Final Project Report: Machine Components Test

Sponsor: Dr. Peter Schuster

Brandon Younger
byounger@calpoly.edu
(951)212-9420

Lauren Romero
lromer01@calpoly.edu
(805)441-4157

Carlos Padilla
capadill@calpoly.edu
(559)356-2532

Table of Contents

List of Figures

List of Tables

Abstract

To enhance California Polytechnic State University's Mechanical Engineering program, Dr. Peter Schuster has sponsored Brandon Younger, Lauren Romero, and Carlos Padilla to design and develop a new lab for students in the Intermediate Design class to test real mechanical components. This report discusses the background and ideation process that led to the development of the Educational Mechanical Breadboard for Transmission System Components (Machine Components Test). Additionally, detailed drawings, 3D modeling, testing plans, and analysis are included to show how the Machine Components Test design will work and be validated.

Chapter 1: Introduction

Currently, intermediate design students in California Polytechnic State University's (Cal Poly) Mechanical Engineering department are in need of more hands on experience with real life mechanical components. The current ME329 curriculum is missing a critical component. Students need something that can clearly demonstrate to them what different mechanical components can do, how they influence each other, and how they influence the system as a whole. The goal of this addition to the curriculum is to help the students learn the material presented in class. Cal Poly has a strong "learn by doing" philosophy so it is important that a more hands on experience is provided in the intermediate design curriculum.

Dr. Schuster saw the need for a hands on interactive lab that would bridge the gap between the material presented in class and the real world. We were assigned to the task of designing something that would meet the need for ME329 students with Dr, Schuster as our sponsor. Ideally the project would be funded by CP Connect with a budget of $2,000. CP Connect is a program that allows students the opportunity to collaborate on interdisciplinary projects by providing funding and resources. If we are denied funding by CP Connect, $1,000 will be allocated by the Mechanical Engineering department to start a design project that will fill the void in the intermediate design curriculum.

The goal for the project is to give intermediate design students the opportunity to obtain a better understanding of how different components influence machine performance including shafts, belts, chains, gears, and bearings. The purpose of this project is to design a mechanism that will lead intermediate design students to gain the understanding required to become successful engineers. The mechanism will allow students to measure motor performance curves, contain real mechanical components, allow students to experiment with the configuration of the power transmission system, and also to observe how changing different components can affect the system performance. These are some of the requirements that the final design for this project will meet. Additional requirements are discussed in the objective section.

Chapter 2: Background

The ME329 curriculum involves learning how common mechanical components used in real mechanical systems work. The course introduces the following components: motors, gears, belts, chains, shafts, bearings, brakes, fasteners, and springs. The students review how each component works to get an idea of how to choose components for specific design criteria. Part of the reason for implementing this lab is to help give students a more intuitive feel about how different components affect a system. This is important for engineers because it allows the engineer to have a general idea of how a system is going to perform before a formal analysis is conducted.

Because labs are usually only three hours long, not all the concepts covered in ME329 can be demonstrated. Some concepts that are ruled out due the time constraint are fatigue, wear, and corrosion. These aspects of design simply take too long to demonstrate. Concepts that can be demonstrated in a three hour lab include: gear positioning effect on performance, motor performance analysis, deflection in shafts, component failure mechanisms (like slipping belts, or a chain skipping a tooth), lubrication effects on bearings, shaft critical speed, and the effect of different components on the system efficiency.

In Cal Poly’s intermediate design class, the only experience students have with real mechanical components is what Dr. Schuster calls the “machine teardown”. In the “machine teardown”, students have the opportunity to take apart old hand power tools to examine how they work. The students are also assigned a design project where they make a prototype of their design using LEGO Technics as seen in Figure 1. The core of the student’s design project is usually to design a power transmission system using what they learned in class. The LEGOs allow the students to produce their designs using plastic gears and plastic shafts, but Dr. Schuster is concerned that students do not really understand how different components influence the system. He is concerned that when students work with small scale plastic parts they fail to make the connection between the system and its components. In other words, because these products are made out of plastic and are small scale models, they are an unrealistic comparison to common components used in industry.

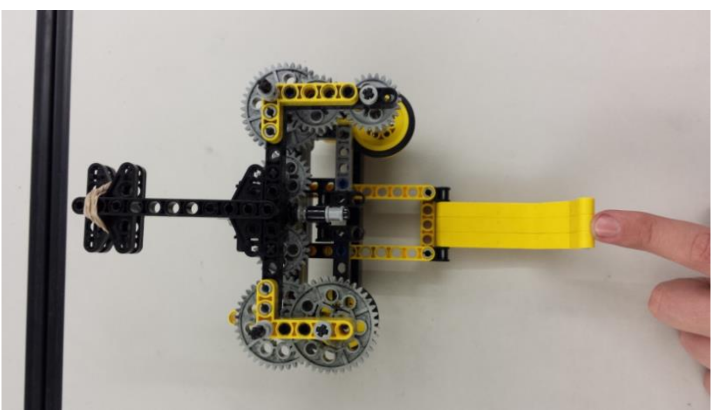


Figure 1: Lego Model from an intermediate design class.

Existing Labs

Initial research has revealed that there are no comparable products on the market. We researched the Cal Poly library database, Google, and the ASEE site for projects that might be similar to what we are trying to accomplish. Our problem with finding something similar to what Dr. Schuster wants is not that no such project exists, but that many of the universities and educational institutions have not published details of their machine design labs. Another possibility is that different instructors of intermediate design have different ways of managing the course that include different projects or labs to explain component interaction.

Although a product that matches the requirements of our project was not found, some examples of what other universities are doing to educate their engineering students were found. Central Washington University has developed two labs for their machine design students. The first is the examination of a three-speed manual transmission with part of the casing removed as shown in Figure 2. The students get a general introduction about how the transmission works. Then they are asked to observe the mechanism and determine the input and output ratios by counting the teeth on the gears. The second lab is an examination of the Ford Model T planetary transmission seen in Figure 3. Again the students are introduced to the transmission and given some background information. They then have to analyze the planetary transmission using the analytical skills they learned in their dynamics course. More information about these labs can be found by looking at Reference [1].

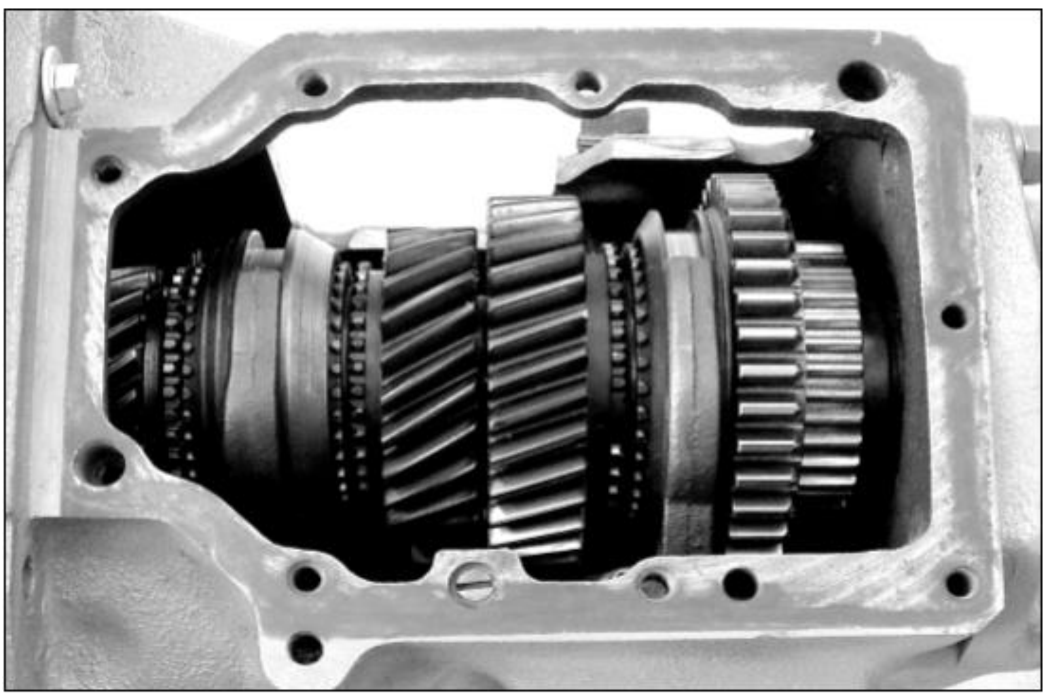


Figure 2: The Ford three-speed manual transmission used in the Central Washington University lab.

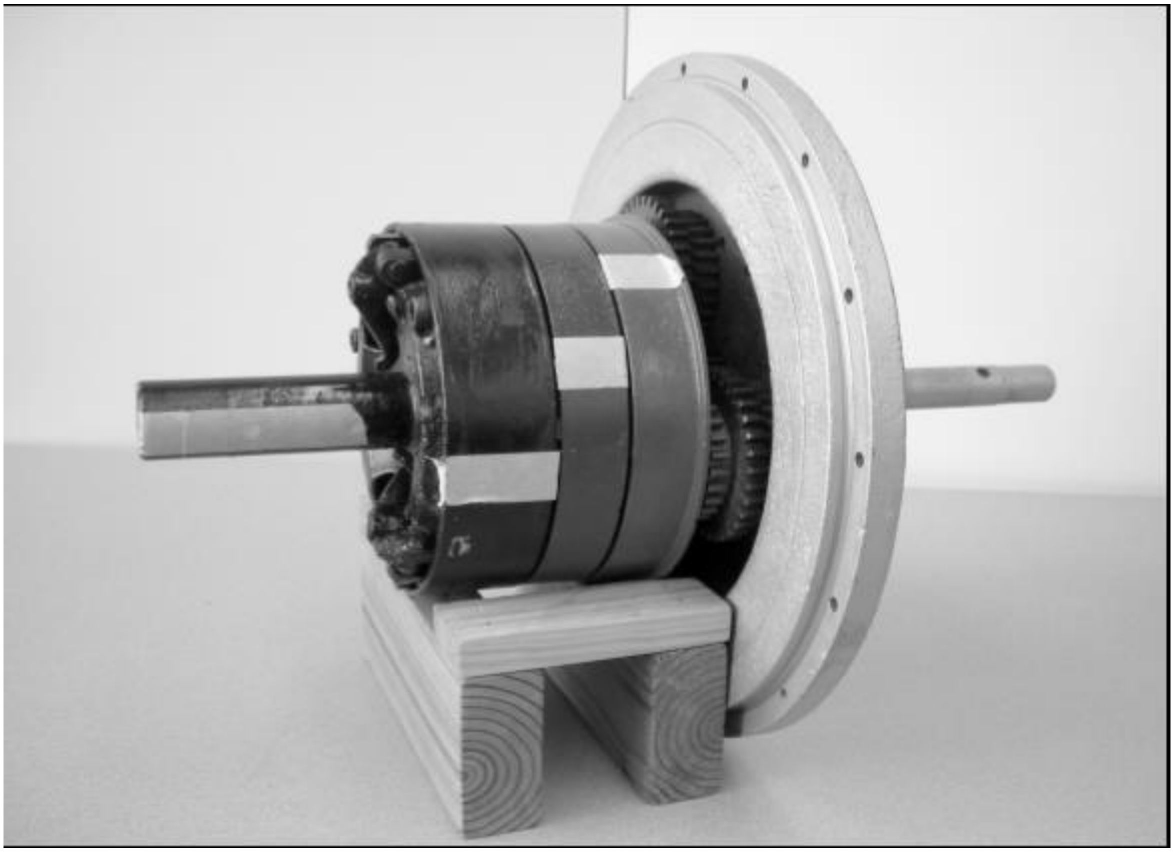


Figure 3: The Ford Model T planetary transmission used in Central Washington University's second lab.

John Hopkins University was facing the same problem Cal Poly is facing now, namely that the students required more hands on experience. In response they developed a new design laboratory course. The new course includes a hands on laboratory activity that focuses on a topic discussed in lecture. Unlike Cal Poly and Central Washington University, John Hopkins University has individual labs that focus on fasteners, torsion rods, bearings, gears, gear trains, belts, pressure vessels, and failure modes seen in Figures 4 through 8. Some of the labs even require the students to use fabrication tools like mills and lathes. Below are pictures of some of the experiments described in Reference [2].

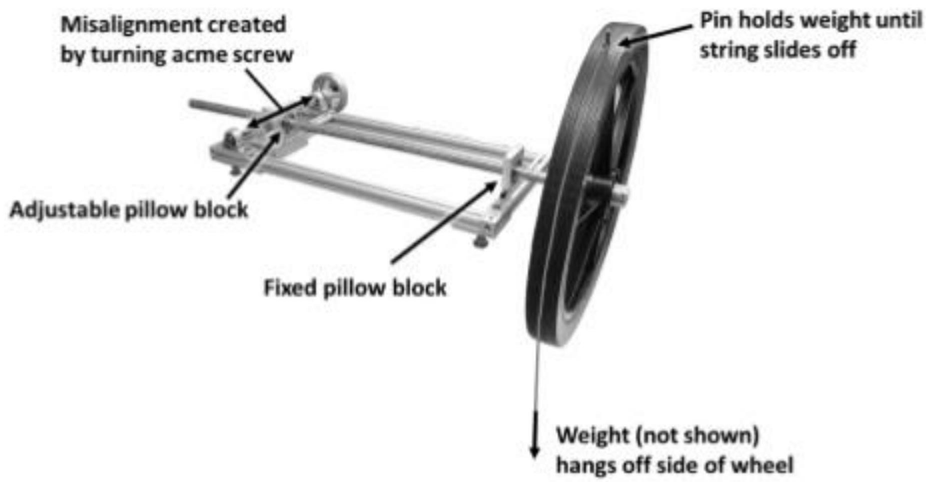


Figure 4: Bearing misalignment fixture for John Hopkins University bearing misalignment lab

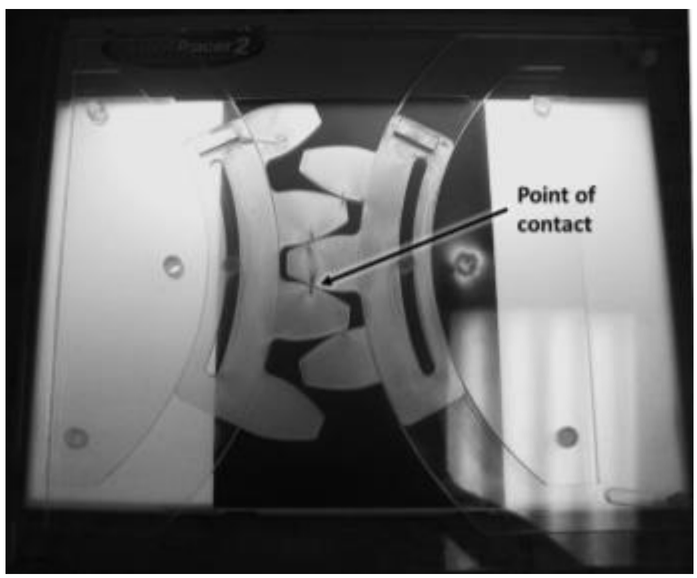


Figure 5: John Hopkins University's gear stress visualization lab using photoelastic gears.

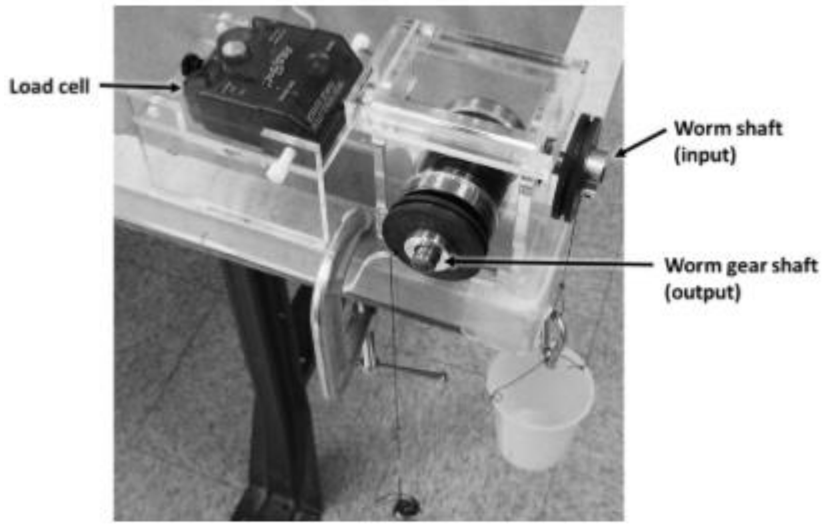


Figure 6: Worm gearbox analysis lab used in John Hopkins University's machine design course.

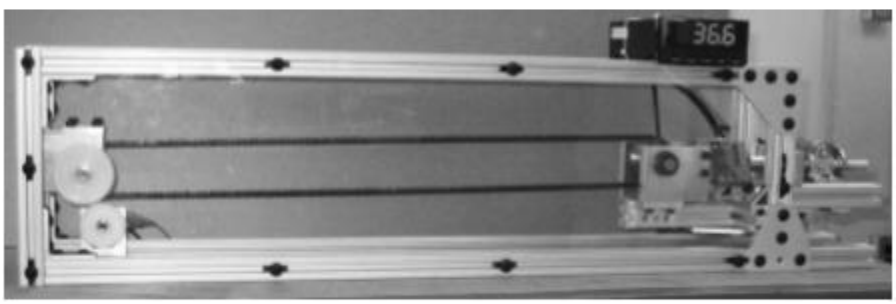


Figure 7: Timing belt drive apparatus for John Hopkins University's lab.

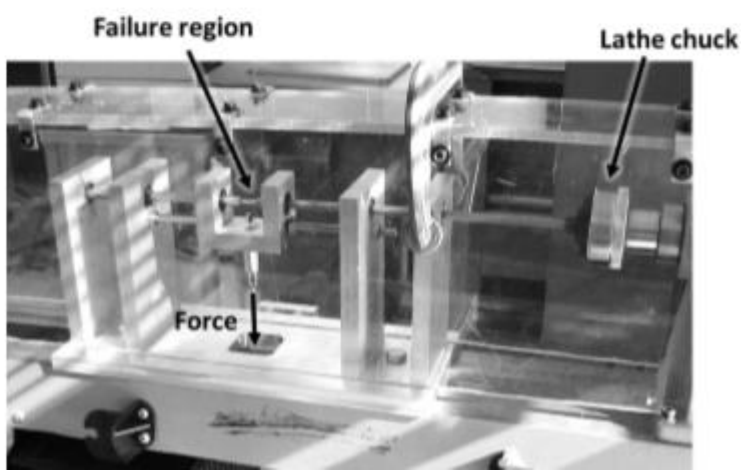


Figure 8: Fatigue testing apparatus for John Hopkins University's machine design course.

State of the Art: Mechanical Breadboards

As stated above, an initial search did not reveal any products that met the requirements for the design. The problem was that a refined search term was needed for the information to surface. After some brainstorming, an analogy between what we were trying to accomplish and the concept of a breadboard used in the Electrical Engineering department was made. This led to a new search term, the “mechanical breadboard”. A mechanical breadboard uses the same concept of an electrical breadboard. The difference is that instead of the ability to create different circuits; the mechanical breadboard allows the use to create different mechanical power transmission systems.

Mechanical breadboarding is a concept that has been around since the 1950’s. It is not a new concept, but has not yet been developed to improve student understanding in mechanical systems. A search revealed only two companies that make a mechanical breadboard kits. Pic Design and V.M. Berg both make a mechanical breadboard kit that you can buy as shown in Figures 9 and 10 below. The downside to these products is cost. They have a price range of $500 for a basic system to $4,000 for a complete kit [4]. These products involve precise components and are designed more to prototype concepts rather than demonstrate mechanical principles. According to a patent search performed by James Mikes, author of *The Analysis and Development of a Mechanical Breadboard Structure*, no patents exist on mechanical breadboards.

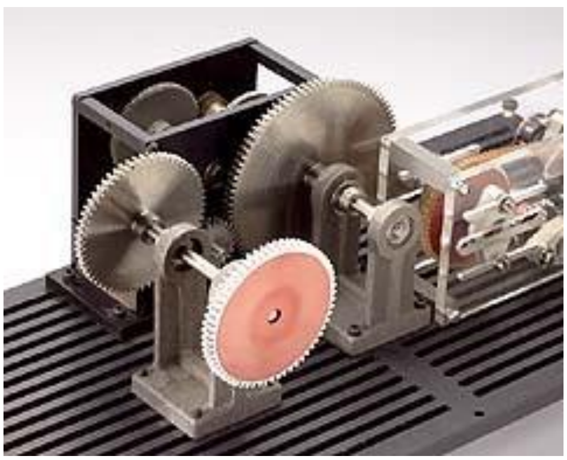


Figure 9: V.M Berg mechanical breadboard design [4]

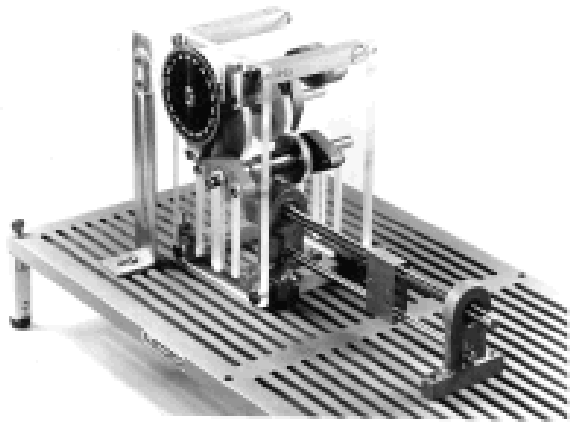


Figure 10: Pic Design mechanical breadboard example [4]

Industry mechanical breadboards have not been used to demonstrate mechanical principles to improve student understanding in the classroom; however, "home-made" mechanical breadboards have. The first example was developed by Dr. Van and Dr. Ward of Union University. It is a cost effective way to create a mechanical breadboard to aid in teaching engineering statics to students. The design utilizes multiple hinged pegboards to create its base seen in Figure 11 below. This design allows the user to attach components to the pegboard in a 3D configuration, manually apply forces by pulling a string or pushing on a component, and observe what happens. For more information on the statics mechanical breadboard please see reference [5]. The second example was created by Dr. Mountain and is called a "Process Control Breadboard" [6]. Dr. Mountain's mechanical breadboard consists of a equipotential backplane made of separate tubes with quick disconnect fittings along various points on each tube seen in Figure 12. The backplane allows students to connect components across the board by connecting one tube to another with different components to generate a system. The components for the process control breadboard include valves, pumps, heat exchangers, and heat generators. The ability to change components in a system and see their effect on the overall system makes mechanical breadboards advantageous for educational purposes.

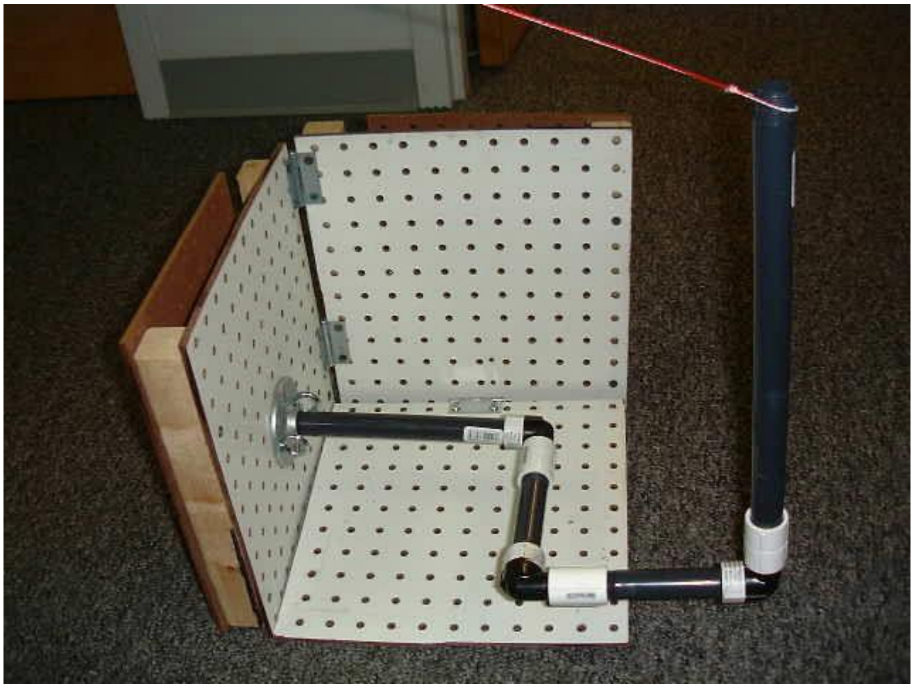


Figure 11: Mechanical Breadboard for teaching engineering statics [5].

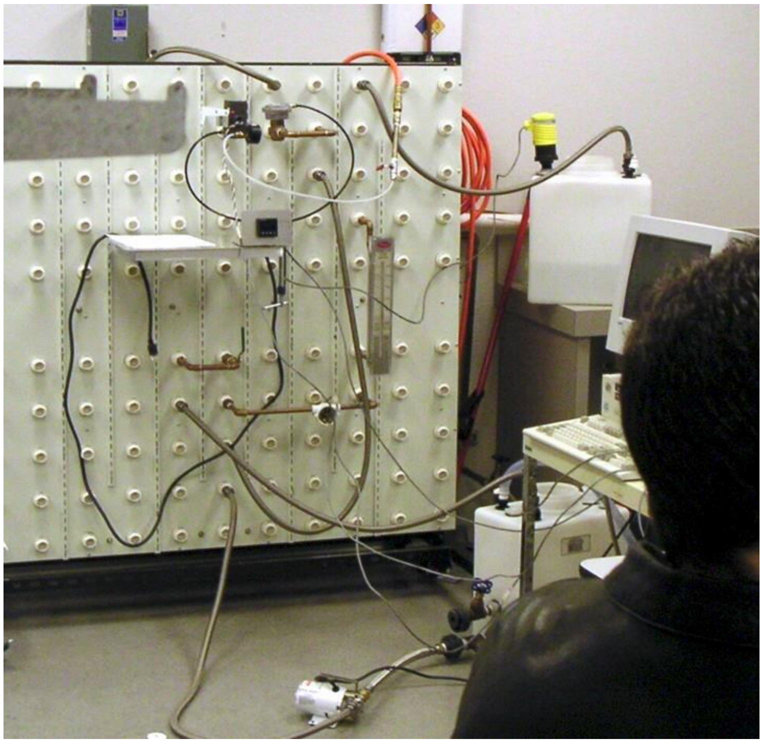


Figure 12: Mechanical breadboard for teaching thermal fluid process control [6].

Standards

We also researched safety codes for rotating machinery. According to Title 29 of the Code of Federal Regulations (CFR) Section 1910.212, “The point of operation of machines whose operation exposes an employee to injury, shall be guarded... One or more methods of machine guarding shall be provided to protect the operator and other employees in the machine area from hazards such as those created by point of operation, ingoing nip points, rotating parts, flying chips and sparks.” This describes how safety guarding is a concern that must be addressed. In Section 1910.219 for “Mechanical power-transmission apparatus,” it says that “Each continuous line of shafting shall be secured in position against excessive endwise movement.” It continues to describe regulations for belts, gears, and chains as well. More information can be seen in Reference [3]. However, the motors we will be using have a low enough power to ensure safety for students as it will not expose operators to points of injury.

Chapter 3: Design Development

Design Objectives

Our overall objective is to create a machine containing a power transmission system with real mechanical components that is configurable, allows for power loss measurements, and allows for motor analysis to help further the knowledge of intermediate design students in the Mechanical Engineering department.

In an effort to meet all our customer's interests we used quality function deployment to develop a house of quality, shown and explained in Appendix B, to identify all customer requirements. We then used the results of our house of quality to generate a table of the engineering requirements for this product. Additionally, risk is included with three levels of importance, high (H), medium (M), and low (L). The compliance will be assessed by methods of analysis (A), test (T), similarity to existing designs (S), and/or inspection (I) as seen in the Table 1 below.

This product will be handled by students and teachers who need to move the product across the room. Therefore, a reasonable weight limit of 20 pounds is required. Additionally, the size of the product must fit within a 3 feet wide by 2 feet deep by 1 foot 'X2'X1' shelf, and thus the dimensions are limited as well. Our product may be reproduced for future classes. This means the machining and assembly time for reproducibility must be reasonable, 12 and 3 hours respectively.

Dr. Shuster would like multiple breadboards to be used in class so that a team of two or three students can work on an individual board. The cost must then be low, around $300 a piece, to be in the Mechanical Engineering Department's budget.

The purpose of the project is for students to visually see the difference between real mechanical components, therefore a minimum of five types of components: chains, belts, gears, shafts, and bearings, is our goal. Additionally, at least two types of these five components will be included to see how different materials affect power loss. We hope to buy as many different components as possible, but cost will be the limiting factor. These components will all be bought, so we aim for 90% of our product to include standard parts.

Labs are three hours long, so we need to make a product that can be set up relatively quickly, ten minutes at most. There also must be no pinch points to allow for the safety of students. The main measurable parts of our project will be motor characteristics and transmission efficiency. We will provide the tools and instructions on how students will be able to do this. The will then be able to compare these measured values to different transmission set ups (at minimum 4).

Finally, we plan to survey and quiz the students after they use our product to see if it enhanced their learning. The student survey involves asking students if they thought our new lab was helpful in their understanding of mechanical components, what they feel was missing or difficult, and if they think the lab should be offered to future design students. The quiz would assess student understanding of mechanical components before and after this product was used to see if there was any improvement.

Table 1: Machine Components Testing project formal engineering requirements.

Spec. #	Parameter Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Weight	20 lb	max	H	A,T
2	Size	3’x2’x1’	max	H	A,T
3	Machining Time	12 hr	max	L	T
4	Assembly Time	3 hr	max	L	T
5	Production Cost	$300	max	M	A,T
6	Real Mechanical Components	5 different types (chains, belts, gears, bearings, shafts)	min	L	I
7	Number of gears, chains, belts, and bearings	2 each	min	M	I
8	% of Standard Parts	90%	min	L	A
9	Setup Time	10 min	max	M	T
10	Measurable Motor Characteristics	3	min	M	A, T
11	Measurable Power Transmission Efficiency	2	min	M	A, T
12	Configurable Components	4 unique configurations	min	M	A,T,I
13	Student Surveys and Quizes	15% improvement	min	M	I

Preliminary Designs

After gaining a strong sense of the problem statement and objectives, we developed a list of functions our product must do. Appendix B displays a QFD chart that was used to compare functions, engineering requirements, users, and existing products. These functions were used when analyzing our different ideas. Once we knew how our product would function, we started formulating ideas. Some techniques used were brainstorming, brainwriting, and SCAMPER. Brainstorming is saying out loud all ideas we could come up with and writing them down, whereas brainwriting is writing down ideas and passing them to another group member to expand on them. Finally, SCAMPER is taking ideas and adjusting them or combining them to come up with new ideas.

Through the design ideation techniques, we developed various ideas to help students better understand mechanical components. Our concepts satisfy specifications because they give students experiences with actual mechanical components in different ways. Each method tries to give students a learning opportunity about gears, belts, chains, and motors. Some ideas are more complex than others and might require more than one lab period to complete. The following are the preliminary ideas we came up with:

Mechanical Breadboard

The mechanical breadboard lab involves a breadboard meant for mechanical components. It is larger than the electrical breadboard students are used to using. Parts are interchangeable on the board to allow for a large range of different transmission systems. Dynamometers and multimeters would be attached throughout the system to record data. Students can calculate power loss and directly observe gear slipping and beam bending with the tangible set up. Power would be supplied by a motor and students would transfer power to a generator through the use of real gears, pulleys, belts, chains, shafts, and bearings. Figure 13 below shows a concept model of this design made from foam board, paper cubs and wood to show this design.

Figure 13: Concept model of the mechanical breadboard.

<u>Machine Teardown</u>

This project idea is similar to the machine teardown in place in some Design II classes. Students would get different mechanical machines such as engines and power tools like the one in Figure 14 that they can disassemble to see how each part relates to the overall transmission of power. This lab will include measurement devices so students can collect data from any motors that might be in the machine and can change motors to see what the effect would be. Gear, belt, and chain calculations can be included in the lab as well.

Figure 14: The mechanical components found in a power drill. [7].

<u>Virtual Lab</u>

Students could design many different transmission systems if they worked in a virtual program. For this idea, we would design a computer program similar to Figure 15 that would allow students to choose from an extensive library of parts and assemble the pieces to transfer power from a motor to an output. The computer program would run through calculations and display the power losses from the system. Students can then “dismantle” their transmission with a hit of a button and work on a different set up with different components.

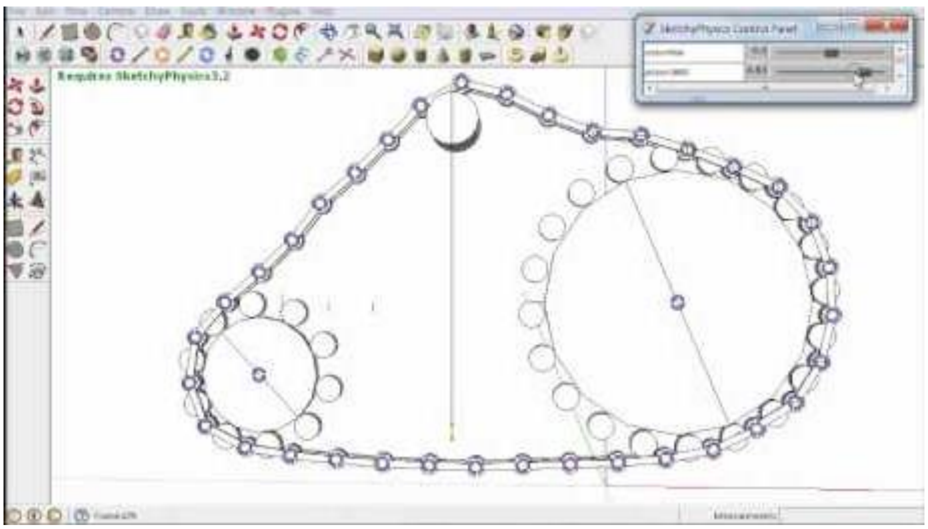


Figure 15: Google Sketchup design of a chain system [8].

Individual Component Labs

The individual component lab would go into depth on gears, belts, chains, and bearings separately. Each station would include different types of the individual component and have fixtures set up to see what difference they make in terms of transferring power. Students can handle each part, see how they fit together, and make calculations. An example of the components that would be seen in the gear section of the lab are seen in Figure 16.

Figure 16: Example of components that can be used in the gear section of the lab [9].

Build Power Tool

Many mechanical engineering students enjoyed their IME classes where they cast products such as keychains and miniature mustang figures that they could take home. This lab would allow students to design and build a power tool such as a simple drill that they could then take home. This project would involve motors, shafts, and gears such as those seen in Figure 17. After assembling the product, students can take measurements in the power tool and record power losses.

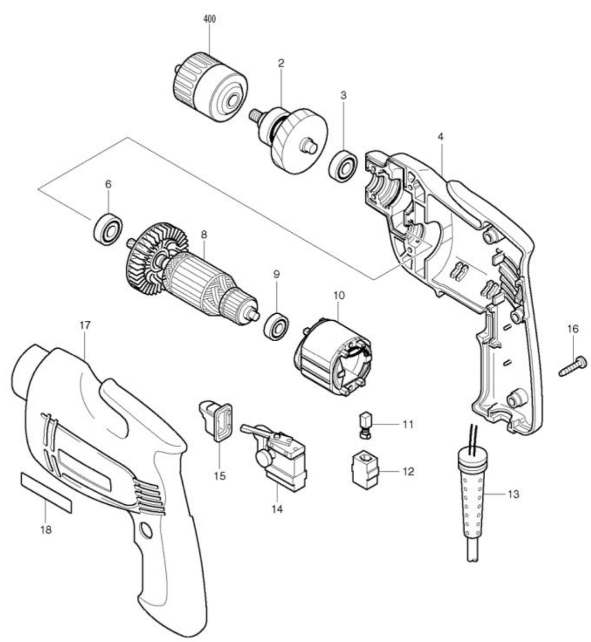


Figure 17: Tool diagram for a Makita 6406 power drill [10].

This idea involves students delving into their creative sides to make a moving sculpture using real mechanical parts. The sculpture could be similar to Figure 18, but would be powered by a motor. Gear reductions and/or belt and chain reductions will be used to give the sculpture a specific speed. Analysis will be made to insure the correct movement is created and measurements will be taken to see the power loss in the system.

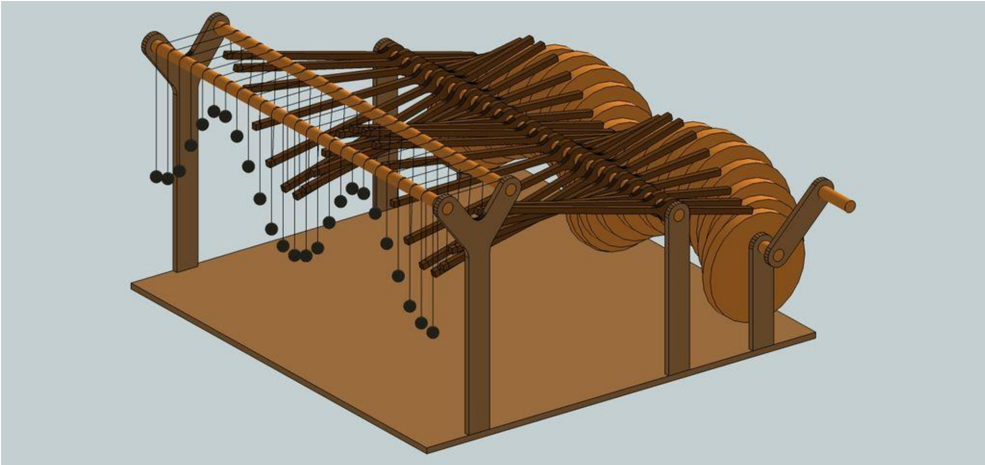


Figure 18: Kinetic sculpture powered by human crank power [11].

Rube Goldberg Machine

The Rube Goldberg Machine would be altered to involve real mechanical components in this concept. It would not have to be as complex as the wine bottle opener in Figure 19, but the same basic idea applies. Additionally, the system would be powered by motors that could be interchanged. Students would have to perform calculations based on the components they used including the motor, and would need to incorporate at least one type of gear, belt, and chain in their designs. The model would then be measured using equipment in lab to see the power losses in the system.

Figure 19: Mechanical Rube Goldberg machine used to open and pour wine [12].

Concept Selection

We put each of these ideas in a Pugh chart to compare each idea to the LEGO Technic lab (used as our datum) seen in Appendix C. The criteria was taken from the QFD from Appendix B. If one of our concepts better fit the criteria than the datum a plus was placed in the corresponding column. If an aspect was worse, a negative was written, and if it was the same, a "S" was written. Through this analysis, the mechanical breadboard design had the most positive aspects and the least amount of negatives compared to the datum. The virtual lab was a close second but it lacked the tangibility of the mechanical breadboard. We chose the mechanical breadboard as our preliminary design concept to develop further.

Decision matrices were written for different aspects of the mechanical breadboard such as method of attachment, output, and storage. These charts can be seen in Appendix D. Different concepts for the design were listed on the left hand side of the chart while functions were written across the top each with their own weightings that added up to one. Each of the concepts were rated up to 100 for how well they met each function. The left hand column totals the weighted ratings of each concept to see which one meets our needs the best.

Through the decision matrices, a threaded fastener method of attachment had the best results between our methods of attachment. Threaded fasteners would be easily replaced and easy for students to use to move components around the base. Additionally, the storage method that proved best was a bin. This would cheaply hold all the mechanical components and condense them to better fit in the designated cabinets. Lastly, the output chart showed that a fan and ball output would be a good visual addition to the lab and add a fluid mechanic aspect. Power output from the transmission system would power a generator that would then power a fan encased in a clear tube. Air from the fan would be concentrated to lift a lightweight ball into the air. Depending on the power losses of the system, the ball would move higher or lower.

To justify our selected concept, analysis was done on the amount of energy it would take to lift a Styrofoam ball, and the stress that power would cause in the system on the board, fasteners, and other components. This analysis can be seen in Appendix F, "Calculations." The results of this analysis lead us to our desired sizes of components to ensure a safe mechanism.

Once these decisions were made, we started to work on a 3D model of our design in SolidWorks. Shown below is some preliminary design of our final concept. As previously stated, power is transferred to the input shaft through a motor which is then used to drive other shafts with various transmission components attached. Although not shown the final shaft in the assembly will be used to power a generator in order to provide electrical power to the fan shown.

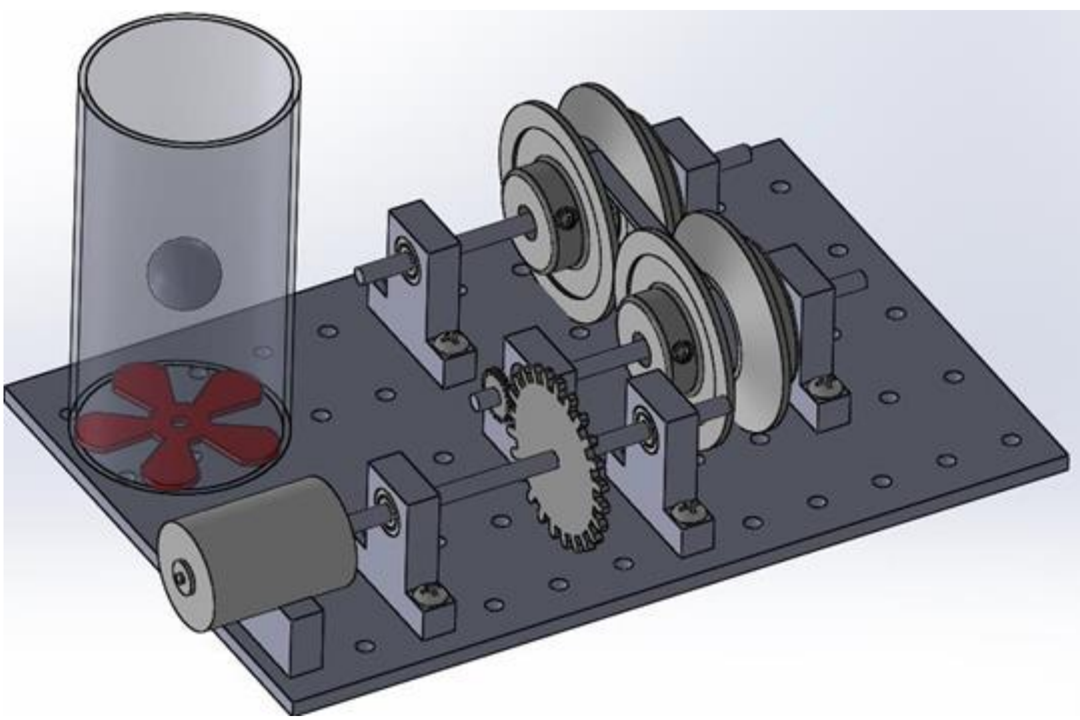


Figure 20: Preliminary 3D model of the chosen concept, the mechanical breadboard

In addition there will be various pre-configured sub-assemblies such as those shown in Figure 21 below, for students to attach gears, pulleys and sprockets of different sizes to see how they affect efficiencies and power loss.

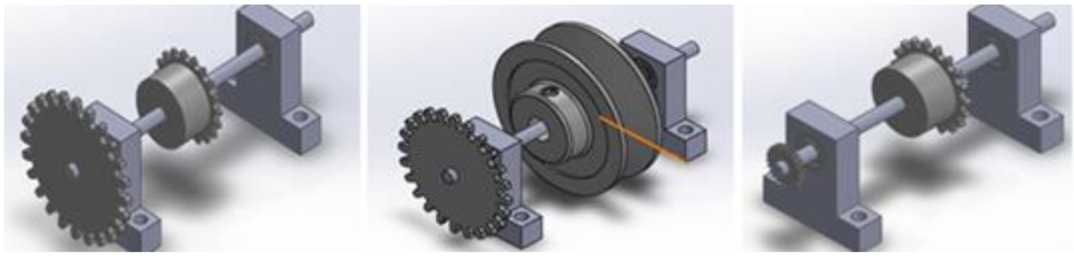


Figure 21: Preliminary component sub-assemblies of mechanical breadboard

Although we have chosen our final concept there are still a few parts of our design that must be added to the final design. After the concept model, we had to determine how many configurations and sub-assemblies we would like to include with our design. In addition we determined how many types of components will be included in this design. These decisions can be seen in Chapter 4.

Chapter 4: Final Design

Description of Final Design

After analyzing the fan apparatus, we discovered that a small change in transmission efficiency would drastically change the height of the ball. This led us to a new output design, a band brake. The band brake allows students to receive a “hands on” experience with a component that was discussed in class but never shown in lab. The analysis for the band brake can be seen in the following section, “Results of Supporting Analysis”.

Additionally, a fine adjustment component was added to the design of the board to allow gear meshes to be slightly too close and slightly too far away so that students may observe the effects of gear slipping and grinding respectively. The following figures, Figure 22 through 25 show the new design using SolidWorks modeling.

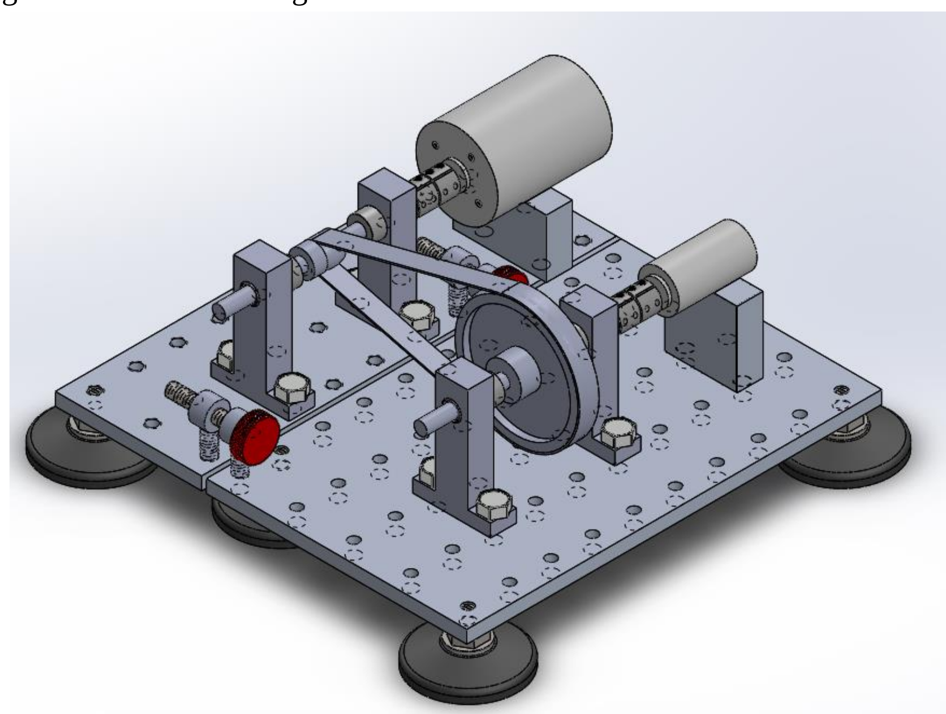


Figure 22: Machine components test with pulley assembly.

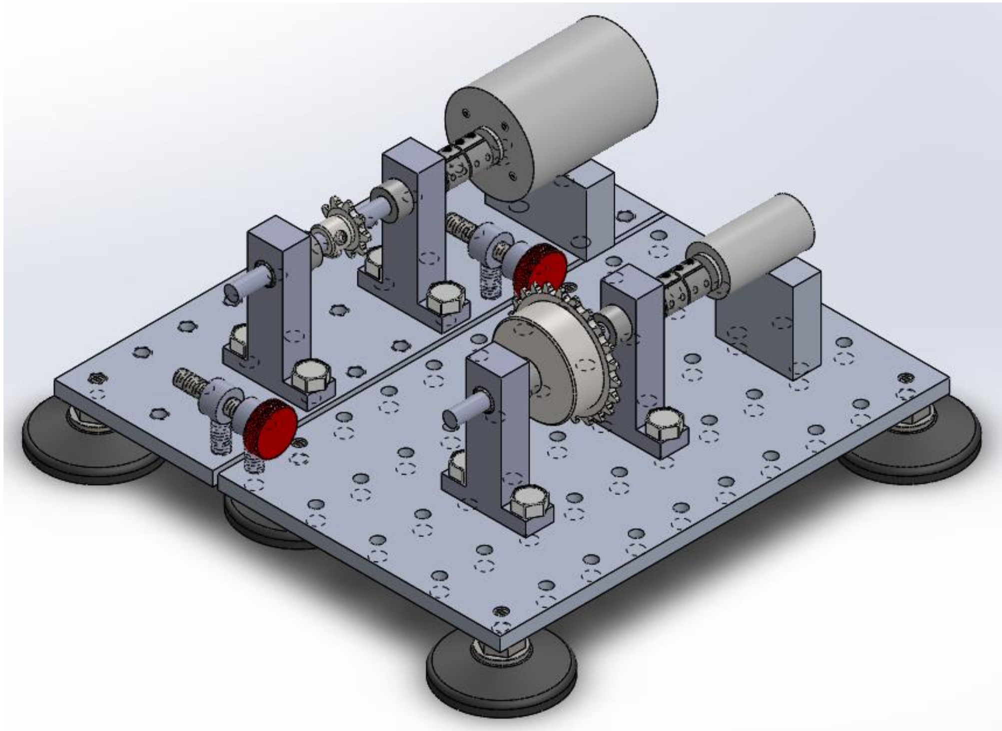


Figure 23: Machine components test with chain assembly.

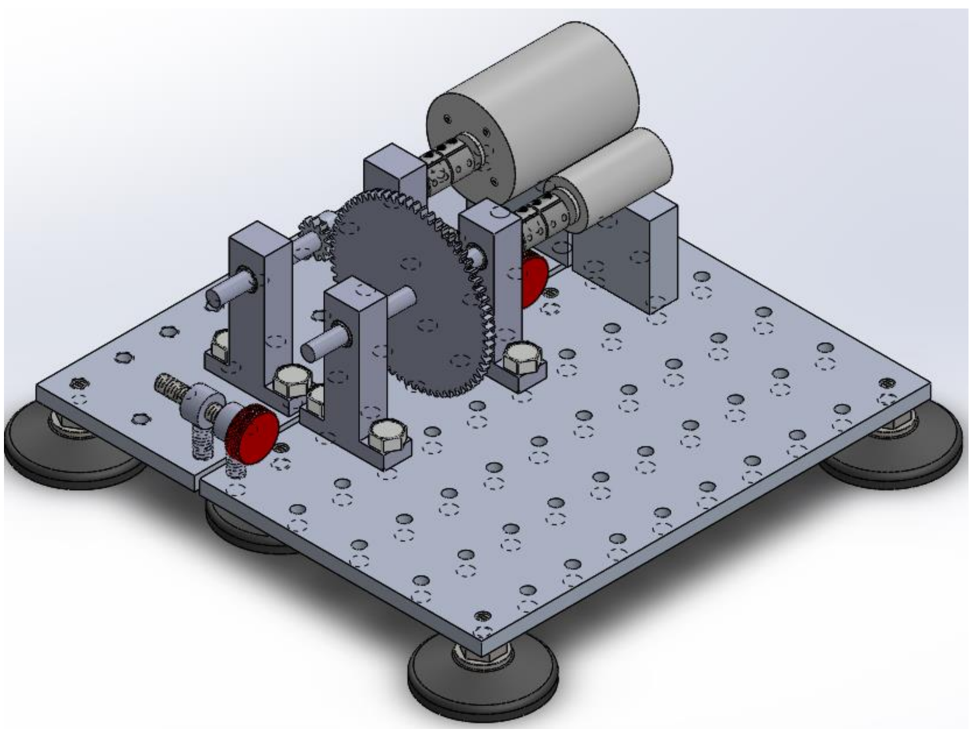
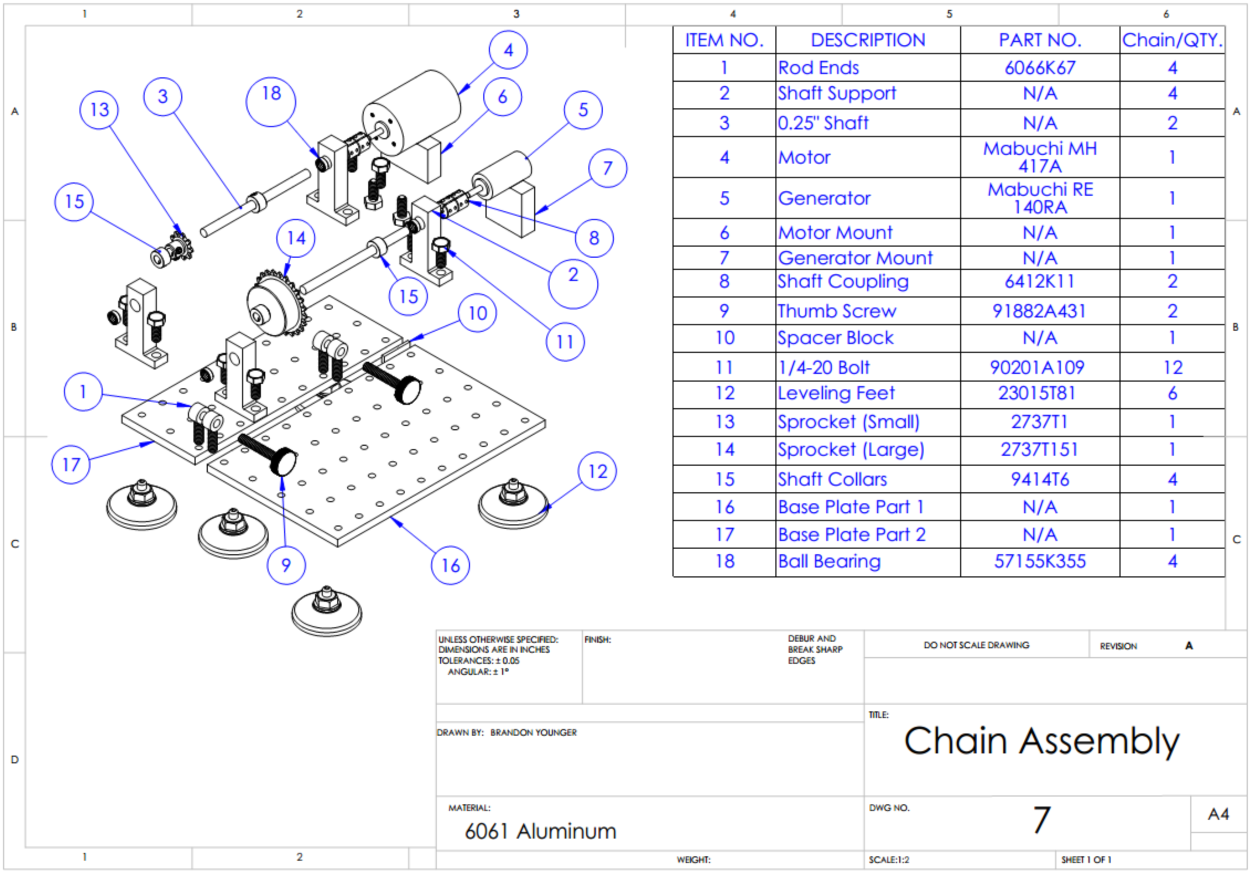


Figure 24: Machine components test with gear assembly.



ITEM NO.	DESCRIPTION	PART NO.	Chain/QTY.
1	Rod Ends	6066K67	4
2	Shaft Support	N/A	4
3	0.25" Shaft	N/A	2
4	Motor	Mabuchi MH 417A	1
5	Generator	Mabuchi RE 140RA	1
6	Motor Mount	N/A	1
7	Generator Mount	N/A	1
8	Shaft Coupling	6412K11	2
9	Thumb Screw	91882A431	2
10	Spacer Block	N/A	1
11	1/4-20 Bolt	90201A109	12
12	Leveling Feet	23015T81	6
13	Sprocket (Small)	2737T1	1
14	Sprocket (Large)	2737T151	1
15	Shaft Collars	9414T6	4
16	Base Plate Part 1	N/A	1
17	Base Plate Part 2	N/A	1
18	Ball Bearing	57155K355	4

Figure 25: Machine components test, exploded chain assembly with bill of materials.

Detailed drawings of the designed components can be found in Appendix K and exploded assembly drawings of the setups are in Appendix L.

Results of Supporting Analysis

A failure analysis on the shaft was performed in order to validate that it would work. A 0.25 inch shaft was chosen prior to the analysis. There are many reasons for choosing a quarter inch shaft prior to the analysis. One reason is that it was very easy to find different components that worked with a quarter inch shaft. Another reason is that a quarter inch shaft seemed like a reasonable size given the magnitude of the project. The design does not deal with large forces so it made sense to use the smallest standard size shaft that we could find. Another positive to using a small diameter shaft is that we save money on material cost. It is also easy to upgrade to a stronger material without a large increase in price.

In order to perform the analysis we had to assume a stall torque. Dr. Schuster was able to provide some sample motors for testing, from which a stall torque of 0.2 Nm was assumed to be reasonable for the analysis. For the analysis the shaft was chosen to be made out of 1018 steel. The failure analysis was performed on both the spur and worm gear subassemblies. Since both gear assemblies had a small pitch diameter of 0.5 inches the reacting forces would be greater than the other assemblies. The detailed analysis can be found in Appendix I. A summary of the results can be found in Table 2. The results of the analysis suggest that a 0.25 inch diameter shaft is more than strong enough to handle the assumed stall torque of the motor.

Table 2: Results of analysis.

Shaft Components	Von Mises Stress (Mpa)	Safety Factor	Max Deflection (in)
Spur Gear	20.26	15.3	0.00032
Worm Gear	31.8	9.74	0.00137

Safety Considerations

According to the United States Department of Labor, Occupational Safety & Health Administration Section 1910.212(a)(3)(ii), for guarding rotating machinery, "The point of operation of machines whose operation exposes an employee to injury, shall be guarded." ; therefore, we are considering making a polycarbonate casing that would cover the board and be secured with magnets. Additionally, there are precautions students must be made aware of. Appendix J shows a hazard checklist to determine where safety may be a concern.

Students will be our target user for this product, therefore, safety is a major concern. To address safety, we will include a safety list in the lab instructions. This list will tell students that long hair must pulled back and long sleeves must be rolled back to prevent hair and clothing from getting caught in the moving components. The following shows what may be included in the beginning of the lab:

Safety Checklist

1. Long hair must be pulled back.
2. Long sleeves must be rolled up.
3. Safety glasses must be worn at all times.
4. Turn motor off, and wait until all components stop before rearranging components.

In addition to the lab manual, stickers with the image in Figure 26 may be placed on the boards to remind students of safety requirements.

Figure 26: Attached sticker for safe use [13].

Additionally, to consider the safety of the product design, a Failure Mode Effect Analysis (FMEA) chart was created. This can be found in Appendix G. With the FMEA, we found all the potential failure modes of our design and their effects and consequences. Afterwards, we rated the occurrence and criticality to determine what our main safety concerns will be. For ranking we used the following scales seen in Tables 3 and 4.

Table 3: Severity rating.

Number	Severity
1	Negligible (no discernible effect)
4	Marginal (appearance or noise issue, not functional)
7	Critical (degradation of primary function)
10	Catastrophic (severe injury)

Table 4: Occurrence rating.

Number	Occurrence
1	Extremely Remote (unlikely to occur)
4	Remote (0.1% chance)
7	Possible (1% chance)
10	Probable (10% or greater chance)

With this analysis, we found the biggest design concern is stripping the threads in the board and in the fasteners. If this were to occur, the components could begin to detach during machine use. This leads to the risk of parts hitting students. Stripping of the holes can be caused by overuse of the board or misuse when attaching and detaching the fasteners. In response, we decided to choose a stronger material for the board in addition to supplying extra fasteners. Students will be notified to not use screws that appear stripped.

More failure modes are described in the FMEA chart which will guide our testing plans. Most solutions involve using lower forces or lubrication. With the low speeds and forces, most standards do not apply. We do not believe our product will pose a high risk, however, more analysis will need to be done during testing to see how safe our product actually is.

Material Selections

Several materials were considered for the base of the Machine Components Test including perforated hardboard, solid wood, and aluminum. The forces that components would be subject to would strip the wood if it were used as the base. As a result 6061 aluminum was chosen as the best material for the board due to its strength and relatively low cost.

Many of the standard parts come in either metal or plastic. Students already get experience with plastic parts using the LEGO Technics. Therefore, we chose to use metal parts as they are more “realistic” and give students an opportunity to use a different material. In deciding what metals should be used, we chose the cheapest option for each component. In most cases the cheapest metal was 1018 steel.

The shaft supports, and motor mounts will be made 6061 aluminum because it is light, relatively cheap and will be strong enough to support the shafts and bearings.

Manufacturing

Our plan for construction is to buy all of the components and material from the appropriate vendors listed in Table 5. We plan on ordering the parts May 8th, allowing two weeks for delivery. The base plate will then be manufactured on the CNC machine in the Mustang '60 machine shop by Brandon Younger. This part of the manufacturing will take three hours and is planned to be completed by May 15th.

Additionally, the shaft supports will also be CNC machined in the Mustang '60 machine shop. We will start with standard rectangular stock and machine 12 housings by May 22. This process should take up to six hours.

Once all of the components have arrived and parts have been made, assembly will be done based on the assembly drawing in Appendix L at the Cal Poly Machine Shop. The tools needed will be wrenches and a hydraulic press and the process will take one hour. We hope to finish this by May 29th.

Maintenance and Repair

Maintenance for our product involves proper care of the components. This includes proper storage in the provided bins. Components should be stored in a dry environment. Lubrication may be used in the gearing to prevent overheating. Any fasteners with stripped threads must be disposed of as they will risk student safety if used. Additional fasteners will be provided. Students must read the lab manual for correct use of the product to ensure maximum product life.

Most of the Machine Components Test will be standard parts that can easily be purchased using the information found in the bill of materials in the detailed drawings. If a component breaks or is worn out, users may go to the website indicated in the references and search the part number. Smaller parts such as the threaded fasteners and shaft supports will be the first to break or get lost, therefore extra parts will be supplied.

The board and shaft supports are not standard parts, and will therefore be machined in house. The dimensions for machining the board and the supports are included in this report. In addition G-code for CNC machining this parts will be included in the final design report. If more boards or shaft supports are desired, or existing pieces have failed, the manufacturing instructions can be given to the shop techs in one of Cal Poly’s machine labs.

Cost Analysis

We will be doing the manufacturing and assembly ourselves, so the budget is mostly concentrated in the materials. Mechanical components can be costly, especially in the smaller quantities that we need (enough for one lab section). Originally our budget was $300 per product; however, we plan to distribute more complex components that each lab section can share. The greater variety of components, the more interesting and educational our product will be. Therefore, the average cost of each product will be slightly higher than originally anticipated. Additionally, some funds must be allocated to prototyping and testing. In Table 5 below, a breakdown of the material costs is illustrated. Table 6 gives the contact information for each vendor. Table 7 includes additional costs for the project.

Table 5: Bill of materials cost analysis.

Component	Vendor	Material	Part #	Quantity	Cost/unit	Cost ($)
Big spur gear	SDP	Aluminum	S1086Z-024A066	1	47.42	47.42
Small spur gear	SDP	Aluminum	S1086Z-024A012	1	16.61	16.61
worm gear	SDP	Bronze	S1C86Z-P064B060Q	1	39.84	39.84
worm	SDP	Steel	S1D96Z-P064SQ	1	20.72	20.72
big sprocket	McMaster	Steel	2737T16	1	12.58	12.58
small sprocket	McMaster	Steel	2737T1	1	8.68	8.68
chain	McMaster	Steel	6261K171	1	5.14	5.14
big pulley	SDP	Polycarbonate/Brass insert	A 6T19-682508	1	9.96	9.96
small pulley	SDP	Polycarbonate/Brass insert	A 6T19-232508	1	6.45	6.45
belt	McMaster	Nitrile-Coated Nylon	6082K51	1	15.75	15.75
ball bearings	McMaster	Steel	57155K355	4	6.00	24.00
shafts	Online Metals	Steel	.25" RD CD 1018 48" LG	1	1.67	1.67
Base Material	Online Metals	Al 6061-T651	.25" PL 8"x8"	2	9.93	19.86
Bearing Housing Material	Online Metals	AL 6061-T6511	2.5"X2.5" X 1'LG	1	33.80	33.80
Rod Ends	McMaster	Steel	3798K35	4	6.24	24.96
Impact Resistant Guard	McMaster	Clear Polycarbonate Sheet	12"x12" x .0625 THK	5	4.83	24.15
Leveling Mounts	McMaster	Steel/Plastic	23015T81	2	1.83	3.66
Thumb Screw	McMaster	Steel	91185A507	1	9.57	9.86
Shaft Collars	McMaster	Steel	9414T6	4	0.98	3.92
Display Driver LM3914	Sparkfun	electronics	COM-12694	4	1.95	7.80
LEDs	Sparkfun	electronics	COM-12903	1	2.95	2.95
Protoboard	Sparkfun	electronics	PRT-08811	1	2.95	2.95
Spring Washers	McMaster	Steel	90073A029	4	2.02	8.08
Shaft Couplings (Final)	McMaster	Aluminum	9861T427	2	37.44	74.88
Project Box	Sparkfun	plastic	WIG-0863	1	5.98	5.98
Leather Belt	TJ Maxx	leather	NA	1	10.00	10.00
Motors	All Electronics	metal	DCM-465	2	2.75	5.50
Bearing Housing Bolts	McMaster	Alloy Steel	92220A183	12	9.15	9.15
Motor Bolts	McMaster	Alloy Steel	91290A073	4	8.20	8.20
Thumb Screw Nuts	McMaster	Steel	95479A115	1	5.39	5.39
Thrust Bearing	McMaster	Steel	6655K13	4	2.21	8.84
Shim Stock	McMaster	Plastic	9513K11	1	3.32	3.32
					Total Cost	460.23

Table 6: Vendor contact information

Vendor	Website	Phone Number	E-Mail
SDP	www.sdp-si.com/estore	1-800-819-1900	SDP-SIsupport@sdp-si.com
McMaster-Carr	www.mcmaster.com	562-692-5911	la.sales@mcmaster.com
Online Metals	www.onlinemetals.com	1-800-704-2157	sales@onlinemetals.com

Table 7: Total costs

Prototype	$460
Testing	$150
5 Models	$2,300
Total	$2,450

Product Management Plan

Appendix E displays a Gantt chart of how our project will be divided between team members and what parts are left to complete. Green check marks indicate the job has been completed. For jobs not yet finished, the blue bars indicate the length of a specific job and the dark blue line inside the bar signifies how much of the job has been completed. Furthermore, each job has a list of names for the individual(s) in charge of the job. The Gantt chart is a helpful tool to keep the team on track with the many aspects of the project, and to record our progress. The next milestones in our project include a final concept review, a progress report, the Senior Project Expo, and a final project report.

The major jobs of this project have been split up in the following manner. Our main contact and direct connection to our sponsor is Brandon Younger. He is in charge of sending our sponsor all reports and other necessary information. By contacting Brandon, our sponsor is contacting our entire team. Manufacturing considerations will also be handled by Brandon Younger. As a machine shop technician in Cal Poly's machine lab, his knowledge of machines and manufacturing will be utilized. He will also have primary responsibility for prototyping. This job involves making a scale model in SolidWorks and editing the design drawings.

Information gathering will primarily be done by Carlos Padilla. This includes gathering information for the background segment of the report. The bulk of the analysis will also be Padilla's responsibility. He will make calculations based on our design ideas to determine whether or not our ideas will be possible as well as to delegate calculations to other team members in order to make the job quicker. Purchasing will be handled by Carlos Padilla as well. Many websites offer similar products, so it is Padilla's responsibility to find which sources will be the most cost effective, and produce a cost analysis based on his findings. Once part lists are approved, Padilla will purchase the parts using project funding.

Lauren Romero is responsible for the documentation of the project. Her job will be to edit reports and be in charge of formatting. Additionally, she is in charge of updating the Gantt chart and product management as the project progresses. She has the role of recorder and will take notes during sponsor meetings and make sure everyone can get the information. Additionally, she will be in charge of safety, making sure the team takes proper precautions and that the final product is safe for student use. Finally, Lauren Romero will be handling testing plans and design revisions. Romero will develop testing apparatuses, and record data from various tests to ensure accuracy and safety with the product.

Chapter 5: Product Realization

Manufacturing Processes Employed

CNC

The shaft supports, base plate and the motor mount were made using the CNC. The reason for making these parts with the CNC is because they would take much longer if made by hand. The shaft supports would require a long set up time and attention to detail to make. The mechanical breadboard also requires many shaft supports. If made by hand, they would take many man hours to complete. The base plate contains several holes that need to be drilled and tapped with high accuracy relative to one another. If made by hand, the tolerances might stack up and the shaft supports may not fit properly on the board. Finally, the motor mount may be made by hand but it is still easier, more efficient, and faster to make them using the CNC machine.

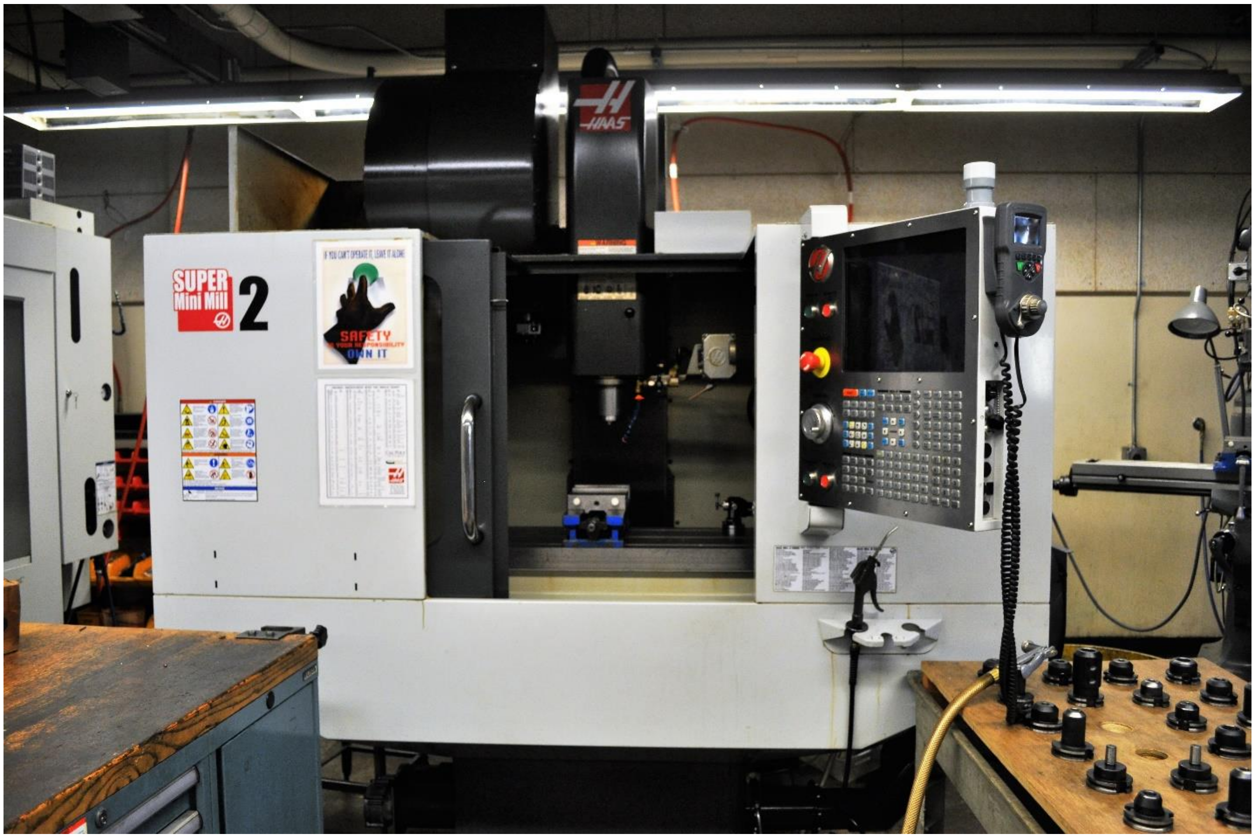


Figure 27**: This is the CNC that Brandon used to make the parts.**

Mill

The mill was used to make the spacer for the motor mount and the shaft supports. These are the spacers that raise the shaft support and motor mount for the worm gear subassembly. The spacer is easily made by hand using a mill because of its simple geometry.

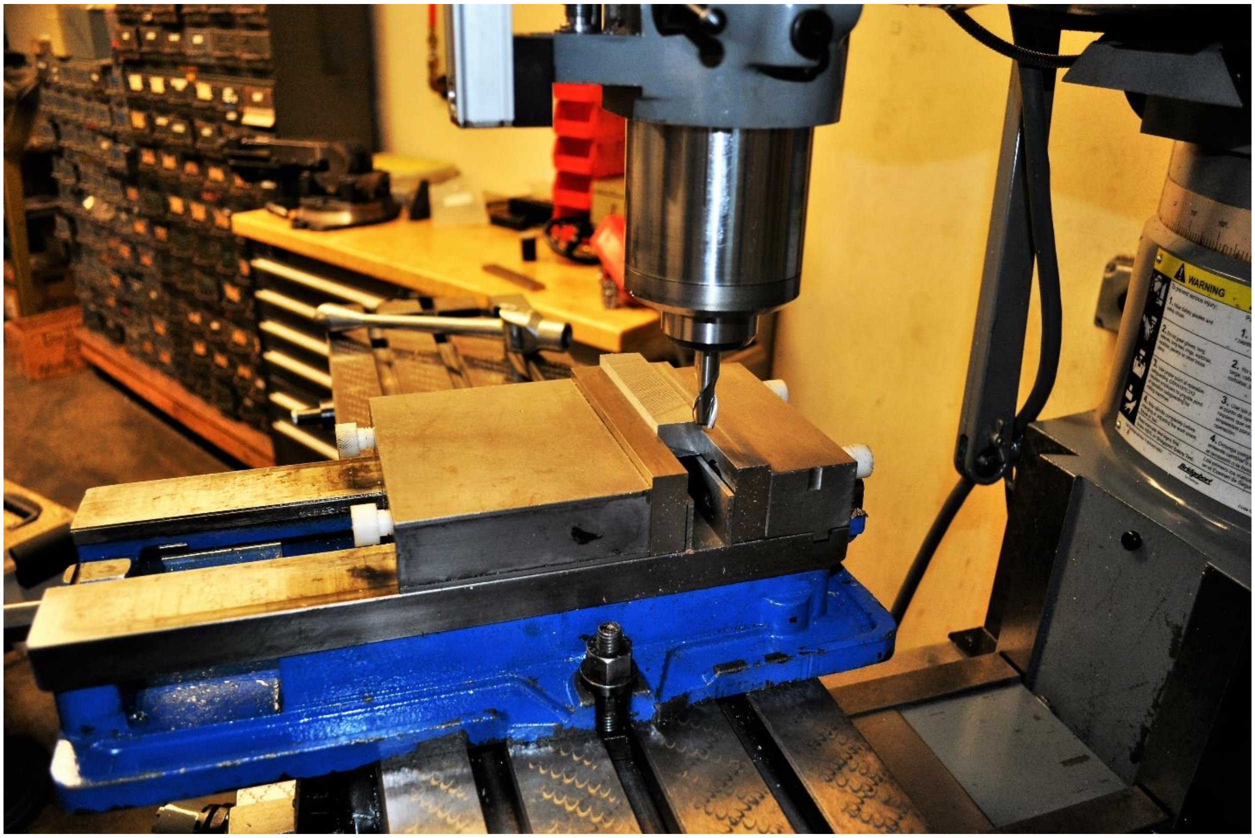


Figure 28: This is a picture of the spacer being made in the mill.

Lathe

The lathe was used to make the brake drum for the band brake dynamometer. The brake drum has a simple round geometry which makes it a perfect candidate for the lathe. The lathe was also used to make temporary shaft couplings for testing the mechanical breadboard with various subassemblies.

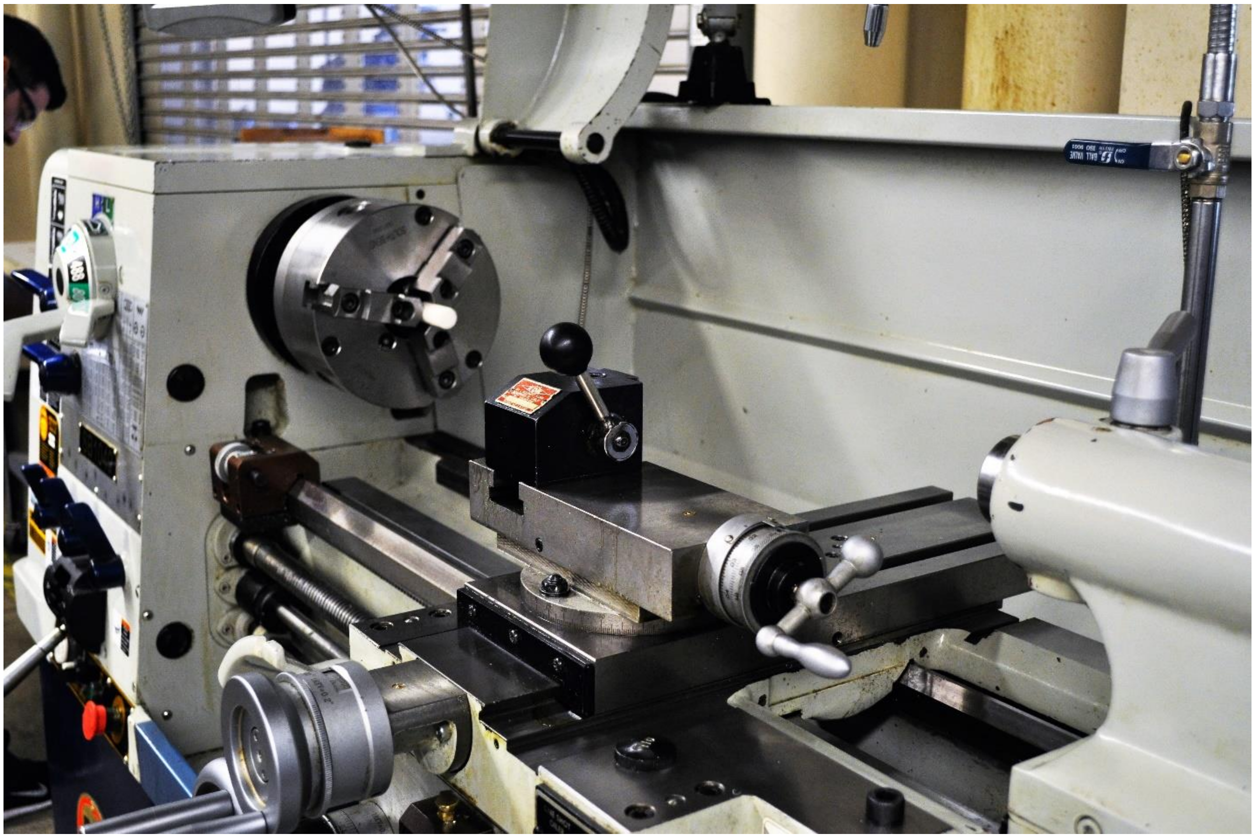


Figure 29**: Temporary shaft couplings were made using delrin plastic on the lathe.**

Prototype Differences

The differences between the prototype and the final design will be minimal. There are only three things that will be different from the prototype and the final design. The first is the shaft couplings, for most of the testing we used temporary shaft couplings made of delrin plastic. The final design will have aluminum shaft couplings that were ordered from McMaster Carr. The second difference will be the prototype polycarbonate cover (not shown) will not have the safety switch circuit as discussed for the design. The third is that the light up circuit that is powered by the generator will not have a cover for the prototype.

Future Manufacturing Recommendations

In the future we recommend making the CNC parts in larger batches to optimize the use of the machine. To make the spacer more efficiently we recommend machining the aluminum bar to the correct height first, making the correct hole pattern, then cutting the aluminum to length. Implementing these two recommendations will help reduce the manufacturing time and cost.

Chapter 6: Testing

Motor

The motor works nicely with the system. It is a Mabuchi RS-385PH and has motor characteristic as shown in Appendix N. It should be noted that the motor is directional and must be connected with the positive terminal connected to the terminal on the motor marked by the red dot.

Spur Gear Assembly

The spur gear assembly was one of the easiest to test. It was easy to put together and did not generate any significant concerns. The first time the spur gear assembly was tested it was done without thrust bearings. Although there should be no thrust, it seemed that when the motor was turned on the vibrations of the assembly would thrust the shaft toward one of the shaft collars. This created a significant amount of friction and slowed the motor down considerably. In order to avoid this we added the thrust bearings in the spur gear assembly. With the thrust bearings on, the system worked more efficiently. The mesh of the gears can also easily be tuned with the thumb screws. When the two base plates touch the gears are slightly under meshed. As the thumb screws are tightened the mesh can be optimized and even over meshed.

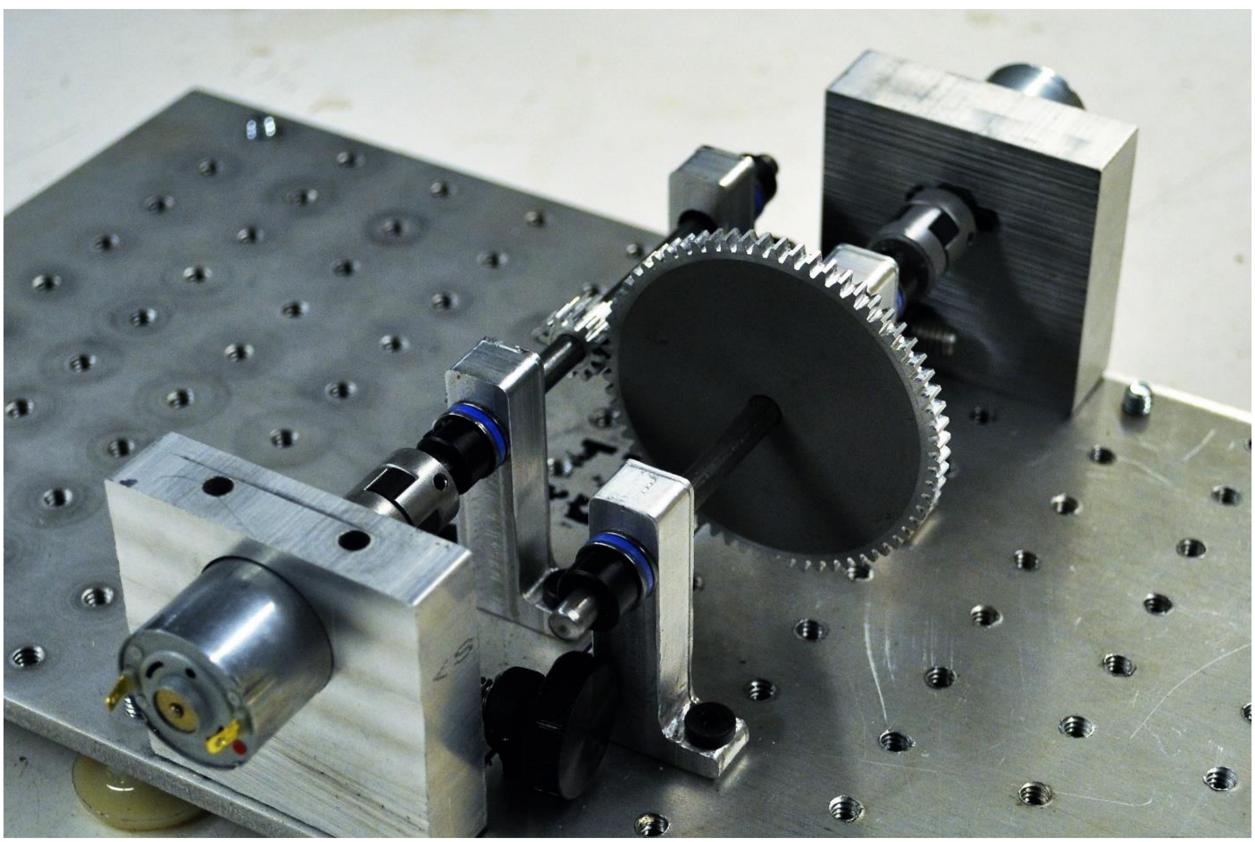


Figure 30: This is a photo of the complete prototype spur gear assembly.

Chain and Sprocket Assembly

The chain and sprocket assembly was the first subassembly to be tested. This assembly was sensitive to misalignment of the sprockets. The sprockets needed to be iteratively adjusted until the system rotated freely. This system was tested without the use of thrust bearings. There was no apparent difference when the thrust bearings were installed. This system was also sensitive to chain tension. It is noisy when the chain is slack and the shafts want to stop rotating if the chain is too tight.

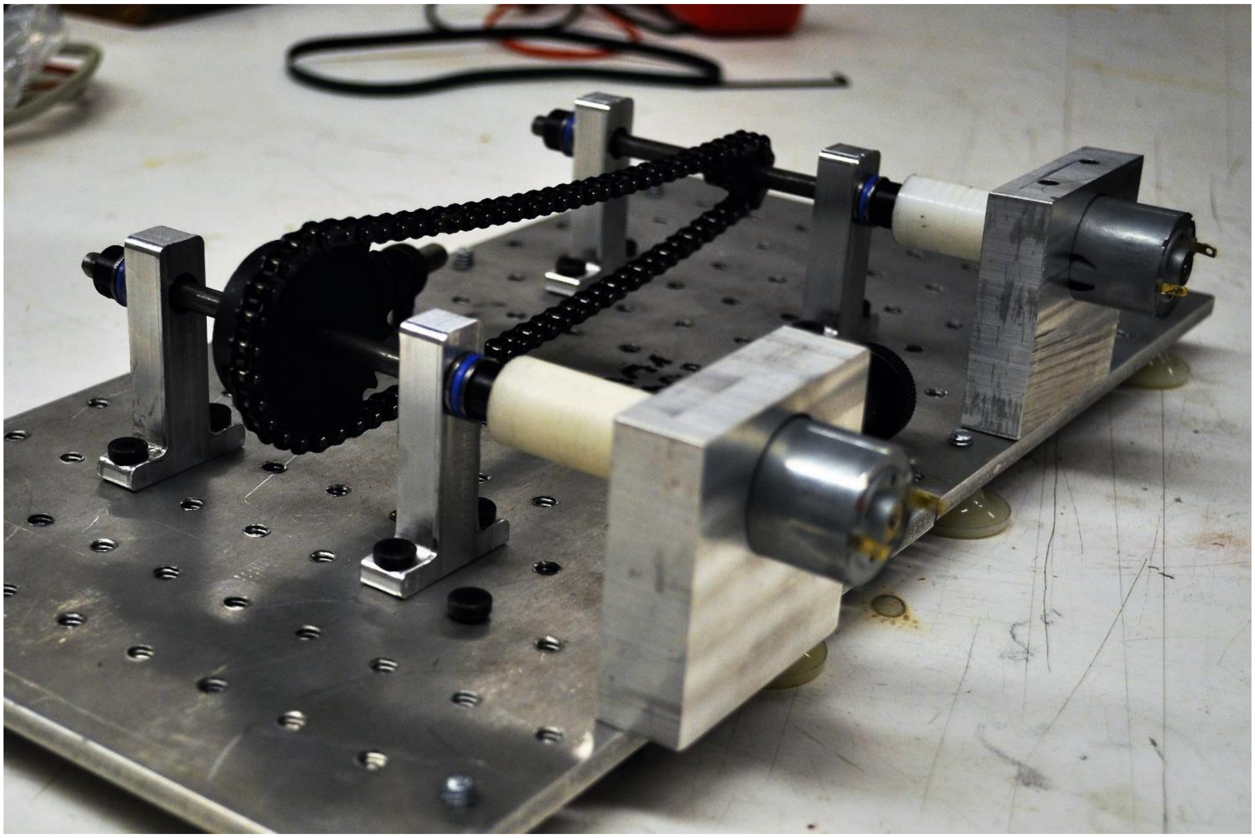


Figure 31**: Picture of the chain and sprocket assembly**

Flat Belt and Pulley Assembly

The flat belt assembly was the easiest to install. The pulleys have to be aligned so that the flat belt does not come off, but other than that it seemed to work nicely. The tension of the belt has to also be optimized for performance. If the belt is loose then it will slip.

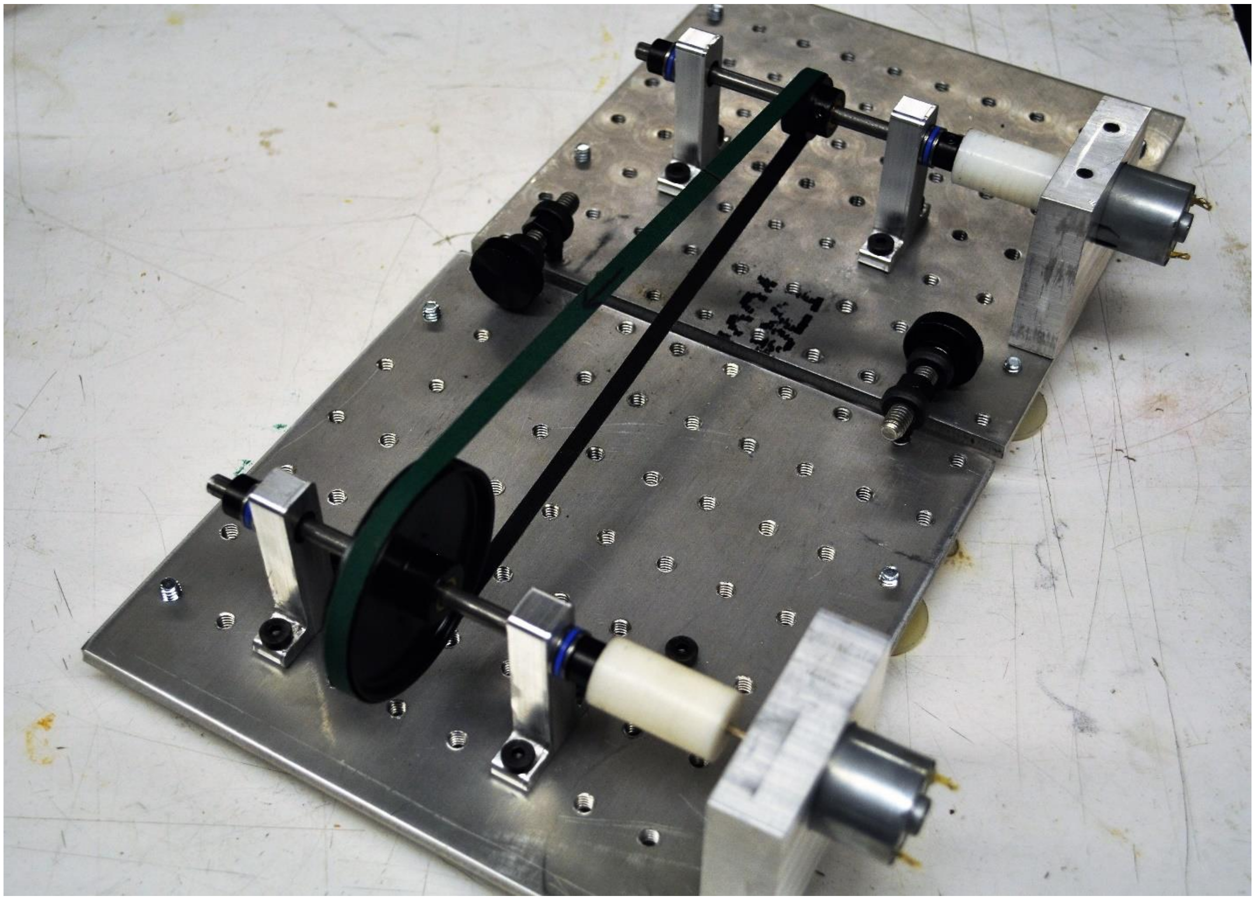


Figure 32: This is the completed belt and pulley assembly. Note that temporary shaft couplings are shown in this picture. Also not the configuration of the motors.

Worm Gear Assembly

This was the most difficult assembly to construct. A special spacer had to be made in order to make this assembly work. The spacer is manufactured to be a littler larger than the correct height for the gears so that the gears are under meshed when the screws first begin to press against the shaft support. As the screws are tightened the meshing of the worm and worm gear can be adjusted and even over meshed by tightening the screws too much.

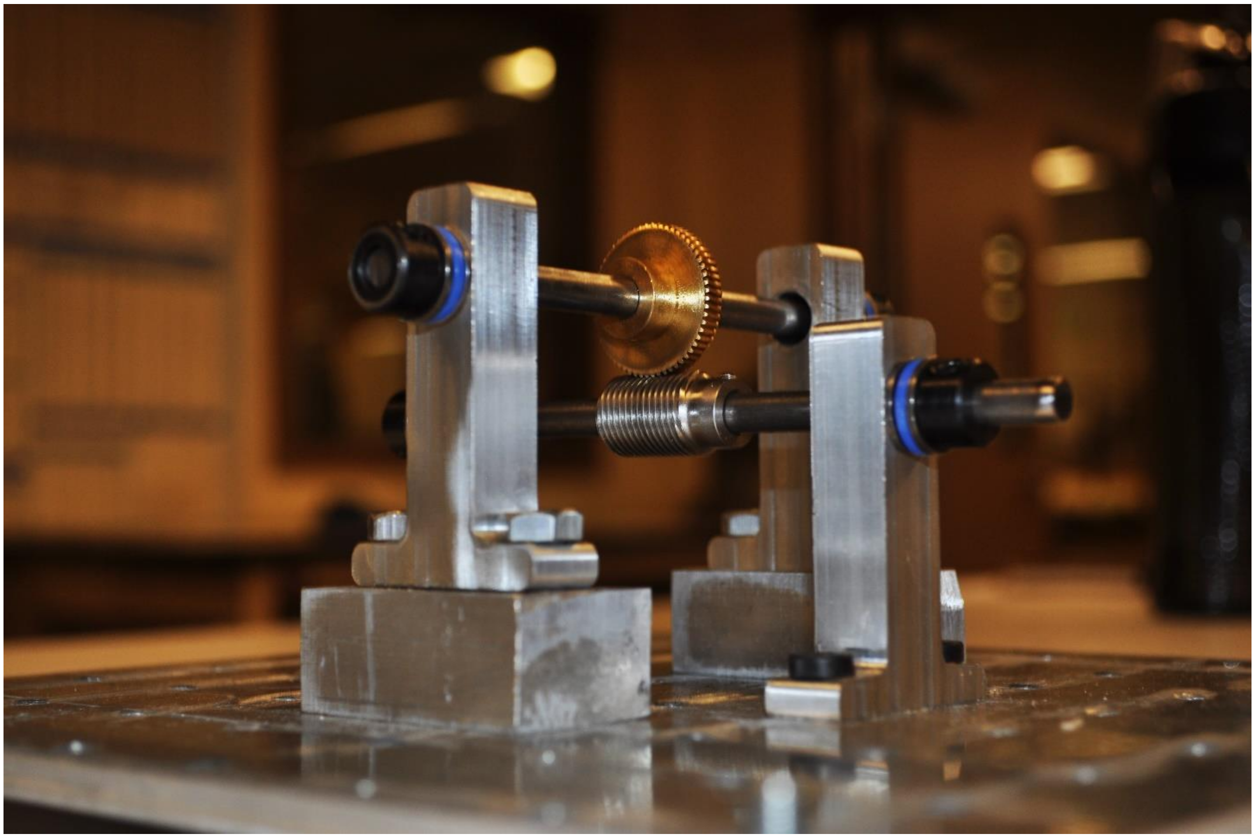


Figure 33: This is a picture of the worm gear assembly without the motor or the generator.

Band Brake Dynamometer

The band brake dynamometer test set up worked better than expected. When the test data was compared to the published motor data, the torque that we calculated was within 2% of the published data. The speed of the motor on the other hand was not as consistent with published data, but it was still within about 12%. In order for the band brake calculations to be valid the motor must be spinning in the direction as shown in Appendix F. There are two critical components to calculating the torque of the motor correctly. The first is the angle of wrap of the belt on the brake drum. This can be easily calculated because the geometry of the dynamometer is known. The second is the friction coefficient between aluminum brake drum and the leather belt. Testing can be conducted to calculate the friction factor or, as in our case, assumed to be 0.4.

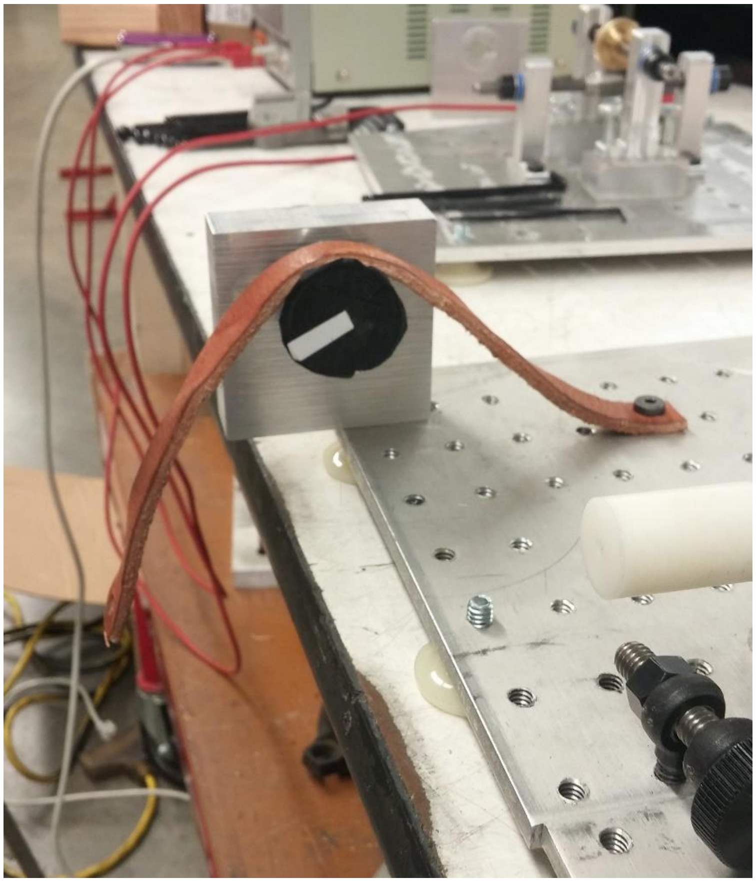


Figure 34: This is a photo of the band brake dynamometer configuration without a hanging weight.

Generator and System Power Loss

The power losses in the system seem to be pretty large. Even with the spur gear system there was a huge difference in the power in versus the power out. The alignment of the drive shafts with the motor shaft seems to be important. With the prototype shaft couplings that are made of delrin plastic it was observed that if there was misalignment, the output power was significantly less versus if we forced the shafts to be in close alignment. The power is measured by a multimeter. Voltage and Current can both be measured using the multimeter. This allows the user to directly compare the power in versus the power out. When measuring the current being generated it was observed that the system as a whole slowed down. Measuring the voltage did not have this effect. Due to this effect, the current measured by the multimeter might not be accurate. Further testing needs to be done in order to validate the accuracy of the current measured by the multimeter.

Circuit

There are some issues that need to be resolved regarding the circuit. The circuit works on its own, but when the power source and the generator output are connected to the circuit it does not function properly. The circuit needs to be adjusted in order to get the desired performance.

Set-Up Time
While testing the time to set up the mechanical breadboard it was evident that subassemblies are required in order to speed up the process. It was found that it takes 6 minutes to set up the base plate with the rod ends and feet. It also takes 10 minutes to set up the chain and sprocket assembly. With the chain and sprocket assembly and the base plate pre-assembled it only took 2.5 minutes to get the mechanical breadboard ready.

Chapter 7: Conclusion and Recommendations

As this project comes to a close it should be noted that the final prototype will be about 90% complete. There are a few things that need to be iterated and retested in order to finalize this project. The system as a whole works very well. The small nuances of each assembly will give students a chance to understand different mechanical systems on a deeper level.

This project did cost more than expected. The target goal was to make a complete system with a budget of only $300. This project cost more than that, but there are a few ways to minimize the cost. One way is to share some of the subassemblies with different groups. This divides the cost of a subassembly over a number of mechanical breadboards. Another way to minimize cost is to use more plastic parts where metal is not needed. For example, the metal gears can be replaced with plastic gears. The initial reasoning behind metal gears was to give students a more “realistic” experience with mechanical components.

There are a few things that need to be addressed in order to successfully implement the mechanical breadboard in lab. The first thing is the circuit needs to be modified to get the desired output. The circuit it not a critical component of the lab, but it does provide fast visual feedback to the user. A critical component of the lab is the ability to measure the power generated by the mechanical components. Power generation measurement needs to be tested further to access its accuracy. While testing the motor generator it was noted that measuring current using a multimeter slowed the system down versus measuring the voltage. This needs to be resolved before the mechanical breadboard can be used successfully in lab.

During our testing we noticed a lot of vibrations. Currently the design does not address a way to reduce mechanical vibrations. The vibrations can be loud and distracting at times. An improvement that can be made is to fix the feet that screw into the base plate since the feet screw in to the base plate and have a tendency to move in or out of the plate. This leads to tilting and uneven mating of the two plates. The rod ends and nut combination that is used to adjust the gap between the two plates can also be improved. The current design works, but it can made to be more user friendly. There may also be a purchasable assembly that performs the desired action, but we could not find one. Lastly, the safety cover can also be improved. The prototype is just a box that surrounds the mechanical breadboard assembly. A circuit can be integrated with the safety cover that would prevent the motor from running if the cover is not positioned correctly. These are just a few things that may be improved during the next iteration of this project.

Appendix A: References

[1] Beardsley, R., & Pringle, C., "Machine Design Lab: Using Automotive Transmission Examples to Reinforce Understanding of Gear Train Analysis: American Society for Engineering Education", Asee.org, 2015. [Online]. Available: http://www.asee.org/public/conferences/1/papers/838/view. [Accessed: 03- Feb- 2015].

[2] Marra, S., "Development and Evolution of a New Mechanical Design Laboratory Course: American Society for Engineering Education", asee.org, 2014. [Online]. Available: http://www.asee.org/public/conferences/32/papers/9027/view. [Accessed: 03- Feb- 2015].

[3] "Cornell University Law School: 29 CFR 1910.219 - Mechanical power-transmission apparatus". [Online]. Available: http://www.law.cornell.edu/cfr/text/29/1910.219. [Accessed: 02- Feb- 2015].

[4] Mikes, J., "The Analysis and Development of a Mechanical Breadboard Structure", http://www.dtic.mil, 2006, [Online]. Available: http://www.dtic.mil/dtic/tr/fulltext/u2/a461564.pdf. [Accessed: 25-Feb-2015].

[5] Van, D., Ward, D., "Designing a Mechanical Breadboard for Effective Teaching of Engineering Statics", asee.org, 2004. [Online]. Available: http://search.asee.org/search/fetch?url=file%3A%2F%2Flocalhost%2FE%3A%2Fsearch%2Fconference%2F28%2FAC%25202004Paper115.pdf&index=conference_papers&space=129746797203605791716676178&type=application%2Fpdf&charset=. [Accessed: 25-Feb-2015].

[6] Mountain, J.R.; Hibbeler, L.C., "Hands-On Process Control Experiences: A Curriculum Integration Experiment," *Frontiers in Education Conference, 36th Annual* , vol., no., pp.7,12, 27-31 Oct. 2006

[7] "Rebuilding the Makita Battery Pack", Kichline.com. [Online]. Available: http://chuck.kichline.com/fixit/makita/default.htm. [Accessed: 03- March- 2015].

[8] "Spur Gears with a chain and tensioner Version 2", Youtube.com, 2015. [Online]. Available: https://www.youtube.com/watch?v=NjTmcUm1QFI. [Accessed: 03- March- 2015].

[9] "Lawler Gears", Lawler Gear Corp., 2015. [Online]. Available: http://www.lawlergear.com/PageContent/services.html. [Accessed: 03- March- 2015].

[10] "Makita 6406", Tool Parts Pro, 2015. [Online]. Available: http://www.toolpartspro.com/makita-parts/makita-6406-parts.html. [Accessed: 03- March- 2015].

[11] MJER, “Kinetic Sculpture: “Sine Machine””, Instructables, 2015. [Online]. Available:http://www.instructables.com/id/Kinetic-Sculpture-Sine-Machine/. [Accessed: 03- March- 2015].

[12] Ehud Riven, “Amazing Steampunk Wine Bottle Opener”, Walyou, 2015. [Online] Available:http://walyou.com/steampunk-wine-bottle-opener/?utm_source=feedburner&utm_medium=email&utm_campaign=Feed:+TheWalyouBlog+(The+Walyou+Blog). [Accessed: 03- March- 2015].

[13] “Warning Safety Label: Moving Parts Can Crush And Cut, Keep Hands Clear While Operating Machine”,My Safety Labels, 2015. [Online] Available:http://www.mysafetylabels.com/Warning-Labels/Moving-Parts-Can-Crush-Safety-Label/SKU-LB-0356.aspx. [Accessed: 09- April- 2015].

Appendix B: Quality Function Development (QFD)

House of Quality

The house of quality is a structured approach to transform qualitative customer needs and requirements into quantitative engineering specifications to ensure the "voice of the customer" is heard. It does this by displaying the relative importance of each customer demand into a more measurable quantity representing design quality.

In our house of quality, shown on the following page, we have our three customers in the far left most columns. The three customers that we are going to satisfy with our device are Dr. Schuster, intermediate design students, and the manufacturers of these machines. The next column over has a list of the customer requirements. In the columns for each customer we rated how important each criterion was to our three customers. Overall, each requirement ended up being about equal due to each customer having different interests.

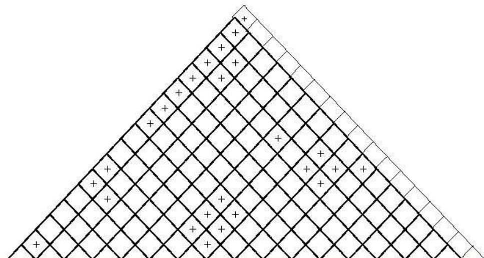
The column headers of the middle section on the house of quality are populated with more specific, measurable engineering specifications to fulfill the desired customer needs. The rest of the middle section has symbols that represent what degree the customer requirements are related to the engineering specifications. The legend for these symbols is shown in the upper right hand corner of the diagram. This helps the QFD to calculate which project parameters are most important. The "roof" of the house of quality serves a similar purpose except it relates the engineering specifications to each other instead of to customer requirements. This house of quality will serve as a powerful tool in making sure all customer demands are met.

QFD: House of Quality
Project:
Revision:
Date:

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

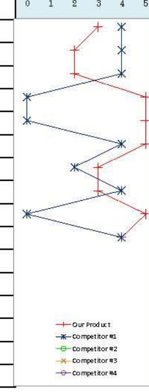
Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



WHO: Customers

Row #	Relative Weight	Dr. Schuster	ME 329 Students	Manufacturer	Technicians	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit)	Our Current Product	Competitor #1: *Lego Design Project*	Row #
1	4%	8	5	5	0	9	Price	3	4	1
2	9%	8	8	8	5	9	Must be supported by cabinet	2	4	2
3	9%	8	8	8	5	9	Must fit in cabinet	2	4	3
4	11%	10	9	7	9	9	Includes real mechanical components	5	0	4
5	4%	10	8	1	0	9	Measureable power transmission efficienc	5	0	5
6	8%	10	8	6	5	9	Configruable components	5	4	6
7	11%	10	5	10	9	9	Easily manufatured	3	2	7
8	8%	10	10	7	3	9	Safe for students	3	4	8
9	4%	10	8	1	0	9	Measurable motor characteristics	5	0	9
10	8%	10	10	3	5	9	Ease of use	4	4	10
11	6%	10	10	6	0	9	Able to change alignment/position			11
12	10%	8	3	10	8	9	Easily reproduce			12
13	4%	10	10	1	0	9	Understand how components affect performance			13
14	4%	10	10	1	0	9	Understand how position affects performance			14
15	0%									15
16	0%									16

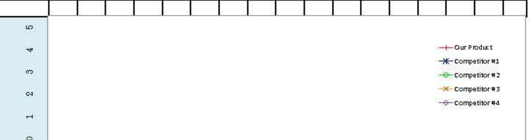
NOW: Current Product Assessment - Customer Requirements



HOW: Engineering Specifications

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Direction of Improvement	▼	▼	▼	▼	▼	◇	◇	▼	▼	▼	◇	◇	▼	◇	◇	▼	▲
Row #	Cost	Weight	Width	Height	Length	Types of Gears	Types of belts	Set up time	Assembly time	Machining time	Motor Measurable Outputs	Measured Transmission outputs	Pinch points	Types of bearings	Types of chains	% of Standard parts	Improvement on quiz
1	●		○	○	○	●	●				○	○	○	●	●	●	▽
2		●	○	○	○	○	○							○	○		
3		○	●	●	●	○	○							○	○		
4	●	○				●	●	▽	▽	○				●	●	●	
5												●					
6	○					●	●	○	○	○				●	●		
7	●									●						●	
8													●				
9											●						
10								●									
11	○					●	●	○	○	○				●	●		
12	●									●						●	
13						●	●				●	●		●	●		○
14											●	●					○
15																	
16																	
HOW MUCH: Target	$200	20 lb	3ft	1ft	2ft	2	2	10 min	3hr	12hr	3	2	0	2	2	90	15%
Max Relationship	9	9	9	9	9	9	9	9	3	9	9	9	9	9	9	9	3
Technical Importance Rating	100	90	90	90	90	70	70	50	50	50	70	70	100	70	70	50	50
Relative Weight	8%	8%	8%														
Weight Chart																	

Current Product Assessment - Engineering Specifications



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Template Revision: 0.9 Date: 4/23/2010
Christopher Battles

Appendix C: Pugh Matrix

Pugh Matrix

Concept	1	2	3	4	5	6	7	8
Criteria								
A	D	S	S	-	-	-	-	S
B		S	S	+	-	+	-	-
C	A	-	-	+	-	+	-	-
D		+	+	-	+	+	+	+
E	T	+	-	-	+	-	+	+
F		S	-	+	-	-	+	-
G	U	-	-	-	-	-	-	+
H		-	S	+	-	-	-	-
I	M	+	-	-	+	+	+	-
J		+	S	S	-	-	-	-
K		S	-	+	-	-	+	-
L		-	S	+	-	-	-	-
M		+	+	-	+	+	-	+
N		+	+	-	+	+	+	+
O		+	+	+	+	-	-	S
Sum +	0	7	4	7	6	6	6	5
Sum -	0	4	6	7	9	9	9	8
Sum S	0	4	5	1	0	0	0	2

Concept Legend

Concept Number	Description
1	Legos (datum)
2	Mechanical Bread board
3	Machine teardown
4	Virtual Lab
5	Individual Component labs
6	Build power tool
7	Build kinetic sculpture
8	Rube Goldberg Design

Criteria Legend

Criteria Letter	Description
A	Price
B	Must be supported by cabinet
C	Must fit in cabinet
D	Includes real mechanical components
E	Measurable power transmission efficiency
F	Configurable components
G	Easily manufactured
H	Safe for students
I	Measurable motor characteristics
J	Ease of use
K	Able to change alignment/position
L	Easily reproduced
M	Understand how components affect performance
N	Understand how position affects performance
O	Durable

Appendix D: Decision Matrices

Methods of Attachment

Design Criteria	A	B	C	D	E	F	G	H	I
Weight	0.2	0.2	0.05	0.05	0.2	0.1	0.15	0.05	1
Alternatives									
Magnets	90	30	90	90	80	50	60	100	
	18	6	4.5	4.5	16	5	9	5	68
Threaded	90	70	80	95	95	90	90	100	
Fasteners	18	14	4	4.75	19	9	13.5	5	**69.25**
Clamps	70	70	60	100	80	70	70	100	
	14	14	3	5	16	7	10.5	5	60.5
Multiple Fixed	100	70	100	70	100	90	100	0	
Setups	20	14	5	3.5	20	9	15	0	66.5
Rod and Cotter	90	100	90	80	80	100	20	100	
Pin Assembly	18	20	4.5	4	16	10	3	5	62.5

Methods of Attachment Legend

Criteria Letter	Description
A	Ease of Use
B	Cost
C	Setup Time
D	Machining Time
E	Safety
F	Durability
G	Vibrations
H	Configurability
I	Overall Satisfaction

Storage

Design Criteria	A	B	C	D	E	F	G	H	I	J
Weight	0.15	0.2	0.05	0.1	0.15	0.05	0.05	0.05	0.2	1
Alternatives										
Foldable	70	60	70	60	70	70	70	70	80	
	10.5	12	3.5	6	10.5	3.5	3.5	3.5	16	69
Detachable	60	70	70	70	80	70	70	70	80	
	9	14	3.5	7	12	3.5	3.5	3.5	16	72
Cover	80	80	90	90	100	90	90	90	50	
	12	16	4.5	9	15	4.5	4.5	4.5	10	80
Bin	100	80	90	100	100	90	90	90	60	
	15	16	4.5	10	15	4.5	4.5	4.5	12	**86**

Storage Legend

Criteria Letter	**Description**
A	Ease of Use
B	Cost
C	Setup Time
D	Machining Time
E	Safety
F	Durability
G	Reliability
H	Reparability
I	Space
J	Overall Satisfaction

Output

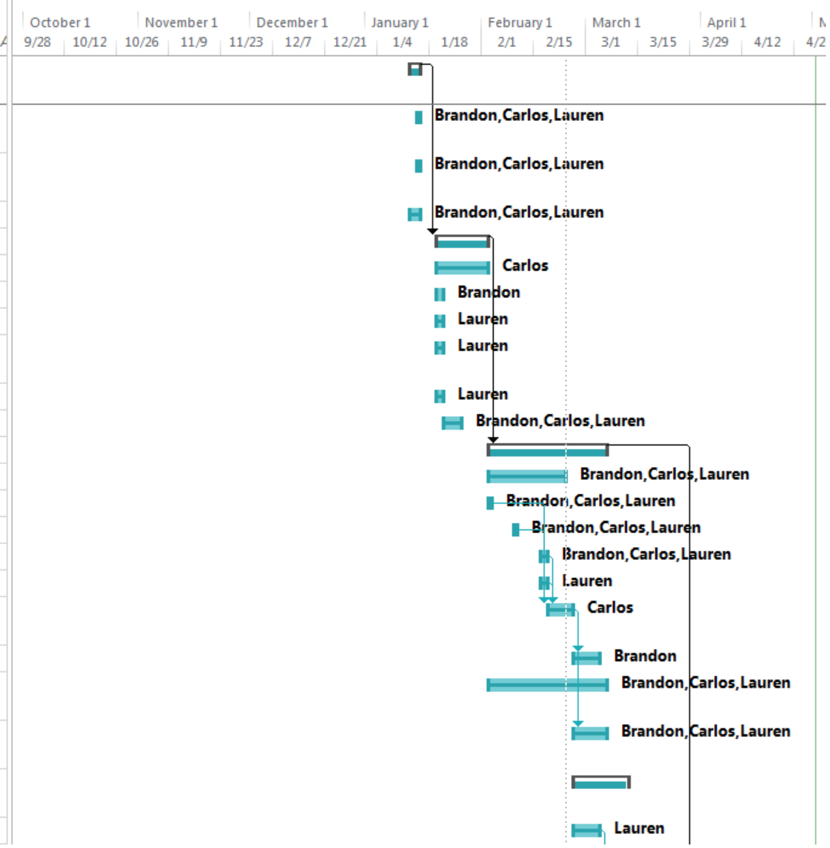
Design Criteria	A	B	C	D	E	F	G	H	I	J
Weight	0.1	0.15	0.05	0.05	0.2	0.05	0.15	0.05	0.2	1
Alternatives										
Ball and Fan	100	100	80	90	80	80	90	50	80	
	10	15	4	4.5	16	4	13.5	2.5	16	**85.5**
Ball Launcher	100	100	60	80	70	80	70	90	60	
	10	15	3	4	14	4	10.5	4.5	12	77
Light	100	80	100	100	100	100	30	50	90	
	10	12	5	5	20	5	4.5	2.5	18	82
Generator	80	80	80	100	70	80	100	50	50	
	8	12	4	5	14	4	15	2.5	10	74.5

Output Legend

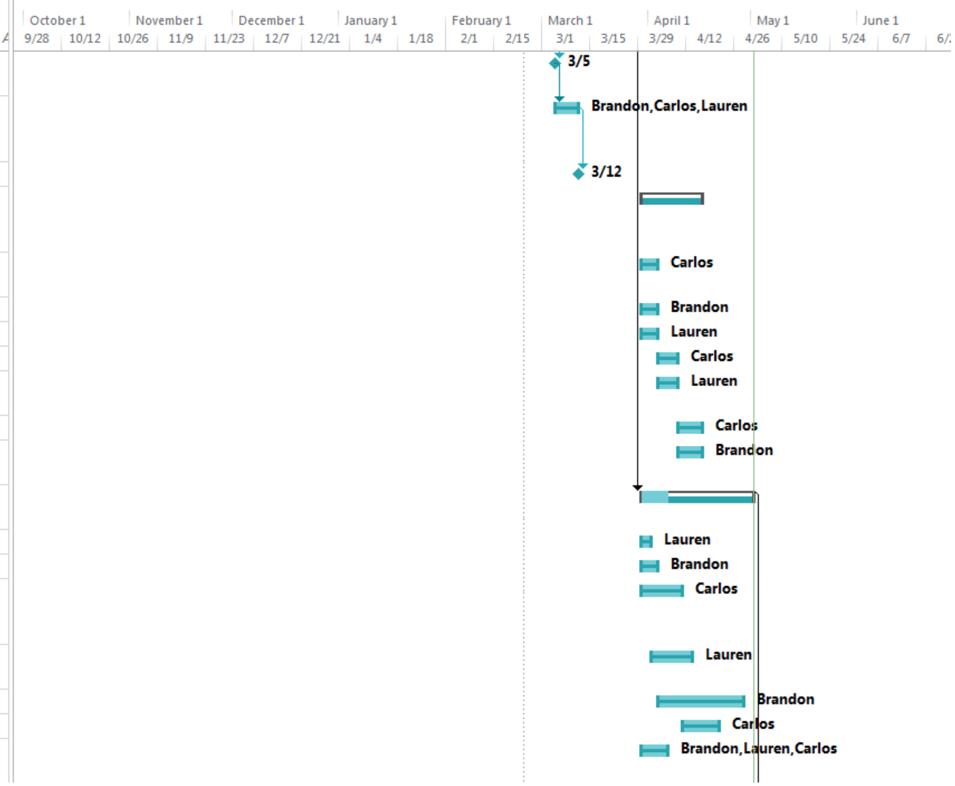
Criteria Letter	**Description**
A	Ease of Use
B	Visual Appeal
C	Setup Time
D	Fabrication Time
E	Safety
F	Durability
G	Measurability
H	Reparability
I	Cost
J	Overall Satisfaction

Appendix E: Gantt Chart

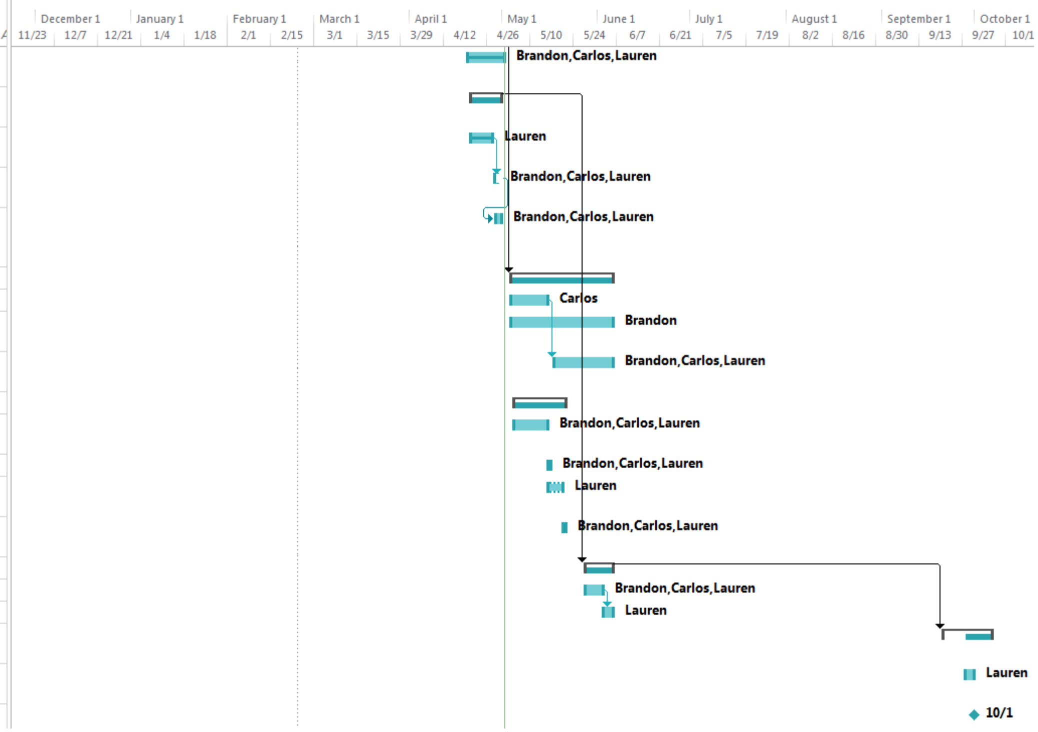
	Indicators	Task Mode	Task Name	Duration	Start	Finish	Predecessors	Resource Names
1	✓		**Letter of Introduction**	**3 days**	**Tue 1/13/15**	**Thu 1/15/15**		
2	✓		Meeting with sponsor	1 day	Thu 1/15/15	Thu 1/15/15		Brandon,Carlos,Lauren
3	✓		Set up weekly meeting	1 day	Thu 1/15/15	Thu 1/15/15		Brandon,Carlos,Lauren
4	✓		Identify problem	3 days	Tue 1/13/15	Thu 1/15/15		Brandon,Carlos,Lauren
5			**Project Proposal**	**10 days**	**Tue 1/20/15**	**Mon 2/2/15**	**1**	
6	✓		Background resarc	10 days	Tue 1/20/15	Mon 2/2/15		Carlos
7			Patent search	2 days	Tue 1/20/15	Wed 1/21/15		Brandon
8	✓		List objectives	2 days	Tue 1/20/15	Wed 1/21/15		Lauren
9	✓		Method of approach	2 days	Tue 1/20/15	Wed 1/21/15		Lauren
10	✓		Management plan	2 days	Tue 1/20/15	Wed 1/21/15		Lauren
11	✓		QFD	3 days	Thu 1/22/15	Mon 1/26/15		Brandon,Carlos,Lauren
12	✓		**Concept Report**	**24 days**	**Tue 2/3/15**	**Fri 3/6/15**	**5**	
13	✓		Brainstorming	15 days	Tue 2/3/15	Mon 2/23/15		Brandon,Carlos,Lauren
14	✓		SCAMPER	1 day	Tue 2/3/15	Tue 2/3/15		Brandon,Carlos,Lauren
15	✓		Concept model	1 day	Tue 2/10/15	Tue 2/10/15		Brandon,Carlos,Lauren
16	✓		Pugh matrix	2 days	Tue 2/17/15	Wed 2/18/15		Brandon,Carlos,Lauren
17	✓		Decision matrices	2 days	Tue 2/17/15	Wed 2/18/15		Lauren
18	✓		Engineering evaluation	5 days	Thu 2/19/15	Wed 2/25/15	14,	Carlos
19	✓		CAD model	5 days	Thu 2/26/15	Wed 3/4/15	18	Brandon
20	✓		Edit project proposal	24 days	Tue 2/3/15	Fri 3/6/15		Brandon,Carlos,Lauren
21	✓		Write remaining report	7 days	Thu 2/26/15	Fri 3/6/15	18	Brandon,Carlos,Lauren
22	✓		**Conceptual Design Review**	**11 days**	**Thu 2/26/15**	**Thu 3/12/15**		
23	✓		Power point	5 days	Thu 2/26/15	Wed 3/4/15		Lauren



		Task Mode	Task Name	Duration	Start	Finish		Resource Names
24	✓		In class presentation	0 days	Thu 3/5/15	Thu 3/5/15	23	Brandon,Carlos,Lauren
25	✓		Make changes based on feedback	5 days	Thu 3/5/15	Wed 3/11/15	24	Brandon,Carlos,Lauren
26	✓		Review	0 days	Thu 3/12/15	Thu 3/12/15	25	Brandon,Carlos,Lauren
27	✓		**Preliminary Testing and Calculations**	**14 days**	**Mon 3/30/15**	**Thu 4/16/15**		**Brandon,Lauren,Carlos**
28	✓		Board calculations	5 days	Mon 3/30/15	Fri 4/3/15		Carlos
29	✓		Gear alignment	5 days	Mon 3/30/15	Fri 4/3/15		Brandon
30	✓		Chain tention	5 days	Mon 3/30/15	Fri 4/3/15		Lauren
31	✓		Belt tension	5 days	Sat 4/4/15	Thu 4/9/15		Carlos
32	✓		Shaft deflection	5 days	Sat 4/4/15	Thu 4/9/15		Lauren
33	✓		Power loss	5 days	Fri 4/10/15	Thu 4/16/15		Carlos
34	✓		Motor characteristics	5 days	Fri 4/10/15	Thu 4/16/15		Brandon
35	✓		**Critical Design Report**	**25 days**	**Mon 3/30/15**	**Fri 5/1/15**	**12**	
36	✓		Safety review	3 days	Mon 3/30/15	Wed 4/1/15		Lauren
37	✓		Material selection	5 days	Mon 3/30/15	Fri 4/3/15		Brandon
38	✓		Fabrication and assembly instructions	10 days	Mon 3/30/15	Fri 4/10/15		Carlos
39	✓		Maintanence and repair	8 days	Thu 4/2/15	Mon 4/13/15		Lauren
40	✓		Detailed drawings	18 days	Sat 4/4/15	Tue 4/28/15		Brandon
41	✓		Cost analysis	8 days	Sat 4/11/15	Tue 4/21/15		Carlos
42	✓		Develop testing procedures	6 days	Mon 3/30/15	Mon 4/6/15		Brandon,Lauren,Carlos

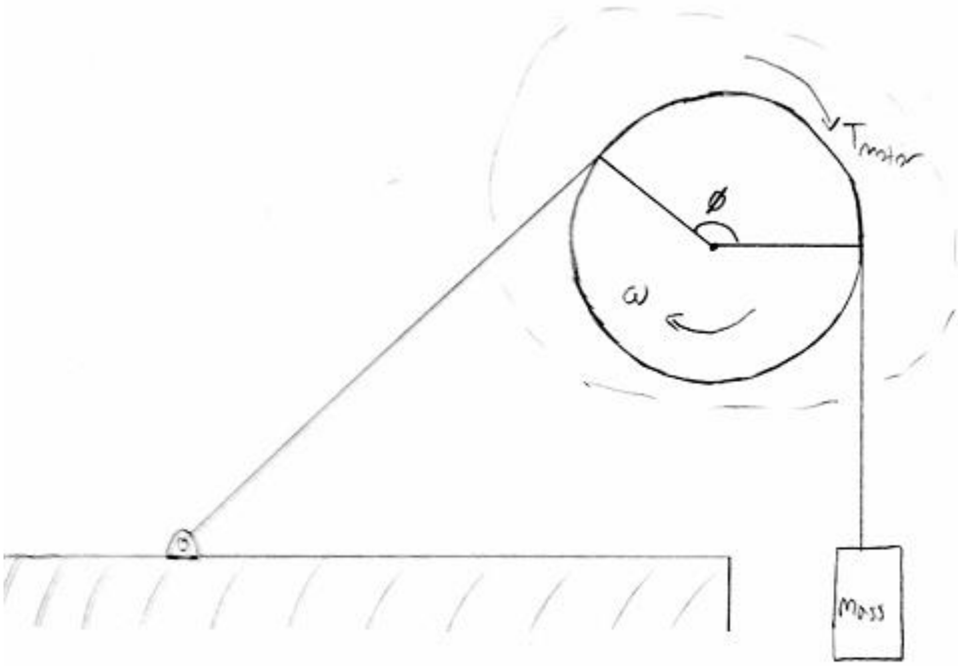


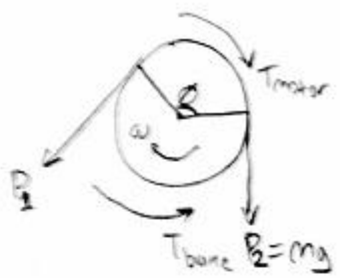
		Task Mode	Task Name	Duration	Start	Finish		Resource Names
43	✓		Write additional material	10 days	Mon 4/20/15	Fri 5/1/15		Brandon,Carlos,Lauren
44			**Critical Design Review**	**8 days**	**Tue 4/21/15**	**Thu 4/30/15**		
45	✓		Make power point	5 days	Tue 4/21/15	Mon 4/27/15		Lauren
46			In class presentation		Tue 4/28/15		45	Brandon,Carlos,Lauren
47			Make changes based on feedback	2 days	Wed 4/29/15	Thu 4/30/15	46	Brandon,Carlos,Lauren
48			**Prototype**	**25 days**	**Mon 5/4/15**	**Fri 6/5/15**	**35**	
49			Order parts	10 days	Mon 5/4/15	Fri 5/15/15		Carlos
50			Manufacture parts	25 days	Mon 5/4/15	Fri 6/5/15		Brandon
51			Assemble	15 days	Mon 5/18/15	Fri 6/5/15	49	Brandon,Carlos,Lauren
52			**Ethics**	**13 days**	**Tue 5/5/15**	**Thu 5/21/15**		
53			Write ethics memo	9 days	Tue 5/5/15	Fri 5/15/15		Brandon,Carlos,Lauren
54			Turn in memo	1 day	Sat 5/16/15	Sat 5/16/15		Brandon,Carlos,Lauren
55			Ethics powerpoint	4 days	Sat 5/16/15	Wed 5/20/15		Lauren
56			Ethics presentation	1 day	Thu 5/21/15	Thu 5/21/15		Brandon,Carlos,Lauren
57			**Progress Report**	**7 days**	**Thu 5/28/15**	**Fri 6/5/15**	**44**	
58			Write report	4 days	Thu 5/28/15	Tue 6/2/15		Brandon,Carlos,Lauren
59			Edit report	3 days	Wed 6/3/15	Fri 6/5/15	58	Lauren
60			**Manufacturing and Testing Review**	**12 days**	**Mon 9/21/15**	**Tue 10/6/15**	**57**	
61			Make power point	3 days	Mon 9/28/15	Wed 9/30/15		Lauren
62			In class	0 days	Thu 10/1/15	Thu 10/1/15		Brandon,Carlos,Lauren



Appendix F: Calculations

Band Brake analysis





Ø = angle of contact between band brake and brake drum

f = coefficient of kinetic friction

D = diameter of brake drum

$$P_1 = P_2 e^{f\phi}$$

$$T_{brake} = (P_1 - P_2)\frac{D}{2}$$

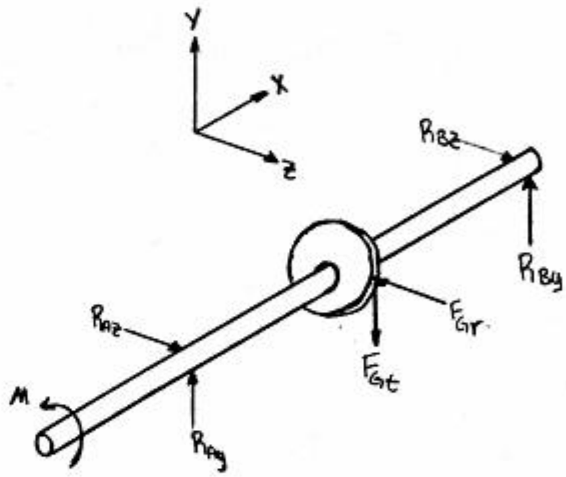
* Since the Drum spins at a constant angular velocity there is no angular acceleration

$$\sum T_{center} = 0$$

$$T_{brake} - T_{motor} = 0$$

$$\therefore T_{motor} = T_{brake}$$

Spur Gear Analysis



Assume:

$M = .2\ N{\cdot}m$ * shear due to transverse force negligable

$l = 0.05715 m$ Shaft Material = 1018 CD steel

$d_{gear} = 0.0127 m$ $\sigma_y = 310\ MPa$ $\phi = 20^\circ$

$D_{shaft} = .00635 m$ $E = 200\ GPa$

$$\Sigma M_x = 0$$

$$F_{Gt}\left(\frac{d_{gear}}{2}\right) - M = 0$$

$$F_{Gt} = \frac{2M}{d_{gear}} = \underline{31.5N}$$

$$F_{Gr} = F_{Gt} \tan\phi$$

$$\underline{F_{Gr} = 11.5\ N}$$

$$\Sigma M_{Az} = 0$$

$$l R_{By} - \frac{l}{2} F_{Gt} = 0$$

$$R_{By} = \frac{1}{2} F_{Gt} = \underline{15.75N}$$

$$\Sigma F_y = 0$$

$$R_{Ay} + R_{BY} - F_{Gt} = 0$$

$$R_{Ay} = \frac{1}{2} F_{Gt} = \underline{15.75}$$

$\Sigma M_{Ay} = 0$

$\frac{l}{2} F_{Gr} - l R_{Bz} = 0$

$R_{Bz} = \frac{1}{2} F_{Gr}$

$R_{Bz} = 5.75 N$

$\Sigma F_z = 0$

$R_{Az} + R_{Bz} - F_{Gr} = 0$

$R_{Az} = \frac{1}{2} F_{Gr} = 5.75 N$

Calculating stress

$M_{z_{max}} = \left(\frac{l}{2}\right) R_{Ay}$

$M_{z_{max}} = \frac{(.05715 m)}{2} (15.75 N)$

$M_{z_{max}} = 0.45 N \cdot m$

$M_{y_{max}} = \left(\frac{l}{2}\right) R_{Az}$

$M_{y_{max}} = 0.164 N \cdot m$

$M_{total} = \sqrt{(.45 N \cdot m)^2 + (0.164 N \cdot m)^2}$

$M_{total} = 0.479 N \cdot m$

$\sigma_{bend} = \frac{32 M_{total}}{\pi D_{shaft}^3} = \frac{32(.479 N \cdot m)}{\pi (.00635 m)^3}$

$\sigma_{bend} = 19.05 MPa$

$\tau = \frac{16 M}{\pi D_{shaft}^3} = \frac{16 (.2 N \cdot m)}{\pi (.00635 m)^3} = 3.98 MPa$

Von Misses Stress

$$\sigma' = \sqrt{\sigma^2 + 3\tau^2}$$

$$\sigma' = \sqrt{(19.05)^2 + 3(3.83)^2}$$

$$\sigma' = 20.26\ MPa$$

Saftey factor

$$SF = \frac{\sigma_Y}{\sigma'}$$

$$SF = \frac{310\ MPa}{20.26\ MPa}$$

$$SF = 15.3$$

Max Gear Deflection

$$F_{total} = \sqrt{F_{Gr}^2 + F_{Gt}^2}$$

$$F_{total} = \sqrt{(31.5)^2 + (11.5)^2}$$

$$F_{total} = 33.5\ N$$

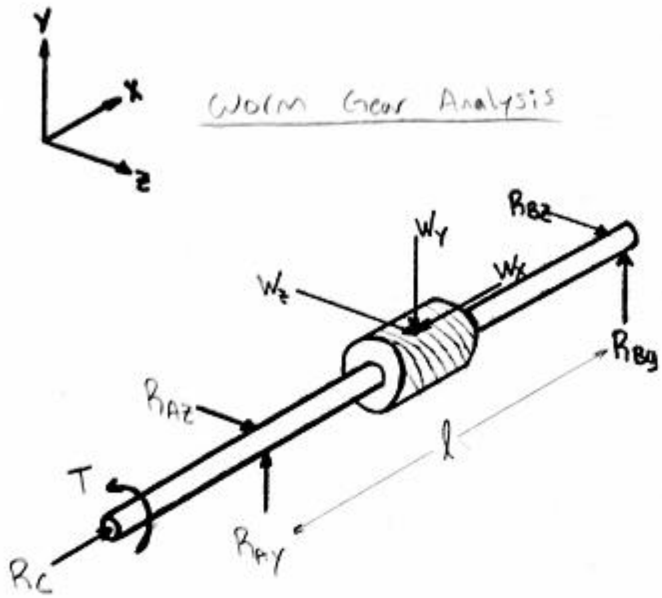
$$I = \frac{\pi}{64} D^4 = \frac{\pi}{64}(0.00635m)^4$$

$$I = 7.98 \times 10^{-11}\ m^4$$

$$y_{max} = \frac{F_{total}\, l^3}{48EI} = \frac{(33.5N)(0.05715m)^3}{48(200 \times 10^9 \frac{N}{m^2})(7.98 \times 10^{-11} m^4)}$$

$$y_{max} = 8.16 \times 10^{-4} m = 0.00032\ in.$$

Worm Gear Analysis



Assume:

* Shear due to transverse force negligable

$M = .2 N \cdot M$

$l = 2.25 \text{ in} = 0.05715 m$

$d_{worm} = .5 \text{ in} = 0.0127 m$

$D_{shaft} = .25 \text{ in} = 0.00635 m$

Shaft material = 1018 CD steel

$\sigma_Y = 310 Mpa$

$E = 200 Gpa$

$\phi = 14.5°$

$\lambda = 7.183°$

$f = 0.1$

Solution:

$$\Sigma T_x = 0$$

$$W_z\left(\frac{d_w}{2}\right) - T = 0$$

$$T = W_z\left(\frac{d_w}{2}\right)$$

$$W_z = \frac{2T}{d_w} = \frac{2(.2 N \cdot m)}{(0.0127 m)} = \underline{31.5 N}$$

$$\Sigma M_{A_y} = 0$$

$$-W_z\left(\frac{l}{2}\right) - R_{Bz} l = 0$$

$$l R_{Bz} = -W_z\left(\frac{l}{2}\right)$$

$$R_{Bz} = -\frac{1}{2} W_z = \underline{-15.75 N}$$

$\Sigma F_z = 0$

$W_z + R_{Az} + R_{Bz} = 0$

$R_{Az} = -W_z - R_{Bz}$

$R_{Az} = (-31.5N) - (-15.75N)$

$\underline{R_{Az} = -15.75N}$

$W_z = W(\cos\phi \sin\lambda + f\cos\lambda)$

$W = \dfrac{W_z}{(\cos\phi \sin\lambda + f\cos\lambda)}$

$W = \dfrac{31.5N}{\cos(14.3^\circ)\sin(7.133^\circ) + 0.1\cos(7.133^\circ)}$

$\underline{W = 143\ N}$

$W_y = W\sin\phi$

$W_y = 143\sin(14.3^\circ)$

$\underline{W_y = 35.3N}$

$W_x = W(\cos\phi\cos\lambda - f\sin\lambda)$

$W_x = 143(\cos(14.3)\cos(7.133) - 0.1\sin(7.133))$

$\underline{W_x = 135N}$

$\Sigma F_x = 0$

$R_C - W_x = 0$

$\underline{R_C = W_x = 135N}$

$\Sigma M_{A_z} = 0$

$l R_{By} - \frac{l}{2} W_y = 0$

$\underline{R_{By} = \frac{1}{2} W_y = 17.65N}$

$\Sigma F_y = 0$

$R_{Ay} + R_{By} - W_y = 0$

$\underline{R_{Ay} = 17.65N}$

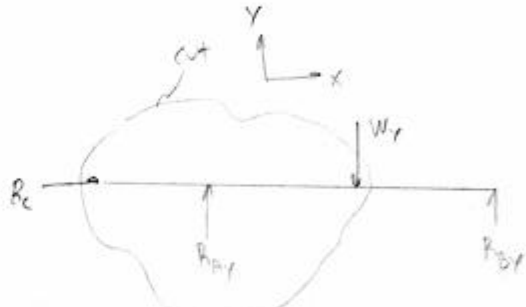
IN SUMMARY

$R_C = 135N$	$W_y = 35.3N$	$R_{Bz} = -15.75N$
$R_{Ay} = 17.65N$	$W_z = 31.5N$	$R_{Az} = -15.75N$
$R_{By} = 17.65N$	$W_x = 135N$	

Calculating Stress

Assume: Critical point is at the center of the worm gear!

$$\tau = \frac{16T}{\pi D_{shaft}} = \frac{16(.2\,N{\cdot}m)}{\pi(.00635m)^3} = 13.98\ MPa$$



Max Moment

$$M_{z\,max} = \frac{l}{2} R_{Ay} = \left(\frac{0.05715m}{2}\right)(17.65N)$$

$$M_{z\,max} = .50\ N{\cdot}m$$

$$M_{y\,max} = \frac{l}{2} R_{Az} = \left(\frac{0.05715m}{2}\right)(15.75N)$$

$$M_{y\,max} = .45\ N{\cdot}m$$

$V = R_{Ay}$ $\quad M = \frac{l}{2} R_{Ay}$

$$M_{total} = \sqrt{M_{z\,max}^2 + M_{y\,max}^2}$$

$$M_{total} = \sqrt{(.5\,N{\cdot}m)^2 + (.45\,N{\cdot}m)^2}$$

$$M_{total} = .673\ N{\cdot}m$$

$$\sigma_{bending} = \frac{32\,M_{total}}{\pi D_{shaft}^3}$$

$$\sigma_{bending} = \frac{32(.673\,N{\cdot}m)}{\pi(.00635m)^3}$$

$$\sigma_{bending} = 26.8\ MPa$$

$$\sigma_{tensile} = \frac{R_c}{\frac{\pi}{4}D_{shaft}^2} = \frac{135N}{\frac{\pi}{4}(.00635m)^2}$$

$$\sigma_{tensile} = 4.26\ MPa$$

Calculating Von Mises Stress

$$\sigma_{total} = \sigma_{tensile} + \sigma_{bending} \qquad \tau = 3.93\,MPa$$

$$\sigma_{total} = 4.26\,MPa + 26.8\,MPa$$

$$\sigma_{total} = 31.06\,MPa$$

$$\sigma' = \sqrt{\sigma_{total}^2 + 3\tau^2}$$

$$\sigma' = \sqrt{(31.06\,MPa)^2 + 3(3.93\,MPa)^2}$$

$$\boxed{\sigma' = 31.3\,MPa}$$

Safety Factor

$$SF = \frac{\sigma_y}{\sigma'}$$

$$SF = \frac{310\,MPa}{31.8\,MPa}$$

$$\boxed{SF = 9.74}$$

Max Deflection

Assume it occurs at center of Gear

$$F_{total} = W = 143\,N$$

$$I = \frac{\pi}{64} D^4 = \frac{\pi}{64}(.00635\,m)^4$$

$$I = 7.98 \times 10^{-11}\,m^4$$

$$y_{max} = \frac{F\ell^3}{48EI} = \frac{(143\,N)(.05715\,m)^3}{48(200\times10^9\,\frac{N}{m^2})(7.98\times10^{-11}\,m^4)}$$

$$y_{max} = 3.48\times10^{-5}\,m = \boxed{0.00137\,in}$$

Appendix G: FMEA Chart

Failure Mode and Effect Analysis for Mechanical Breadbaord

Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Crit	Recommended Action(s)	Responsibility & Target Completion Date
Board	Stripped threads in holes	Components do not secure onto board	5	Overused, too much pulling when removing screws	7	35	Include instructions on how to install components, use harder material than fasteners	Lauren 5/15/15
Shafts	Bending and fracture	Components do not line up	4	High forces on shafts	4	16	Lower forces	Brandon 5/15/15
Belts	Improper operating tension	Belt failure, slipage, and fatigue	5	Installation error, too little or too much tension	4	20	Include instructions on how to install components	Carlos 5/15/15
Belts	Misalignment	Sidewall cracking, belt failure	4	Installation error	4	16	Include instructions on how to install components	Lauren 5/20/15
Chain	Rubbing wear	Chain wears a groove in the fixture	2	Misalignment of chain	4	8	Include instructions on how to install components	Brandon 5/20/15
Chain	Fretting corrosion	Impaired function, unsatisfactory appearance	2	Not enough lubrication	4	8	Lubrication	Carlos 5/20/15
Bearings	Bearing wear	Misalign gears and other components	3	Contaminants, too much force, friction	4	12	Lubrication	Lauren 5/25/15
Gears	Gear wear	Gear slipping	4	Not enough lubrication, misalignment	4	16	Include instructions on how to install components, lubrication	Brandon 5/25/15
Gears	Pitting	Redistributes the load	3	Misalignment, surface irregularities	4	12	Include instructions on how to install components	Carlos 5/25/15
Threaded fasteners	Stripped threads	Components do not stay fixed	5	Over used, too much pulling when removing screws	7	35	Include instructions on how to install components, have extra fasteners	Lauren 5/30/15
Motor	Overheating	Insulation deteriorates, loss of function	4	Overloading the motor	5	20	Automatic shutoff when forces become too high	Brandon 5/30/15
Generator	Overheating	Insulation deteriorates, loss of function	4	Overloading the generator	5	20	Automatic shutoff when voltage becomes too high	Carlos 5/30/15

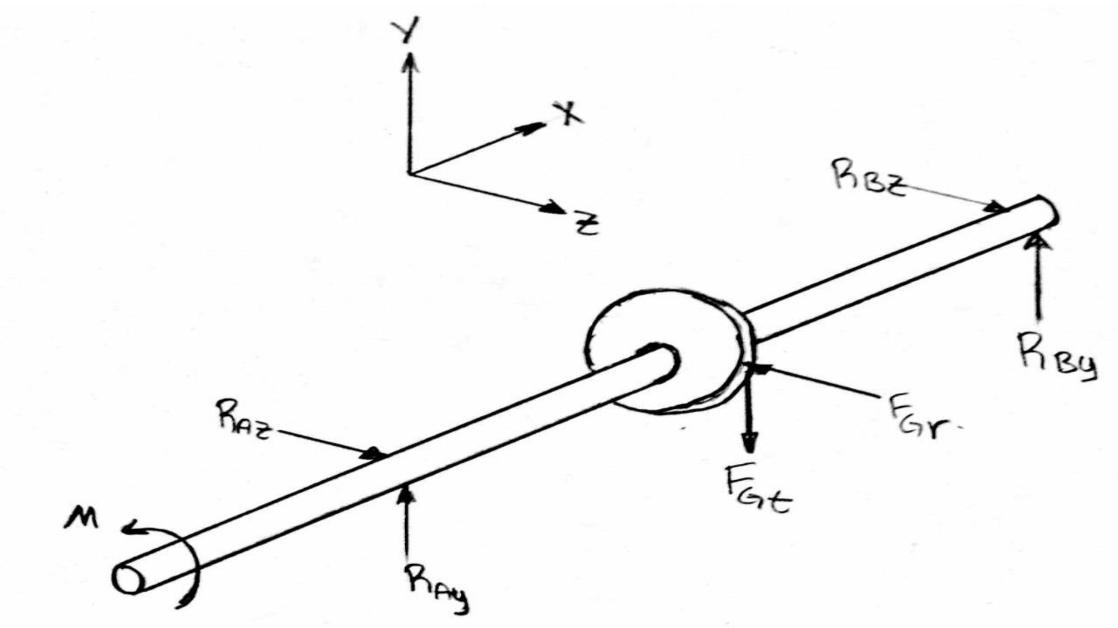
Appendix H: DVP Chart

Design Verification Plan and Report for Mechanical Breadboard

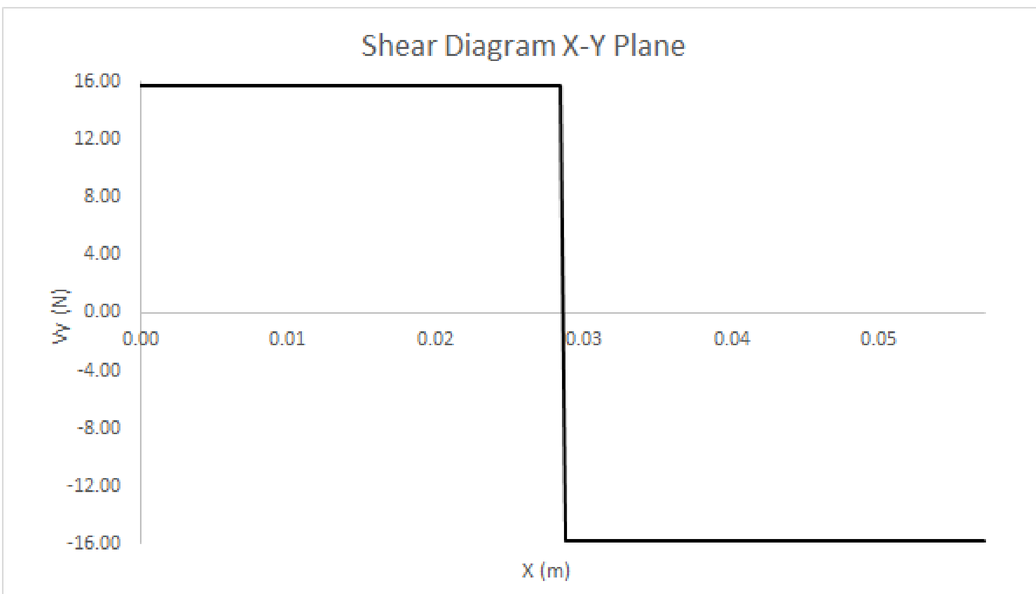
Report Date:		3/12/2015	Sponsor:	Peter Schuster			Component/Assembly:		
TEST PLAN									
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING	
						Quantity	Type	Start date	Finish date
1	Gear Alignment	Test to verify that Gears are in alignment	40 cycles	Brandon Younger	DV	5	PASS	9/28/2015	9/30/2015
2	Chain Tension	Test to verify that sufficient tension exists in chain in proper orientation	40 cycles	Lauren Romero	DV	5	PASS	10/1/2015	10/4/2015
3	Belt Tension	Test to verify that sufficient tension exists in belt in proper orientation	40 cycles	Carlos Padilla	DV	5	PASS	10/5/2015	10/9/2015
4	Bearing Alignment	Test to verify that bearing are aligned successfully	10 cycles	Brandon Younger	DV	5	PASS	10/5/2015	10/9/2015
5	Motor Load	Test to verify that the motor can handle the loads of the various configurations	40 cycles	Lauren Romero	DV	3	PASS		
6	Setup Time	Test to determine how long it takes to set	<10 minutes	Carlos Padilla	DV	3	PASS	10/12/2015	10/12/2015

		up the mechanism							
8	Ability to accurately characterize the motor curve.	Test to determine the accuracy of the band brake dynamometer	±15% error	Lauren Romero	DV	3	PASS		
9	Assembly Time	Test to determine how long it take to assemble each mechanism	<3 hrs	Carlos Padilla	DV	1	PASS		
10	Weight	Test to determine overall weight of mechanism	<20 lbs	Brandon Younger	DV	1	PASS		
11	Size	Test to determine the overall size of the mechanism	3'x2'x1'	Lauren Romero	DV	1	PASS		
12	Production Cost	Test to determine the overall cost of a system	$300	Carlos Padilla	DV	1	FAIL		
15	Configurable Components	Test the number of different configurations the design can do	>4	Brandon Younger	DV	1	PASS		

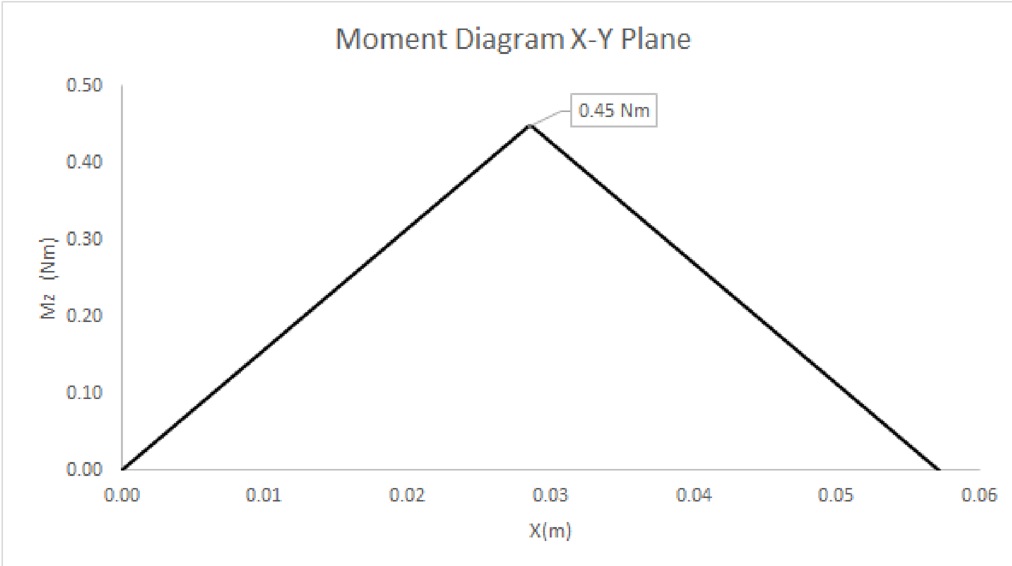
Appendix I: Analysis Plan



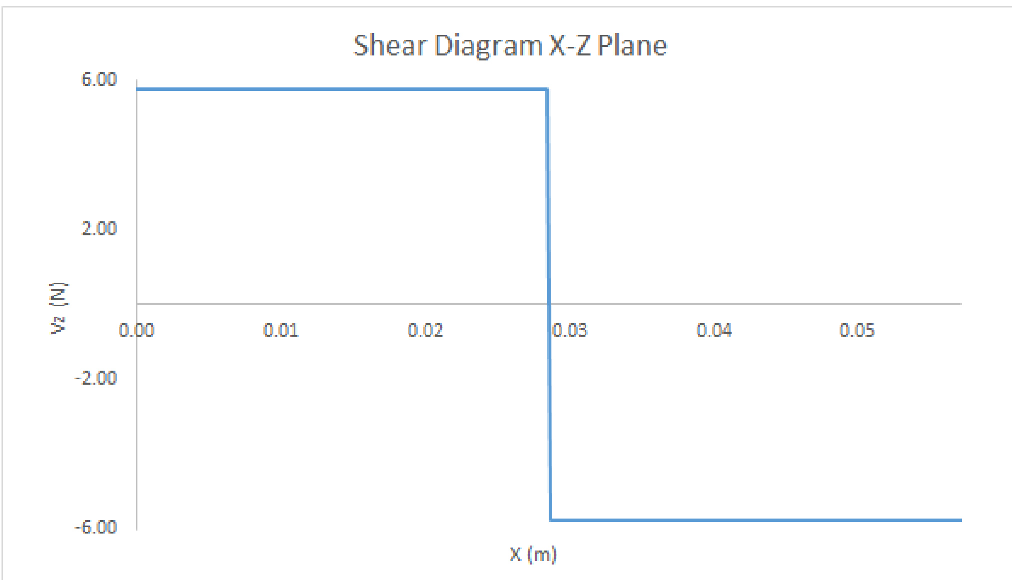
Shaft with spur gear analysis model.



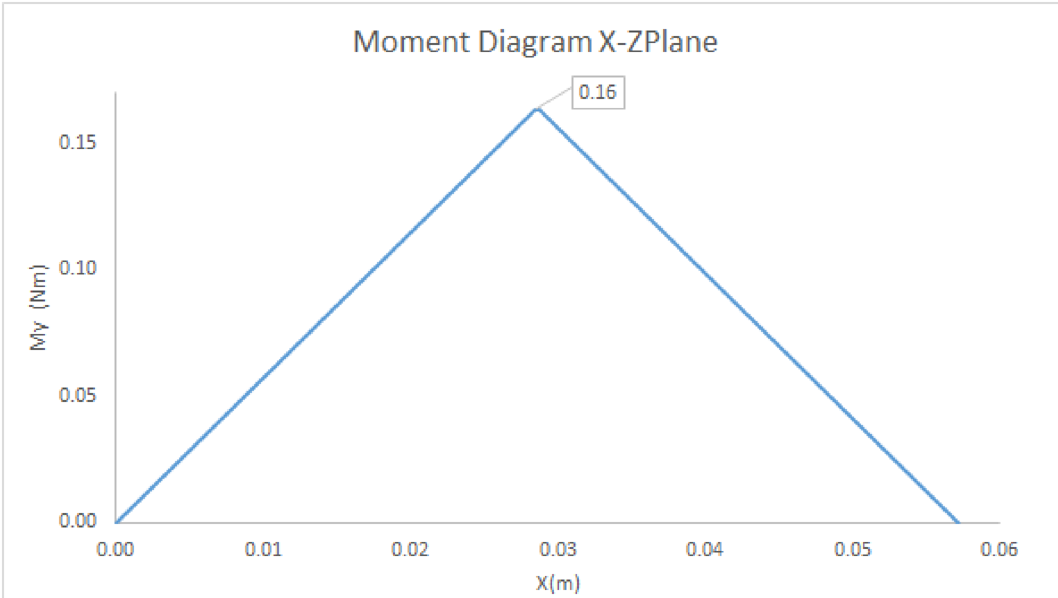
Shear Diagram of the shaft in the X-Y plane.



Moment Diagram for spur gear analysis in the X-Y plane with the moment in the Z direction.



Shear Diagram of the shaft in the X-Z plane.



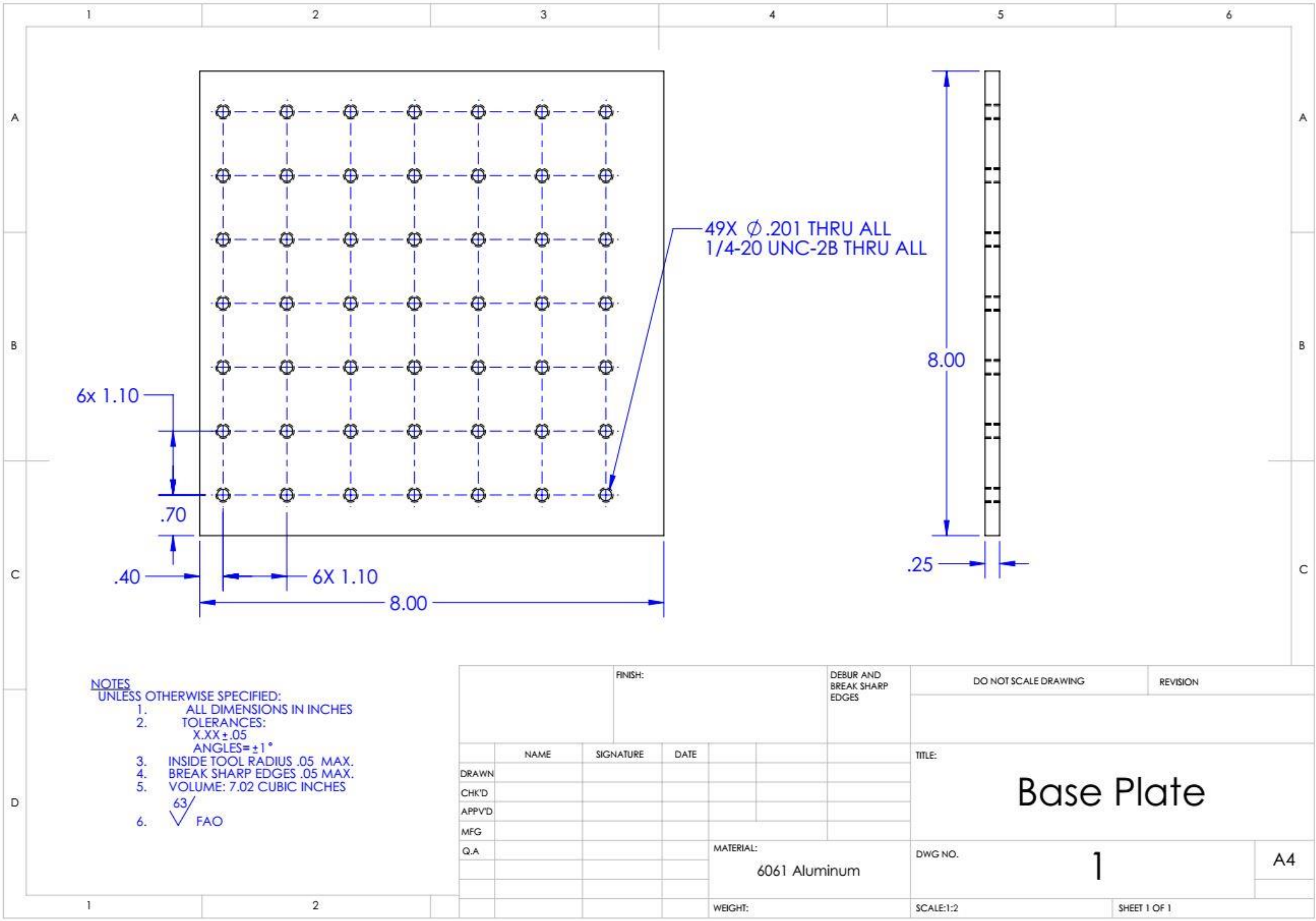
Moment Diagram of the shaft in the X-Z plane with the moment in the Y direction.

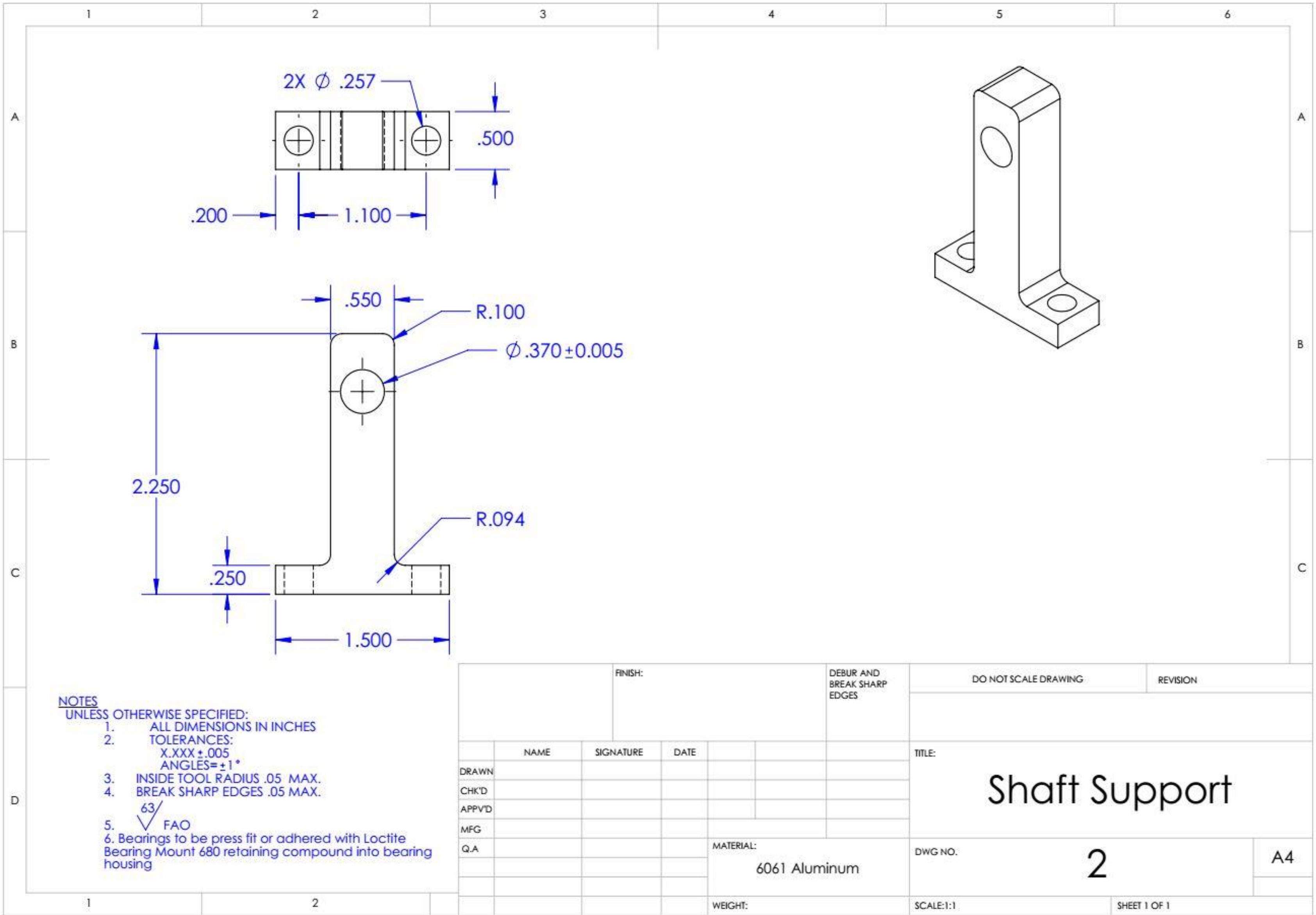
Appendix J: Hazard Checklist

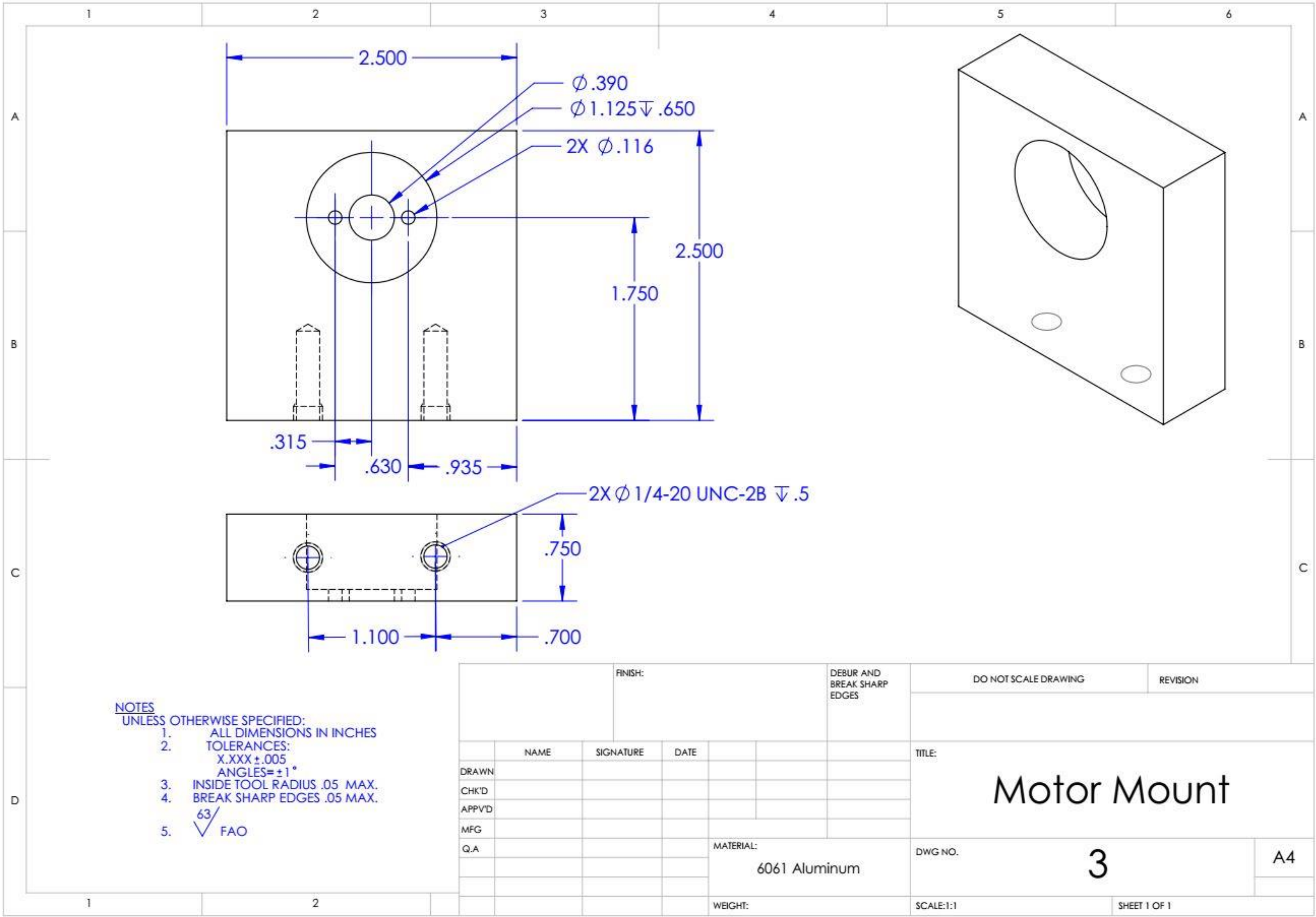
SENIOR PROJECT CONCEPT DESIGN REVIEW HAZARD IDENTIFICATION CHECKLIST

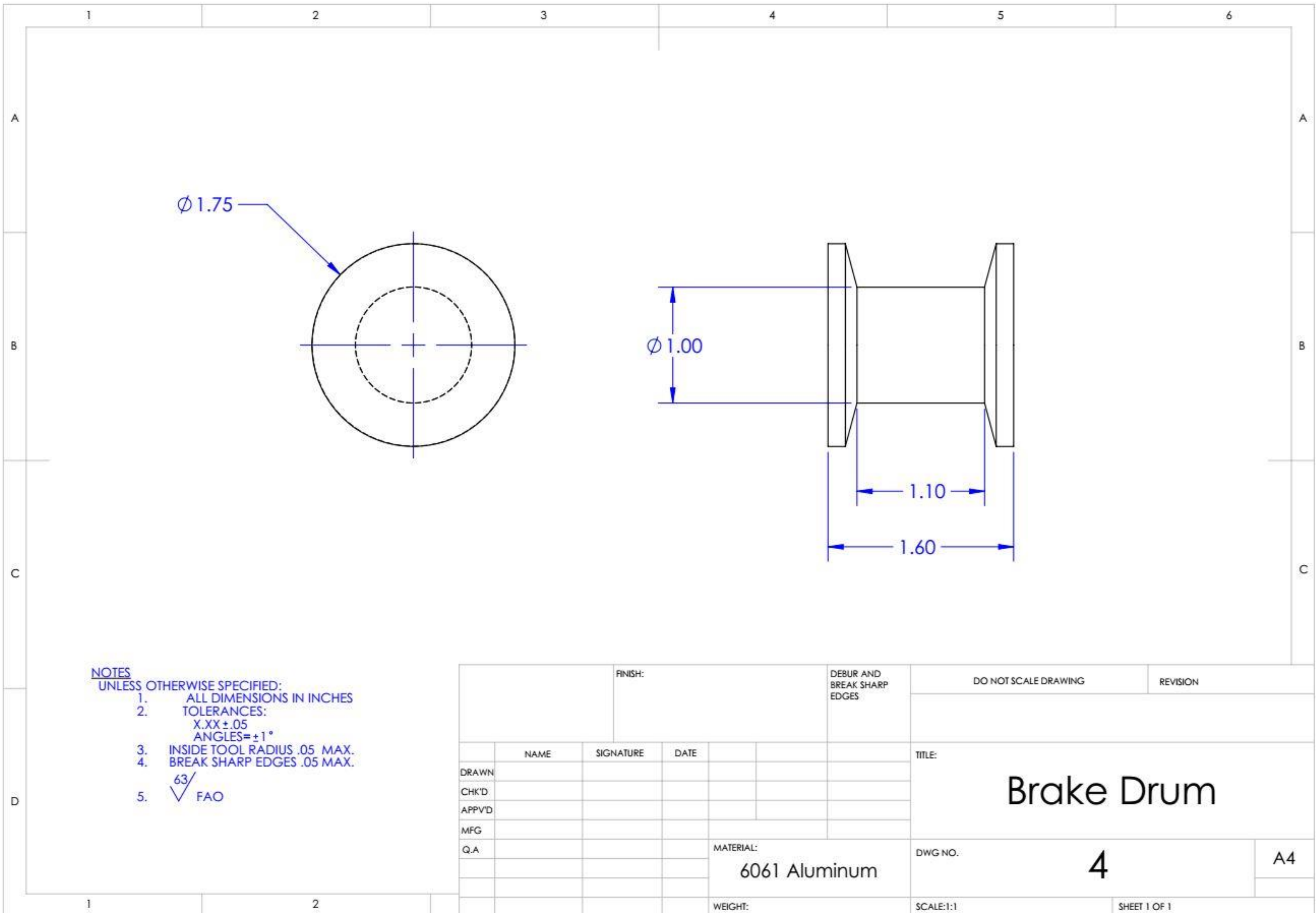
Y	N	
☐	☒	Will any part of the design create hazardous revolving, reciprocating, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing, or similar actions, including pinch points and shear points?
☐	☒	Can any part of the design undergo high accelerations/decelerations?
☐	☒	Will the system have any large moving masses or large forces?
☐	☒	Will the system produce a projectile?
☒	☐	Is it possible for the system to fall under gravity creating injury?
☒	☐	Will a user be exposed to overhanging weights as part of the design?
☐	☒	Will the system have any sharp edges?
☐	☒	Will the system have any ungrounded electrical systems?
☐	☒	Will there be any large batteries or electrical voltage in the system above 40 V (either AC or DC)?
☒	☐	Will there be any stored mechanical energy in the system such as flywheels, hanging weights or pressurized fluids?
☐	☒	Will the system produce high heat (>120°F) at any location?
☐	☒	Will there be any explosive or flammable liquids, gases, or dust as part of the system?
☐	☒	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☒	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	☒	Might the system generate high levels of noise?
☒	☐	Is the system easy to use unsafely?
☐	☒	Will the system be used in extreme environmental conditions such as fog, humidity, cold, high temperatures, etc…?
☐	☒	Are there any other potential hazards not listed above? If yes, please explain below.

Appendix K: Detail Part Drawings



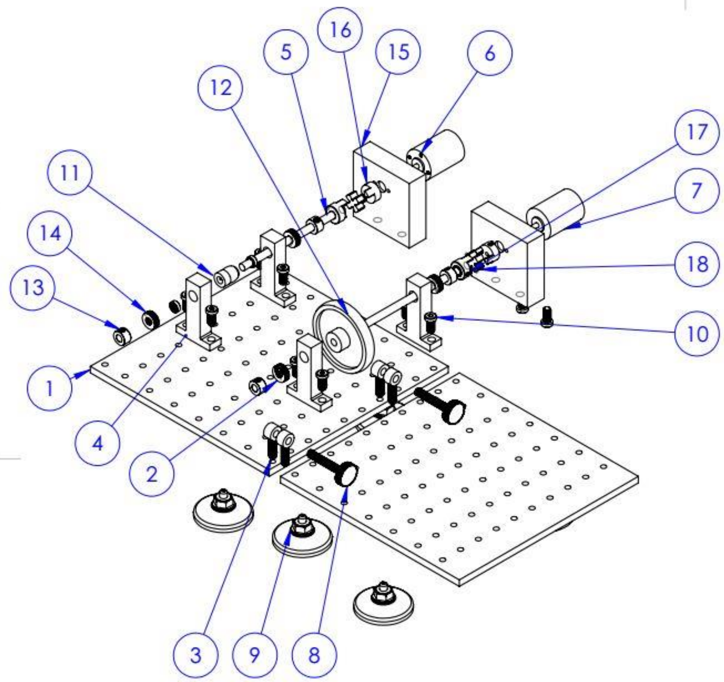

2X ∅ .257
.500
.200
1.100
.550
R.100
∅ .370 ± 0.005
2.250
R.094
.250
1.500
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
X.XXX ± .005
ANGLES= ± 1°
3. INSIDE TOOL RADIUS .05 MAX.
4. BREAK SHARP EDGES .05 MAX.
5. 63 FAO
6. Bearings to be press fit or adhered with Loctite Bearing Mount 680 retaining compound into bearing housing
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Shaft Support
MATERIAL:
6061 Aluminum
DWG NO.
2
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1


2.500
Ø.390
Ø1.125 ↧ .650
2X Ø.116
2.500
1.750
.315
.630
.935
2X Ø 1/4-20 UNC-2B ↧ .5
.750
1.100
.700
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
X.XXX ±.005
ANGLES= ±1°
3. INSIDE TOOL RADIUS .05 MAX.
4. BREAK SHARP EDGES .05 MAX.
63
5. FAO
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Motor Mount
MATERIAL:
6061 Aluminum
DWG NO.
3
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1



Ø1.75
Ø1.00
1.10
1.60
NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS IN INCHES
2. TOLERANCES:
X.XX±.05
ANGLES=±1°
3. INSIDE TOOL RADIUS .05 MAX.
4. BREAK SHARP EDGES .05 MAX.
5. 63 FAO
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
Brake Drum
MATERIAL:
6061 Aluminum
DWG NO.
4
A4
WEIGHT:
SCALE:1:1
SHEET 1 OF 1

Appendix L: Assembly Drawings



ITEM NO.	DESCRIPTION	PART NUMBER	Chain/QTY.
1	Base Plate	1	1
2	Ball Bearing	57155K355	4
3	Rod Ends	6066K67	4
4	Shaft Support	2	4
5	0.25" Shaft	.25" RD CD 1018 48" LG	2
6	Mabuchi DC Motor	DCM-465	1
7	Mabuchi DC Generator	DCM-465	1
8	Thumb Screw	91882A431	2
9	Leveling Mount	23015T81	6
10	Socket Head Cap Screws	92220A183	12
11	Pulley (Small)	A 6T19-232508	1
12	Pulley (Large)	A 6T19-682508	1
13	Shaft Collars	9414T6	4
14	Thrust Bearings	6655K13	4
15	Motor Mount	3	2
16	1/8 inch shaft coupling	6408K911	2
17	1/4 inch shaft coupling	6408K913	2
18	Spider Coupling	6408K61	2

NOTE; FOR A LIST OF PART VENDORS AND BILL OF MATERIALS SEE APPENDIX M

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: 6061 Aluminum

WEIGHT:

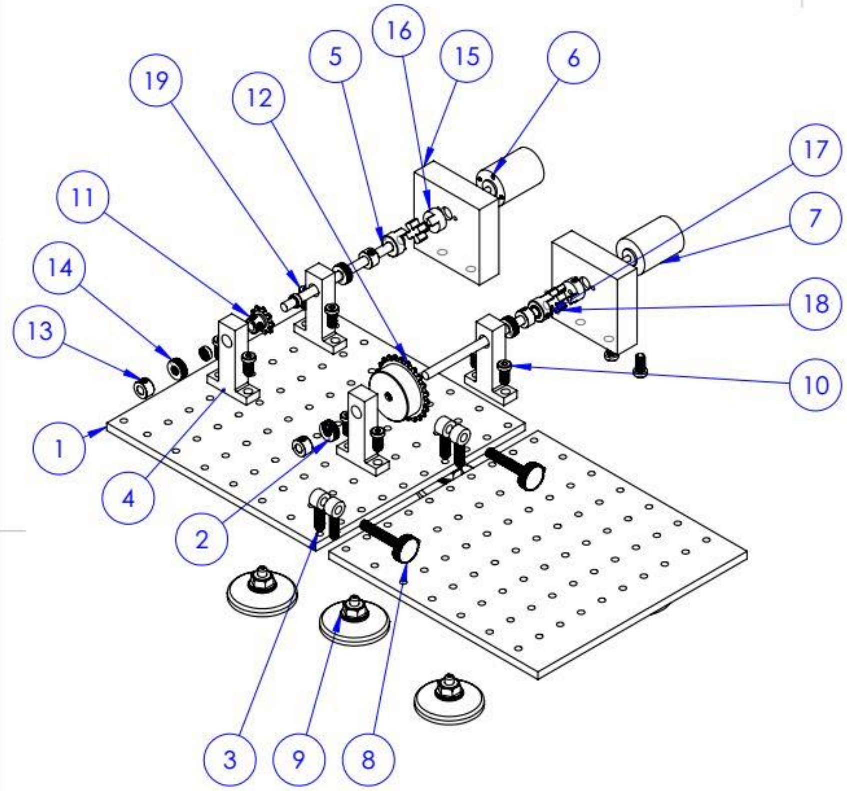
TITLE: Belt Assembly

DWG NO. 6

A4

SCALE:1:8

SHEET 1 OF 1



ITEM NO.	DESCRIPTION	PART NUMBER	Chain/QTY.
1	Base Plate	1	1
2	Ball Bearing	57155K355	4
3	Rod Ends	6066K67	4
4	Shaft Support	2	4
5	0.25" Shaft	.25" RD CD 1018 48" LG	2
6	Mabuchi DC Motor	DCM-465	1
7	Mabuchi DC Generator	DCM-465	1
8	Thumb Screw	91882A431	2
9	Leveling Mount	23015T81	6
10	Socket Head Cap Screws	92220A183	12
11	Sprocket (Small)	2737T1	1
12	Sprocket (Large)	2737T151	1
13	Shaft Collars	9414T6	4
14	Thrust Bearings	6655K13	4
15	Motor Mount	3	2
16	1/8 inch shaft coupling	6408K911	2
17	1/4 inch shaft coupling	6408K913	2
18	Spider Coupling	6408K61	2

NOTE; FOR A LIST OF PART VENDORS AND BILL OF MATERIALS SEE APPENDIX M

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: 6061 Aluminum

WEIGHT:

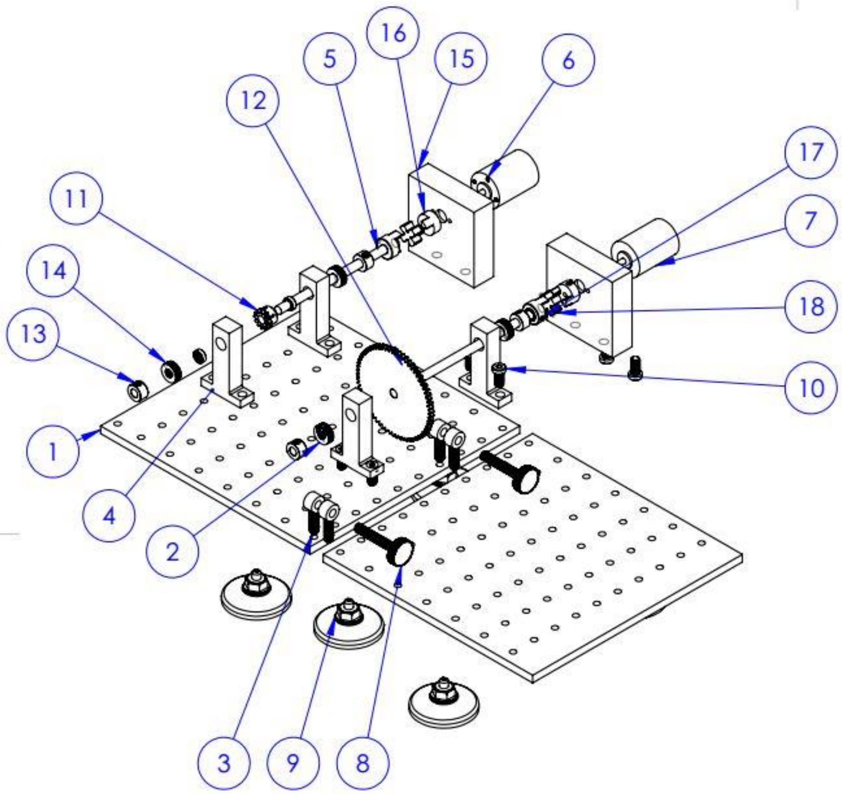
TITLE: Chain Assembly

DWG NO. 5

A4

SCALE:1:8

SHEET 1 OF 1



ITEM NO.	DESCRIPTION	PART NUMBER	Chain/QTY.
1	Base Plate	1	1
2	Ball Bearing	57155K355	4
3	Rod Ends	6066K67	4
4	Shaft Support	2	4
5	0.25" Shaft	.25" RD CD 1018 48" LG	2
6	Mabuchi DC Motor	DCM-465	1
7	Mabuchi DC Generator	DCM-465	1
8	Thumb Screw	91882A431	2
9	Leveling Mount	23015T81	6
10	Socket Head Cap Screws	92220A183	12
11	Spur Gear (Small)	S1086Z-024A012	1
12	Spur Gear (Large)	S1086Z-024A066	1
13	Shaft Collars	9414T6	4
14	Thrust Bearings	6655K13	4
15	Motor Mount	3	2
16	1/8 inch shaft coupling	6408K911	2
17	1/4 inch shaft coupling	6408K913	2
18	Spider Coupling	6408K61	2

NOTE; FOR A LIST OF PART VENDORS AND BILL OF MATERIALS SEE APPENDIX M

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: 6061 Aluminum

WEIGHT:

TITLE: Gear Assembly

DWG NO. 7

A4

SCALE:1:8

SHEET 1 OF 1

Appendix M: List of Vendors, Contact Information and Pricing

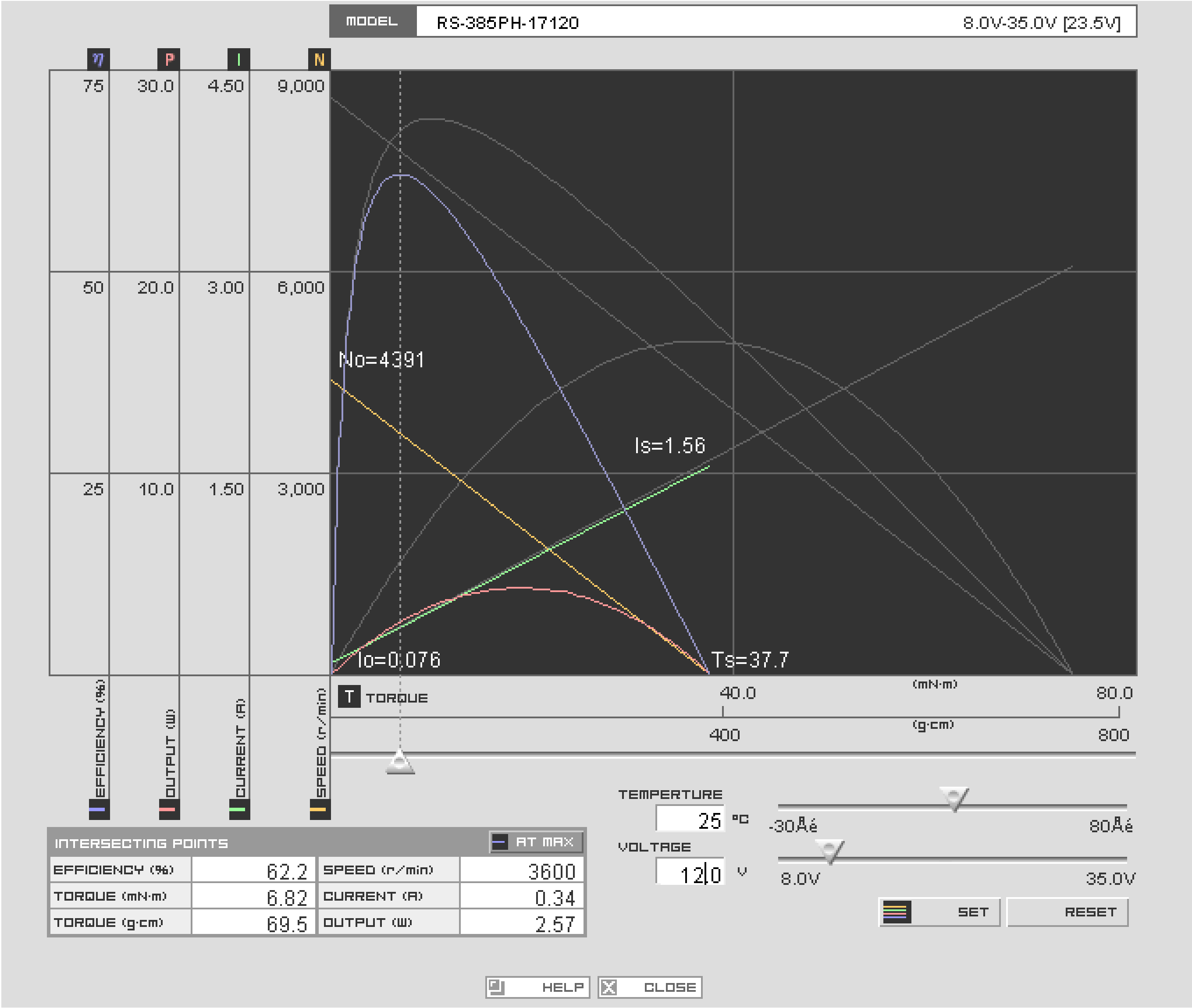
Bill of materials cost analysis.

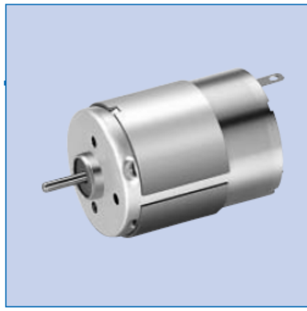
Component	Vendor	Material	Part #	Quantity	Cost/unit	Cost
Big spur gear	SDP	Aluminum	S1086Z-024A066	1	47.42	47.42
Small spur gear	SDP	Aluminum	S1086Z-024A012	1	16.61	16.61
worm gear	SDP	Bronze	S1C86Z-P064B060Q	1	39.84	39.84
worm	SDP	Steel	S1D96Z-P064SQ	1	20.72	20.72
big sprocket	McMaster	Steel	2737T16	1	12.58	12.58
small sprocket	McMaster	Steel	2737T1	1	8.68	8.68
chain	McMaster	Steel	6261K171	1	5.14	5.14
big pulley	SDP	Polycarbonate/Brass insert	A 6T19-682508	1	9.96	9.96
small pulley	SDP	Polycarbonate/Brass insert	A 6T19-232508	1	6.45	6.45
belt	McMaster	Nitrile-Coated Nylon	6082K51	1	15.75	15.75
ball bearings	McMaster	Steel	57155K355	4	6.00	24.00
shafts	Online Metals	Steel	.25" RD CD 1018 48" LG	1	1.67	1.67
Base Material	Online Metals	Al 6061-T651	.25" PL 8"x8"	2	9.93	19.86
Bearing Housing Material	Online Metals	AL 6061-T6511	2.5"X2.5" X 1'LG	1	33.80	33.80
Rod Ends	McMaster	Steel	3798K35	4	6.24	24.96
Impact Resistant Guard	McMaster	Clear Polycarbonate Sheet	12"x12" x .0625 THK	5	4.83	24.15
Leveling Mounts	McMaster	Steel/Plastic	23015T81	2	1.83	3.66
Thumb Screw	McMaster	Steel	91185A507	1	9.57	9.86
Shaft Collars	McMaster	Steel	9414T6	4	0.98	3.92
Display Driver LM3914	Sparkfun	electronics	COM-12694	4	1.95	7.80
LEDs	Sparkfun	electronics	COM-12903	1	2.95	2.95
Protoboard	Sparkfun	electronics	PRT-08811	1	2.95	2.95
Spring Washers	McMaster	Steel	90073A029	4	2.02	8.08
Shaft Couplings (Final)	McMaster	Aluminum	9861T427	2	37.44	74.88
Project Box	Sparkfun	plastic	WIG-0863	1	5.98	5.98
Leather Belt	TJ Maxx	leather	NA	1	10.00	10.00
Motors	All Electronics	metal	DCM-465	2	2.75	5.50
Bearing Housing Bolts	McMaster	Alloy Steel	92220A183	12	9.15	9.15
Motor Bolts	McMaster	Alloy Steel	91290A073	4	8.20	8.20
Thumb Screw Nuts	McMaster	Steel	95479A115	1	5.39	5.39
Thrust Bearing	McMaster	Steel	6655K13	4	2.21	8.84
Shim Stock	McMaster	Plastic	9513K11	1	3.32	3.32
					Total Cost	460.23

Vendor contact information

Vendor	Website	Phone Number	E-Mail
SDP	www.sdp-si.com/estore	1-800-819-1900	SDP-SIsupport@sdp-si.com
McMaster-Carr	www.mcmaster.com	1-562-692-5911	la.sales@mcmaster.com
Online Metals	www.onlinemetals.com	1-800-704-2157	sales@onlinemetals.com
All Electronics	http://www.allelectronics.com	1-888-826-5432	allcorp@allcorp.com

Appendix N: Published Motor Characteristics





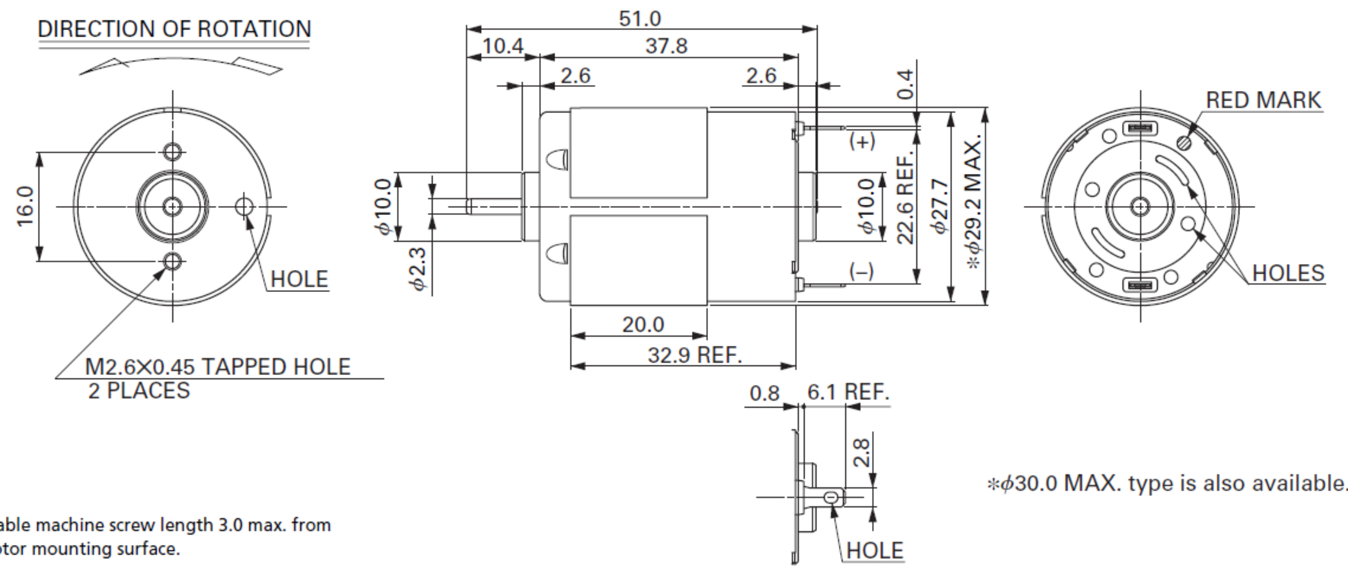
RS-385PH

MABUCHI MOTOR
Carbon-brush motors

OUTPUT : 0.9W~40W (APPROX) WEIGHT : 82g (APPROX)

Typical Applications **Automotive Products :** Automatic Cruise Control / Intake Manifold Control Valve
Home Appliances
Precision Instruments : Printer / Copy Machine / Laser Printer

MODEL		VOLTAGE		NO LOAD		AT MAXIMUM EFFICIENCY					STALL		
		OPERATING RANGE	NOMINAL	SPEED	CURRENT	SPEED	CURRENT	TORQUE		OUTPUT	TORQUE		CURRENT
				r/min	A	r/min	A	mN·m	g·cm	W	mN·m	g·cm	A
RS-385PH-16140	(*1)	12~30	24V CONSTANT	8700	0.070	7420	0.41	8.30	84.6	6.44	56.4	575	2.35
RS-385PH-17120	(*2)	8~35	23.5V CONSTANT	8600	0.076	7430	0.48	10.1	103	7.82	73.8	752	3.05

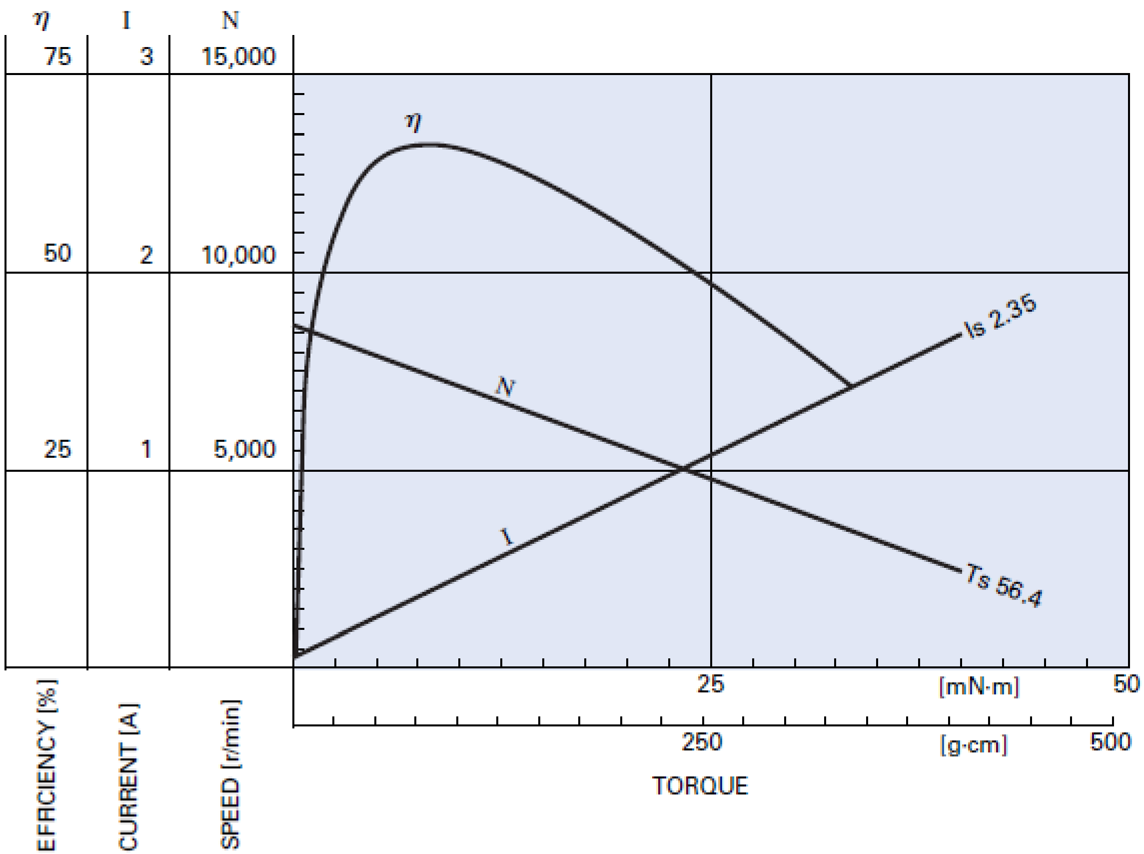


*ϕ30.0 MAX. type is also available.

Usable machine screw length 3.0 max. from motor mounting surface.

UNIT: MILLIMETERS

RS-385PH-16140 24.0V



Appendix O: Example Laboratory Instructions

Objective: Students will learn what different mechanical components (chains, belts, and gears) can do, how they influence each other, and how they influence the system as a whole.

Safety Checklist:

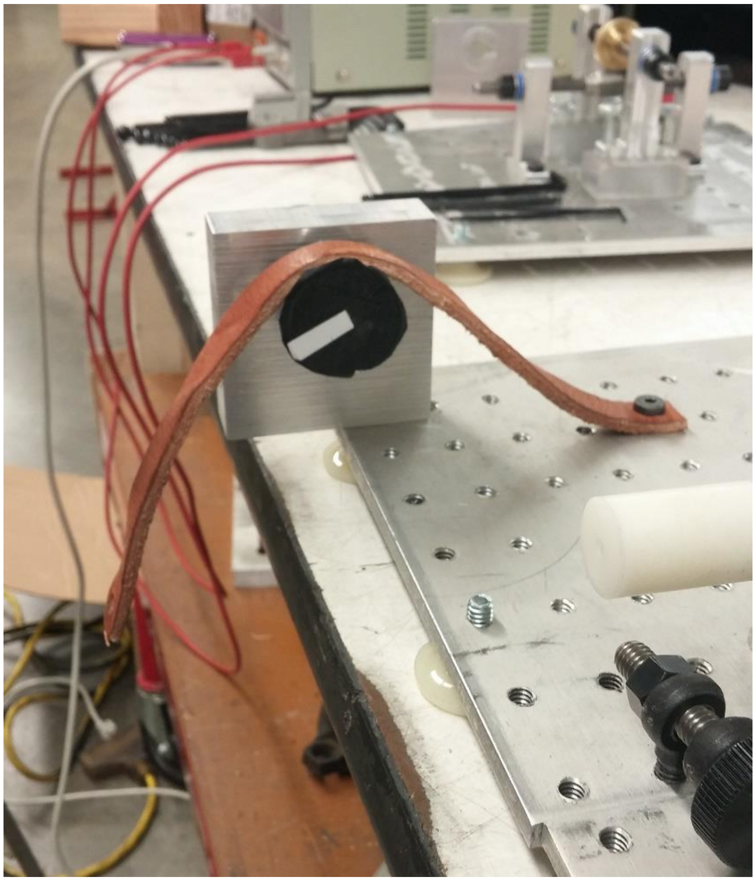
1. Long hair must be pulled back.

2. Long sleeves must be rolled up.

3. Safety glasses must be worn at all times.

4. Turn motor off, and wait until all components stop before rearranging components.

Part 1 - Motor Curve



1. Attach the motor mount to the screw coming out of one of the outer legs.

2. Attach belt to the fifth hole away from the motor mount one row forward as seen in the picture above.

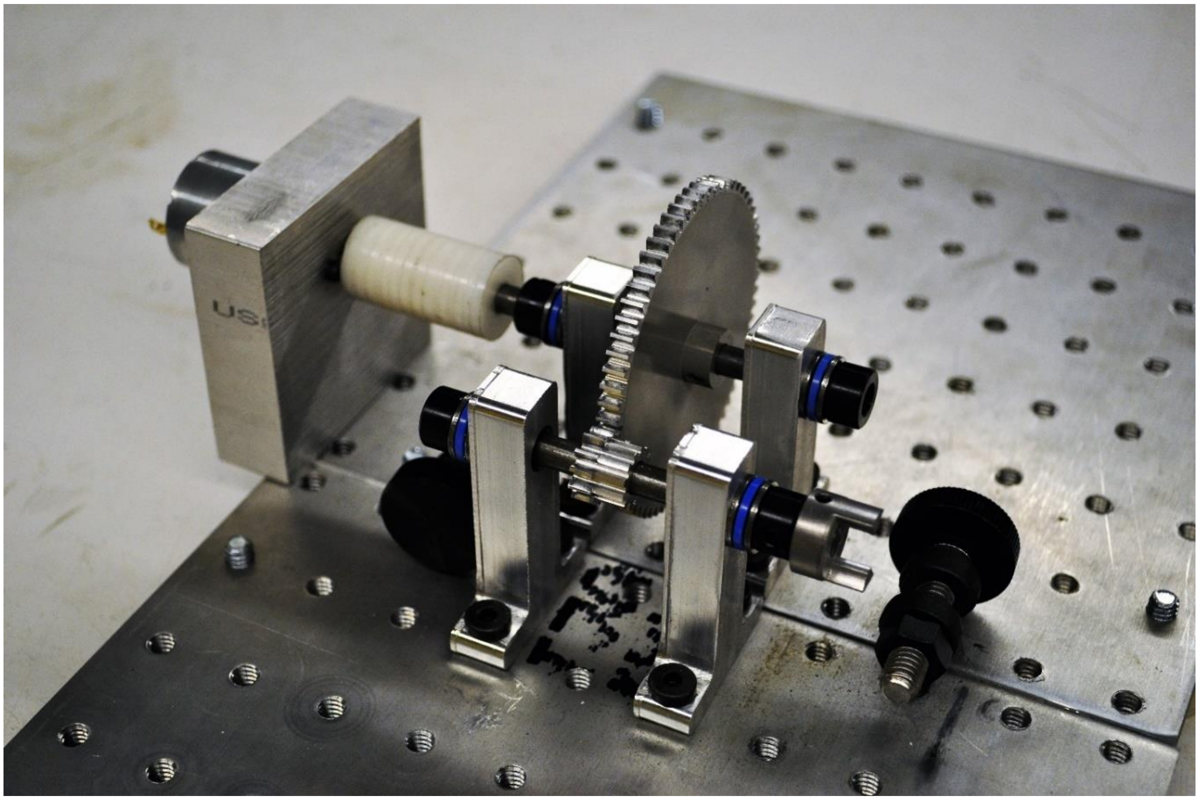
3. Attach testing drum to the motor's shaft.

4. Use the tachometer to measure the no load speed of the motor.

5. Add weights to the belt incrementally collecting data on weight and speed until you reach stall torque.

6. Use this data to develop a motor curve by converting weight to torque and compare to manufacturer's data.

Part 2 - Spur Gear Setup



1. Attach shaft supports using the holes along the edge of the plate with the thumb screws, making sure they are 1 hole apart and perpendicular to the edge of each plate.

2. Slide one shaft through one shaft support, then slide in the pinion.

3. Push shaft through the second shaft support and add the thrust bearing and shaft collar.

4. Tighten the shaft collar set screw and do the same to the other side.

5. Attach the shaft coupling to one side of the shaft.

6. Attach the motor mount to the shaft coupling.

7. Repeat on the other side using the large gear and the generator mount instead of the pinion and motor mount respectively.

8. Using the spacer in between in the middle of the two plates, tighten the thumb screws.

9. Align the gears so they mesh and tighten their set screws.

10. Attach power source to the motor making sure to attach the positive end of the power supply to the terminal of the motor that has a red circle next to it and slowly increase the voltage until the gears start to move.

11. Record the input and output voltages.

12. Now remove the spacer and tighten the plates to perfectly mesh.

13. Again record the input and output voltages.

14. Repeat steps 10 and 11 after over meshing the gears.