Design for Manufacturing, Reliability, and Economics Report

Team 13

No Contact Gap Measurement

Members:

Samuel Giaquinto – sdg11b

Matt Nagy – man11b

Forrest Parker – fjp12b

Faculty Advisors:

Dr. Nikhil Gupta

Dr. Jim P. Zheng

Sponsor:

General Capacitor

Dr. Jim P. Zheng

Instructors:

Dr. Nikhil Gupta

Submitted: 4/1/16

Contents

Table of Figures

Table of Tables

Abstract

This project arose from the necessity of measuring a micro gap between two cylinders that are used to hot roll raw material into thin films. The thickness of these films varies between 80 to 200 microns, and it is important to accurately gauge the thickness of the film samples as they are used in material property testing. The rollers used in this process are about 30 cm long, 6 inches in diameter, and are made of highly polished steel, making them expensive to manufacture and important to keep from scratching or denting. The current method used in measuring the gap employs the use of feeler gauges, which are thin metal wands with known thickness that are placed in the gap. Initial ideas for a non-contact method leaned heavily on the concept of laser triangulation systems or micrometers that would shine light through the gap to determine its thickness, however, laser products proved to be entirely too expensive for the project budget of $2,000. The final design involves rigidly mounting arms to the roller positioning blocks and measuring the gap with strain gauge based load cells. The displacement and bending of the designed load cell will result in voltage variances that can be used to determine the gap between rollers. A microcontroller is necessary to handle inputs of the capacitance sensors and the device will be calibrated to account for thermal expansion and irregularities in the rollers through experimentation and analysis.

1. Introduction

General Capacitance is the company sponsoring this project, and the problem they presented to the design team stems from measuring a micro gap between two polished steel cylinders used to hot work raw material into thin films. These thin films are made of a variety of materials that are used in batteries, and they are fabricated with the intention of doing material property testing, specifically capacitance. The specifics of the materials being used and the details of their future application was spoken of in general terms to protect the intellectual property.

The problem presented breaks down to solving the problem of measuring a microscale gap without making contact with the rollers. The early stages of designing a solution to this problem revolved around trying to determine a sensor to measure the gap. The sponsor initially suggested implementing the use of laser technologies in the form of laser triangulation or laser micrometers in order to measure the gap, but these instruments were outside of the budget restrictions. After researching the most appropriate sensors, strain gauges were determined to have the necessary resolution and fit inside the budget restrictions. The final design involves rigidly mounting arms to the roller positioning blocks and measuring the gap with strain gauge based load cells. The displacement and bending of the designed load cell will result in voltage variances that can be used to determine the gap between rollers. Once the design concept was finalized, it was deemed important to begin implementing the design with manufacturing, reliability, and economics in mind, and many decisions were made with the intent of optimizing these factors.

1.1 Background Research

Determining what products were available and currently being used in non-contact gap measurement was a significant portion of the work involved in developing a design that was in the project scope, accomplished the defined objectives, and remained under the allotted budget. Dozens of products were considered and researched through product catalogue data sheets, email correspondence with engineering specialists of companies, and feedback from the project sponsor and advisors. The reoccurring themes that surfaced while researching available technology typically fell under the umbrella of either lasers, optics, capacitance, or load cell based sensors.

Each option had its advantages and disadvantages, with load cells eventually prevailing because of their relatively low cost and its practicality to the project scope.

1.2 Need Statement and Goal Statement

General Capacitance is currently determining the gap between the rollers of their hot rolling machine in AME with feeler gauges. The feeler gauges are of known thickness so that if they fit between the rollers, it can be determined that the gap is at least that wide. The problem with this method is that these feeler gauges can scratch and dent the rollers when they don’t fit into the gap, and any resulting damage to the rollers has the potential to ruin them and they are incredibly expensive. The current use of feeler gauges to gap a pair of rollers is unreliable, time consuming, and potentially damaging. The goal statement adopted by the design team is to design a non-invasive, user friendly, accurate method of measuring the roller gap.

1.3 Constraints and Objectives

The constraints outlined from the sponsor were that the design must have a 2 μm resolution, stay within a $1,500 budget, and not come into contact with the rollers. The constraints provided a hard outline of the project, but the design team also established objectives including making the system easily attachable and removable, unaffected by the heat of the rollers, and easily operated without any formal training.

2. Design For Manufacturing

The design was initially completed without concern for difficulty in manufacturing. The arms that attach to the roller positioning blocks were dimensioned and designed to originally be cut out of solid aluminum. When the drawings were procured and delivered to the machine shop, they suggested that the solid aluminum concept be thrown out and replaced with Aluminum 80/20 components. Aluminum 80/20 is a t-slotted aluminum based “erector set” company that has what are essentially Lego pieces available to download, design, purchase, and fabricate for a fraction of the price of solid aluminum.

2.1 Assembly

Assembly time for the mechanical portion of the design with the necessary 80/20 parts, solid aluminum parts, and screwdriver is approximately 30 minutes. The incorporation of 80/20 parts and minimizing of custom parts paid dividends in manufacturing repeatability and assembly. A team starting from scratch with the provided bill of materials and assembly guidelines could complete the entire project as fast as the turnaround time for ordering materials would allow. A full parts listing is available in Appendix D.

2.2Timeline

The timeline for the completion of this project was spaced out over a semester. Having the final design outline and plans would allow the fabrication and assembly to be done in an incredibly timely manner by any team who wanted to repeat, replicate, or improve on the final design. The manufacturing and assembly involved was only a fraction of the total time spent on this design project, with most of the time and effort spent on initial design concepts and research into potential solutions.

Major Task	**Date Completed**
Strain Gauges Ordered	2/11/16
Strain Gauges Applied to Cantilever	2/25/16
80/20 Aluminum Ordered	3/10/16

Aluminum Drawings Submitted Shop	3/23/16
All Parts Arrived / Assembled	3/29/16
Prototype Testing and Calibration	3/31/16

Table 1. Major tasks and dates of project assembly.

2.3 Parts

The parts that were machined and/or required assembly included the strain gauge load cell, the 80/20 arms, and the aluminum block portions of the device. The process of applying the strain gauges to a cantilever arm to make a load cell required the use of a Strain Gauge Application Kit, which was leant to the team by Dr. Raphael Kampmann of the Civil Engineering Department. There is extensive material available online that outlines the process of applying strain gauges, so with the proper materials and instruction, this process took approximately 3 hours. Figure 1 shows some of the contents of the application kit used to apply the strain gauges to an aluminum cantilever arm, including sandpaper, conditioner, neutralizer, catalyst, and adhesive. Figure 2 shows the final product after the strain gauges had been attached.

Figure 1. Strain Gauge Application Materials

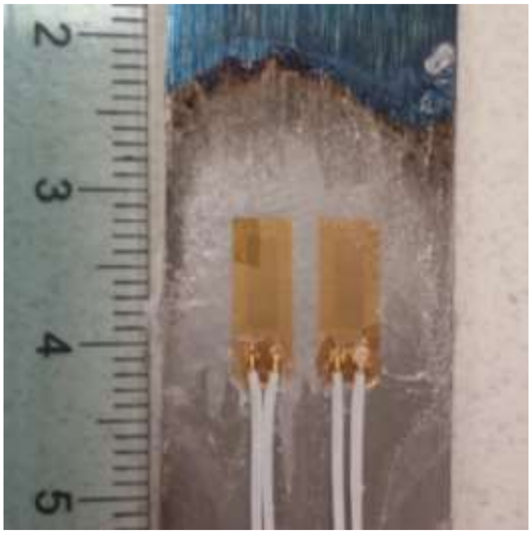


Figure 2. Load Cell Assembled

The mechanical framing of the measuring device was constructed of Aluminum 80/20, which is assembled with ease using a screw driver to rigidly attach the pieces. The CAD drawings of the parts were downloaded and assembled prior to ordering the 80/20 to ensure proper dimensioning and to assemble a bill of materials. The exploded view of the entire assembly is available in Appendix

2.4 Challenges

The main challenges came initially from budget restrictions, as all of the sensors that satisfied the technical specifications of the design were too expensive for the allotted budget. By the time the strain gauge design was researched and developed, time became the biggest challenge to overcome. Getting the solid aluminum pieces machined would make repeatability an issue, as it has typically a 2-3 week lead time. Further research into using off the shelf parts from 80/20 or other vendors for the entire assembly would reduce the complexity of the assembly.

3. Design For Reliability

The technical challenges in designing for reliability arose from the heat of the rollers and the vibration of the machine. The rollers heat up to a maximum of 300°C, and run at a working temperature of 100°C, so the design had to be spatially removed from these rollers and heat resistant. Finite Element Analysis was used to determine the ambient temperature of the air space above the rollers in order to determine how far the sensors should be removed. Figure 3 shows is a 2D cross-section of the airspace above the rollers, and this profile allowed for the conclusion to be made that any sensor placed above 2 roller radius' would be essentially unaffected by the heat rising from the rollers.

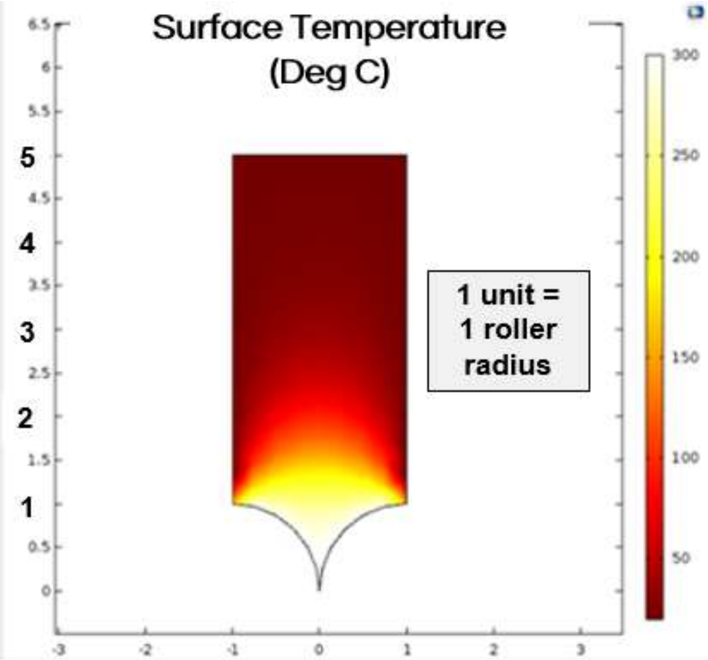
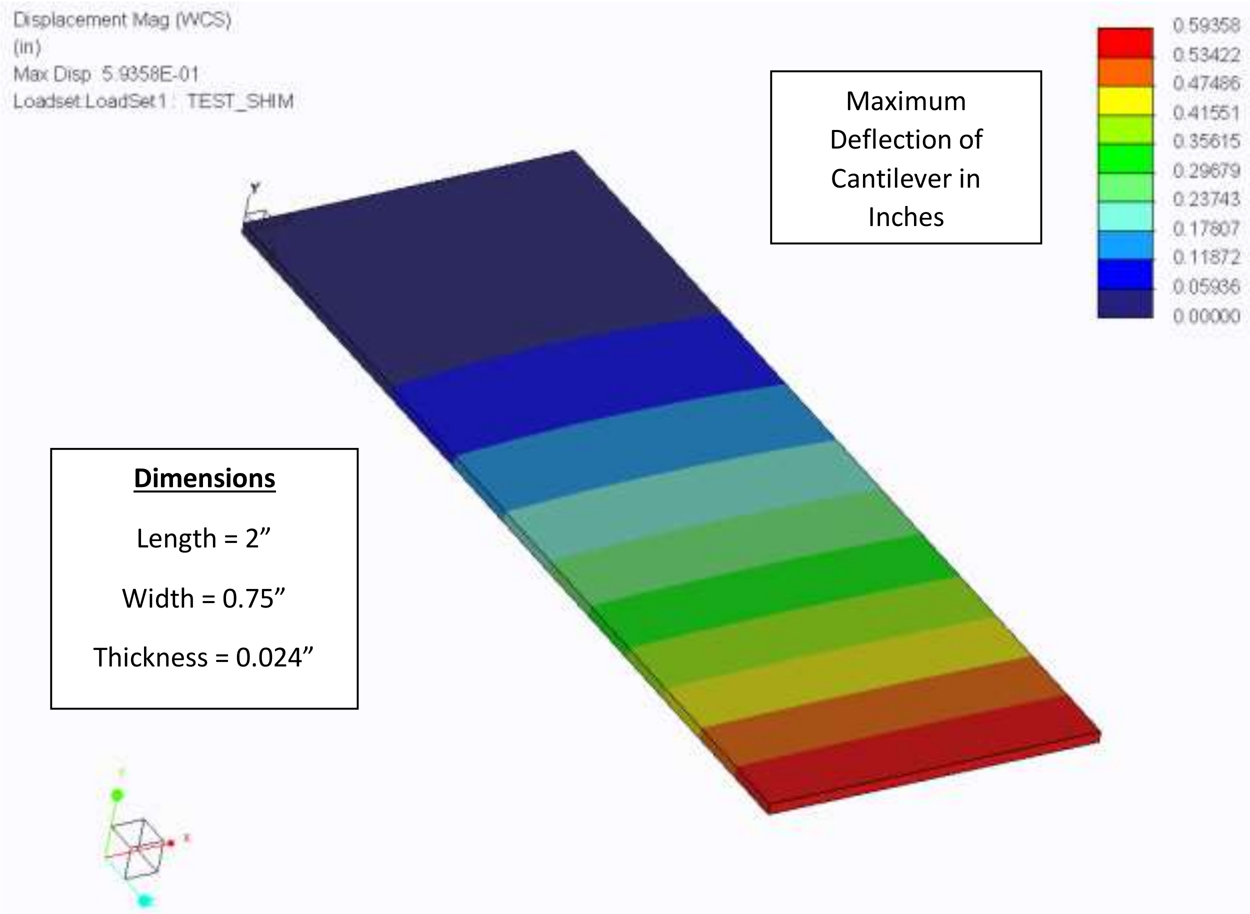


Figure 3. FEA done to analyze the temperature profile in the air above the hot rollers.

The final design incorporated removing the strain gauges as far away from the hot rollers as possible, which was about 12 inches, as the safety bars would be in the way at any higher position. The cantilever arm that the strain gauges were attached to had to be signed to get voltage variations in response to displacements of micrometers while keeping reliability in mind. The mathematics were worked out in cooperation with Dr. William Oates of the Continuum Mechanics Department, and it was determined that an ideal ratio of length to thickness of the cantilever should be greater than 10. The lifetime of the assembly is directly related to the lifetime of the strain gauge load cell, as it is essentially the only thing experiencing any physical cyclical loading. Stress equations were used to calculate the maximum deflection that the cantilever could stand before plastic deformation, as seen in Figure 4.



Maximum Deflection of Cantilever in Inches

Dimensions

Length = 2”

Width = 0.75”

Thickness = 0.024”

Figure 4. Maximum deflection before plastic deformation analysis.

The cantilever can be deflected approximately half of an inch before experiencing plastic deformation, and the maximum deflection it will experience while in use is .005 inches, which allows for the conclusion to be drawn that the life cycle of this setup, with this minimal micro strain, is indefinite assuming proper use and maintenance.[1]

The biggest frustration in reliability was the challenge of going from analog to digital signal. The quality of each electrical component in the circuit turned out to be incredibly important because signal noise had to be minimized in order to accomplish the desired resolution requirements. High quality wires, amplifier, and analog to digital converter are necessary to attain the 2 micron resolution.

4.Design For Economics

The aluminum portion of this design accounted for the majority of the expenditures, but economics was at the forefront of deciding to go with 80/20 aluminum rather than machining the whole frame from scratch. The original design for the rigidly attached arms that was drafted on CAD had an estimated cost of approximately $450 as it would have required a 24”x24” sheet of aluminum. The machine shop employees pointed out the waste and unnecessary expense of this design, and encouraged that a new design be considered using 80/20. This design still minimized machining required and dropped the price of aluminum down to $109.80, as seen in Table 3.

Mechanical Arms Attached to Machine					
Component	**Part #**	**Vendor**	**Cost**	**Qty.**	**Total**
3” x 3” x .75” Aluminum Plate	6061-T651	Online Metals	$4.36	2	$8.72
2” x 2” x 1” Aluminum Plate	6061-T651	Online Metals	$3.57	1	$3.57
Four Open T-Slotted, 10 Series 8020	1010	Adams Air & Hydraulics	$18.51	72”	$18.51
10 Series 5 Hole – Tee Flat Plate	4140	Adams Air & Hydraulics	$6.80	2	$13.60
10 Series 4 Hole – 90 Degree Angled Flat Plate	4150	Adams Air & Hydraulics	$5.10	4	$20.40
10 Series Single Flange Short Linear Bearing with Brake Holes	6415	Adams Air & Hydraulics	$38.60	1	$38.60
¼ - 20 Slide-in Economy T-Nut	3382	Adams Air & Hydraulics	$0.21	40	$8.40
¼ - 20 x 0.5” Socket Cap Screws	3625	Home Depot	$0.28	24	$6.60
		Adams Air & Hydraulics	25% OFF	Student Discount	-$21.82
Total Cost (after taxes, charges, and shipping)					**$109.85**

Table 2. Cost of Aluminum in Final Design.

The electronics portion of the design was also relatively cheap when compared to design alternatives. A basic microcontroller was needed to collect and analyze the analog data from the strain gauges. The simplicity, price, and availability of related open source code made the Arduino Uno optimal for design purposes. The strain gauges themselves were ordered in a ten pack from Omega Engineering for $165, and came pre-wired and ready to apply to the cantilever arm. The final design employs the use of four of these strain gauges and they are placed in a full Wheatstone bridge. The full listing of electrical parts is available in Appendix D. The pie chart of the total project cost can be seen in Figure 4.

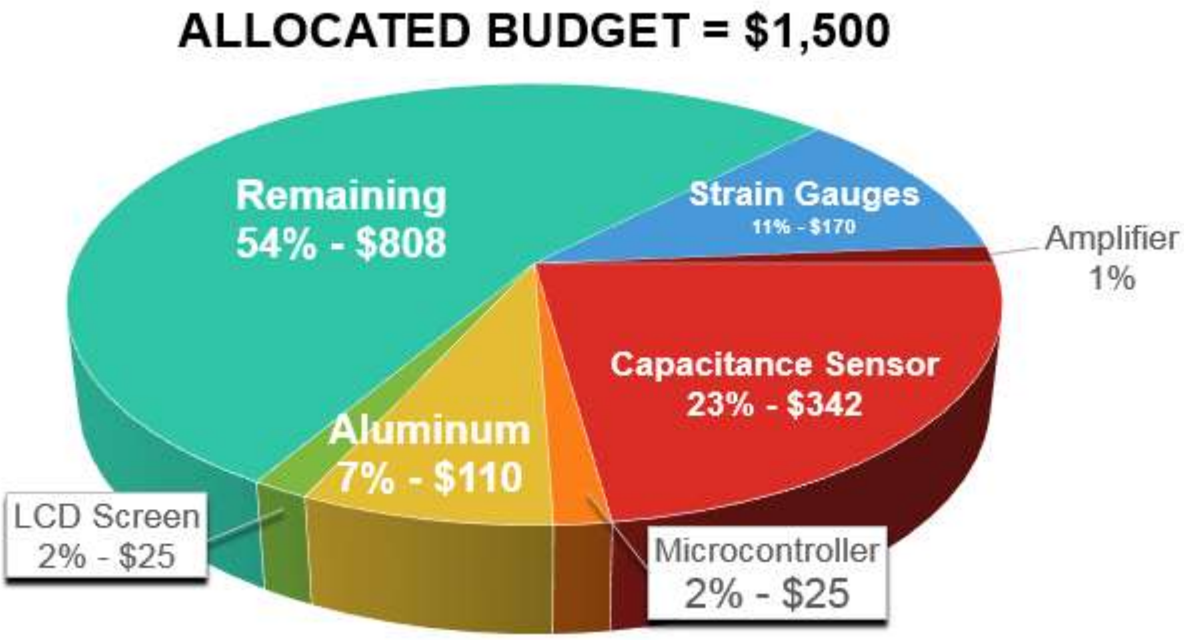


Figure 5. Total project cost, including Capacitance Sensor which was not used in final design.

4.1 Design Alternatives

Researching design alternatives was essential to making an informed decision on the design team’s final design. Many alternatives were considered and researched through product catalogue data sheets, email correspondence with engineering specialists of companies, and feedback from the project sponsor and advisors. Laser, optic, and capacitance sensors were all seriously considered and even pursued but these options all fell short of the economic design requirements. Each option had its advantages and disadvantages, with load cells eventually prevailing because of their relatively low cost and its practicality to the project scope.

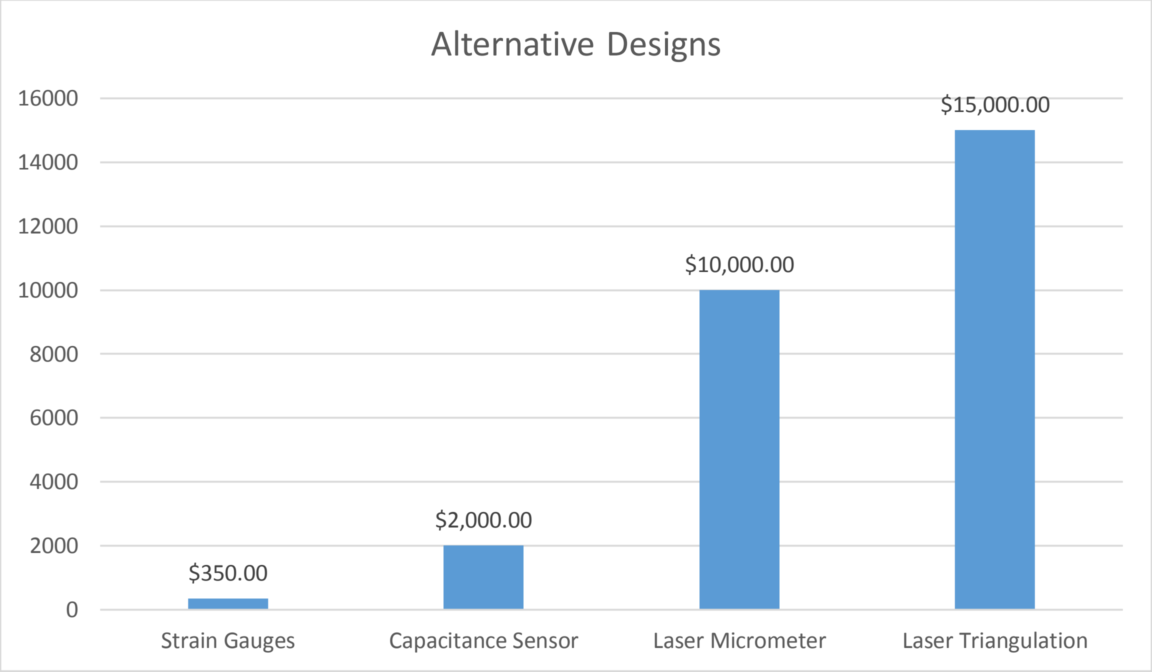


Figure 6. Alternative Design Cost Comparison.

Figure 5 shows how comparing design alternative costs to the final design cost was one of the major deciding factors in developing the design using strain gauges. The cost of a final design that made use of strain gauges as its primary displacement sensor was far and away the most cost effective, and the only design that stayed within the allotted budget of $1,500.

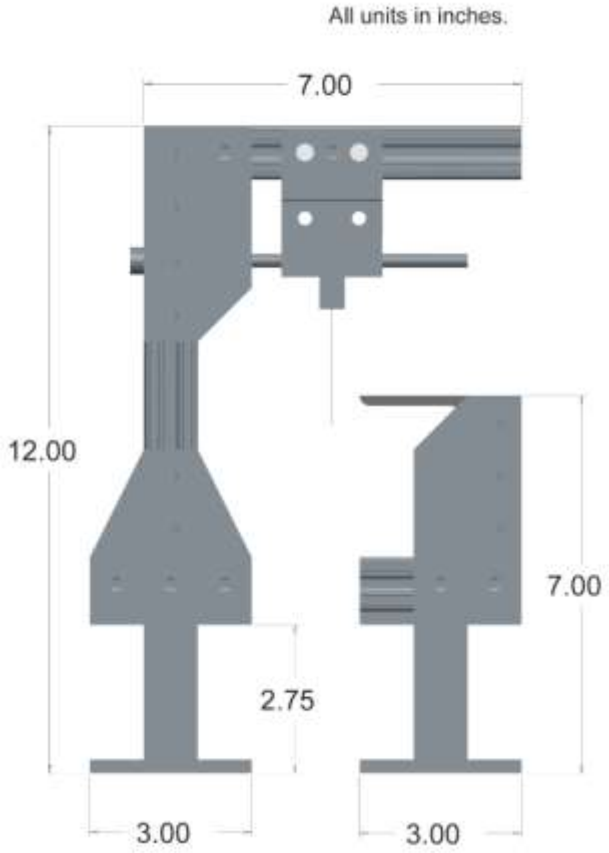
5.Conclusion

The final design concept was implemented with manufacturing, reliability, and economics in mind, and many decisions were made with the intent of optimizing these factors. The manufacturing went better than expected, as the 80/20 made the mechanical portion of design and assembly incredibly straightforward, and the machine shop was able to machine our parts with ease and get them back quicker than anticipated. The reliability of the final design turned out to be one of the pitfalls because there was a lot of noise when trying to go from analog to digital signal. The economic portion of design was successful, as the final design is much cheaper than anything else on the market for similar use, and the project was able to remain well under budget.

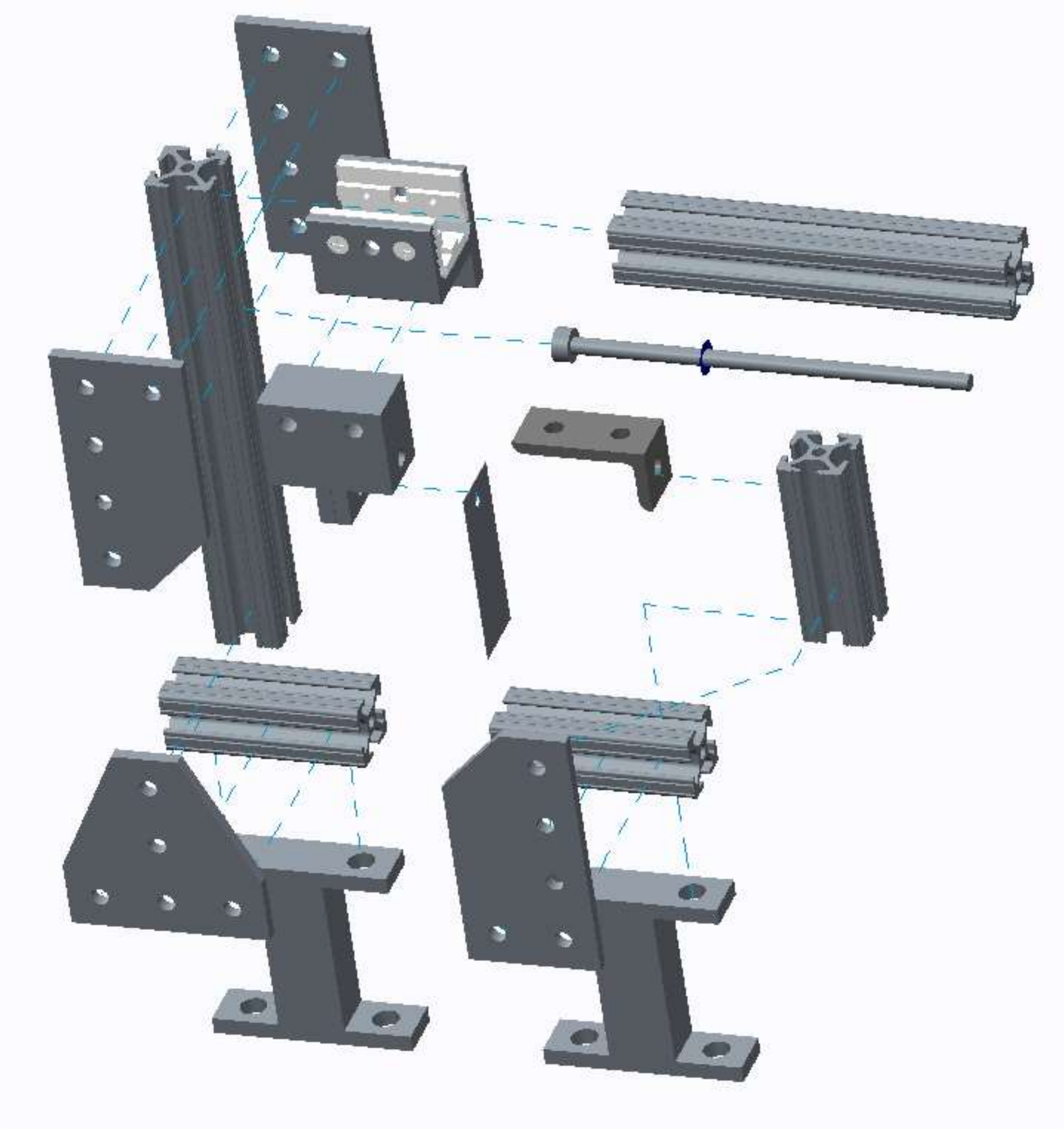
References

1. **http://www.vishaypg.com/docs/11058/tn5081.pdf**

Appendix A – Exploded View Assemblies

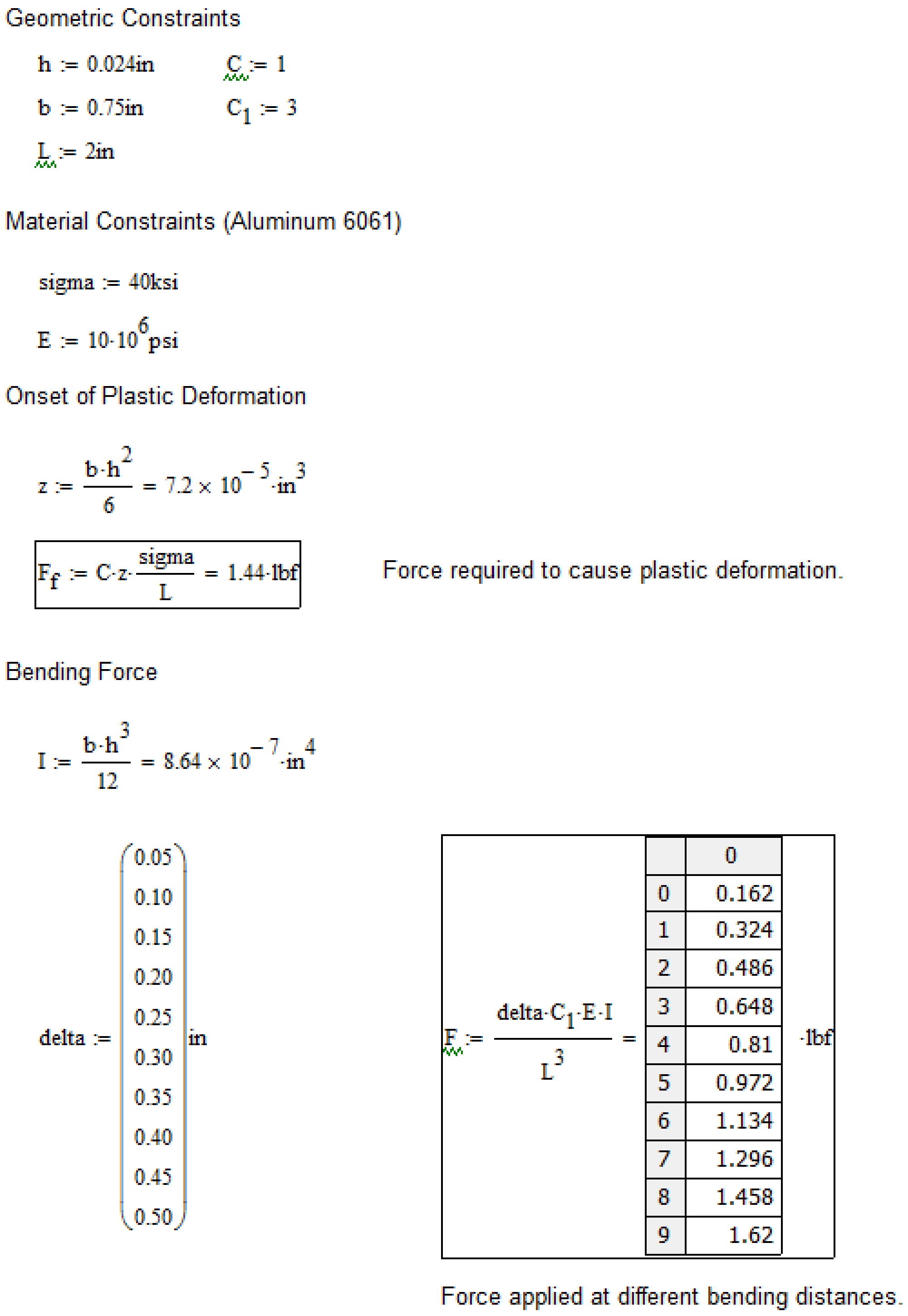


Appendix A.1 – Assembled View with Dimensions



Appendix A.2 – Exploded View of Assembly.

Appendix B – Cantilever MathCAD Analysis



Geometric Constraints

$h := 0.024\,\text{in}$ $C := 1$

$b := 0.75\,\text{in}$ $C_1 := 3$

$L := 2\,\text{in}$

Material Constraints (Aluminum 6061)

$\text{sigma} := 40\,\text{ksi}$

$E := 10 \cdot 10^6\,\text{psi}$

Onset of Plastic Deformation

$$z := \frac{b \cdot h^2}{6} = 7.2 \times 10^{-5} \cdot \text{in}^3$$

$$\boxed{F_f := C \cdot z \cdot \frac{\text{sigma}}{L} = 1.44 \cdot \text{lbf}}$$

Force required to cause plastic deformation.

Bending Force

$$I := \frac{b \cdot h^3}{12} = 8.64 \times 10^{-7} \cdot \text{in}^4$$

$$\text{delta} := \begin{pmatrix} 0.05 \\ 0.10 \\ 0.15 \\ 0.20 \\ 0.25 \\ 0.30 \\ 0.35 \\ 0.40 \\ 0.45 \\ 0.50 \end{pmatrix} \text{in}$$

$$F := \frac{\text{delta} \cdot C_1 \cdot E \cdot I}{L^3} = \ \cdot \text{lbf}$$

	0
0	0.162
1	0.324
2	0.486
3	0.648
4	0.81
5	0.972
6	1.134
7	1.296
8	1.458
9	1.62

Force applied at different bending distances.

Appendix C – Cantilever MathCAD Analysis

Fatigue Characteristics of Micro-Measurements Strain Gages

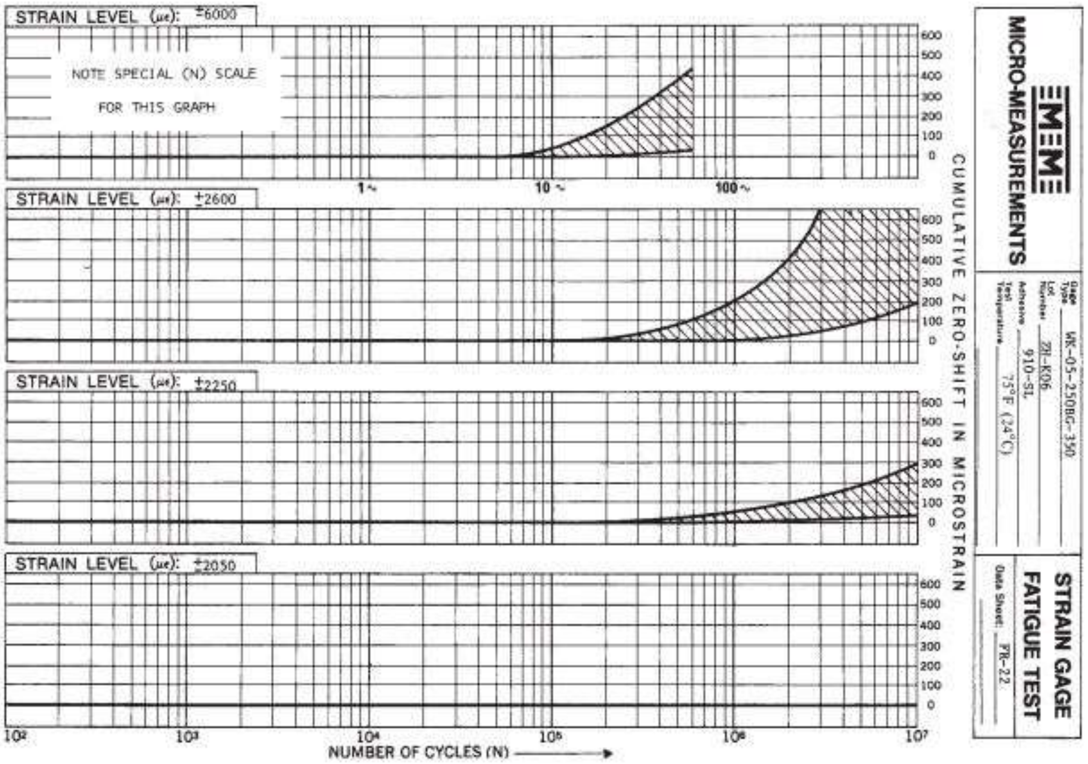


Figure 1 – Strain gage fatigue test results.

Appendix C.1 – Strain Gauge Fatigue Test Data.

Appendix D – Complete Parts List

Mechanical Arms Attached to Machine					
Component	**Part #**	**Vendor**	**Cost**	**Qty.**	**Total**
3” x 3” x .75” Aluminum Plate	6061-T651	Online Metals	$4.36	2	$8.72
2” x 2” x 1” Aluminum Plate	6061-T651	Online Metals	$3.57	1	$3.57
Four Open T-Slotted, 10 Series 8020	1010	Adams Air & Hydraulics	$18.51	72”	$18.51
10 Series 5 Hole – Tee Flat Plate	4140	Adams Air & Hydraulics	$6.80	2	$13.60
10 Series 4 Hole – 90 Degree Angled Flat Plate	4150	Adams Air & Hydraulics	$5.10	4	$20.40
10 Series Single Flange Short Linear Bearing with Brake Holes	6415	Adams Air & Hydraulics	$38.60	1	$38.60
¼ - 20 Slide-in Economy T-Nut	3382	Adams Air & Hydraulics	$0.21	40	$8.40
¼ - 20 x 0.5” Socket Cap Screws	3625	Home Depot	$0.28	24	$6.60
		Adams Air & Hydraulics	25% OFF	Student Discount	-$21.82
Total Cost (after taxes, charges, and shipping)					**$109.85**

Appendix D.1 Cost of aluminum in final design.

Electrical Portion of Design					
Component	**Part #**	**Vendor**	**Cost**	**Qty.**	**Total**
Arduino Uno	A000066	Arduino	$24.95	1	$24.95
Cytron LCD Keypad Shield	RB-Cyt-73	Robot Shop	$29.14	1	$29.14
Total Cost (after taxes, charges, and shipping)					**$54.09**

Appendix D.2 Cost of the electrical portion of the final design.