Memo

To: Dr. Ciocanel
From: Matthew Batten, Cody Burbank, Thaddeus Grudniewski, Jonathan McCurdy, and Joy Weber
Date: 12/13/13
Re: Final Design

The final design for the MSMA lateral testing device has been completed. This design contains one Ultra Motion Digit NEMA 17 Stepper Electromechanical Actuator, one ST5-S Stepper drive controller for the actuator, and one Honeywell Model 11 Subminiature Tension/Compression Load Cell. The electromechanical actuator and load cell will be supported using two separate round columns made out of low-carbon steel which simply screw into the existing base plates. These support columns require additional hardware for assembly. The system is designed specifically for ease of installation and removal. The column from the actuator can be easily removable, and the column for the load cell will allow for the load cell to be positioned safely out of the way when not in use.

Adding up the costs of the items to be purchased, along with the cost of the raw materials and hardware necessary for assembly, the total cost expected for construction and testing comes out to be $978.20. This final number does not include the cost of the one Honeywell Model 11 Subminiature Tension/Compression Load Cell, since this is a part that we already have on-shelf. For reference, these load cells cost $771.00. There is no cost associated with manufacturing parts, as that will be done in house, and is free of charge. The cost breakdown can be seen in Table 1.

Table 1: Total Cost Breakdown

Component	Quantity	Cost
Digit NEMA 17 Stepper	1	$620.00
ST5-S Stepper Drive	1	$302.00
Low-Carbon Steel Rod, 1", 3' Length	1	$26.71
Low-Carbon Steel Bar, 3''-6''-1/4''	1	$7.67
Flathead Screw, 5 pack	1	$5.24
Wing Nuts, 25 pack	1	$7.21
Socket Head Cap Screw, 25 pack	1	$5.61
Set Screw, 25 pack	1	$3.76
Total Cost		$978.20

MSMA Lateral Loading Device

By
Matthew Batten, Cody Burbank, Thaddeus Grudniewski,
Jonathan McCurdy, and Joy Weber
Team 10

Final Proposal

Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Fall 2013

Department of Mechanical Engineering
Northern Arizona University
Flagstaff, AZ 86011

List of Contents

List of Nomenclature

The following symbols and variables were used in the by-hand calculations necessary in the engineering analysis of our design components. All are conventional terms used in basic stress mechanics.

σ	Axial stress
τ	Shear stress
A_c	Cross sectional area of component
F_{max}	Maximum force occurring on a component
I	Moment of inertia
b, h	Base and height of member with respect to moment axis
M	Moment in beam

List of Figures

Chapter 1: Introduction

Chapter 2: Concept Generation and Selection

Chapter 3: Engineering Analysis

Chapter 4: Cost Analysis
Chapter 5: Conclusions
Appendix A: Engineering Drawing

Appendix B: Project Planning

List of Tables

Chapter 1: Introduction

Chapter 2: Concept Generation and Selection

Chapter 3: Engineering Analysis

Chapter 4: Cost Analysis

Abstract

This document contains the information regarding the Magnetic Shape Memory Alloy lateral loading project. Specifically this document provides an introduction to the problem currently experienced by the client Dr. Constantin Ciocanel. Given this problem the project's goals, objectives, operating environment, and constraints are identified. To provide an introduction to recent relevant information pertaining to the topics covered in this report a brief state of the art research section has been provided.

After establishing the basis for the project this document will cover the concepts generated as solutions. Including the methodology for why certain design concepts were looked at. After introducing the different design options for each concept this document establishes criteria and weightages used for concept selection. These criteria are than used in decision matrices to begin the concept selection process.

After objectively evaluating the different design options based upon the client objectives this document shifts to engineering analysis. Taking the top design options several specific setups were constructed for analysis. This document looks at the designs for material and structural integrity. Eventually specific materials are selected based upon the engineering analysis and numerical modeling shown within. Using the selected material this document creates a proposal design for the project.

The proposed design specifically states the material to be used. These materials are than broken down into a specific bill of materials. Combining the bill of materials with manufacturing costs this document is able to show a total cost of production associated with the proposed design. Possibilities for payback and mass production are briefly touched upon following the cost analysis.

This document concludes all the information gathered during the course of this project. By displaying all critical information from the various report sections in a single location. The last section of this report simply restates the proposed design and mentions some of the tasks that will follow during the construction and testing phase.

Following the formal report this document contains various computer generated drawings for all relevant design parts. Ensuring that all dimensions are readily available to the client. In

addition there is a fully assembly view, exploded view, and sectional view of the device. These allow for a complete understanding of how the assembly will be constructed and could be disassembled.

Following the drawings are the schedules of the team in the form of Gantt charts. These schedules include a breakdown of the work that has already been done this semester and of the work that will be performed during the spring of 2014.

Finally by-hand calculations have been provided in detail for validation of the calculations performed during the engineering analysis.

Chapter 1. Introduction

1.1 Introduction

At the Northern Arizona University, Dr. Constantin Ciocanel is experimenting with a magnetic shape memory alloy (MSMA). This MSMA is comprised of Nickel, Manganese, and Gallium, and exhibits strain under a magnetic field. The mechanical properties of this material are not well known, and it is Dr. Ciocanel's goal to find them. He and his team of graduate students have set up a number of experiments in order to do so, which primarily use a machine which applies and measures forces on a sample. This machine is called an Instron machine. Coupled with the Instron is a set of electric dipoles which creates the magnetic field which in turn induces strain in the MSMA. Even with the current set up, all of the properties which Dr. Ciocanel is searching for cannot be found.

1.2 Problem Description

Dr. Ciocanel and his research team hopes to shed some light on the potential uses of this particular MSMA. He speculates that this material, given its apparent magnetic shape memory properties, may be used as an electro-magnetic linear actuator, or possibly be used within the realm of power harvesting. By further understanding the mechanical properties of this material, even more potential uses will be discovered. All in all, understanding the potential uses of this newer material will help the engineering world advance. Unfortunately, the current method of testing this material is limited in nature. The current process and equipment are not capable of performing tests which are required to determine the sought after properties of the material.

1.3 Identification of Needs & Constraints

In order to run tests which result in accurate data a piece of equipment needs to be designed that will facilitate the testing process in a third dimension. This equipment is required to be effective, cost efficient, and precise. It must also be able interface with the already existing equipment. In order to meet these goals the following set of constraints were set:

1. Full cost under $2,500: This includes all the parts and materials used within the design.
2. Capable of applying a force greater than or equal to 75 N: The actuator must apply a constant force ranging from 0 to at least 75 N. This force is required to get a complete understanding of the MSMA material properties during testing.
3. The material used must be non-magnetic: The apparatus has high powered electro dipoles creating a powerful electric field. Therefore, the material selected must be resist the magnetism and function normally.

4. The width of the material in contact with the MSMA must be no greater than 10 mm: The distance between the electro dipoles is 10 mm. If our design has a width greater than the specified value it will not be able to make contact with the MSMA.
5. The height of the material in contact with the MSMA must be no greater than 12 mm: The distance between the grips that hold the MSMA in the testing apparatus during maximum material compression is 12 mm. The design must be equal to or less than the specified value to make contact with the MSMA and allow for a force to be applied.
6. Able to be installed by two individuals: On average two individuals will be working within the lab at any given moment. Therefore, the design must be such that two lab workers could install or uninstall the device for testing purposes. This will apply limits on the designs size and weight.

Along with constraints, there are requirements which must be met for this project. A Quality Function Deployment (QFD) compares the customer's requirements with the applicable engineering requirements. Our QFD, Table 1.1, shows the relationships between these requirements and helps to highlight the importance of each.

Table 1.1: The QFD

		Engineering Requirements							
		Length	Width	Cost	Weight	Magnetic Response	Strain	Material Strength	Voltage
Customer Requirements	1. Inexpensive			*X*					
	2. Withstand Force						*X*	*X*	
	3. Applied Force						*X*		
	4. Provide Feedback								*X*
	5. Limited Area	*X*	*X*						
	6. Portable	*X*	*X*		*X*				
	7. Non-magnetic					*X*			
	8. Adaptable with Current System	*X*	*X*		*X*				
	Units	mm	mm	$	kg	T	%	Pa	V
	* To be determined	10	10	2500	*	0	*	*	*
		Engineering Targets							

It is important for us to compare the engineering requirements to see how they affect each other. This helps make important engineering decisions during the design process. The House of Quality (**Fig. 1.1**) represents this information.

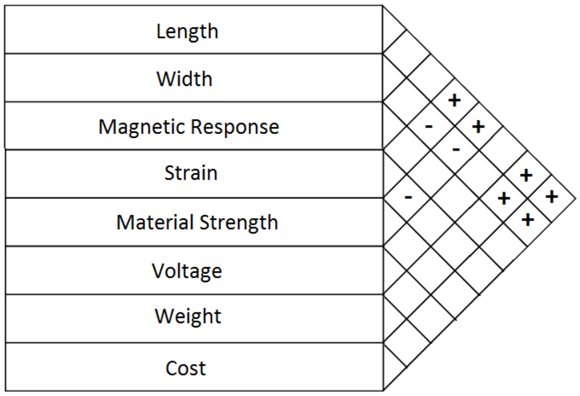


Figure 1.1: House of Quality

1.4 Project Goal & Objectives

The main goal of the project is to provide a means for Dr. Ciocanel to understand the properties of the MSMA in its third direction. Doing this will require a plethora of different tasks. These tasks root from the problem definition and from QFD seen in Table 1.1. The main objective of the final design is to design a piece of equipment that will facilitate the already established testing procedure and enable forces in a third dimension.

1.5 Operating Environment

The primary application of the final design will be in one of the research laboratories at Northern Arizona University. This research lab operates at room temperature which is approximately 68°F.

The final design itself will be within very close proximately of an Instron machine as well as very powerful magnets. This poses significant design constraints on the design. The parts of the design that are within the magnetic area of the machine will have to be nonmagnetic as to provide a lower error reading from the feedback control portion. The entire design must be very compact as it must fit between the components of the magnets and the Instron.

1.6 State of the Art Research

1.6.1 Introduction

Before beginning the design process, it was necessary to do research on every aspect of the design. The research can be broken down into 3 categories: research on the known mechanical properties of MSMAs, force sensing options, and actuation options.

1.6.2 Mechanical Properties of MSMAs

Magnetic Shape Memory Alloys are alloys which are comprised of variants. These variants reorient based on the conditions placed upon them. Seen in **Fig 1.2** below, the MSMA begins with a magnetic field, B, placed in the horizontal direction. As the compressive stresses are applied the variants will begin to reorient. Once the compressive stresses are at a maximum, the variants will then be oriented to either up or down.

Finally, once the compressive stresses are removed from the material, the variants will move back to their original state [1].

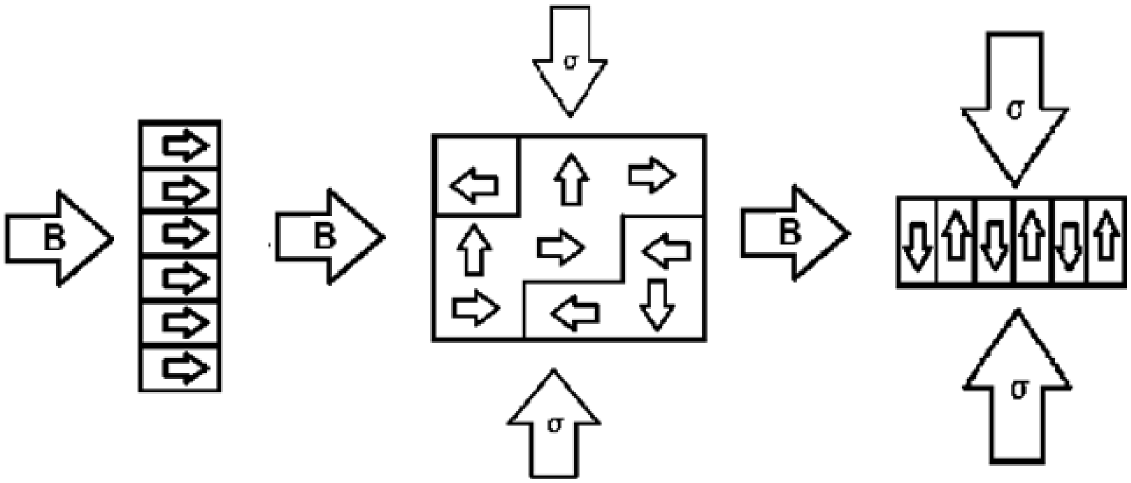


Figure 1.2: Variant Orientation for MSMAs

1.6.3 Force Sensing Options

Force sensors come in a variety of types and parameters. The maximum displacement that the MSMA will have will be 0.18 mm. For the type of sensing that will need to happen, the force sensor will have to be extremely sensitive. However, as the precision increases in a product so does the cost. It will be imperative that middle is met between the cost and the precision. The force sensor will need to be small in size because it will be located on the backside of the MSMA, the side with the least area to work with. It will also have to be small so that the sensor can be easily removed, as Dr. Ciocanel performs a variety of tests on the specimens of MSMAs.

There are a variety of types of force sensors that will be applicable for these constraints. Piezoelectric sensors provide a high precision. However, they are very expensive [5]. Strain gages are another viable option because of their size as well as their sensitivity. Force sensing resistors are like strain gages in principle. Their difference is that force sensing resistors have a lower precision [7].

1.6.4 Actuation Options [5]

The actuation that will need to happen is very precise since the maximum displacement that will happen is 0.18 mm. Although the actuator will be place on the front of the MSMA, the space will still be limited. Another thing is that, much like the force sensor, as the actuator becomes more precise, the cost increases. Some actuators need a special feedback controller which is another cost addition.

There are four types of actuators that are applicable to the current description: electromechanical, hydraulic, pneumatic, and piezoactuators. Electromechanical actuation devices come in a variety of force increments. Since the force needed is at most 200 N and the maximum displacement is 0.18 mm, finding electromechanical actuators that fit into the design description will be difficult. Hydraulic actuators require many hoses as well as a supply for the hydraulic fluid. The pneumatic actuators are easy to find and the simplest in design. The piezoactuators are the most expensive, since they use multiple stacks of piezoelectric materials. These, however, are the most precise because piezoelectrics are very precise in nature.

Chapter 2. Concept Generation and Selection

2.1 Introduction

Due to the small space within the testing environment, it was decided that there was only one basic design that could be implemented. Within this basic design there were however two main variable components. This decision was reached as the design process began, it became evident that each design apparatus was too similar in their setup to deem separate designs. Therefore the designs for the overall concept generation were split into two main categories: sensing devices and actuating devices. These two categories are completely different in their functionality and allow for a large range of options to select from when selecting the final design. The team chose to select three possible options for each design category. The basic overall design with the two variable devices can be seen in **Fig. 2.1** below. The basic design works by placing the actuator and sensor an undecided distance from the MSMA, allowing for more design and size options to solve this problem.

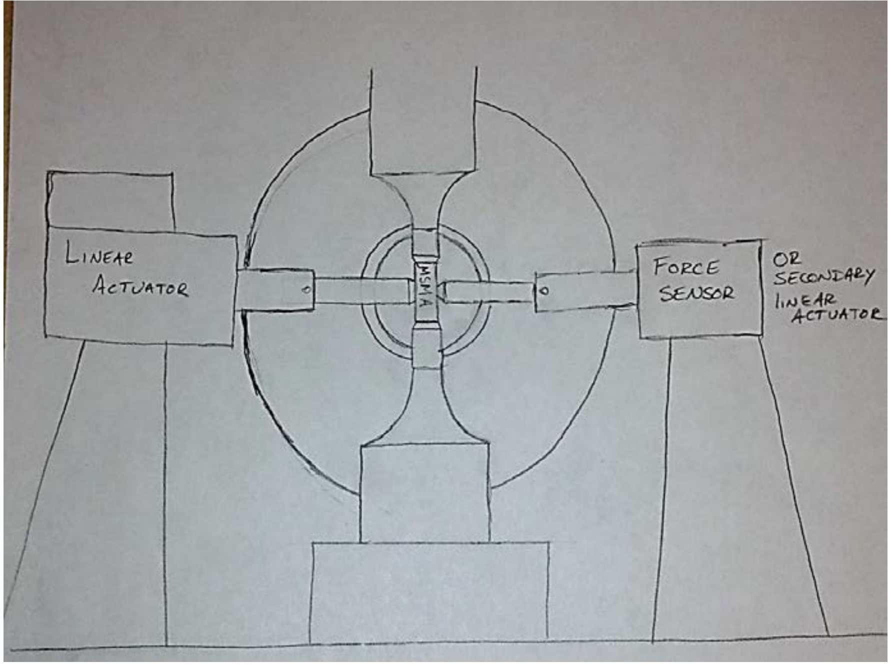


Figure 2.1: Initial System Design

2.2 Design Category 1: Force Sensing

For the force sensing device, three different designs can be chosen. These designs consist of piezoelectric, strain gage, and force sensing resistor (FSR) sensors. These three sensors are very diverse from one another, which allows for more options on the final design.

The first option is a piezoelectric (PZT) sensor. This PZT is mounted onto a piece of aluminum that will be flush with the MSMA and as the MSMA experiences a variant transformation and changes in width, the PZT will deflect and then output a voltage [1]. This voltage will then be transferred to the chosen actuating device to allow for a full feedback control system. The PZT is capable of high sensitivity, but does have some pitfalls since they are rather expensive and very fragile.

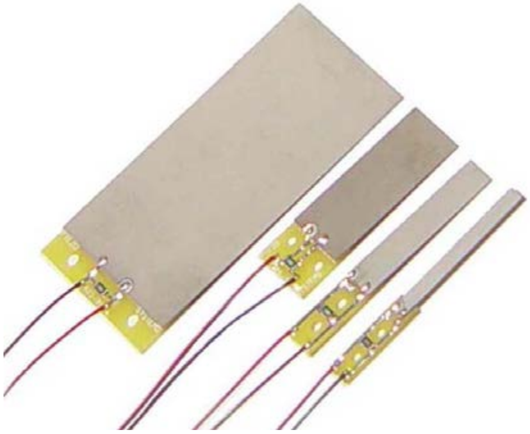


Figure 2.2: PZT Sensor in Various Sizes [9]

The second option is a strain gage. In this design two strain gages would be implemented on the ends of the chosen actuator and positioned on both sides of the MSMA, where the force is being applied. Using a virtual instrument this design would measure the strain associated with a range of known applied forces [5]. During testing, the vertical force will cause increased forces in the lateral direction. The virtual instrument and strain gage will work together to read and adjust the lateral force being applied on each end on the MSMA. This two gage design enables equal forces to be applied on the respective sides of the MSMA.

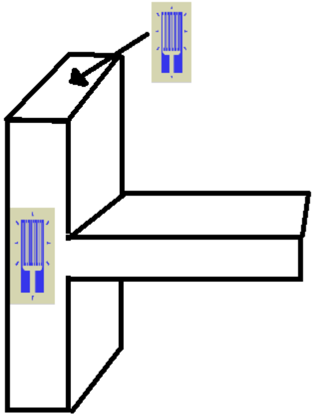


Figure 2.3: Basic Strain Gauge Design [5]

The third option is a force sensing resistor (FSR), seen below in **Fig. 2.4**. This force sensing device is a lot like a strain gage in principal, however instead of measuring lateral deformations, it measures electrical resistance created by direct compressive forces [7]. These devices can come in small sizes, and are inexpensive. Unfortunately they are not as precise as the other options.

Figure 2.4: General FSR Used to Sense Forces [8]

2.3 Design Category 2: Actuating Device

From the actuation device, again, three different designs were selected to be chosen from. These types are electromechanical, pneumatic, and hydraulic. These three allow for a range of design opportunities within the final design layout.

The first option is an electromechanical actuation device, as seen in **Fig. 2.5**. An electromechanical actuator uses an electric motor which turns a screw. This screw moves in a linear motion. These types of linear actuators can have very fine resolution, and can even be fitted with force sensors that give feedback [6]. This could prove useful for this project, as there is a need to adjust the actuator force based on force feedback in order to maintain a constant force as the MSMA changes shape. However, to use this actuator there must be a constant power source and they are generally large in proportion to our required design.

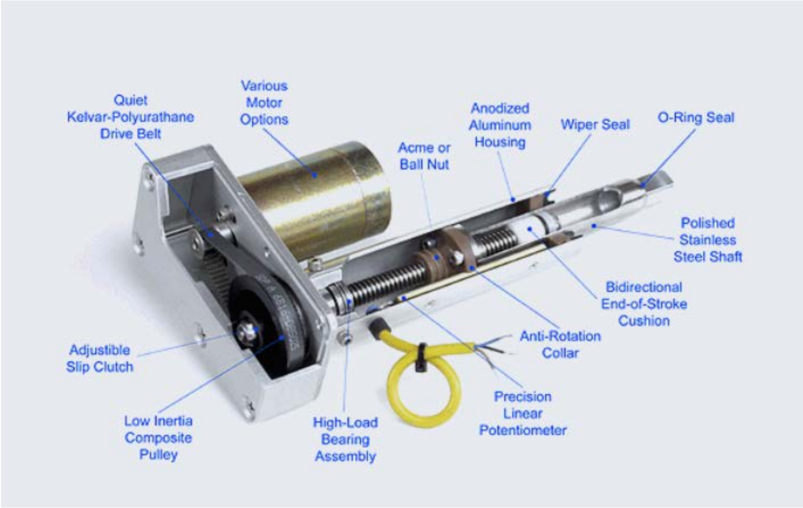


Figure 2.5: Linear Electromechanical Actuator with its Components [4]

The second option is a pneumatic actuator. This pneumatic actuator would have a piston and cylinder design scaled down to fit the required forces. The problem with this type of actuator is that it does not stop in the middle of its cycle. From this lack of flexibility in the design, the precision of force applied is low, whereas for this particular problem, the precision needs to be much higher. Along with this, the actuator must have a constant power and compressed air source.

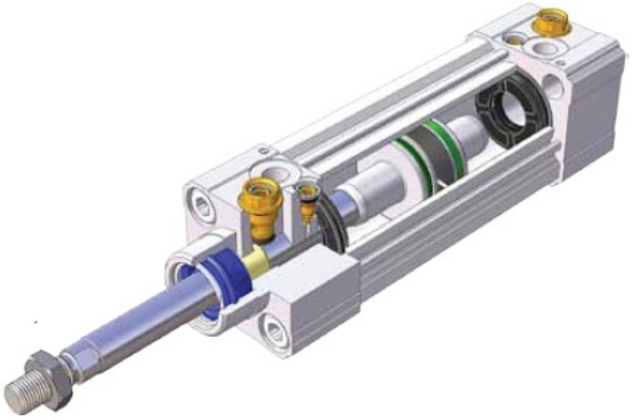


Figure 2.6: General Pneumatic Actuator [3]

The third option is a hydraulic actuator. This would consist of a computerized servo controlling one piston attached to a small hose filled with hydraulic oil and an actuator on the other end. Since the fluid is incompressible, the actuation is directly linked to the motion of the piston, unlike the pneumatic option. Since a hose is used to transmit actuation, the actuation component will fit in the cramped space allowed. Ideally, the back pressure could also be measured, and would allow for feedback control of the actuation [2]. The question is whether this will work at the small-scale required. There also needs to be a reservoir of hydraulic fluid and a power source to successfully implement this actuator.

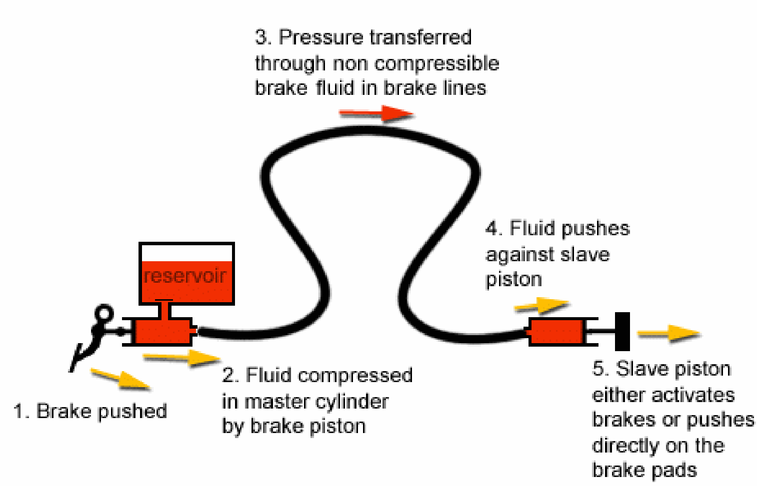


Figure 2.7: Schematic of a Hydraulic Actuator [2]

2.4 DECISION MATRICES

Since the properties of our design are so unique there is no clear best decision. Therefore the next step was to construct decision matrices to allow for an objective look at each design option.

The first devices compared are the sensing devices. Whilst looking at the design as a whole several requirements for the sensors were developed. These requirements, along with their given weights of importance (on a scale from 1-5) are as follows:

- **Sensitivity:** Defined as how fine of a measurement each of these sensors is able to take. This is rated as a 4 because while it is important to be able to sense minute changes and adjust for them there is a point at which the extra sensitivity is useless in this application.
- **Cost:** Defined as the cost of the sensors in relation to one another. It has a rating of 1 because the overall cost of these sensors is going to be relatively similar in scale. While the cost of the sensors will not be one of the major contributing to the overall cost of the project, it is important in design comparison.
- **Size:** Defined as the size of the sensor, and ability to be implemented within the system. This is important to the design because of the limited amount of space available to us; the sensor must be able to be applied in small areas. While size is important it received a weight of a 3 because it is not as important as sensitivity and other criteria.
- **Effectiveness in a magnetic field:** Defined as how precise the sensor will be under a magnetic field. This will be a relative measurement of how much a magnetic field will affect the readings and how feasible it will be to apply one of these sensors within the field. This is weighted as a 5 because most sensors will be operating within the magnetic field and they need to be able to provide accurate readings.
- **Durability:** Defined as how well the sensor will hold up under the testing conditions and the materials ability to not break. This is weighted as a 3 because the conditions are not extreme so the sensor should not have to be extremely durable but if the sensor breaks then the rest of the design will be ineffective.

Once the requirements were decided, the decision matrix was developed and can be seen in Table 2.1. The corresponding numbers were decided upon by researching the different types of sensors and their different capabilities and properties.

Table 2.1: Decision Matrix for the Sensing Devices

	Weight	**Piezoelectric**	**Strain Gage**	**Force Sensing Resistor**
Sensitivity	4	8	7	4
Cost	1	4	7	9
Size	3	9	5	5
Effectiveness in a magnetic field	5	6	7	7
Durability	3	4	6	7
Total	n/a	105	103	96

In the end, the piezoelectric sensor had a total of 105. Its high sensitivity and small size allowed it to overcome the high cost and low durability thanks to the weighting factors associated. The strain gauge was a close second with a total of 103. The strain gauge scored fairly consistent during evaluation in all criteria. In the end it lost because of the complications that could arise with the size restrictions. Finally the FSR ended with a total of 96. Although it is very cost effective and durable the low sensitivity made this option not viable for our design. Although the PZT scored higher than the strain gauge the difference between them is extremely close. To combat the subjective nature of decision matrices, it was decided that both the PZT and strain gauge are viable options. Therefore both sensors were further analyzed and applied toward the final design.

After the sensors were compared, the actuators could be compared. Looking at the design, several requirements were decided upon. These requirements along with their respective weights of importance (on a scale from 1-5) were found below:

- **Controllability:** Defined as the amount of control that each of these actuation methods allows in regards to the force applied. This is a sub-category for precision specifically looking at the precision of control during feedback. It is weighted at 5 because this criterion is crucial to the implementation of the design. Controllability was one of the major requirements for the project as a whole. Without good controllability the project could be considered ineffective.
- **Cost:** Defined as the total cost of the actuation device and associated fluids, or power sources. It is weighted at 1 because each of the different types is going to be fairly close in cost so the change in cost is going to be pretty miniscule. Still it is expected that we develop an inexpensive design.
- **Precision:** Defined as the ability of the actuation unit to provide consistent results for a specific actuation force. It is weighted at 5 because this criteria is crucial to the implementation of the design. The idea is to keep the accuracy of the already established testing procedure therefore any new component must provide accurate results.
- **Amount of applied force:** Defined as how much force each of these actuation types is able to apply. This is weighted as a 2 because each of these actuators are required to have an actuation force of at least 75 N otherwise the design would be unsuccessful. Normally this is not a large amount of force to apply but the small size required of these actuators could affect some designs.
- **Size:** Defined as the size of the actuator being used. This is important because of the limited space we have to work in. If the actuator is too large to be implemented then it is useless. This is rated a 3 because there is some leeway on the area available depending on where the actuator is placed.

Once the requirements and their weights were decided upon, the decision matrix was formed, as seen in Table 2.2. After researching the three difference actuators, numbers were chosen for each requirement for the various design options.

Table 2.2: Decision Matrix for the Actuation Devices

	Weight	**Electromechanical**	**Hydraulic**	**Pneumatic**
Controllability	**5**	9	7	4
Cost	**1**	3	5	3
Precision	**5**	6	7	3
Amount of Applied Force	**2**	5	8	8
Size	**3**	4	8	6
Total	n/a	100	115	72

Once the numbers were then calculated, it was clear that the pneumatic actuator was a fairly poor choice for the design with a total of 72. The low level of controllability and precision eliminate it as a viable option for this application. The electromechanical actuator ended with a total of 100. This design had a very high controllability but its large size proved to be problematic for this application. The hydraulic actuator was the preferred design choice with a total of 115. The good controllability combined with the applicable size made this a highly viable option.

2.5 Final Designs Chosen for Analysis

2.5.1 Product Selection

Upon further analysis of product costs and ease of manufacturing it became apparent that a strain gauge would be the only viable option for force sensing giving the current budget. Following a meeting with the client Dr. Ciocanel, it was also expressed that a hydraulic actuator was not desired. In its place he requested that the team pursue option for piezoactuators. From there the following products were selected. The force sensor product is a Honeywell Model 11 Subminiature Tension/Compression Load Cell [11]. As for the actuators, the Ultra Motion Digit NEMA 17 Stepper [13] and N-216 Nexline Linear Actuator [12], were selected. The forces exerted and experienced by both actuators would be very similar. Therefore for the purpose of analysis the only differences would be in the dimensions and design differences in the mounting systems.

2.5.2 Concept 1: Piezoactuator

The following mounting setup was tested using the piezoactuator as seen in **Fig 2.8**. This mounting setup contains a semicircle base plate with towers attached on opposite sides by screws. The semicircle allows the system to be easily and accurately placed within the Instron. This allows for the assembly to be removed or implemented for various tests. The tower on the right of the figure contains the back end mounting for the force sensor. The corner is cut to allow the tower to fit within the existing magnetic field structure. In the figure, the actuator is held by a single, thick tower. The MSMA held by Material Testing Fixtures [10] is compressed by the add-ons of the actuator and force sensor.

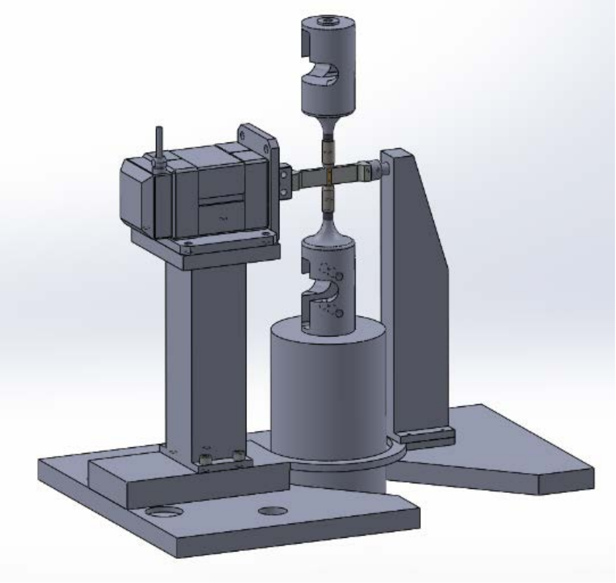


Figure 2.8: Solidworks Model of Piezoelectric Stack Mounting Design

2.5.3 Concept 2: Electromechanical

The following mounting setup was tested using the electromechanical actuator as seen in **Fig 2.9**. This design uses a cylindrical tower design, where each tower would have a threaded end and screw directly into the existing Instron base plate. A circular base would then be screwed into the top of the actuator tower to provide a suitable area for the actuator mounting system. Again, the MSMA is held by the Material Testing Fixtures [10] and is compressed by the add-ons of the actuator and force sensor.

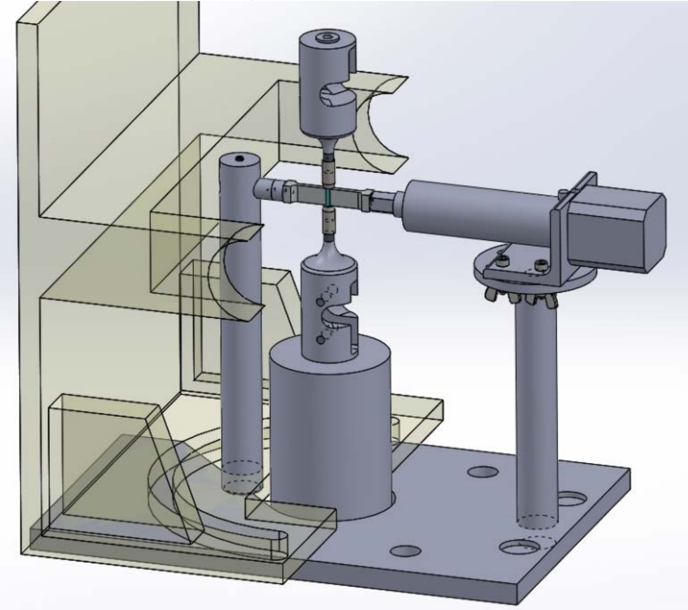


Figure 2.9: Solidworks Model of Electromechanical Mounting Design

Chapter 3. Engineering Analysis

3.1 Analysis Breakdown

After creating the unique designs, the team broke the system into sub-components for better analysis of the locations of failure. These sub-components are the towers holding the force sensor, the towers holding the actuator, and the screws to assemble the parts. After meeting with the client regarding the maximum stress that will be applied to the MSMA to acquire the required results, the team calculated a maximum force of 200 N. Since that is not a large force most materials should be capable of handling the stress without failure. Therefore the team calculated the maximum required material properties for each failure point and used them in material selection.

3.2 Failure Calculations

For failure in the towers, it is important to consider both bending and compressive forces. The following equations were used to calculate the associated stressed.

$$\sigma = \frac{M}{I} \tag{Eq. 1}$$

$$I = \frac{bh^3}{12} \qquad \text{(Eq. 2)}$$

$$\tau = \frac{F_{max}}{A} \qquad \text{(Eq. 3)}$$

$$\sigma = \frac{F_{max}}{A_c} \qquad \text{(Eq. 4)}$$

All stress calculations can be seen in ***Appendix C***. In the end it was seen that the maximum stress was 5.82 MPa for the piezoactuator setup and 8.4Mpa for the electromechanical setup. Assuming a constant material selection for the mounting fixture, if a material can handle the maximum stresses it will not fail.

When calculating for the screw failure the team looked toward shear failure. The location that was focused on for having the highest probability of failure is the set screw holding the force sensor extension into the tower. This has the smallest diameter and there is only one screw to bear the 200 N load. Using equation 3 above, where A is the area of a circle equivalent to the screw diameter, it was calculated that the maximum shear stress is equal to 69MPa.Using the calculated stress as a minimum basis, a single material can be found for all the screws. Ever other screw used will either have a larger diameter or there will be multiple screws present to split the associated force.

3.3 Material Selection

For material selection the team took the calculated forces and applied a factor of safety of 2. This seemed a suitable factor as it is used in most structural calculations. The new design loads were 11.7 MPa, 16.8 MPa, and 138Mpa for the piezoactuator model, electromechanical model, and screws respectively. Most materials have yield strengths above these values so the team looked toward common, lower cost materials. Two materials were selected for the mounting fixtures, 1018 low-carbon steel and 6061 aluminum alloy. The steel's yield strength, approximately 370Mpa, is satisfactory and it is fairly inexpensive. The aluminum's yield strength, approximately 240Mpa, also satisfies the requirements but it is more expensive. The aluminum is presented as an option because although the fixture should not be directly in the magnetic field it may be more desirable to have a non-magnetic material.

Looking now to material selection for the screws, the team has selected grade 316 stainless steel. The yield strength is approximately 205Mpa and should prevent shear failure in the system.

3.4 Numerical Modeling

The by-hand calculations proved that most materials would be sufficient for the construction of the mounting fixtures. However the team felt it was important to also numerically model the results using Solidworks 2013 for the proposed materials. This ensure the validity of the calculations and also creates a visual representation of where the failures would occur. **Fig. 3.1** and **Fig. 3.2** below show the model for the piezoactuator towers constructed from 6061 aluminum alloy.

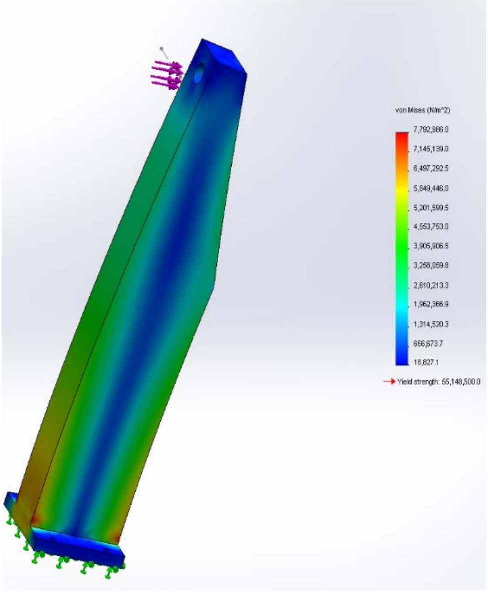


Figure 3.1: Force Sensing Tower Analysis

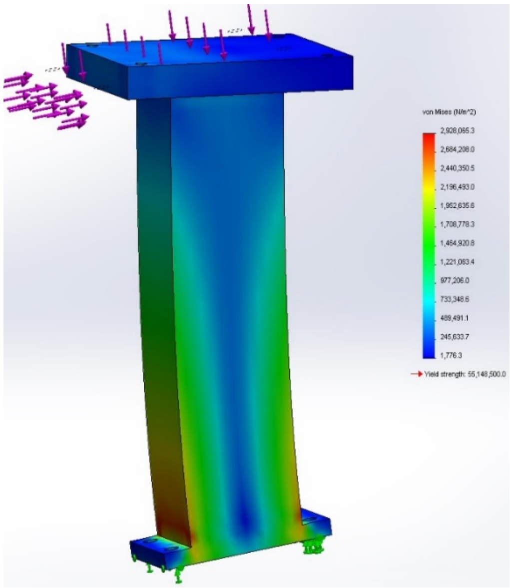


Figure 3.2: Piezoelectric Tower Analysis

As expected the materials yield strength is much higher than the stress experienced. Continuing the modeling **Fig. 3.3** and **Fig. 3.4** below show the analysis for the electromechanical system towers constructed from 1018 low-carbon steel.

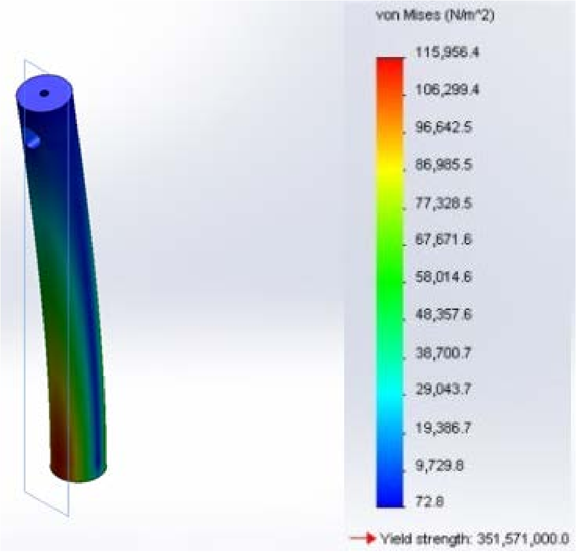


Figure 3.3: Force Sensing Tower Analysis

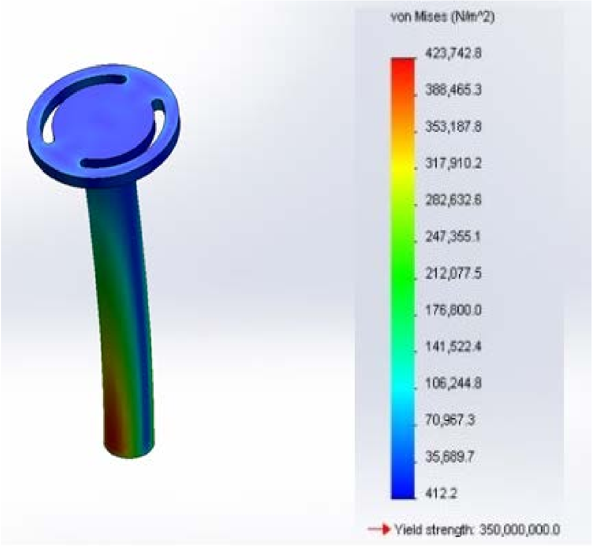


Figure 3.4: Electromechanical Tower Analysis

3.5 Design Proposal

The proposed design to satisfy this project is the electromechanical style mounting fixture. Constructed from 1018 low-carbon steel and grade 316 stainless steel screws. This setup will use the Honeywell Model 11 Subminiature Tension/Compression Load Cell [11] in combination with the Ultra Motion Digit NEMA 17 Stepper [13]. Communication between the actuator and force sensor will be facilitated through the use of a virtual instrument. A Solidworks model of the design can be seen in **Fig. 3.5** below.

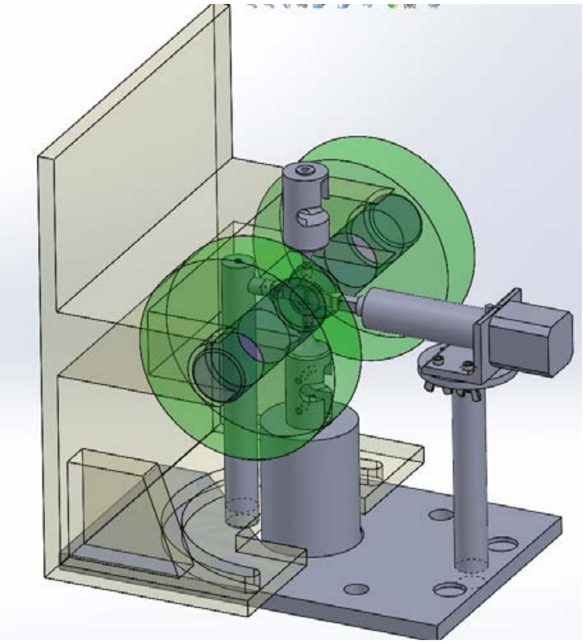


Figure 3.5: Fully Assembled Design

The mounting geometry was selected because it will have a higher quality of manufacturing compared to the piezoactuator geometry. This is because there will less manufacturing required from our team members. The selected geometry is also more simplistic in terms of integration with the current system. The electromechanical product was selected because it is more cost effective.

Chapter 4: Cost Analysis

4.1 Bill of Materials

The bill of materials needed to construct the electromechanical design can be seen in Table 4.1 below.

Table 4.1: Bill of Materials

Component	Quantity	Cost
Digit NEMA 17 Stepper	1	$620.00
ST5-S Stepper Drive	1	$302.00
Model 11 Load Cell	1	$771.00
Low-Carbon Steel Rod, 1", 3' Length	1	$26.71
Low-Carbon Steel Bar, 3''-6''-1/4''	1	$7.67
Flathead Screw, 5 pack	1	$5.24
Wing Nuts, 25 pack	1	$7.21
Socket Head Cap Screw, 25 pack	1	$5.61
Set Screw, 25 pack	1	$3.76
Total Cost		$1,749.20

The Digit NEMA 17 Stepper is the selected electromechanical actuator. It is an Ultra Motion product and contains a custom mounting fixture. The ST5-S Stepper drive is an external control device required to accurately run the selected actuator. The Model 11 Load Cell is the selected Honeywell transducer. This product is currently owned by the client and has be approved for application in this device. Its cost will therefore be removed from the total cost breakdown. The carbon steel rods will be manufactured into the final cylindrical towers of the mounting setup, while the steel bar will be used to create the actuator mounting plate.

4.2 Manufacturing and Total Production Costs

The manufacturing for all parts of the mounting system will be performed by the members of our team. This will occur in Northern Arizona Universities Manufacturing Shop, under appropriate supervision. Thanks to this manufacturing costs will not need to be added in the total cost of production. Taking into account the materials already available to in Dr. Ciocanel's laboratory the total cost analysis can be seen in Table 4.2.

Table 4.2: Cost Analysis for Total Production

Component	Quantity	Cost
Digit NEMA 17 Stepper	1	$620.00
ST5-S Stepper Drive	1	$302.00
Low-Carbon Steel Rod, 1", 3' Length	1	$26.71
Low-Carbon Steel Bar, 3"-6"-1/4"	1	$7.67
Flathead Screw, 5 pack	1	$5.24
Wing Nuts, 25 pack	1	$7.21
Socket Head Cap Screw, 25 pack	1	$5.61
Set Screw, 25 pack	1	$3.76
Total Cost		$978.20

This total is below half of the allotted budget. This low cost of production allows for the possibility of more expensive materials or outsourcing the manufacturing of the parts at the client's discretion.

4.3 Payback and Mass Production

Due to the fact that this project is being used to assist in new types of research there is not a payback period. The client received a grant upfront for his research and this project is just a deduction, since there is no additional income for the current research. Additionally do to the specific nature of research there would never be a need for mass production of this product. The testing environment used by the client is too specific and would vary from other possible client setups. Hypothetically speaking though, in a mass production environment the total cost of the product would rise. There would be less waste in terms of material because the full stock amount could be used and there would be reduced prices from purchasing in bulk. However, the manufacturing costs would have to be included regardless of if the product was made by hand or with an automated process.

Chapter 5: Conclusions

5.1 Problem Description

Dr. Ciocanel and his research team are performing research on a specific MSMA, with hopes to better understand the materials reactions and application. He has requested the construction of a device that will enable a constant lateral force to be applied to the MSMA. This device must be able to apply a constant force between 0-75 N to the face of an MSMA that is 10mm by 12mm in length. This device must be adaptable with the current Instron machine setup, and will operate near a magnetic field at room temperature. The full cost to construct this device must be within $2500. Finally there must be feedback control present to maintain the set force during the MSMA reorientation and deformation.

5.2 Concept Generation and Selection

The design choices that were originally addressed were broken into two categories: force sensors and actuating devices. The options for the force sensors were piezoelectric sensor, strain gage, and force sensing resistor. The piezoelectric sensor has a very high sensitivity, however, they are much more costly than the other options. The strain gage option would need to have two gages in the design to ensure accuracy. The force sensing resistor is similar to the strain gage, however it does not provide the accuracy needed for the design. The options for the actuating device were linear electromechanical actuator, general pneumatic actuator, and a hydraulic actuator. The linear electromechanical actuator is a viable option, however, the actuator itself is much larger in size than what is needed. The pneumatic actuator has a very low precision, whereas for this application, the precision needs to be much higher. The hydraulic actuator would need a series of hoses and a water supply nearby.

The two final design choices comprise of two systems: one with a strain gage force sensor coupled with a piezoactuator and the other with a strain gage force sensor coupled with an electromechanical actuator. The first design consists of two square towers holding the sensor and the actuator, while being held to the Instron by a base. The second design consists of two cylindrical towers that will hold the sensor and actuator. The towers will then connect to the Instron by a screw that will screw into the actual Instron.

5.3 Engineering Analysis

Through by-hand calculations it was found that the maximum stress exhibited on the mounting fixture was 8.4MPa for the towers and 69MPa for the screws. Even after applying a factor of safety of 2 the design stresses are still quite low. This opens up low strength and cost materials as possible building options. In an attempt to find a low cost material two possible materials were found. The first is 1018 low-carbon steel and the other is 6061 aluminum alloy. These two materials offer bot a ferrous and non-ferrous low cost option. Using numerical modeling it was seen that both materials have sufficient yield strengths for this application.

In the end the team recommended the cylindrical electromechanical mounting design constructed from 1018 low-carbon steel. The material was selected because of a lower cost. In addition, the fixture will not be directly in the magnetic field and should not be affected by the instrument.

5.4 Cost Analysis

Using the selected products: the Ultra Motion Digit NEMA 17 Stepper, the ST5-S Stepper drive, the Honeywell Model 11 Load Cell, and a low-carbon steel assembly the cost of materials totaled $1,749.20. The cost for products already available in the client's laboratory were removed. In addition it was decided that team members will manufacture the mounting setup from the stock material. With these reductions the total cost of production for this project totaled at $978.20. This is significantly lower than the given budget of $2500. This will allow for changes in material selection of outsourcing of manufacturing at the client's discretion. If no alterations are made to the design the lower budget will be a benefit to the client.

5.5 Final Design

The design proposed in this report meets all requirements the client has requested. It is well below the allotted budget, is capable of applying and sensing forces up to 300N to the MSMA face. Using the stepper drive this device can be connected to a computer, where a virtual instrument (VI) can enable feedback control. The VI will be constructed during the next semester through product testing.

References

[1] Leo, Donald J. Engineering Analysis of Smart Material Systems. Hoboken, NJ: John Wiley & Sons, 2007.

[2] Longhurst, Chris. "Brakes - What Do They Do?" *Car Bibles : The Brake Bible*. N.p., 24 July 2013. Web. 27 Oct. 2013. <http://www.carbibles.com/brake_bible.html>.

[3] Reese, Cale, PhD. "The Ins and Outs of Single Axis Actuation." *Design World*. N.p., 1 Aug. 2012. Web. 27 Oct. 2013. <http://www.designworldonline.com/the-ins-and-outs-of-single-axis-actuation/>.

[4] "Ultra Motion Bug Linear Actuator." *Ultra Motion Bug Linear Actuator*. Ulta Motion, n.d. Web. 27 Oct. 2013. <http://www.ultramotion.com/products/bug.php>.

[5] Fassler, Matthias. "Force Sensing Technologies." *Study on Mechatronics* (2010): Page 1-49.

[6] Toyota Motor Sales, USA, Inc. *Sensors and Actuators*.

[7] Nikonovas, A., A. Harrison, S. Hoult, and D. Sammut. "The Application of Force-sensing Resistor Sensors for Measuring Forces Developed by the Human Hand." *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* 218.2 (2004): 121-26. Print.

[8] Tekscan, Inc. "FlexiForce® Sensors." *FlexiForce Force Sensors*. N.p., n.d. Web. 27 Oct. 2013. <http://www.tekscan.com/flexible-force-sensors>.

[9] Piezo Systems, Inc. "Piezo Systems: Quick-Mount Piezoelectric Bending Sensors, Piezoelectric Generators, Piezoceramic, PZT, Piezoelectric Transducers, Piezoelectric Actuators and Sensors, Piezoelectric Engineering, Ultrasonics, and Energy Harvesting." *Piezo Systems: Quick-Mount Piezoelectric Bending Sensors, Piezoelectric Generators, Piezoceramic, PZT, Piezoelectric Transducers, Piezoelectric Actuators and Sensors, Piezoelectric Engineering, Ultrasonics, and Energy Harvesting*. N.p., n.d. Web. 28 Oct. 2013. <http://www.iezo.com/prodbg7qm.html>.

[10] Garcia, Matt, Randy Jackson, Jeremy Mountain, Qian Tong, and Hui Yao. *Material Testing Fixture*. *Material Testing Fixture*. Dr. Ciocanel, 2012. Web. 15 Nov. 2013. <http://www.cefns.nau.edu/capstone/projects/ME/2013/DFMTM/index.html>.

[11] "Model 11." *Model 11*. Honeywell International Inc, 2013. Web. 6 Nov. 2013.

[12] "N-216 NEXLINE Linear Actuator." *PIEZO NANO POSITIONING*. Physik Instrumente (PI) GmbH & Co. KG, n.d. Web. 15 Nov. 2013.

[13] "The Digit." *http://www.ultramotion.com/products/digit.php*. Ultra Motion. Web. 1 Dec. 2013.

Appendix A: Engineering Drawings

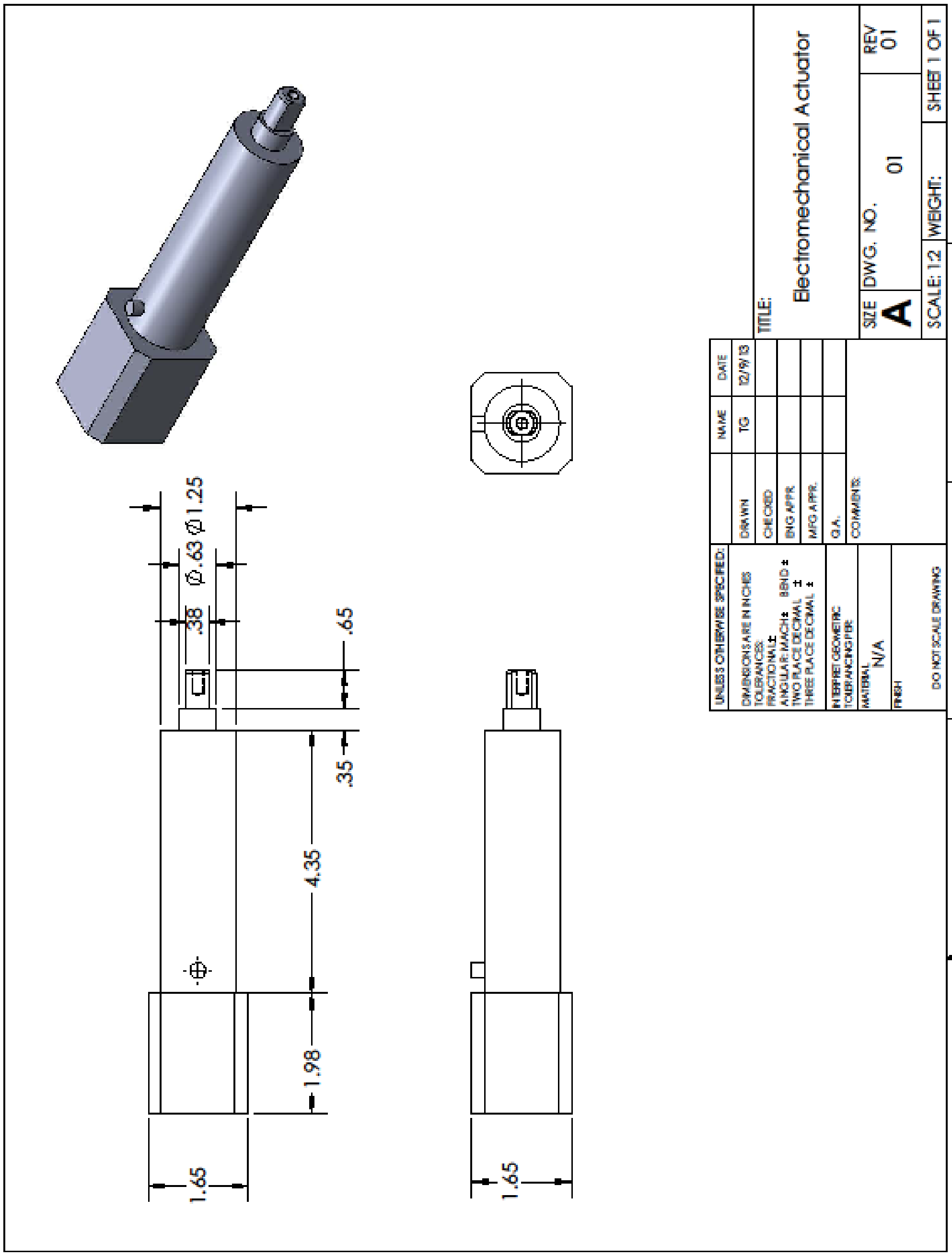


Figure A.1: Electromechanical Actuator Drawing

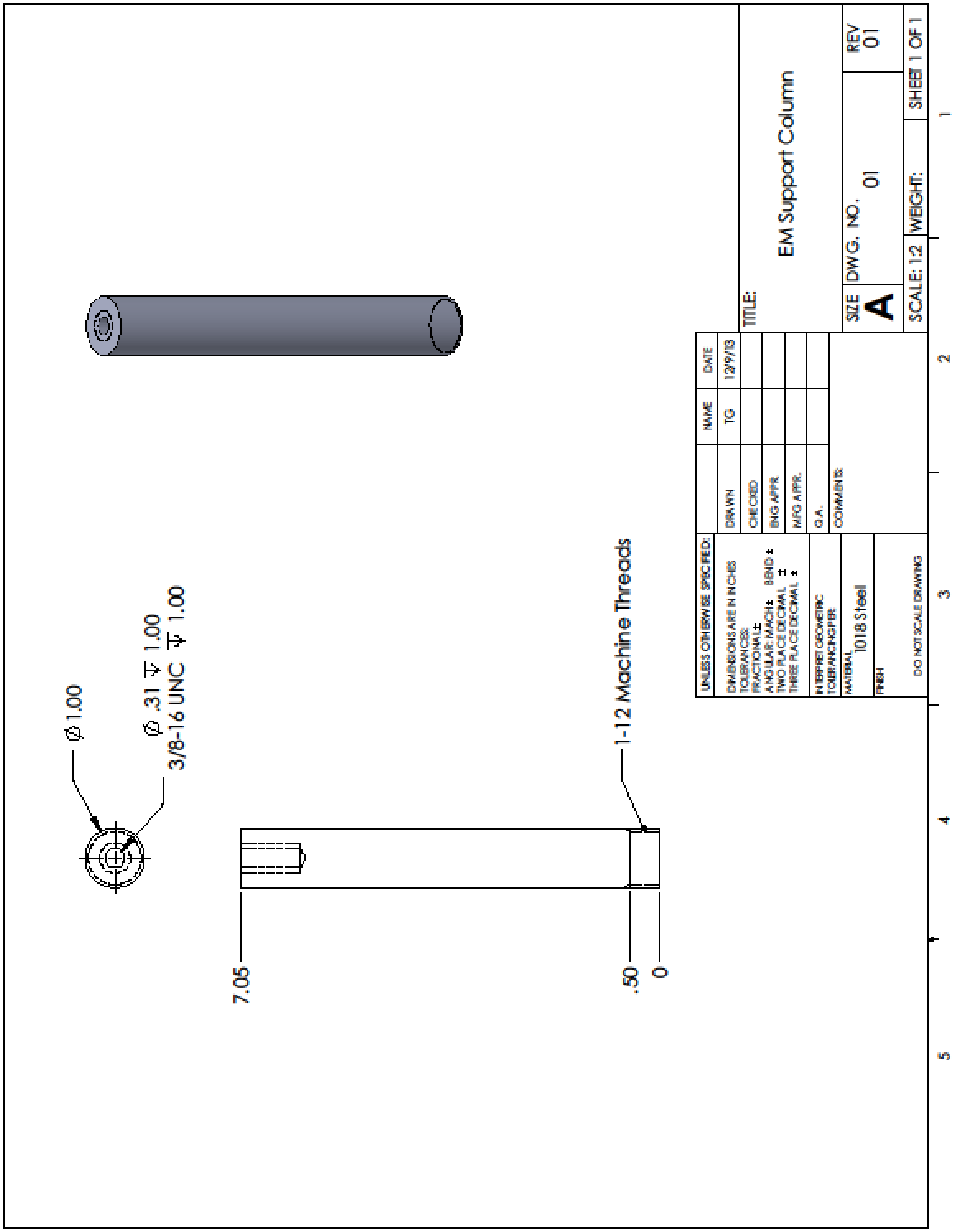


Figure A.2: EM Support Column Drawing

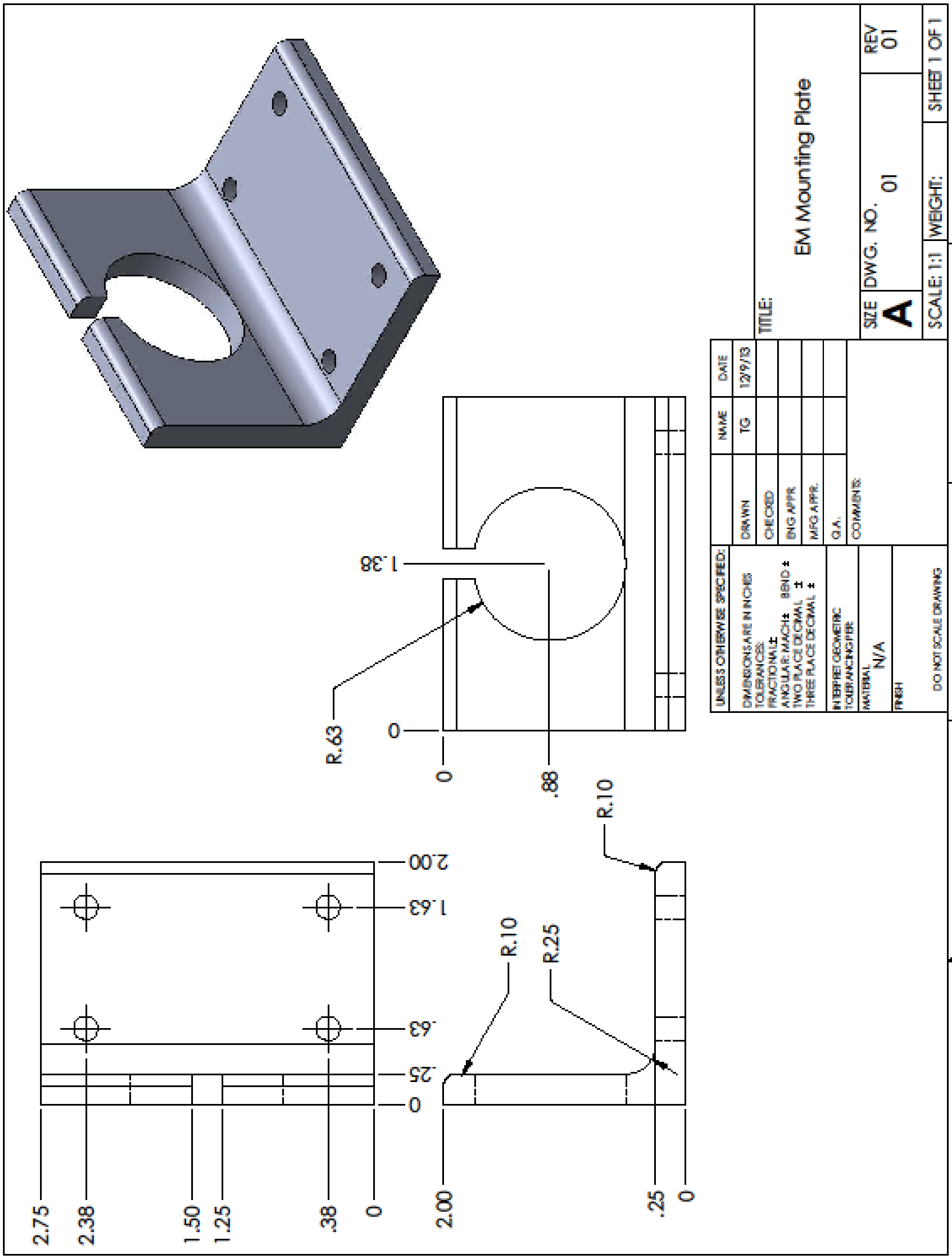


Figure A.3: EM Mounting Plate 1 Drawing

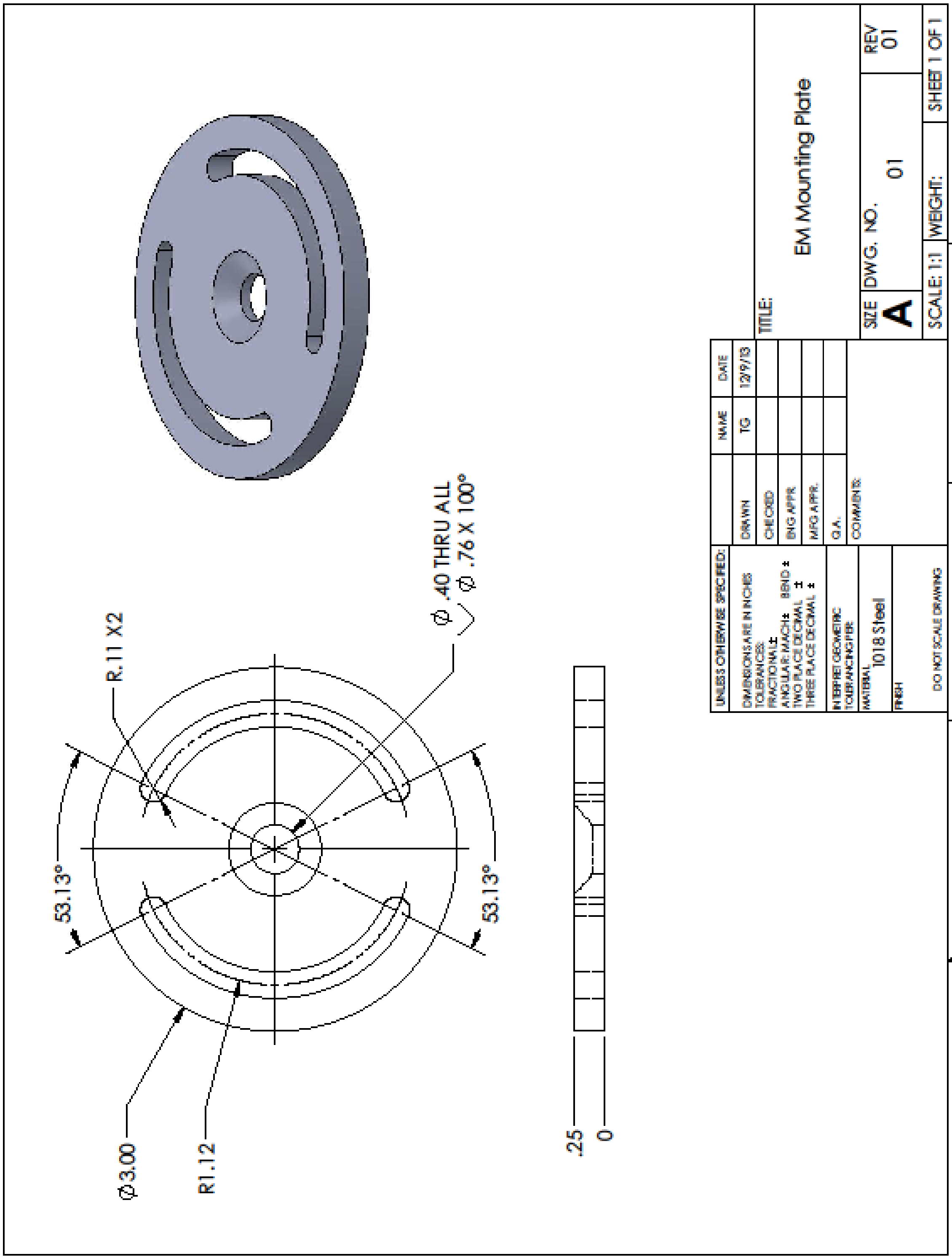


Figure A.4: EM Mounting Plate 2 Drawing

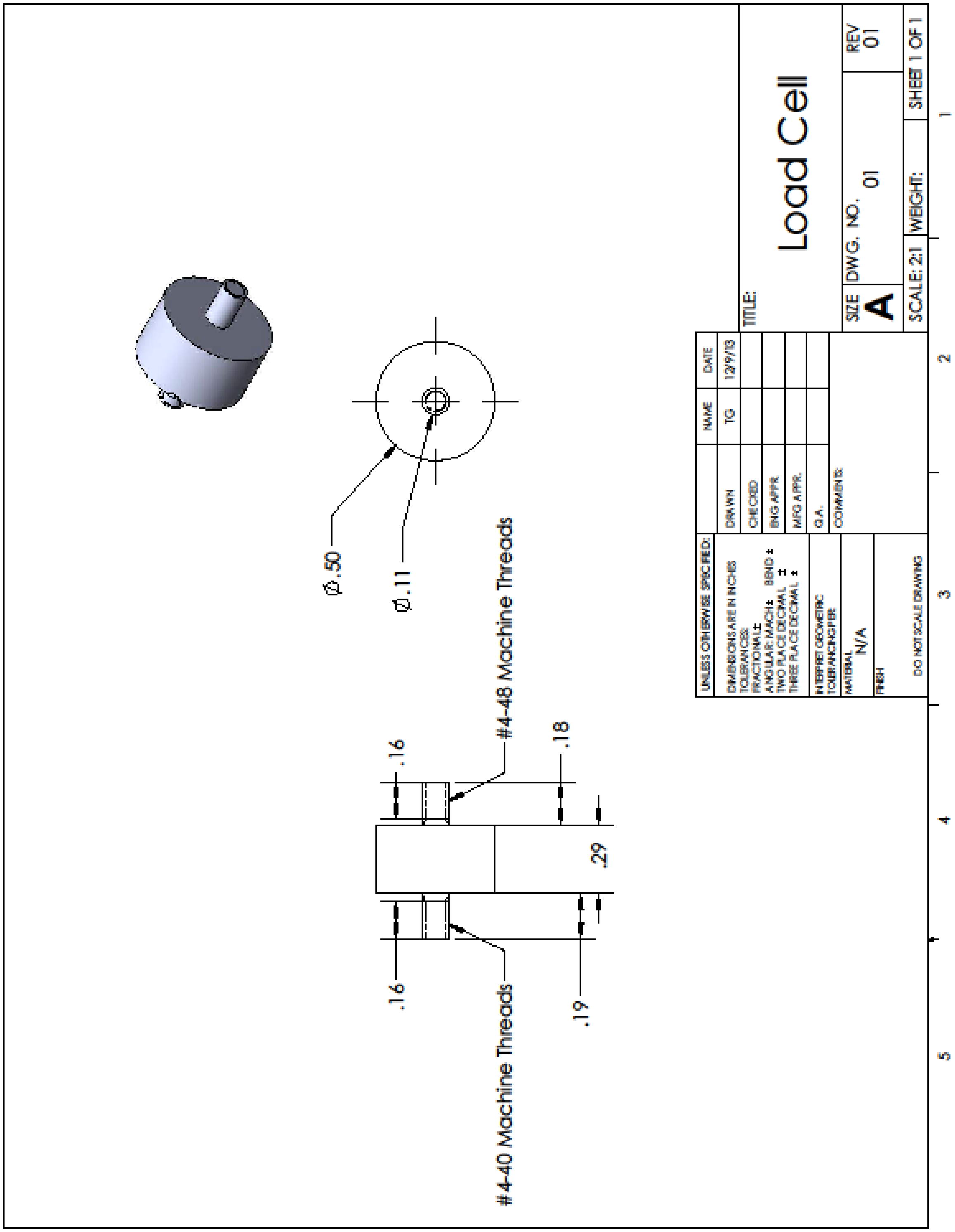


Figure A.5: Load Cell Drawing

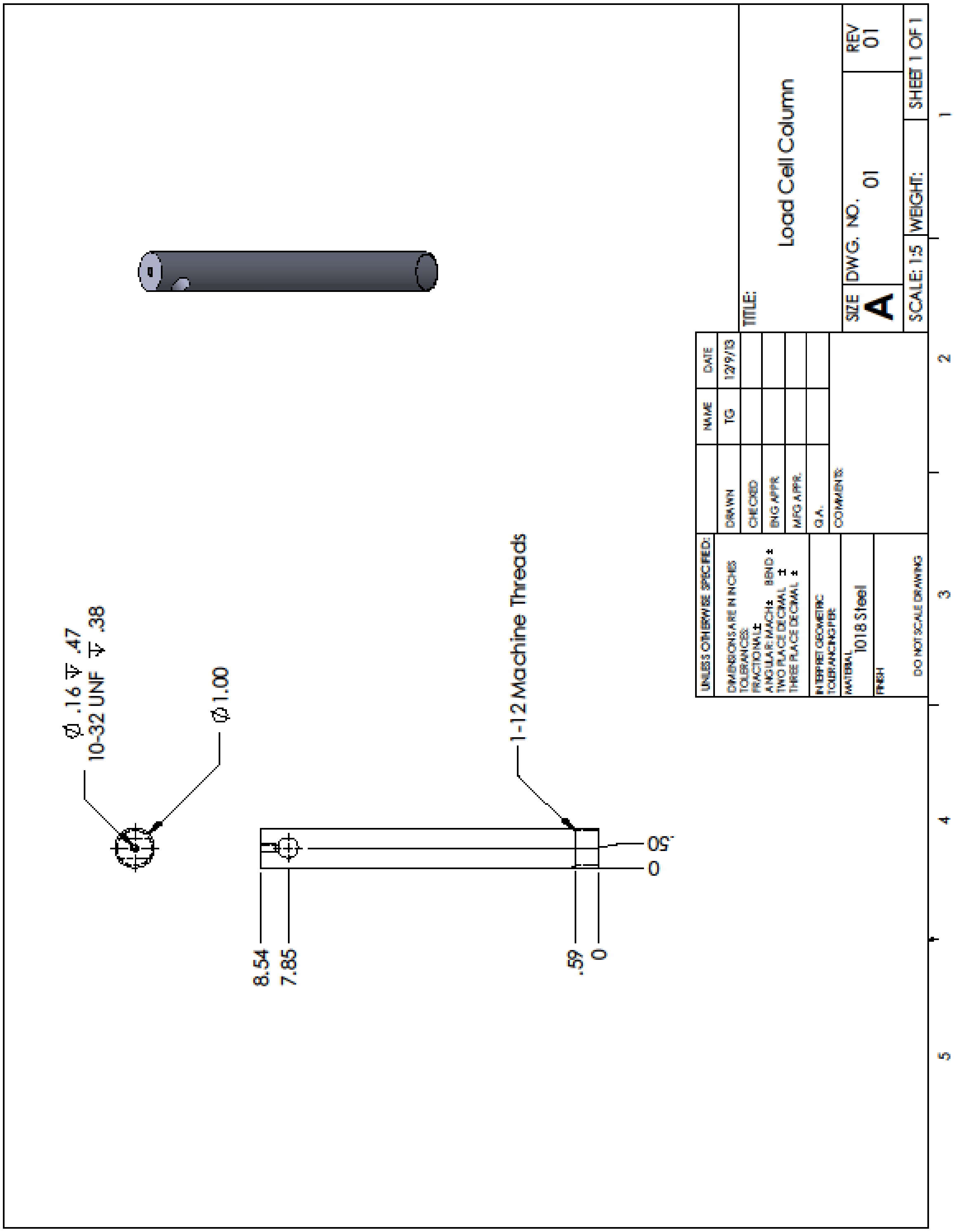


Figure A.6: Load Cell Column Drawing

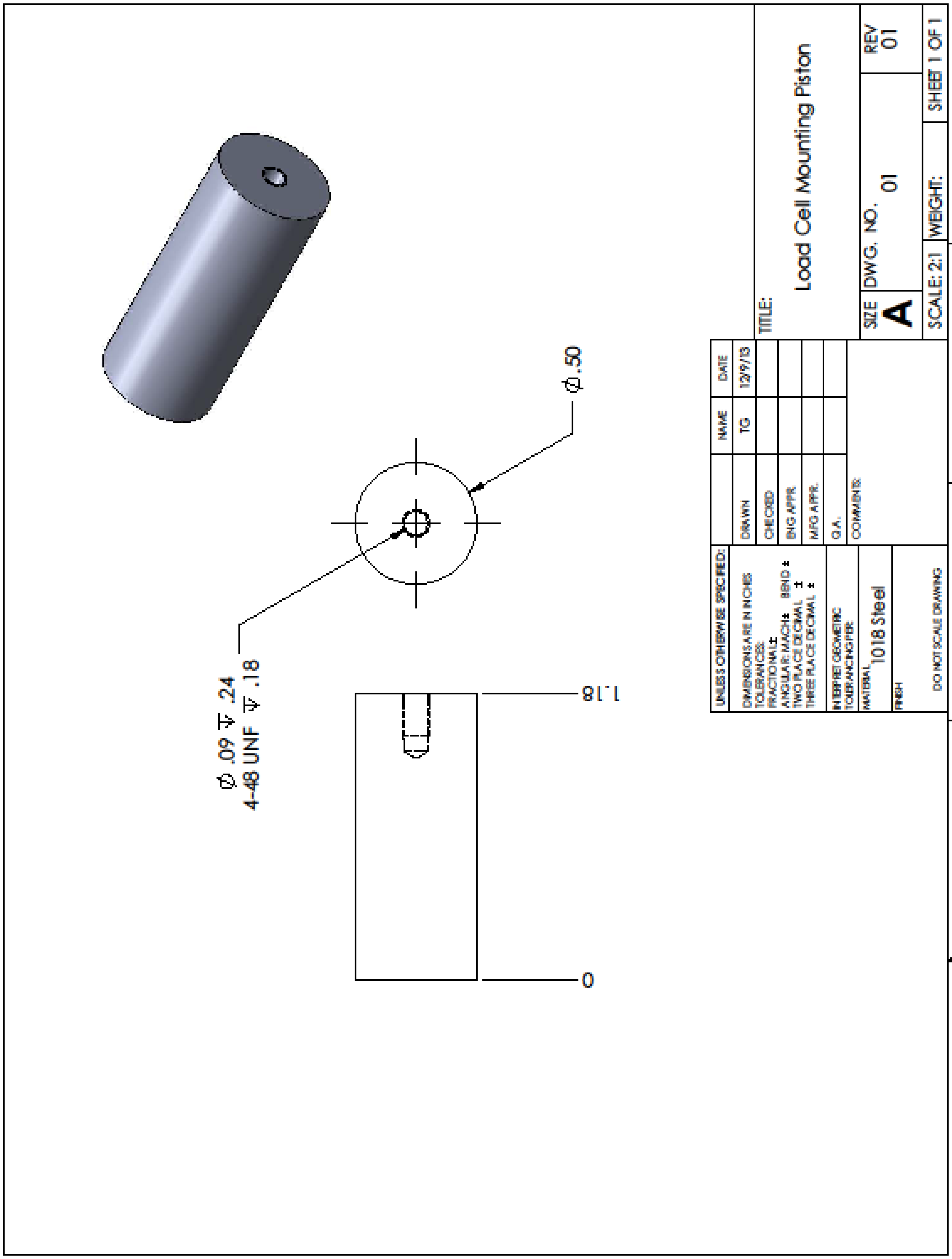


Figure A.7: Load Cell Mounting Piston Drawing

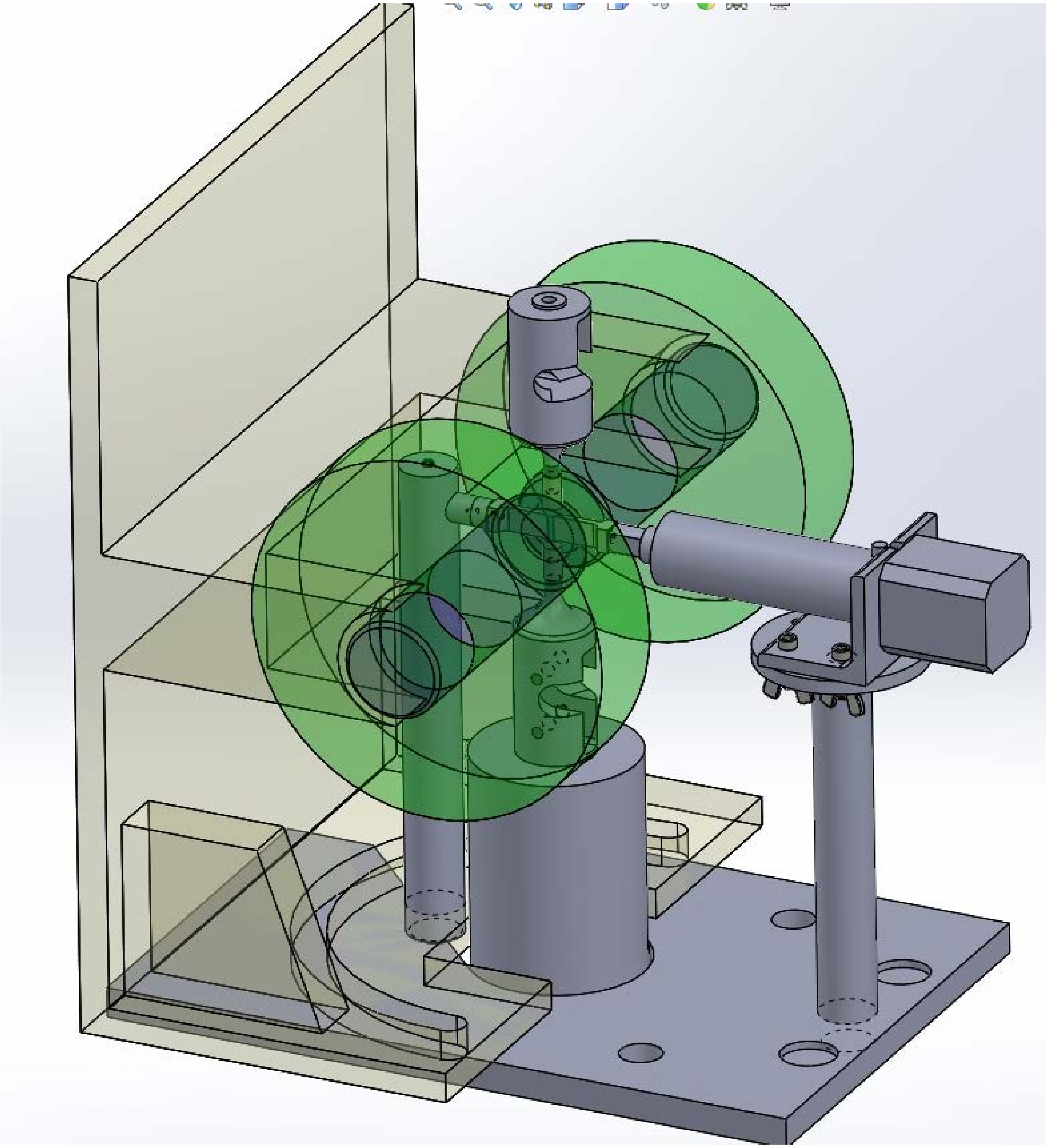


Figure A.8: Assembly Drawing

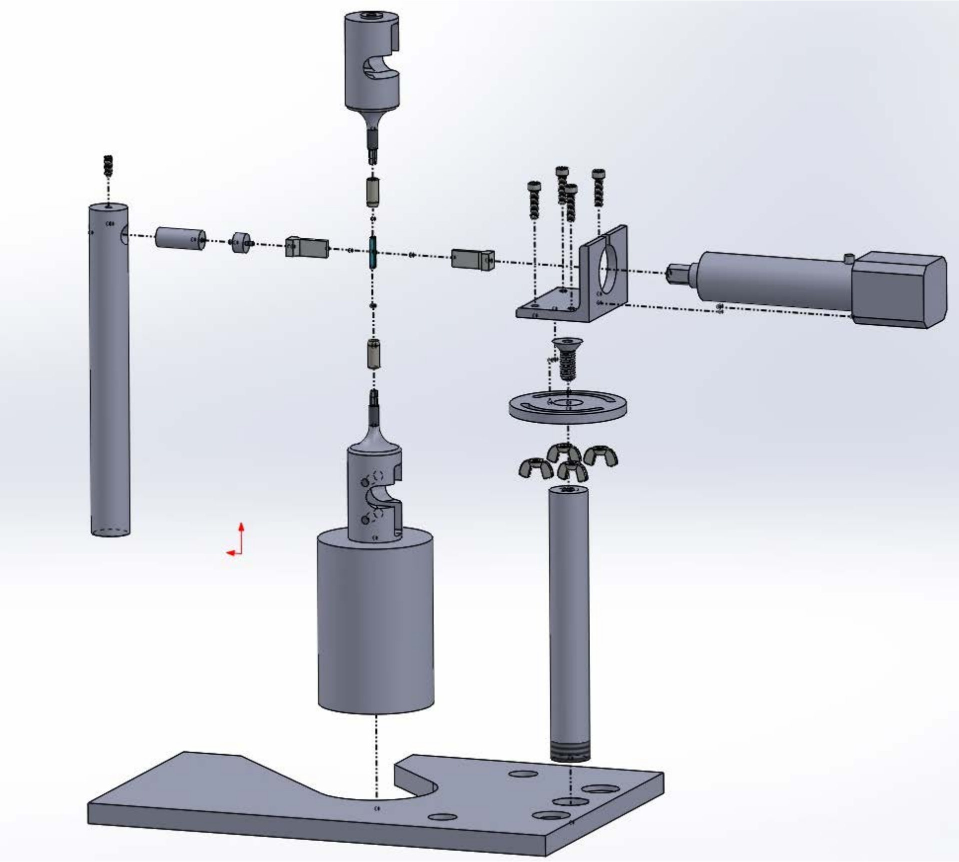


Figure A.9: Exploded View

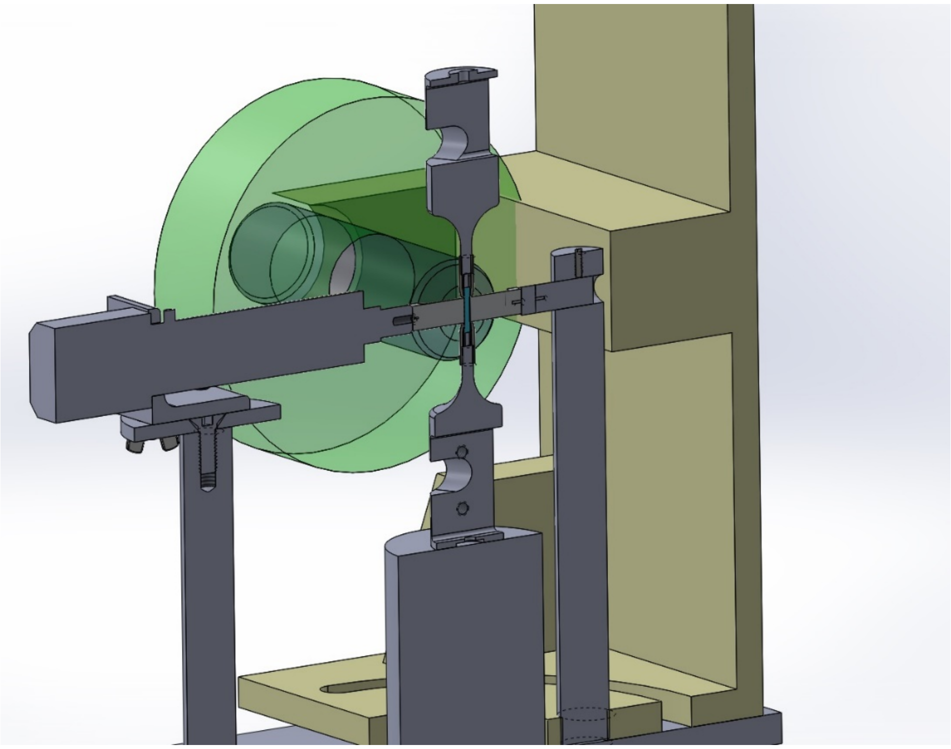
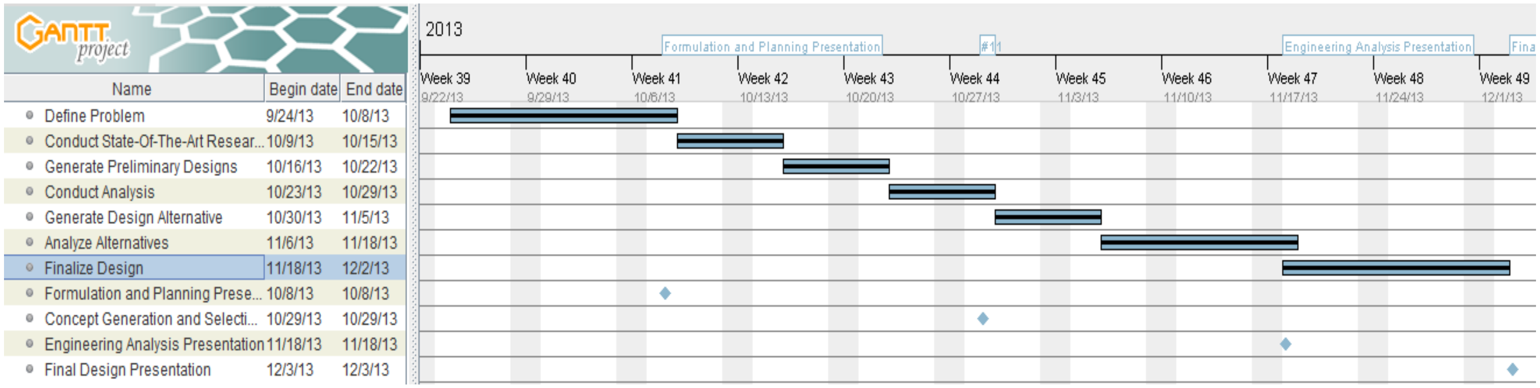


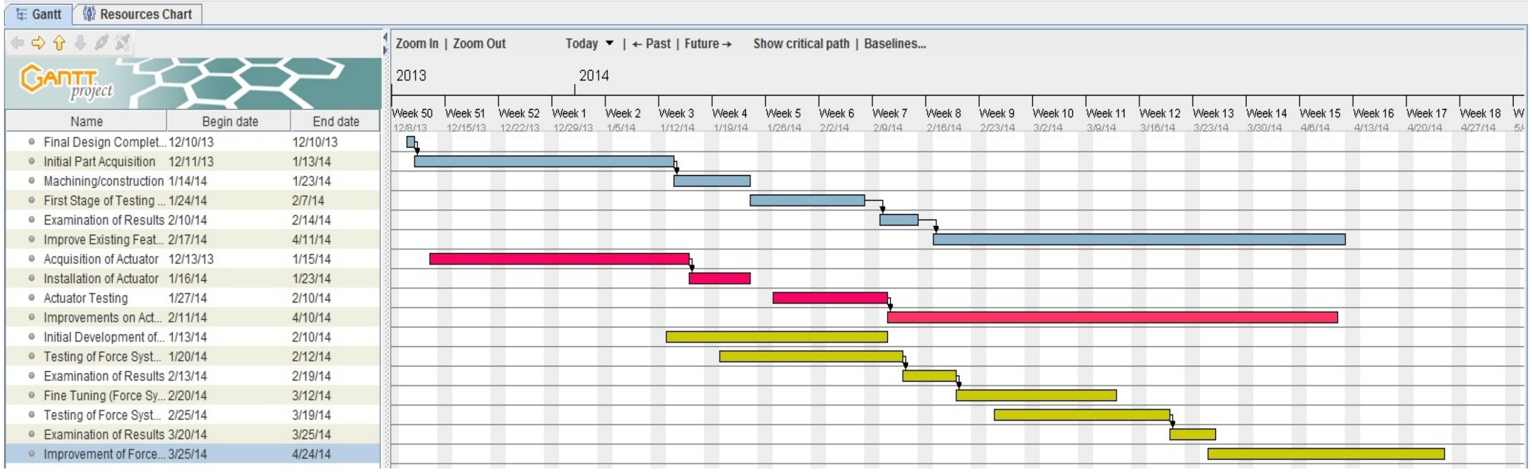
Figure A.10: Sectional View

Appendix B: Project Planning



Name	Begin date	End date
Define Problem	9/24/13	10/8/13
Conduct State-Of-The-Art Resear...	10/9/13	10/15/13
Generate Preliminary Designs	10/16/13	10/22/13
Conduct Analysis	10/23/13	10/29/13
Generate Design Alternative	10/30/13	11/5/13
Analyze Alternatives	11/6/13	11/18/13
Finalize Design	11/18/13	12/2/13
Formulation and Planning Prese...	10/8/13	10/8/13
Concept Generation and Selecti...	10/29/13	10/29/13
Engineering Analysis Presentation	11/18/13	11/18/13
Final Design Presentation	12/3/13	12/3/13

Figure B.1: Gantt Chart for Completed Fall 2013 Semester



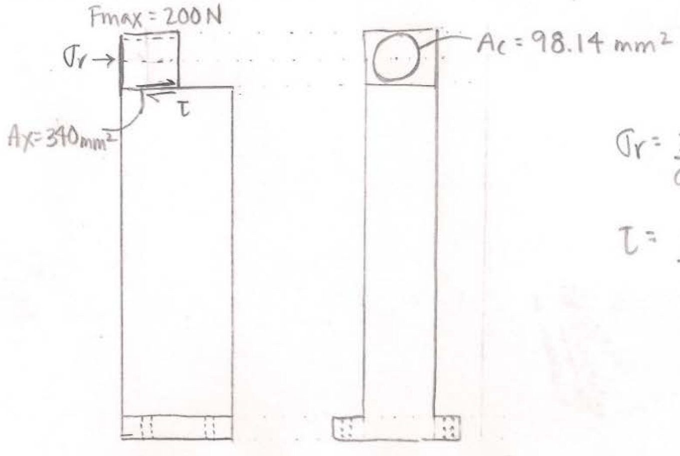
Name	Begin date	End date
Final Design Complet...	12/10/13	12/10/13
Initial Part Acquisition	12/11/13	1/13/14
Machining/construction	1/14/14	1/23/14
First Stage of Testing ...	1/24/14	2/7/14
Examination of Results	2/10/14	2/14/14
Improve Existing Feat...	2/17/14	4/11/14
Acquisition of Actuator	12/13/13	1/15/14
Installation of Actuator	1/16/14	1/23/14
Actuator Testing	1/27/14	2/10/14
Improvements on Act...	2/11/14	4/10/14
Initial Development of...	1/13/14	2/10/14
Testing of Force Syst...	1/20/14	2/12/14
Examination of Results	2/13/14	2/19/14
Fine Tuning (Force Sy...	2/20/14	3/12/14
Testing of Force Syst...	2/25/14	3/19/14
Examination of Results	3/20/14	3/25/14
Improvement of Force...	3/25/14	4/24/14

Figure B.2: Gantt Chart for Spring 2014 Semester

Appendix C: By-Hand Calculations

BASIC STATIC STRESS ANALYSIS OF TOWERS AND SCREWS

1. COMPRESSIVE STRESS IN CLAMP ON ACTUATION TOWER & SHEAR STRESS

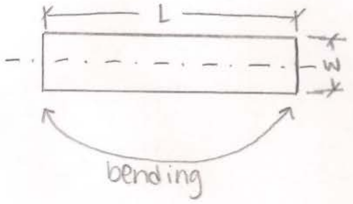


$$\sigma_r = \frac{200N}{98.14mm^2} = 2.04\ MPa$$

$$\tau = \frac{200N}{340\ mm^2} = 0.59\ MPa$$

2. BENDING IN ACTUATION TOWER

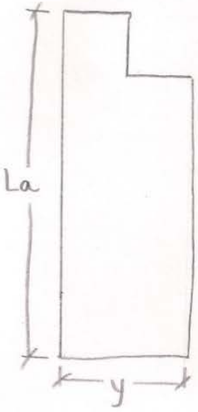
*SIMPLIFIED TO BEAM WITHOUT COMPONENTS *



$L = 169.5mm$

$w = 39.24\ mm$

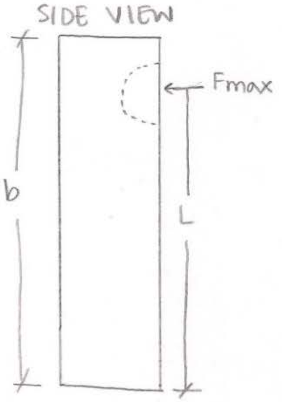
$$I = \frac{bh^3}{12} = \frac{(169.5)(39.24)^3}{12} = 853495\ mm^4$$

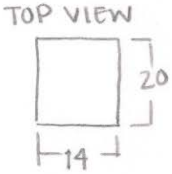


$$M = FL = (200N)(167mm) = 33.4\ N \cdot m$$

$$\sigma = \frac{My}{I} = \frac{(33400)(0.5 \times 39.24)}{853495} = 768\ kPa$$

3. STRESSES IN THE FORCE SENSOR TOWER





$b = 191.37\,\text{mm}$

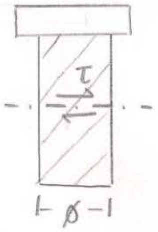
$L = 181.84\,\text{mm}$

$$I = \frac{bh^3}{12} = \frac{(191.37)(14)^3}{12} = 45759.9\,\text{mm}^4$$

$$M = F_{max} L = (200)(181.84) = 36368\ \text{N}\cdot\text{mm}$$

$$\sigma_{max} = \frac{M}{I} = 5.82\ \text{MPa}$$

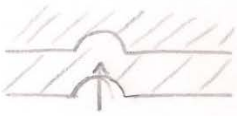
4. SHEAR STRESSES IN SCREWS



$\varnothing \cong 4.8\,\text{mm}$

$$\tau = \frac{F_{max}}{\frac{\pi D^2}{4}} = \frac{200\ \text{N}}{\frac{\pi (4.8\text{mm})^2}{4}} = 11.1\ \text{MPa} / \#\text{screws}$$

5. SHEAR STRESS AT THE BASE



$$\tau = \frac{F_{max}/\#\text{screws}}{A}$$

$$= \frac{200\text{N}/4}{4(8\text{mm})(5\text{mm})} = 2.083\ \text{MPa}$$