SWITCH
SPDT_3-PIN_5A
C
NC
NO
IPX_AT250W
3.3V
5V
12V
GND
-12V
PWR_ON
3.3V_SENSE
PWR_GOOD
POWER_SWITCH
PWR
ACC
GND
S-22-200-H
SOLENOID
VIN_B
VIN_A
BRAKE
+12V
-12V
BRK-18H

Appendix H: Mechatronics Code

See Files on included CD (Folder: CNC Label Cutter)